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Alpo Ranta-Maunus

Strength of European timber

Part 1. Analysis of growth areas based on existing test results

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Strength of European timber. Part 1. Analysis of growth areas based on existing test results [Eurooppalaisen rakennepuutavaran lujuus. Osa 1. Kasvualueiden vaikutuksen analyysi olemassa olevien testitulosten perusteella]. Ed. by Alpo Ranta-Maunus. Espoo 2009. VTT Publications 706. 105 p. + app. 63 p.

Keywords timber, spruce, Scots pine, Douglas fir, strength, grading, growth area

Abstract

Joint analysis of existing strength data for major commercial European timber species is presented in this report. The work has been carried out as a co-operative venture between 6 research institutes from 6 countries. The main objective of the work was the analysis of growth area issue for European grading standard: in which regions common grading machines settings can be used.

This research is mainly based on laboratory measurements of grade indicating properties: static and dynamic modulus of elasticity, knot area ratio (*KAR*), density, tension and bending strength. Results for thousands of test specimens from Central and Northern Europe are analyzed.

The results indicate that it is reasonable to determine different settings for Central and Northern Europe. In the case of grading spruce for glued laminated timber where tension strength is determined, differences between Central and Northern Europe are small and it may be possible and economically feasible to use the same settings for a large area when advanced grading methods based on measurement of stiffness and knot size related properties are used. When grading Scots pine for bending properties it is obvious that different settings are needed for Germany, France and UK, whereas the Nordic countries may use the same settings.

After the analysis of existing data the project continues with a new experimental programme after which more definitive conclusions can be expected.

Strength of European timber. Part 1. Analysis of growth areas based on existing test results [Eurooppalaisen rakennepuutavaran lujuus. Osa 1. Kasvualueiden vaikutuksen analyysi olemassa olevien testitulosten perusteella]. Toim. Alpo Ranta-Maunus. Espoo 2009. VTT Publications 706. 105 s. + liitt. 63 s.

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Tiivistelmä

Tämä tutkimus perustuu olemassa olevan puun lujuuden testausdatan koordinoituun analysointiin. Työhön osallistui kuusi tutkimuslaitosta Pohjois- ja Keski-Euroopasta. Tutkimuksella pyritään vastaamaan kysymykseen, millä alueilla voidaan käyttää samoja asetusarvoja kuusi- ja mäntysahatavaran ja liimapuulamellien koneellisessa lujuuslajittelussa.

Tutkimuksessa käytetään lähinnä laboratorioissa mitattuja puun lujuuden mallinnuksessa tarvittavia suureita, kuten staattista ja dynaamista kimmokerrointa, oksa-alasuhdetta (*KAR*), tiheyttä ja rikkovissa kokeissa saatuja taivutus- ja vetolujuuden arvoja. Tutkijoilla oli käytettävissä useiden tuhansien koekappaleiden tulokset.

Tulokset vahvistavat käsitystä jonka mukaan Pohjoismaissa ja Keski-Euroopassa kasvaneelle kuuselle on syytä käyttää eri asetusarvoja. Kuitenkin vetolujuuden vaihtelu on vähäisempää kuin taivutuslujuuden, ja yhteisten asetusarvojen määritys liimapuulamelleille voisi olla mahdollista. Männyn ominaisuuksien vaihtelu on suurempaa kuin kuusen, ja on ilmeistä että Iso-Britannia, Ranska ja Saksa tarvitsevat kukin omat asetusarvonsa. Pohjoismaiden kesken vaihtelu on pientä, ja nykyinen käytäntö pohjoismaisesta kasvualueesta on perusteltu.

Tämän olemassa olevien tulosten analysoinnin jälkeen projekti jatkuu uudella koeohjelmalla, minkä jälkeen tulokset tarkentuvat.

Preface

The present report documents research performed in Work Package 2 of the Gradewood-project. Gradewood (Grading of timber for engineered wood products) is a transnational project belonging to the WoodWisdom-net programme. The project is funded by several national funding organizations and industries. Gradewood-project was started as an initiative of European wood industries (Building With Wood). The project is lead by a Steering Committee (chair Raimund Mauriz, Doka) and the management of work is lead by a Project Management Group (chair Mattias Brännström, Stora Enso Timber). This analysis of existing data was made by close co-operation of several individuals and research institutes. The roles of participating persons were as follows:

Alpo Ranta-Maunus, VTT Finland
Co-ordination of the analysis of existing data, combination of the results and main author of this report

Mikael Fonselius, VTT Finland
Analysis of Finnish data and it's description in this report

Rune Ziethén, SP Sweden
Analysis of Swedish data and it's description in this report

Chris Holland, BRE UK
Analysis of UK data and it's description in this report. Checking of language

Peter Stapel, Technical University of Munich, Germany
Analysis of German data and it's description in this report

Didier Reuling, FCBA France
Analysis of French data and it's description in this report

Goran Turk, University of Ljubljana, Slovenia
Analysis of Slovenian data and it's description in this report
Derivation of joint European regression equations.

The authors

Contents

List of symbols

COV	Coefficient of variation
E	modulus of elasticity
E_{dyn}	dynamic modulus of elasticity in longitudinal vibration
f_m	bending strength
$f_{m,adj}$	bending strength adjusted to reference size
f_t	tension strength
$f_{t,adj}$	tension strength adjusted to reference size
$f_{0,05}$	best estimate of lower five percent fractile of strength
$f_{0,05,lower}$	lower 90% confidence limit of lower five percent fractile of strength
$f_{0,05,upper}$	upper 90% confidence limit of lower five percent fractile of strength
h	height or width of timber (larger of cross-section dimensions)
KAR	total knot area ratio
r^2	coefficient of determination
ρ	density

1. Introduction

1.1 European standard EN14081

European standard EN14081-1...4 (CEN 2005) specifies conditions for CE-marking of strength graded structural timber. Grading can be based on visual or machine strength grading, and there are two alternative systems for control of machine grading: “machine control” and “output control” methods. “Machine control” method is commonly used and it is based on settings determined for each growth area according to the standard and published in standard EN14081-4. Standard defines that growth area is one country, unless there is experimental evidence that more countries can belong to the same growth area. Today the same settings can be used for timber grown in the Nordic region based on several grading machines. Germany and Austria are considered to form a joint growth area.

The present situation is problematical for Central Europe where there are many countries that might have similar growth conditions, but experimental data does not exist. After the analysis of existing data, which is the topic of this publication, this project will produce new test data for further information on growth area issue.

1.2 Industrial background

In principle, the system now requires different machine settings depending on the “nationality” of the logs, which is a geo-political construct, and not according to the biologically relevant growth conditions (growth areas). To obtain new settings for all countries is very expensive, because it requires extensive testing. Because certain (historically based) customary practises exist for acceptance of timber graded by the old system of visual grading, it is easier (especially for SME’s) to keep the old visual system, rather than to start acquiring new machine settings, even if the old manual visual system is less accurate, more laborious and much slower than machine grading. Also, it may prohibit progress in other aspects of the sawmilling process.

Furthermore, the grading equipment developers / manufacturers are small companies and do not have sufficient resources alone to develop the methods. This is the second reason for the slow take-up of technologies with regard to machine grading. For example, the acceptance of a new machine requires the testing of at least some 1 000 pieces of timber.

Machine strength grading offers economic benefits to wood producers in the form of better yield(s) for higher grades and consequently better competitiveness for timber as a structural material, as well as improving the efficiency of the production process. Unfortunately, machine strength grading has not yet been properly utilized in many countries and most wood industries are not familiar with the opportunities it offers.

Many new machine technologies, which are already available to the wood industry would offer great opportunities to optimize the use of raw material and to produce more competitive products for the construction market, as well as enhance the production process. For example, if sufficient scientific knowledge was available for the prediction of strength based on digital image analysis of boards, automated visual machine methods that are already in use for appearance grading of wood products could be extended to strength grading. In addition, other machine strength grading methods that are available, are suitable for application in the sawmilling process and also have the potential to be further developed. Unified grading practices would facilitate the development of efficient methods because the return on investment would be sufficient.

A breakthrough in technology and processing is needed to form an economic platform for SMEs and for the whole industrial sector to take full advantage of the raw material properties through strength grading. This project is aimed at addressing these kinds of developments on a pan-European level. Developers and manufacturers of NDT equipment are involved in this project so that settings for many machines using different measurement techniques can be obtained from the same sample of timber. At the same time, a harmonised data bank will serve as a test bench of grading equipment and as the basis of checking of strength values of European timber in the standard EN338.

1.3 Objective of this research

This research aims to test the borders of growth areas where the same settings for grading machines can be used.

The work to be published here is based on a joint analysis of existing laboratory test data. New experimental research will follow to supplement the identified areas where data is lacking.

This research includes European spruce, Scots pine, Douglas fir and Sitka spruce. Main emphasis is on results obtained from tests performed in several countries.

Project participants have in total 15 000 bending test results of spruce from several countries (more than 1 000 from Finland, Sweden, Russia, Germany, and France). Density and modulus of elasticity has been measured in all cases according to EN408 (CEN 2003b). As it is known that stiffness and knots combined with stiffness are the main strength indicating properties, project analyses dependences between strength, static and dynamic modulus of elasticity, knot area ratio (*KAR*) and density. All this information is available for 3 000 bending and tension specimens of spruce, and for bending tests of pine, mainly from Germany and Finland. For other species and for tension of pine much more limited data is available.

Observed variation of measured timber properties is a mixture of real difference of properties and statistical variation which is further mixed with not representative sampling. Especially small sample size leads easily to poor representation of the sample. One objective of the work is to study the effect of sample size to the results.

2. Materials

2.1 VTT data

The VTT data base available in this project consists of both spruce (*Picea abies*) and pine (*Pinus sylvestris*). The spruce was grown in Finland, Estonia, Latvia and Russia while the pine was grown in Finland, Latvia and Russia. The timber has been sampled and tested in different projects of which only some are in the public domain (Hanhijärvi et al 2005, 2008). However, the industry owns data that is not in the public domain but gave VTT the permission to include this data in this analysis. All the timber was sampled and tested between 1995 and 2008.

2.1.1 Spruce

The spruce (*Picea abies*) grown in Finland was split into three growth areas. The growth areas are west, east and south-east Finland (Fig. 1). No timber has been sampled from north and south-west Finland. Timber from these two areas are not commonly strength graded but used for other purposes. Spruce grown in Estonia and Latvia were not split into growth areas less than the country itself. Finally, spruce grown in Russia represented four growth areas. The growth areas were in Karelia, Novgorod, Vologda and Onega, all in North-Western Russia. These four growth areas have been selected since they represent the areas from which timber are exported to Finland. The number of sub-samples within a growth area is given in Table 1 for bending data and in Table 3 for tension data. Furthermore, the number of timber pieces available for analysis related to bending or tension strength, static modulus of elasticity, density, dynamic modulus of elasticity and knot area ratio is given in the same tables.

The mean and coefficient of variation values for bending strength, static modulus of elasticity, density, dynamic modulus of elasticity and knot area ratio are given in Table 2. It should be noted that the static and dynamic modulus of elasticity are given for different sample sizes and can therefore not directly be compared. The average of static modulus of elasticity of the same 1 380 Finnish timber pieces for which the dynamic value of 12 500 N/mm^2 is given is 11 700 N/mm^2 in stead of 12 000 N/mm^2 given in Table 2.

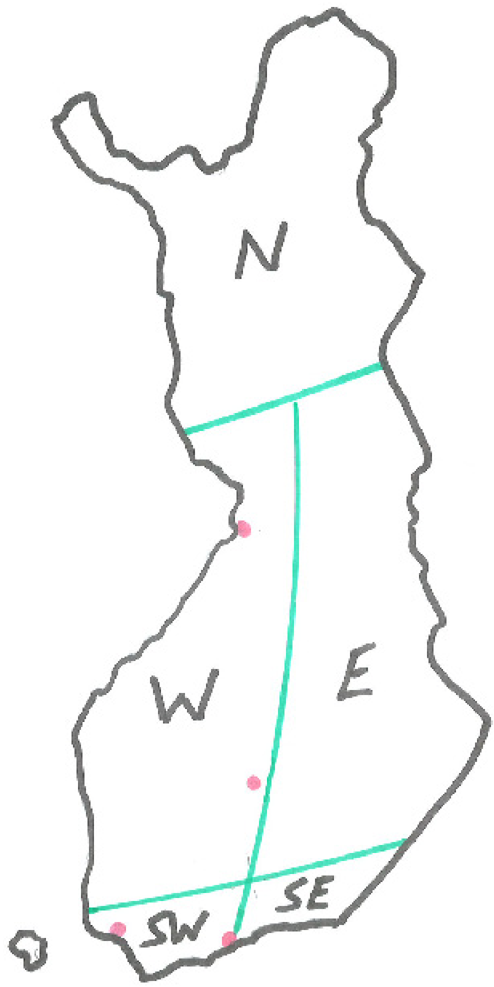

Figure 1. Growth areas in Finland. The cities Helsinki, Turku, Jyväskylä and Oulu are marked as reference.

The average and coefficient of variation values for tension strength, mechanical modulus of elasticity, density, dynamic modulus of elasticity and knot area ratio are given in Table 4.

Table 1. Growth areas and number of specimens available for spruce in bending.

Country and growth region	Number of sub-samples	Number of timber pieces for analysis of				
		f_m	E	ρ	E_{dyn}	KAR
Finland-All	16	2 846	2 846	2 846	1 380	1 214
Finland-West	7	906	906	906	179	360
Finland-East	6	1 164	1 164	1 164	871	660
Finland-Southeast	2	625	625	625	330	194
Finland-Unknown	1	151	151	151	0	0
Estonia-All	4	535	535	535	235	0
Latvia-All	3	300	300	300	0	0
Russia-All	7	1 031	1 031	1 031	579	368
Russia-Karelia	3	362	362	362	226	183
Russia-Vologda	2	323	323	323	186	185
Russia-Novgorod	1	167	167	167	167	0
Russia-Onega	1	179	179	179	0	0

Table 2. Characteristics for spruce in bending. The number of timber pieces is given in Table 1.

Country and growth region	f_m		E		ρ		E_{dyn}		KAR	
	Mean	Cov	Mean	Cov	Mean	Cov	Mean	Cov	Mean	Cov
Finland-All	44.1	0.264	12 000	0.209	449	0.093	12 500	0.170	0.177	0.515
Finland-West	43.8	0.267	12 200	0.205	442	0.093	12 700	0.148	0.183	0.487
Finland-East	44.2	0.264	11 800	0.217	440	0.096	12 300	0.178	0.171	0.521
Finland-Southeast	43.9	0.262	12 300	0.204	438	0.087	12 800	0.155	0.184	0.541
Finland-Unknown	45.0	0.258	11 700	0.177	430	0.084	-	-	-	-
Estonia-All	43.5	0.278	12 700	0.202	434	0.087	12 300	0.173	-	-
Latvia-All	42.6	0.250	12 300	0.204	440	0.094	-	-	-	-
Russia-All	42.4	0.283	11 500	0.216	427	0.100	12 000	0.174	0.179	0.541
Russia-Karelia	41.0	0.291	11 100	0.233	424	0.105	11 800	0.178	0.192	0.559
Russia-Vologda	43.2	0.228	11 900	0.178	430	0.092	12 800	0.137	0.166	0.502
Russia-Novgorod	37.9	0.348	10 800	0.257	418	0.102	11 500	0.190	-	-
Russia-Onega	47.8	0.255	12 100	0.189	434	0.098	-	-	-	-

Table 3. Growth areas and number of specimens available for spruce in tension.

Country and growth region	Number of sub-samples	Number of timber pieces for analysis of f_t	E	ρ	E_{dyn}	KAR
Finland-All	5	611	611	611	270	246
Finland-West	2	278	278	278	87	83
Finland-East	3	333	333	333	183	163
Russia-All	2	186	186	186	186	172
Russia-Karelia	1	98	98	98	98	91
Russia-Vologda	1	88	88	88	88	81

Table 4. Characteristics for spruce in tension. The number of timber pieces is given in Table 3.

Country and growth region	f_t		E		ρ		E_{dyn}		KAR	
	Mean	Cov	Mean	Cov	Mean	Cov	Mean	Cov	Mean	Cov
Finland-All	31.9	0.343	11 800	0.185	445	0.099	12 500	0.173	0.208	0.473
Finland-West	31.4	0.335	12 200	0.176	446	0.106	12 700	0.135	0.211	0.436
Finland-East	32.3	0.349	11 500	0.189	444	0.093	12 400	0.189	0.206	0.493
Russia-All	33.7	0.290	11 900	0.166	429	0.106	12 500	0.164	0.172	0.460
Russia-Karelia	32.2	0.305	11 500	0.181	426	0.112	12 000	0.180	0.180	0.424
Russia-Vologda	35.3	0.269	12 400	0.141	433	0.098	13 000	0.139	0.163	0.501

2.1.2 Pine

The pine (*Pinus sylvestris*) grown in Finland was split into two growth areas. The growth areas are west and east Finland (Fig. 1). No timber has been sampled from south-west, south-east and north Finland. Pine grown in Latvia was not split into growth areas. Finally, spruce grown in Russia represented two growth areas. The growth areas were in Novgorod and Vologda, both in North-Western Russia. The number of sub-samples within a growth area is given in Table 5 for bending. For tension no data was available. Furthermore, the number of timber pieces available for analysis related to bending strength, static modulus of elasticity, density, dynamic modulus of elasticity and knot area ratio is given.

The mean and coefficient of variation values for bending strength, static modulus of elasticity, density, dynamic modulus of elasticity and knot area ratio are given in Table 6. As for spruce it is to be noted that the static and dynamic modulus of elasticity are given for different sample sizes and can therefore not directly be compared. The average of static modulus of elasticity of the same 662 Finnish timber pieces for which the dynamic value of 12 100 N/mm^2 is given is 11 600 N/mm^2 in stead of 11 900 N/mm^2.

Table 5. Growth areas and number of specimens available for pine in bending.

Country and growth region	Number of sub-samples	Number of timber pieces for analysis of				
		f_m	E	ρ	E_{dyn}	KAR
Finland-All	5	849	849	849	662	834
Finland-West	2	368	368	368	181	364
Finland-East	3	481	481	481	481	470
Latvia-All	1	100	100	100	0	0
Russia-All	2	379	379	379	379	368
Russia-Vologda	1	192	192	192	192	186
Russia-Novgorod	1	187	187	187	187	182

Table 6. Characteristics for pine in bending. The number of timber pieces is given in Table 5.

Country and growth region	f_m		E		ρ		E_{dyn}		KAR	
	Mean	Cov	Mean	Cov	Mean	Cov	Mean	Cov	Mean	Cov
Finland-All	44.9	0.309	11 900	0.239	493	0.114	12 100	0.191	0.190	0.648
Finland-West	45.8	0.306	12 100	0.232	500	0.115	12 000	0.168	0.188	0.689
Finland-East	44.2	0.312	11 700	0.244	488	0.112	12 200	0.200	0.192	0.616
Latvia-All	41.8	0.257	12 200	0.226	486	0.099	-	-	-	-
Russia-All	32.5	0.344	9 200	0.256	438	0.102	9 900	0.192	0.264	0.446
Russia-Vologda	33.6	0.337	9 200	0.258	436	0.104	9 900	0.200	0.244	0.477
Russia-Novgorod	31.3	0.348	9 200	0.254	440	0.099	9 900	0.184	0.284	0.408

2.2 SP data

Material for the analysis of Swedish timber has been sampled from a number of prior research projects. All the samples are taken from saw falling populations without any pre-grading. Visual rejects due to shape (twist, warp or bow) or length are for some of the samples excluded from the results.

The samples represent a period of time of 15 to 20 years. Test results are obtained according to relevant standards and adjusted according to EN 384. In Tables 8 and 9 for spruce have the samples been subdivided into four areas within Sweden. The areas are separated from south to north with the Northern growth area, which basically covers half of Sweden divided into a coastal area and an inland area covering timber sourced over a distance of wood with a distance more than approximately 70 km from the coast (Fig. 2).

The sub-division is made to make it possible to analyse and compare larger future growth area with the today minimum accepted growth area, one country.

There are too few pine samples to make it reasonable to use the sub areas. Sample information is given in Table 7.

Table 7. List of samples for bending tests of pine.

Growth area	Pieces in sample	Dimensions
Central Sweden	198	45 x 140
Samples from all over Sweden	191	45 x 145

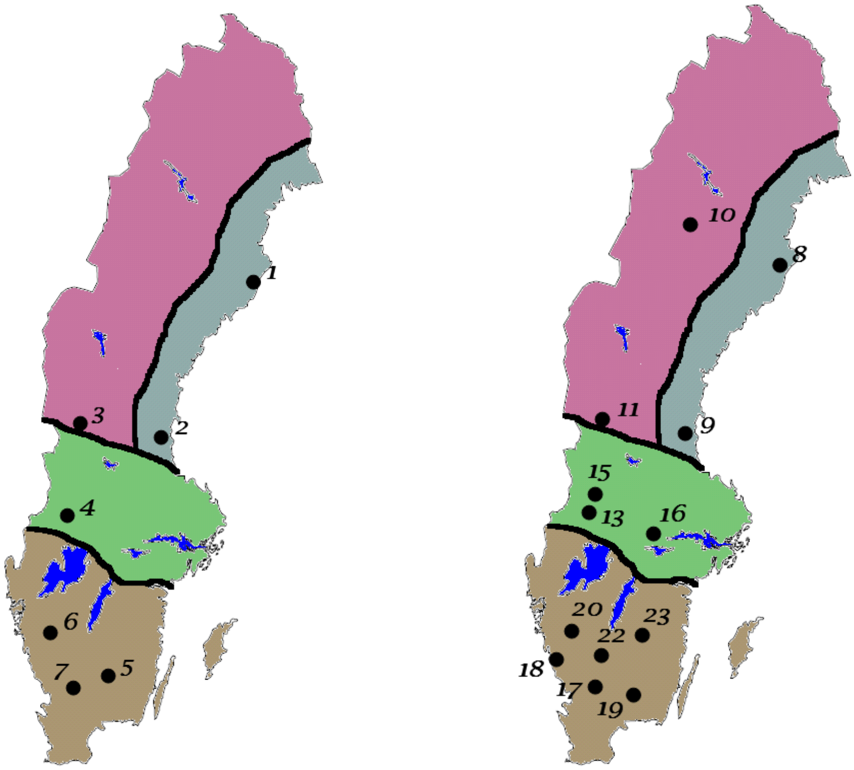

Figure 2. Division of Sweden to four regions: North inland (pink, noted in results by SWE Nin), North coastal (grey, SWE NCo), Central (green, SWE C), South (brown, SWE S) and location of sampling by number (tension left, bending right).

Table 8. List of samples for tension tests of spruce.

Sample number	Growth area	Region	Pieces in sample	Dimensions
1	Coastal Västerbotten	North coastal	203	40 x 95, 40 x 145, 40 x 195
2	Coastal Hälsingland	North coastal	78	45 x 145
3	Inland, Dalarna	North inland	151	40 x 145
4	Värmland	Central	139	40 x 145
5	Småländska höglandet, Sweden	South	211	40 x 95, 40 x 145, 40 x 195
6	Västergötland Sweden	South	49	34 x 145
7	Western Småland	South	74	45 x 145

For the analysis small samples within a region are combined, and results are given for North costal (SWE NCo), North inland (SWE NIn), Central (SWE C) and South Sweden (SWE S) and also combined for the country. Basic statistics of the properties of ungraded timber is shown in Table 10.

Table 9. List of samples for bending tests of spruce.

Sample number	Growth area	Region	Pieces in sample	Dimensions
8	Coastal Västerbotten	North coastal	142	45 x 145
9	Coastal Hälsingland	North coastal	79	45 x 145
10	Southern Lappland	North inland	40	45 x 145
11	Central Dalarna	North inland	40	45 x 145
12	Northern Sweden *)	North inland	152	45 x 145
13	Värmland Sweden	Central	132	58 x 120, 34 x 145
14	Central Sweden *)	Central	673	45 x 70, 34 x 70, 34 x 170, 45 x 190
15	Värmland Sweden	Central	268	34 x 100, 44 x 125, 44 x 175, 50 x 150, 50 x 200
16	Central Sweden (Bergslagen)	Central	182	45 x 145
17	South Western Småland	South	191	40 x 145, 45 x 145
18	Coastal Halland (south west coast)	South	40	45 x 145
19	Southern Småland	South	41	45 x 145
20	Västergötland Sweden	South	178	45 x 120
21	Southern Sweden *)	South	616	45 x 145, 60 x 195, 70 x 220
22	Western Småland	South	828	45 x 145
23	North West Småland	South	202	47 x 75, 47 x 278, 75 x 255
24	Sweden *)		589	34 x 145, 45 x 145, 34 x 95, 45 x 195, 70 x 220

*) Sample is not marked on the map. The growth area given is too wide

Table 10. Averages and COV of strength of Swedish spruce per region, samples used for Model 1.

Region	**Bending**		**Tension**	
	f_m **[N/mm²]**	***COV*[%]**	f_t **[N/mm²]**	***COV* [%]**
SWE NCo	47.0	26.9	33.4	32.3
SWE Nin	45.6	27.8	31.6	31.5
SWE C	45.8	30.2	30.9	35.4
SWE S	43.7	29.8	32.0	32.2
All Sweden	44.8	29.8	32.2	32.7

2.3 BRE data

For all three of the species used in this project the data was collected from the testing carried out at BRE during the pre-harmonisation period of British Standard methods of structural testing and European Standard methods. Therefore, it was possible to provide data based on the testing methods that were finally adopted for EN 408. At this time a large number of UK species were tested in preparedness for the proposed harmonisation of European structural codes in 1995.

Scots pine is the only species that is native to the UK with Sitka spruce and Douglas fir being introduced from the North American Continent in the 18th and 19th centuries. Like many introduced species the material that results from these introduced species shows differences in properties when compared to material derived from the native source.

2.3.1 Sitka spruce

This is by far the most commercially important softwood species grown in the UK and accounts for around 60% of all UK grown structural material. Although grown to varying extents throughout the UK the main growth regions for structural applications are Scotland and Wales. Most plantations are in the more hilly areas of these countries were the soil is predominately too poor for other species. However, extensive plantations have been developed in the past 30 years on the English/Scottish boarder around Kilder reservoir (Northumberland); this currently produces some of the better quality material. Northern Ireland produces Sitka spruce that is machine graded within the province but sawmills in the area also draw in Sitka spruce grown within the Republic of Ireland, this material usually has a higher rate of growth than the rest of the UK. Being predominantly a hill crop the material is prone to reaction wood which can result in post processing distortion.

For structural application UK grown Sitka spruce is graded to predominantly C16, returning yields of 90 to 95% of sawn material. For higher grades the potential is limited by a combination of relatively low stiffness and density.

Table 11. Geographical location, dimensions and sample sizes of Sitka spruce.

Geographical location	Sample size	Dimensions (mm)
Scotland		
Scottish Highlands	299	35 x 120
Scotland (West)	196	47 x 228 & 73 x 154
Scotland (Mid West)	281	50 x 100
Scotland (Forest of Ae)	296	50 x 100
Scotland (mixed)	800	47 x 97
Wales		
Wales (North)	97	72 x 254
Wales (Mid)	369	50 x 100 & 47 x 97

Material used in the project

Table 11 gives the breakdown of the Sitka spruce sample in terms of geographical location, dimensions and sample sizes. The geographical distribution is shown in Fig. 3.

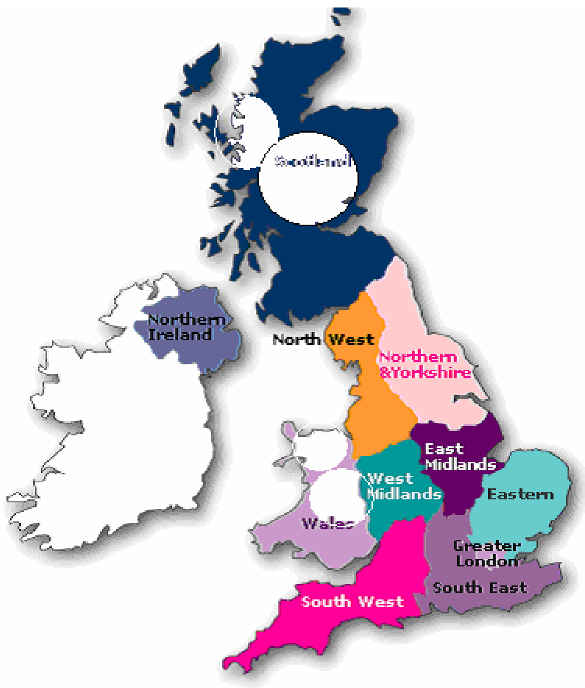

Figure 3. Geographical location of the Sitka spruce data sets.

2.3.2 Scots Pine

Scots pine is grown across the UK but the main timber production areas for structural use are primarily the Scottish highlands, with a smaller growth area in England from Thetford Forest. Though the geography of these two regions vary greatly the major difference in quality arises from the ownership of the resource. The ownership is split between the public sector and the private, the public sector encompasses the Forestry Commission, whilst the private sector constitutes a large number of private estates with forestry as one of the main income streams. In general the higher quality material is drawn from the private estates as they maintain higher forest practices than the public sector and these practices are reflected in the quality of the timber and this tends to override variation due to geographical distribution.

Like Sitka spruce Scots pine is primarily machine graded to C16 with a little C16/ C24, Graded C16 / reject the yield is around the 95% region.

Scots pine accounts for approximately 20% of UK grown timber for structural use though usually results in slightly lower structural performance, in terms of strength class attribution, than redwood drawn from Northern Europe. It is a seasonal felled timber, winter felling, as felling the summer usually results is blue staining of the sapwood.

Material used in this project

Table 12 gives the breakdown of the Scots pine sample in terms of geographical location, dimensions and sample sizes and Fig. 4 illustrates the locations of sampling.

Table 12. Geographical location, sample size and dimensions of the Scots pine data.

Geographical location	Sample size	Dimensions (mm)
Scotland		
Scottish Highland	442	48 x 192, 46 x 148, 38 x 147, 38 x 97
England		
Southeast England	351	47 x 147, 38 x 97

Figure 4. Geographical location of the Scots pine data sets.

2.3.3 Douglas fir

Douglas fir is grown in all parts of the UK but in only limited qualities, though grown throughout Scotland where it makes impressive trees it does tend to suffer from frost damage to the main leaders during the early periods of growth in the spring resulting in split leaders and poor tree form. It is grown in Wales in lower laying situations than Sitka spruce but grows particularly well in the Southwest of England, where growth is not checked by frost damage. However, material grown in England tends to be faster grown than in other areas of the UK, though it does show a good distribution of latewood within the wide growth rings.

As a structural timber it accounts for around 5% of UK grown softwoods, and is currently considered not to be meeting its full potential as a species. It is one of the few UK grown timbers that can produce large clear bulks of timber suitable for heavy structural and marine work. The high modulus of elasticity for the strength of the UK material is resulting in growing interest for glulam production.

No current machine settings exist for the EN338 strength classes (CEN 2003a) for UK grown Douglas fir though BS5268 machine settings do.

Material used in this project

Table 13 gives the breakdown of the Douglas fir sample in terms of geographical location, dimensions and sample sizes and Fig. 5 illustrates the locations.

Table 13. Geographical location, sample size and dimensions of the Douglas fir data.

Geographical location	Sample size	Dimensions (mm)
Central Scotland and Highlands	230	47 x 100
Southwest England	363	47 x 170, 47 x 97
Mid Wales	206	38 x 100

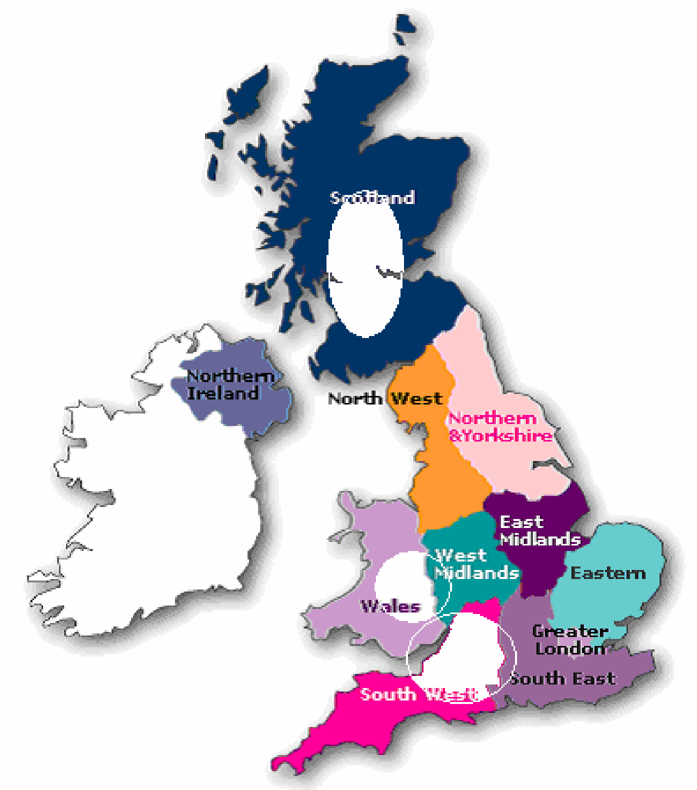

Figure 5. Geographical location of the Douglas fir data sets.

2.4 TUM data

More than 9 000 datasets of bending and tension tests taken from the database of Holzforschung München have been used. The laboratory measurements on Norway spruce, Scots pine, Douglas fir and Sitka spruce were done between the years 1996 and 2008. Although the major part of the tested timber originates from Germany, timber from the United Kingdom, Austria, Czech Republic, Poland and Estonia was also available. Additional to the mechanical properties, most datasets included dynamic modulus of elasticity and knot values.

2.4.1 Norway spruce

The lion's share of the available data is made up from bending und tensile tests of Norway spruce. In order to get reliable information, especially on the characteristic strength, big sub-samples were formed. Table 14 shows the mean values for the bending strength, the modulus of elasticity and density as well as corresponding coefficients of variation for the three regions from TUM. The sub-samples "north" and "east" consist of timber from Germany only, while the sub-sample "west" also includes timber from Austria and the Czech Republic. For the static E models used in the analyses, 3 538 data values were considered, the dynamic modulus of elasticity and knot values were available for 1 920 test specimens.

Table 14. Averages and COV of strength, modulus of elasticity and density of spruce (bending) from TUM per region for models without dynamic MOE and knots.

Region	n	f_{mean}	COV	E_{mean}	COV	ρ_{mean}	COV
	[-]	[N/mm²]	[%]	[N/mm²]	[%]	kg/m³	[%]
north	456	36.4	37.0	11 200	29.2	449.0	13.0
west	1 437	42.6	32.0	12 400	24.9	436.8	10.6
east	1 645	42	34.1	12 200	24.9	441.0	10.5

2 678 datasets for tension tests have been included in the analysis. Dynamic modulus of elasticity and knot values were available for all datasets. The datasets were split up into 5 sub-samples. The sub-samples Schwaben and Fügen only contains timber from south Germany. The sub-samples Czech Republic (CZ) and Austria (AT) consist of timber from the according countries, while the biggest sub-sample "unknown" is mainly based on German timber for which the exact growth region is unknown. In Table 15 the mean values for the sub-samples are shown.

Table 15. Averages and COV of strength, modulus of elasticity and density of spruce (tension) from TUM per region.

Region	***n***	f_{mean}	***COV***	E_{mean}	***COV***	ρ_{mean}	***COV***
	[-]	**[N/mm²]**	**[%]**	**[N/mm²]**	**[%]**	**kg/m³**	**[%]**
Schwaben	588	32.6	37.4	12 100	20.5	451	10.7
Fügen-DE	517	29.7	44.1	11 100	24.9	442	12.9
AT	311	25.1	41.8	10 100	25.6	435	12.0
CZ	373	28.8	40.3	11 000	23.8	440	12.7
Unknown	889	29.3	35.8	11 200	21.7	453	10.4

2.4.2 Scots pine

Scots pine data was available from tension as well as from bending tests. In each case two growth areas were defined. The bending results were separated for timber from north and south Germany, the tension results for timber from Germany and from Poland. Table 16 shows the mean values for the results of pine in bending. Results for pine in tension (1 072 specimens) are not shown, because they are not analyzed in this study due to the lack of results in the other parts of Europe.

Table 16. Mean values and COV of strength, modulus of elasticity and density of pine (bending) from Germany per region.

Region	***n***	f_{mean}	***COV***	E_{mean}	***COV***	ρ_{mean}	***COV***
	[-]	**[N/mm²]**	**[%]**	**[N/mm²]**	**[%]**	**kg/m³**	**[%]**
north	421	38.6	31.2	12 200	21.4	522	11.8
south	429	36.7	23.4	11 400	23.4	498	9.9

2.4.3 Douglas fir and Sitka spruce

For the development of the European regression models for Douglas fir and Sitka spruce, test results from 630 Douglas fir specimens from Germany and 900 Sitka spruce specimens from the United Kingdom have been used. For Sitka spruce all 900 data sets are available for the calculation of models including the dynamic modulus of elasticity. For 265 Douglas fir data sets the eigenfrequency was not available.

2.5 FCBA data

2.5.1 Spruce

The national resources for spruce in France are estimated at 629 000 ha for an approximate volume of 190 million m³, i.e. 21% of coniferous timber in France. Ownership of forest is shown in Table 17. Spruce is found in 74 French departments, but 4 areas have three quarters of it both in terms of surface area and timber volume as shown in Table 18.

110 stands were selected and 565 trees sampled in 29 forest subdivisions defined by IFN (IFN 2004). Each tree was sawn into lumber pieces Each tree was converted into structural timber. The different timber pieces were identified to know what tree they came from. To be representative of spruce resource, the stands and trees were selected according to:

1. Geographical distribution: sample taken within 29 forest subdivisions in 10 administrative areas
2. Altitude (from 200 to 1 700 m)
3. Forest density
4. Classes of growth : a high and a low class
5. DBH: from 0.35 to 0.80 m.

Table 17. Structure of French spruce forest ownership (source IFN 2007).

Ownership	Area (%)	Volume (%)
State and Common land forest	39	38
Private forest	61	62
Total	100	100

Table 18. National volume distribution in France (source IFN 1999 proportional update to 2007).

Administrative areas	Forest volume	
	M m³	%
Rhône Alpes	65	34
Franche Comté	30	16
Lorraine	29	15
Alsace	18	10
Auvergne	13	7
Champagne Ardennes	12	6
Limousin	8	4
Bourgogne	7	4
Midi Pyrénées	4	2
Languedoc Roussillon	2	1
Other	2	1
Total	190	100

The mature resource for spruce has narrow annual growth rings. Its summer wood (Latewood) percentage (16%) is low compared to other resinous species such as larch (37%) or Douglas fir (38%). Anatomical and morphological properties of the sample are given in Table 19.

Table 19. Anatomical and morphological properties of the sample.

565 trees	**Average**	**COV**	**Min**	**Max**
Age (year)	86	49%	27	239
DBH (m)	0.36	31%	0.19	0.65
Summer wood (%)	16	33%	5	35
Annual growth ring (mm)	2.9	48%	0.8	9.0

For determination of physical and mechanical properties there are two origins of information:

- One is the results which come from 565 trees. 18 stands. 3 cross section (40*100; 50*150; 65*200 mm) with 1 820 results of edgewise four point bending tests and 109 results of tensile tests.
- One is a complement of data for two French areas (Lorraine and Rhône Alpes) with 6 cross section (50*150; 80*200 ; 80*250; 120*250 and 120*250 mm)
- 643 pieces were used for E_{dyn} based models 2 (a part of areas Rhône Alpes and Lorraine); 1 740 pieces were used for models with *E* and density and 1 647 pieces for *KAR* (all the areas).

Sample sizes from different areas are given in Table 20 and mechanical properties in Table 21.

Table 20. Number of pieces for bending test in the different sub-samples.

Administrative areas	**Total sample tested**	
	Number	**%**
Rhône Alpes	839	35
Franche Comté	325	14
Lorraine	532	22
Alsace	101	4
Auvergne	169	7
Champagne Ardenne	79	3
Limousin	146	6
Bourgogne	87	4
Midi Pyrénées	47	2
Languedoc Roussillon	58	2
Total	2 383	100

Table 21. Mechanical values for bending test material.

	Average	COV	Min.	Max.	N
Density to 12% (kg/m^3)	448	10%	304	797	2 383
KAR (%)	22.5	57%	0	71	1 647
Annual growth ring (mm)	3.1	48%	0.6	8.9	1 647
E_{ml} 12% (MPa)	11 800	27%	3 000	26 000	2 383
f_m (MPa)	41.0	34%	5.0	83.5	2 383

When compared to values for the strength class C30 the following conclusions can be made related to potential yields:

- Modulus of elasticity (E_{ml} at 12% MC) 45% of timber pieces > 12 GPa
- Modulus of rupture (f_{m}) 76% of timber pieces > 30 MPa
- Density (adjusted to 12% MC) 95% of timber pieces > 380 kg/m^3.

2.5.2 Scots Pine

The national resources of Scots pine in France are estimated at 906 000 ha for an approximate volume of 143 million m^3, i.e. 16% of the coniferous woodland in France. These resources are distributed by the nature of the of ownership as given in Table 22. Thus, as whole of the French forest, we can note that most of Scots pine forest is a private forest. Although Scots pine is found in 41 French departments, and 4 areas have 75% of the total surface area and three quarters of the production (Table 23).

Table 22. Structure of French Spruce forest ownership (source IFN 2007).

Ownership	Area (%)	Volume (%)
State and Common land forest	22	28
Private forest	78	72
Total	100	100

Table 23. National volume distribution in France (source IFN 1999 proportional update to 2007).

Administrative areas	**Forest volume**	
	in M m³	**%**
Auvergne	24	17
Provence Alpes côte d'azur	19	13
Rhône Alpes	17	12
Centre	12	9
Languedoc Roussillon	12	8
Alsace	9	6
Lorraine	8	6
Limousin	7	5
Bourgogne	4	3
Champagne-Ardenne	3	2
Ile-de-France	3	2
Aquitaine	3	2
Other	22	15
Total	143	100

55 stands were selected and 245 trees sampled in 18 forest subdivisions defined by IFN. Each tree was sawn into lumber pieces. The different timber pieces were identified to know what tree they came from. To be representative of Scots Pine resource, the stands and trees were selected according to:

1. Geographical distribution: sample taken within 18 forest subdivisions in 5 administrative areas
2. Altitude (from 100 to 1 500 m)
3. Forest density
4. Classes of growth: a high and a low class
5. DBH: from 0,24 to 0,60 m.

The mature resource of Scots pine has narrow annual growth rings. Its summer wood (latewood) percentage (27%) is low compared to other resinous species such as larch (37%) or Douglas fir (38%). Anatomical and morphological properties of the sample are given in Table 24.

Table 24. Anatomical and morphological properties of the sample.

565 trees	Average	COV	Min	Max
Age (year)	100	22%	49	160
DBH (m)	0.39	14%	0.24	0.60
Summer wood (%)	27	40%	9	51
Annual growth ring (mm)	1.9	48%	1.1	4.0

For determination of physical and mechanical properties there are two origins of information:

- 2 133 results of edgewise four point bending tests which come from 245 trees. 55 stands. 1 cross section (50*150 mm)
- 317 results of tensile test according EN 408 which come from 132 trees. 34 stands. 1 cross section (50*150 mm).

Sampling areas and timber properties are given in Tables 25 to 27 and in Fig. 6.

Table 25. Number of pieces for bending test in the different sub-samples.

Administrative areas	Total sample tested	
	Number	%
Auvergne	640	30
Centre	614	29
Alsace	410	19
Provence Alpes côte d'azur	298	14
Limousin	171	8
Total	2 133	100

Table 26. Average Mechanical values for bending test.

	Average	COV	Min.	Max.	N
Density to 12% (kg/m^3)	557	10%	408	796	2 133
KAR (%)	24.8	56%	0	78	2 133
Annual growth ring (mm)	2.0	40%	0.7	7.0	2 133
E_{ml} 12% (MPa)	12 500	31%	3 400	32 700	2 133
f_m (MPa)	44.4	44%	5.0	121.5	2 133

When compared to values of strength class C30 following conclusions can be made related to potential yields:

- Modulus of elasticity (E_{ml} at 12% MC) 52% of timber pieces > 12 GPa
- Modulus of rupture (f_m) 73% of timber pieces > 30 MPa
- Density (adjusted to 12% MC) 100% of timber pieces > 380 kg/m³.

Table 27. Average Mechanical values for tensile test.

	Average	COV	Min.	Max.	N
Density to 12% (kg/m^3)	571	12%	424	807	317
KAR (%)	18.9	62%	0	61	143
Annual growth ring (mm)	-	-	-	-	-
E_{ml} 12% (MPa)	12 500	28%	5 060	23 500	317
f_m (MPa)	27.2	42%	6.5	63.8	317

When compared to values of strength class C30 following conclusions can be made related to potential yields:

- Modulus of elasticity (E at 12% MC) 51% of timber pieces > 12 GPa
- Tension strength (f_t) 76% of timber pieces > 18 MPa
- Density (adjusted to 12% MC) 100% of timber pieces > 380 kg/m³.

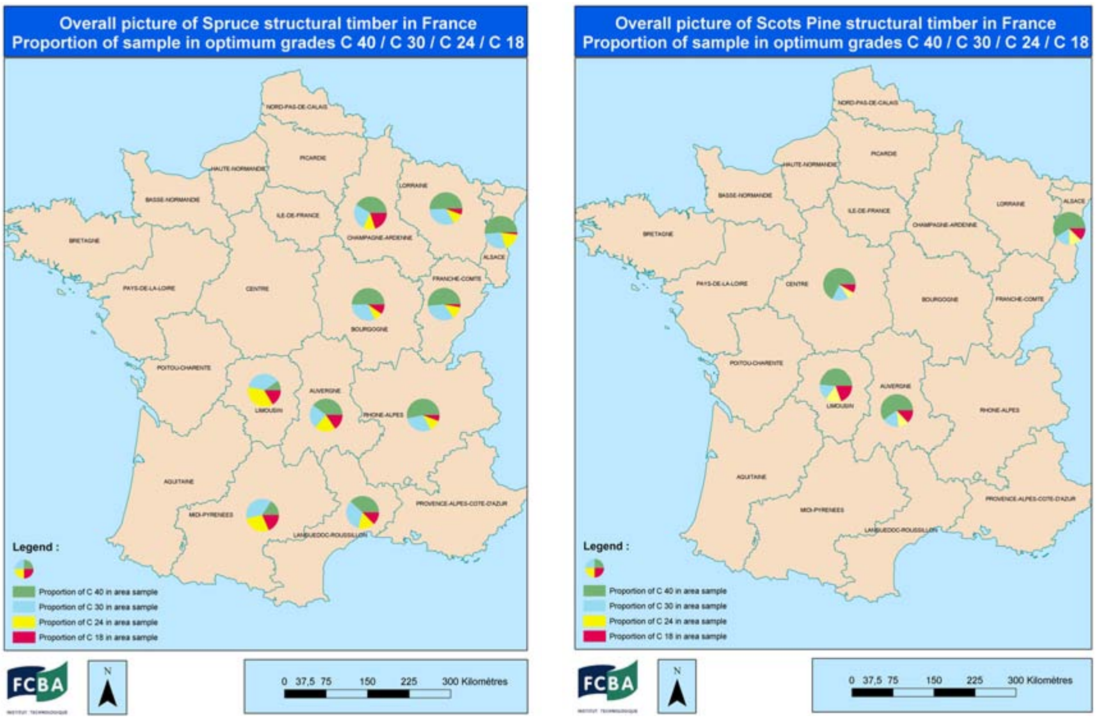

Figure 6. Geographical locations of French spruce and pine samples.

2.6 UL data

Slovenian timber was sampled during the research project "Timber strength grading" (2004–2007). Three hundred pieces were sampled in three saw mills in central Slovenia. The locations of these saw mills are shown in Fig. 7. The basic aim of the project was to commence timber strength grading in Slovenia. The three saw mills prepared 100 pieces each of the dimensions shown in Table 28. Basic statistics for the strength of Slovenian timber is shown in Table 29.

Figure 7. The location of saw mills contributing the samples.

Table 28. List of samples for bending tests in Slovenia.

Sample number	Saw mill	Pieces in sample	Dimensions (mm)
1	Egoles	100	20 x 130 x 4 000
2	Hoja	100	38 x 175 x 4 000
3	Jelovica	100	60 x 80 x 4 000

Table 29. Bending strength of Slovenian samples.

Sample number	Saw mill	f_{mean} [N/mm^2]	COV [%]
1	Egoles	32.2	30.3
2	Hoja	34.2	39.9
3	Jelovica	41.6	27.4

3. Methods

3.1 Determination of European regression equations

Partners of the Gradewood project hold the data from previous research activities. Since the data is not held in the public domain it is not possible to share complete data sets. Therefore it has been decided to share some properties of the data in order to obtain the basic regression equations which would include all data.

First, the variables to be used in linear regression equations were agreed to be:

- bending/tension strength
- static modulus of elasticity E (local, edgewise in bending)
- dynamic modulus of elasticity (longitudinal)
- density
- total knot area ratio (KAR)
- ratio of E and density (analogical to E_{dyn} based on assumed density).

Testing is made in accordance with EN408 or EN1194 and characteristic values are determined as defined in EN384 (CEN 1995, 1999, 2003b). A definition as to how some variables are derived from measured values is given in Appendix B.

Second, 14 linear regression equations were selected to be used in the analysis:

Model 1: $f_{\mathrm{model}} = c_1 + c_2 E$ (1)

Model 2: $f_{\mathrm{model}} = c_3 + c_4 E_{dyn}$

Model 3: $f_{\mathrm{model}} = c_5 + c_6 \rho$

Model 4: $f_{\mathrm{model}} = c_7 + c_8 KAR$

Model 5: $f_{\mathrm{model}} = c_9 + c_{10} \dfrac{E}{\rho}$

Model 6: $f_{\mathrm{model}} = a_0 + a_1 b + a_2 h + a_3 \rho + a_4 E$

Model 7: $f_{\mathrm{model}} = a_0 + a_3 \rho + a_4 E$

Model 8: $f_{\mathrm{model}} = a_0 + a_1 b + a_2 h + a_3 \rho + a_5 KAR$

Model 9: $f_{\mathrm{model}} = a_0 + a_3 \rho + a_5 KAR$

Model 10: $f_{\mathrm{model}} = a_0 + a_1 b + a_2 h + a_4 E + a_5 KAR$

Model 11: $f_{\mathrm{model}} = a_0 + a_4 E + a_5 KAR$

Model 12: $f_{\text{model}} = a_0 + a_1 b + a_2 h + a_3 \rho + a_4 E + a_5 KAR$

Model 13: $f_{\text{model}} = a_0 + a_3 \rho + a_4 E + a_5 KAR$

Model 14: $f_{\text{model}} = a_0 + a_1 b + a_2 h + a_3 \rho + a_5 KAR + a_6 E_{dyn}$.

The statistics required to obtain the combined regression equations are: sample size *n*, averages $\overline{X}$ and variances/covariances S_X^2 and S_{XY} .

The goal is to obtain the estimates of multiple regression coefficients and coefficient of determination r^2 (often referred as Pearson's coefficient of regression).

3.1.1 Combined average and variance/covariance matrix

The average, variance and covariance are evaluated by the following equations:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

$$S_X^2 = \frac{1}{n}\sum_{i=1}^{n}\left(x_i - \overline{X}\right)^2 = \frac{1}{n}\sum_{i=1}^{n} x_i^2 - \overline{X}^2 \tag{3}$$

$$S_{XY} = \frac{1}{n}\sum_{i=1}^{n}\left(x_i - \overline{X}\right)\left(y_i - \overline{Y}\right) = \frac{1}{n}\sum_{i=1}^{n} x_i\, y_i - \overline{X}\,\overline{Y} \tag{4}$$

When the total sample x_i ($i = 1,\ldots,n$) consists of *m* sub-samples for which only the sizes n_j, averages $\overline{X}_j$, variances $S_{X_j}^2$ and covariances S_{XY_j} ($j = 1,\ldots,m$) are known, we can use these values to evaluate averages, variances and covariances for complete sample.

The sample size of complete sample is the sum of sub-samples sizes

$$n = \sum_{j=1}^{m} n_j \tag{5}$$

The average is obtained by the following equation:

$$\overline{X} = \frac{1}{n}\sum_{j=1}^{m} n_j \overline{X}_j \tag{6}$$

since the sum of x_i is easily obtained from (2)

$$\sum_{i=1}^{n} x_i = n\,\overline{X} \tag{7}$$

In order to evaluate variances and covariances of the complete sample, the sums of x_i^2 and $x_i y_i$ need to be found. Similarly as in the case of averages, the sums of squares and sum of products are evaluated by using (3, 4)

$$\sum_{i=1}^{n} x_i^2 = \left(S_X^2 + \overline{X}^2\right)n \quad \rightarrow \quad \sum_{i=1}^{n} x_i^2 = \sum_{j=1}^{m}\left(S_{X_j}^2 + \overline{X}_j^2\right)n_j \tag{8}$$

and

$$\sum_{i=1}^{n} x_i\, y_i = \left(S_{XY} + \overline{X}\,\overline{Y}\right)n \quad \rightarrow \quad \sum_{i=1}^{n} x_i\, y_i = \sum_{j=1}^{m}\left(S_{XY_j} + \overline{X}_j \overline{Y}_j\right)n_j \tag{9}$$

After introducing equations (6, 8, 9) into (3, 4) we obtain the final equations for combined variance and covariance:

$$S_X^2 = \frac{1}{n}\sum_{j=1}^{m}\left(S_{X_j}^2 + \overline{X}_j^2\right)n_j - \left(\frac{1}{n}\sum_{j=1}^{m}\overline{X}_j\, n_j\right)^2 \tag{10}$$

$$S_{XY} = \frac{1}{n}\sum_{j=1}^{m}\left(S_{XY_j} + \overline{X}_j \overline{Y}_j\right)n_j - \left(\frac{1}{n}\sum_{j=1}^{m}\overline{X}_j\, n_j\right)\left(\frac{1}{n}\sum_{j=1}^{m}\overline{Y}_j\, n_j\right) \tag{11}$$

Equations (6, 10, 11) are used to determine the combined average vector **X** and variance-covariance matrix **S**.

3.1.2 Regression analysis

The basic linear regression equation is

$$y_i = p_0 + p_1 x_{i1} + p_2 x_{i2} + \cdots + p_k x_{ik} + \varepsilon_i \tag{12}$$

where p_j are unknown parameters, k is the number of independent variables X_j, x_{ij} denotes the sample of independent variable X_j, whereas y_i denotes the sample of dependent variable Y; ε_i is the approximation error assumed to be normally distributed with zero mean and standard deviation equal to σ.

Multivariate regression is determined by the standard procedure from the system of normal equations

$$\mathbf{A}\,\mathbf{p} = \mathbf{b} \tag{13}$$

where

$$\mathbf{A} = \begin{bmatrix} n & \sum x_{i1} & \sum x_{i2} & \cdots & \sum x_{ik} \\ \sum x_{i1} & \sum x_{i1}^2 & \sum x_{i1}x_{i2} & \cdots & \sum x_{i1}x_{ik} \\ \sum x_{i2} & \sum x_{i1}x_{i2} & \sum x_{i2}^2 & \cdots & \sum x_{i2}x_{ik} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \sum x_{ik} & \sum x_{i1}x_{ik} & \sum x_{i2}x_{ik} & \cdots & \sum x_{ik}^2 \end{bmatrix},$$

$$\mathbf{b} = \begin{bmatrix} \sum y_i \\ \sum x_{i1} y_i \\ \sum x_{i2} y_i \\ \vdots \\ \sum x_{ik} y_i \end{bmatrix}.$$

All sums in the last two equations run for $i = 1,\ldots,n$, where n is the sample size.

The vector of unknown parameters is

$$\mathbf{p} = \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ \vdots \\ p_k \end{bmatrix}$$

The coefficient of multiple determination r^2 is defined as

$$r^2 = \frac{SS_R}{S_Y^2} \tag{14}$$

where sum of residual squares is determined by

$$SS_R = \sum_{j=1}^{k} p_k S_{x_k,Y} \tag{15}$$

Coefficients of regression equations and coefficients of determination are calculated for each species and for all 14 regression models.

3.2 Use of regression models as *IP* in grading

Selected regression equations with the same coefficients of variables are used as strength indicating properties (*IP*) and virtual grading of laboratory data is made by using a 10 MPa bandwidth. Each data holder performed the analysis separately and submits the resultant data to be jointly analyzed. This data includes averages and coefficients of variation for strength and modulus of elasticity for all bandwidths. Also information on density was collected in a similar way when models 1 and 2 are used as *IP*. Combined data for a country and also for regions within a country, when adequate data is available, are submitted for joint analysis. Example of submitted data is in Table 30.

Table 30. Example of format of submitted regional results (spruce in bending, IP = model 9, Finland).

Range of f_{model} N/mm²	**f_{mean} N/mm²**	**COV %**	**E_{mean} N/mm²**	***COV* %**	***N***
–10					0
10–20	26.2	24.0	8 159	25.7	5
20–30	28.2	25.4	8 290	25.4	31
30–40	35.8	23.8	10 387	18.0	263
40–50	43.8	19.9	12 178	15.0	600
50–60	53.4	15.9	14 425	13.0	289
60–70	65.8	7.6	17 184	8.5	26
70–					0
all	44.4	25.3	12 317	20.3	1 214

For each bandwidth (grade) the best estimate and confidence limits of 5% fractile for strength are calculated. A best estimate of the 5th percentile is calculated by using Normal distribution fitting

$$f_{0,05} = f_{mean}\left(1 - 1{,}65 \cdot COV\right) \tag{16}$$

Upper and lower confidence limits of the 5 percentile value are calculated

$$f_{0,05,upper} = f_{0,05}\left(1 + 1{,}65 \cdot \frac{\beta}{\sqrt{N}} COV\right) \tag{17}$$

$$f_{0,05,lower} = f_{0,05}\left(1 - 1{,}65 \cdot \frac{\beta}{\sqrt{N}} COV\right) \tag{18}$$

where *COV* is coefficient of variation of strength, and *N* is number of tests belonging to the bandwidth of concern. The basis of equations (17) and (18) are in numerical simulation and is explained in Appendix A. β = 3 will be used in this analysis. It corresponds to a 90% probability (α = 0.1) that the five percentile value is between the confidence limits when strength values are normally distributed and *COV* = 0.2. If strength values are log-normally distributed β = 2 would correspond to the same confidence level, and β = 3 would correspond to 99% probability of having characteristic strength between the limits independently of *COV*.

An example of the calculated 5th percentile values and confidence limits is given in Table 31. When $N < 30$ the results will not be shown, but they are used in calculation of weighted average of values. If non-parametric method would be used for calculation, $f_{0,05}$ values would be normally a little higher but more variable. In order to avoid unnecessary random variation equation (16) was chosen.

Table 31. Example of calculated confidence limits (spruce in bending, IP= model 9, Finland).

Range of f_{model} N/mm²	**f_{mean} N/mm²**	***COV* %**	**$f_{0,05}$ N/mm²**	**$f_{0,05,upper}$ N/mm²**	**$f_{0,05,lower}$ N/mm²**	***N***
–10						0
10–20	26.2	24	15.82	24.23	7.42	5
20–30	28.2	25.4	16.38	20.08	12.68	31
30–40	35.8	23.8	21.74	23.32	20.16	263
40–50	43.8	19.9	29.42	30.60	28.24	600
50–60	53.4	15.9	39.39	41.21	37.57	289
60–70	65.8	7.6	57.55	61.79	53.30	26
70–						0
all	44.4	25.3	25.87	26.79	24.94	1 214

3.3 Growth area analysis

Term “growth area” is used here for an area where the same settings for grading machine can be used and are normally defined as geo-political areas (CEN 2005). Growth area analysis is primarily based on comparison of 5 percentiles of strength of the bands and 90% confidence limits (Eqns (17) and (18)). Two slightly different values are calculated for confidence limits, one based on average sample size and average *COV*, and a more accurate one based on sample size and *COV* of each sub-sample separately. Later these are called average confidence limits and individual confidence limits (Chapter 3.2) and used in different illustrations of results. Firstly, average confidence limits are used for a rough comparison of results (see Fig. 8), and when more precise analysis is needed, especially if the sample sizes have large differences, individual confidence limits are applied to the main bandwidths of the results (see Fig. 9).

When all the best estimate values for the 5 percentiles are within the confidence limits, it is concluded that these regions may belong to the same growth area, because the same machine grading settings can be used to achieve a common characteristic value for strength. In addition, attention will be paid to the trends; if the same region gives higher (or lower) values than the average in all bandwidths, the material may be different from the others even if the values are within the confidence limits. If values fall outside the confidence limits on the same side for several bandwidths it confirms that the region does not belong to this growth area.

Table 32. Example of combination of results of 5 regions, average confidence limits are given (spruce in bending, IP = model 9, total 7 117 tests).

Range of	Weighted averages						Upper	Lower
f_{model} N/mm^2	$f_{adj,mean}$ N/mm^2	*COV* %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	*COV* %	*N*	$f_{adj,0,05}$ N/mm^2	$f_{adj,0,05}$ N/mm^2
–10								
10–20								
20–30	26.2	31.4	12.6	8 376	17.5	125	14.38	10.87
30–40	35.0	26.9	19.5	10 472	13.8	414	20.79	18.24
40–50	45.3	23.2	27.9	12 638	12.3	566	29.22	26.52
50–60	54.6	20.2	36.4	14 634	12.0	266	38.61	34.16
60–70	61.8	18.6	43.0	16 654	12.2	30	50.26	35.73
70–								
all		30.8			18.1	1 423		

Confidence interval limits are not strict limits known to be correct in the analysis of growth areas. Instead, the chosen limits are used as reference which are used both in regions which the present standard accept to belong to the same growth area, and to broader areas which are not considered to form one growth area. A criterion for adoption of new larger growth areas can be that the results obtained are within the confidence limits with the same probability as they are in established growth areas.

Examples of two illustrations of the results are shown in Figs. 8 and 9 which are based mainly on Central European material. It can be seen that Finnish results are in all 4 bandwidths outside the average confidence limits (Fig. 8), whereas Swedish and Russian results, based on smaller sample size can be found both on upper and lower side of the confidence interval. Fig. 9 which uses individual confidence limits, reveals that lower confidence limit of Finnish results is close to the average in all cases, Russian values are within the confidence limits except bandwidth 30–40, and Swedish values are nearly within the limits. In most cases German and French values are on a lower limit.

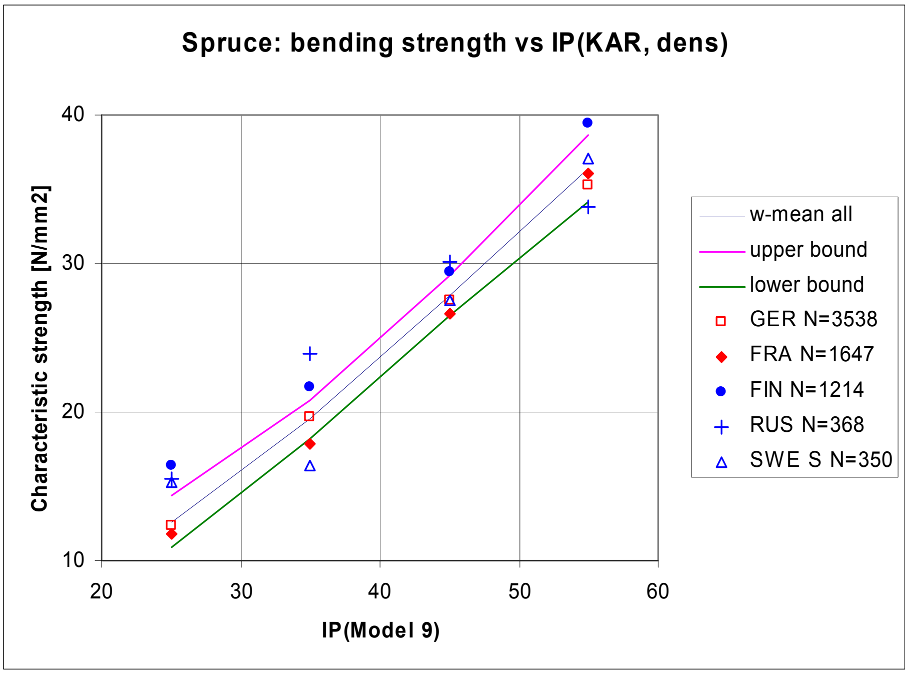

Figure 8. Example of presentation of the results. $f_{0,05}$ of each sample and average confidence limits around the average of $f_{0,05}$ are shown.

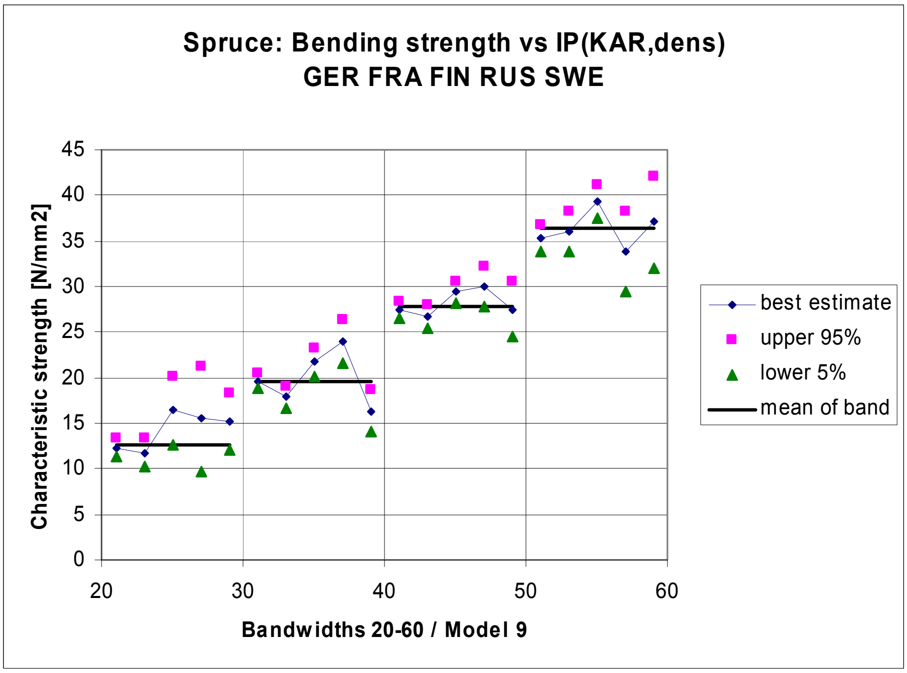

Figure 9. Example of presentation of the results. $f_{0,05}$ and individual confidence limits are shown. In each band, results from left are in order: Germany, France, Finland, Russia and Sweden as indicated in figure. $f_{0,05}$ best estimate values are same as in Fig. 8.

3.4 Analysis of strength profiles

In European standardization, term "strength profile" is used for a vector which includes mechanical properties needed in structural design such as bending strength, tension strength, shear strength ... modulus of elasticity and density. This research enables comparison of bending strength, tension strength, modulus of elasticity and density. Comparison is not a straight forward task, because there are some differences in the measurement of E in tension and bending tests.

Information on density is collected in cases, when models 1 and 2 are used as *IP*, in a similar way as information for strength and *E* was collected in all cases. In Table 33 an example is shown of the data delivered by participants when static modulus of elasticity was used as grade indicating parameter.

Table 33. Example of data submitted when using Models 1 and 2 as IP (Swedish spruce in bending).

Range of f_{model}	f_{mean}	***COV***	E_{mean}	***COV***	ρ_{mean}	***COV***	***N***
N/mm²	**N/mm²**	**%**	**N/mm²**	**%**	**kg/m³**	**%**	
–10	5.13		2 737		442		1
10–20	15.86	20	5 043	13	390	13	16
20–30	25.71	26	7 568	9	387	11	302
30–40	35.63	23	10 046	8	414	11	1 213
40–50	46.46	20	12 531	6	437	10	1 704
50–60	55.63	18	15 124	5	463	9	925
60–70	63.91	15	17 587	4	487	8	198
70–	71.85	19	20 446	5	504	10	34
all	44.84	30	12 309	22	435	12	4 393

Relation of bending strength, modulus of elasticity and density is analyzed directly on basis of information obtained from different countries in the form of Table 33. In addition, tension strength can be directly included in the comparison in the case of Model 2, because the dynamic modulus of elasticity is the same when measured before tension and bending tests. We just transform model 2 values to E_{dyn} values and can include tension and bending test results in the same analysis.

4. Results for spruce

4.1 Bending

4.1.1 European regression models

14 regression equations are used in the analysis. Regression equations are given Eqn. (1) and coefficients for bending of spruce in Table 34, which includes also the coefficient of determination (r^2), the total sample size and countries from where the timber was harvested.

From the single variable models the highest coefficient of determination $r^2 = 0.61$ is obtained when static modulus of elasticity is the variable, and the second highest $r^2 = 0.49$ is when E/ρ is the variable and only $r^2 = 0.20$ is achieved when density is the variable. These values are based on 15 000 individual test values.

Surprisingly, the value for the coefficient of determination obtained for E_{dyn} was only $r^2 = 0.43$ when based on 5 500 test values. Previous experience suggests that static and dynamic E are equally as good indicators of bending strength.

Knot area ratio (*KAR*) alone gives a $r^2 = 0.34$, and when combined with density (Model 9) $r^2 = 0.48$. Addition of cross-section dimensions to the model increase coefficient of determination only marginally to $r^2 = 0.49$. Strength values used in the analysis are already adjusted to European reference size $h = 150$ mm, and this seems to be an adequate adjustment for spruce in bending. Other models in Table 34 give the same conclusion on size effect.

When combining other variables with E in modeling the conclusions are:

1. addition of density with or without dimensions does not improve the model ($r^2 = 0.61$)
2. addition of *KAR* improves the model to $r^2 = 0.67$
3. adding *KAR*, density and dimensions to E leads practically to the same coefficient of determination independently, if E is based on static or dynamic testing.

Table 34. Coefficients of European regression models for bending of spruce.

Model	Coefficient of variable								r^2	N	Data included
	1	b mm	h mm	ρ kg/m³	E N/mm²	*KAR*	E_{dyn} N/mm²	E[N/mm²]/ ρ [kg/m³]			
1	-1.16				0.003658				0.61	15 129	FIN, SWE, GER, FRA, EST, LAT, RUS, SLO, NOR
2	-0.51						0.003371		0.43	5 520	FIN, GER, FRA, SWE, EST, RUS, SLO
3	-13.61			0.12953					0.20	15 129	FIN, SWE, GER, FRA, EST, LAT, RUS, SLO, NOR
4	57.41					-68.14			0.34	7 117	GER, FRA, FIN, RUS, SWE
5	-5.40							1.60	0.49	15 129	FIN, SWE, GER, FRA, EST, LAT, RUS, SLO, NOR
6	2.23	0.0035	-0.0038	-0.01084	0.003805				0.61	15 129	FIN, SWE, GER, FRA, EST, LAT, RUS, SLO, NOR
7	0.92			-0.00646	0.003720				0.61	15 129	FIN, SWE, GER, FRA, EST, LAT, RUS, SLO, NOR
8	-1.71	0.0790	-0.0013	0.11894		-56.13			0.49	7 117	GER, FRA, FIN, RUS, SWE
9	3.08			0.11731		-57.42			0.48	7 117	GER, FRA, FIN, RUS, SWE
10	12.49	0.0464	-0.0044		0.002946	-32.90			0.68	7 117	GER, FRA, FIN, RUS, SWE
11	14.23				0.002957	-33.19			0.67	7 117	GER, FRA, FIN, RUS, SWE
12	12.43	0.0465	-0.0044	0.00018	0.002944	-32.90			0.68	7 117	GER, FRA, FIN, RUS, SWE
13	14.63			-0.00219	0.002983	-33.10			0.68	7 116	GER, FRA, FIN, RUS, SWE
14	1.16	0.0318	0.0185	-0.01889		-25.50	0.004125		0.67	3 283	GER, FIN, RUS, SWE

4.1.2 Growth area analysis

European regression equations (Table 34) are used as strength indicating properties (*IP*) and test material held by participants is graded simultaneously to several grades by using *IP* = 10, 20, 30 etc as settings. In other terms we use 10 N/mm^2 as bandwidth. Comparison of the 5 percentile values of each grade of the wood grown in different regions is the main result of this analysis.

First, variation of strength values within a growth area as defined in EN 14081 is studied. Present growth areas which are larger than one country are the Nordic area and the German-Austrian area, which are used as reference. In this analysis also relatively small samples are utilized, starting from *N* = 200. Second, variation between such countries is analyzed that have a large number of test data, a minimum of 1 000.

All calculated results are illustrated in Appendix C, only a few are shown in the text. In Appendix C the order of figures is: spruce in bending, spruce in tension, pine in bending. Within species and loading type, the order follows the numbers of models, the first comparison is between countries, then variation within the Nordic growth area, and then variation within Central Europe.

It is known from previous research that the bending strength of timber is strongly correlated to *E*, and this correlation can be only marginally improved by adding other variables. Therefore we start from Model 1 (*E*), and compare results of Models 11 (*E* + *KAR*), and 12 (*E* + *KAR* + *density*) to it.

4.1.2.1 Models with *E* as primary variable

Model 1 based results

For Model 1 we have a large number of test results available: 9 000 Nordic and 6 000 Central European. The yield to the higher grade *IP* > 50 is about 25% being slightly higher in Central Europe than in the Nordic data (27 vs. 24%).

The Nordic growth area results are shown in Fig. 10. Most of the results are inside the 90% confidence limits. However one third of the calculated 44 points are outside the 90% confidence limits based on individual values for sample size and *COV*. Accordingly, it can be stated that the adopted confidence limits are quite strict in comparison to the present practice in standardization. Another conclusion is that a sample size of N = 200 may be too small to obtain representative sampling, which leads to strange situations, even if all the points shown in Fig. 10 are based on at least 30 observations. For instance, the Swedish North costal area result is below the lower confidence limit for *IP* = 50...60, but above the upper confidence limit on the previous bandwidth. Results from the inland regions of North Sweden and East Finland are above average in all bandwidths, and above the upper confidence limit based on the average *COV* and sample size, in some bandwidths. Fig. 10 based on individual confidence limits shows that Inland North Sweden (first dots) results are within the confidence limits, and East Finland (second from right) results slightly above the upper limit and South Sweden results are below the confidence limit on three bandwidths. All other results are well within the limits or have deviation only on a single band.

Central European data (including Slovenia) based on Model 1 is shown in Fig. 11. Considering only German values, one fourth of data points are outside of the 90% confidence limits. "German West" values are above average on 3 bandwidths and above the confidence limit on one bandwidth. AT/CZ results are below the average, and in one bandwidth below the confidence limit. Slovenian values are the lowest in all bandwidths, and below the confidence limit in two bandwidths of four. Combined French sample values are within the confidence limits.

The hypothesis that all data would belong to the same growth area is studied in Fig. 12 where data from countries which have more than 1 000 test values are compared. The results are that 13 out of 20 values are outside the 90% confidence limits. This indicates strongly that more than one growth area is needed for spruce in bending.

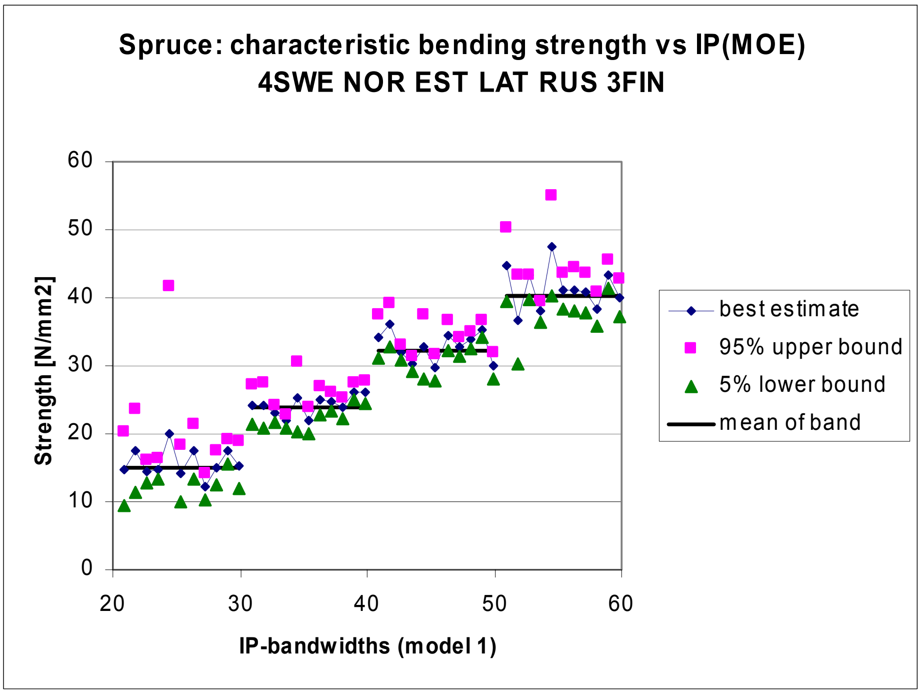

Figure 10. Comparison between Nordic regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 1.

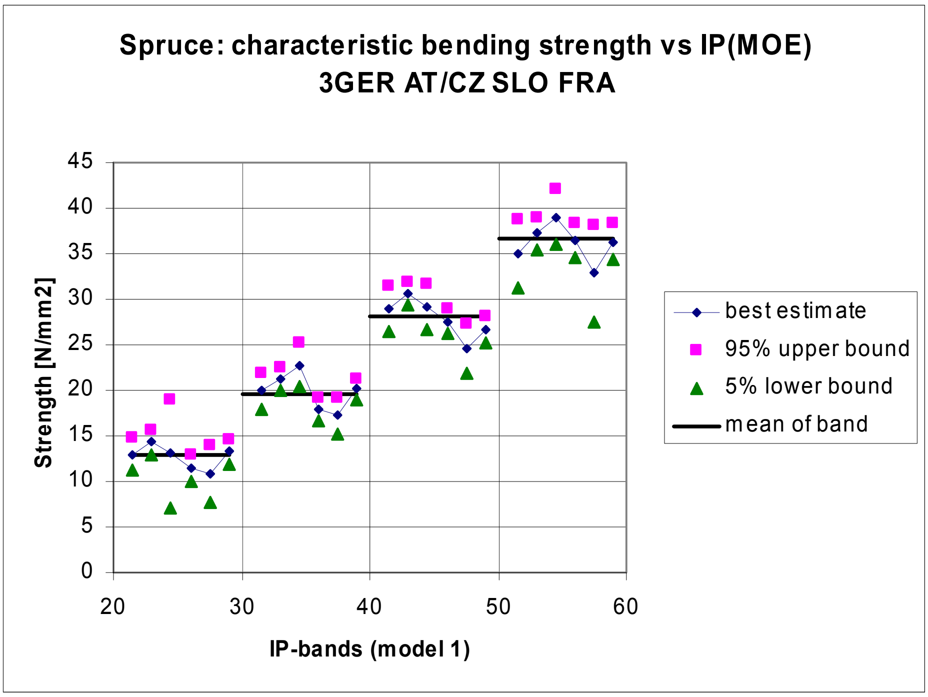

Figure 11. Comparison between CE-regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 1.

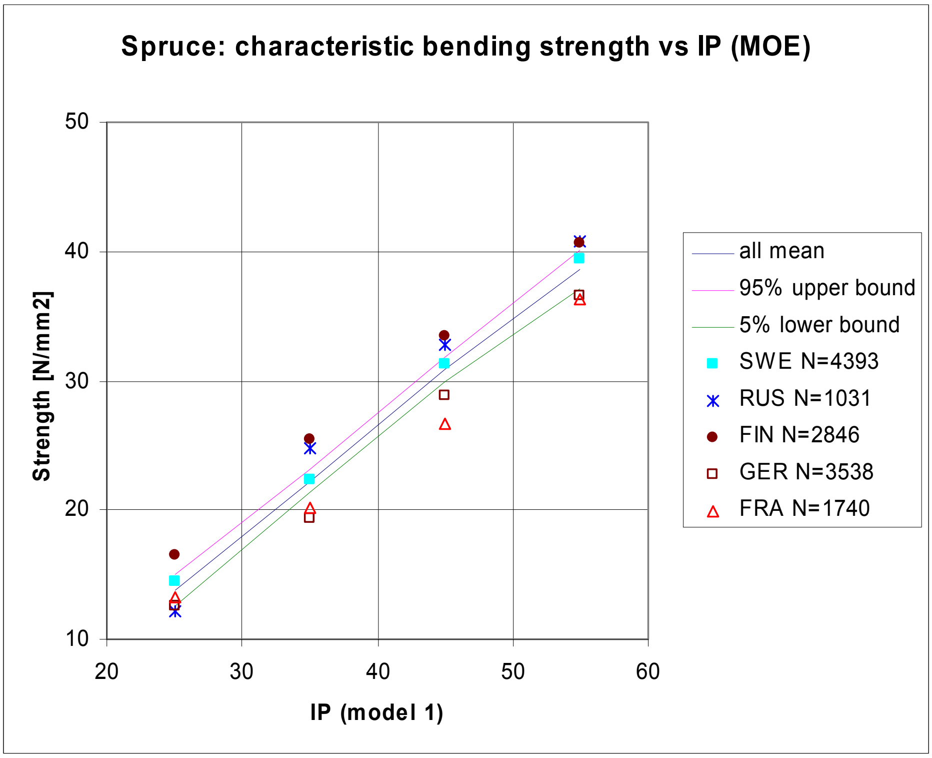

Figure 12. Comparison between countries, characteristic strength values with average confidence limits. Spruce in bending, Model 1.

Model 11 and 12 based results

In model 11 *KAR* and *E* are variables in the regression model, and the r^2 is improved from 0.61 to 0.67. In comparison to Model 1 a different sample has been used: there are 7 000 specimens instead of 15 000. The same 7 000 specimens are used also in model 12. .
All *E* based models produce practically the same yield to the higher grade (*IP* > 50). The strength of higher grades is the highest for model 12 followed by Model 11 and 1. These differences are small but existent for Central European timber. For Nordic timber all the models produce practically same strength values, Model 1 being the lowest. As the results for Models 11 and 12 are similar, only model 11 results are illustrated here.

Variation inside the Nordic growth area is studied based on three samples from Finland, one from South Sweden and one from North Western Russia and are shown in Fig. 13. Values are within the confidence limits except for South Eastern Finland which shows one value below, and South Sweden which has one value below and one value above the limits. In total, 80% of the data points are inside the 90% confidence limits.

Central European results are based on 3 German samples and a joint French sample. All values are within the confidence limits when using Models 11 or 12. Model 11 results are shown in Fig. 14.

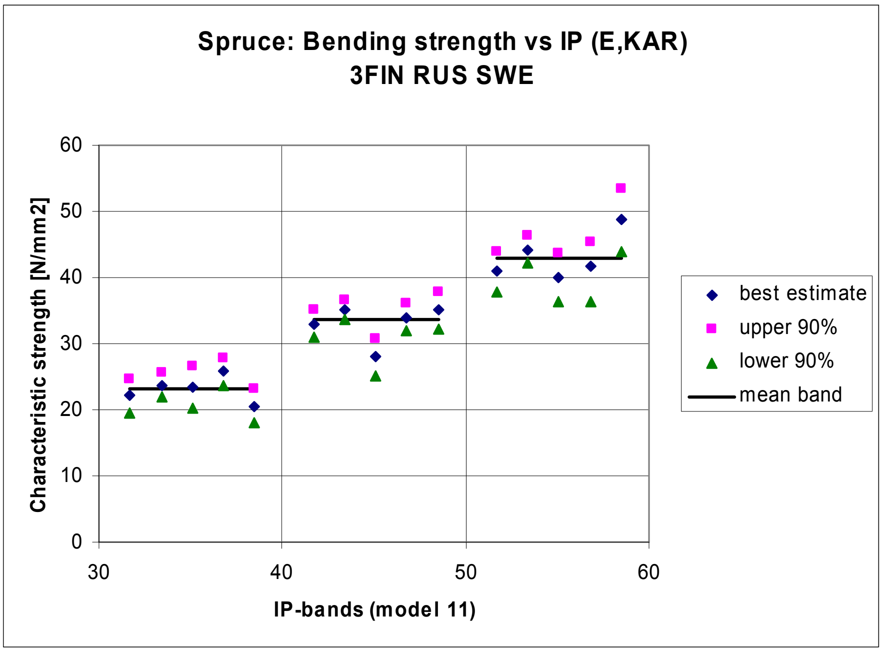

Figure 13. Comparison between Nordic regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 11.

Comparison between countries includes Germany (N = 3 538), France (N = 1 647) and Finland (N = 1 214), the averages are shown in Table 35, and results are illustrated in Fig. 15. The findings show that the Finnish results are above the confidence limits for this mainly Central Europe based model, and the German and French results are within the limits. When comparing to Model 1 results, the difference noted between countries are here smaller.

Table 35. Combined results of Germany, Finland and France for Model 11. Weighted averages of mean values, 5 percentiles and COV's and averages of sample sizes per country and band, and upper and lower confidence limits of 5 percentiles obtained by using average COV's and sample sizes.

Range of	Weighted averages					Average	Upper	Lower
f_{model} N/mm²	$f_{adj,mean}$ N/mm²	*COV* %	$f_{adj,0,05}$ N/mm²	E_{mean} N/mm²	*COV* %	*N*	$f_{adj,0,05}$ N/mm²	$f_{adj,0,05}$ N/mm²
–10	12.6	45.0		4 088	30.9	8		
10–20	19.2	29.8	9.8	6 014	13.0	55	11.75	7.84
20–30	25.3	25.2	14.8	8 001	9.1	230	15.97	13.54
30–40	34.7	22.3	21.9	10 201	8.1	554	22.96	20.91
40–50	44.6	19.1	30.5	12 532	7.1	716	31.59	29.43
50–60	54.1	16.5	39.4	15 096	5.3	445	40.88	37.82
60–70	63.8	14.2	48.8	17 868	3.9	116	51.99	45.60
70–	72.2	13.4	56.4	21 126	3.8	10	68.38	44.40
all		31.4			15.4	2 133		

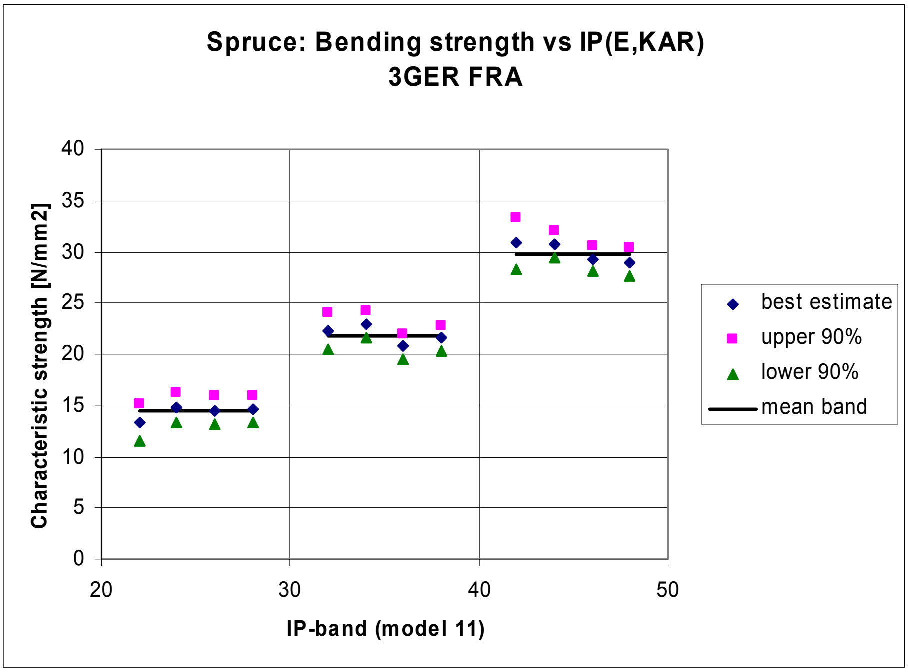

Figure 14. Comparison between CE-regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 11.

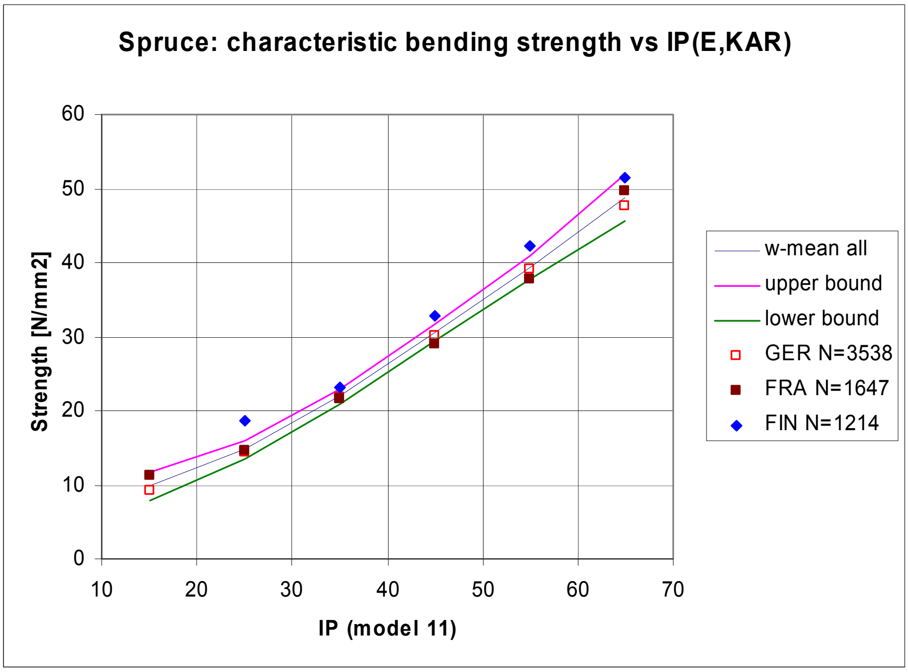

Figure 15. Comparison between countries, characteristic strength values with average confidence limits. Spruce in bending, Model 11.

4.1.2.2 Models with E_{dyn} as primary variable

Model 2

Model 2 is based on E_{dyn}. The Nordic sampling consists of 6 regions: North Western Russia (N = 579), Sweden (N = 470), Estonia (N = 235), Western Finland (N = 179), Eastern Finland (N = 871) and South Eastern Finland (N = 330). The results are shown in Fig. 17. Two of the 18 data points are on the 90% confidence limit line.

Central European data consists of 4 regions: Northern Germany (N = 456), Western Germany (N = 1 337), Lorraine and Rhône Alpes in France (N = 643) and Slovenia (N = 293). The results in Fig. 16 show that Slovenian strength values are significantly lower than the others. If Slovenian data are ignored, 1 of 9 points in the main bandwidths is outside the 90% confidence limit.

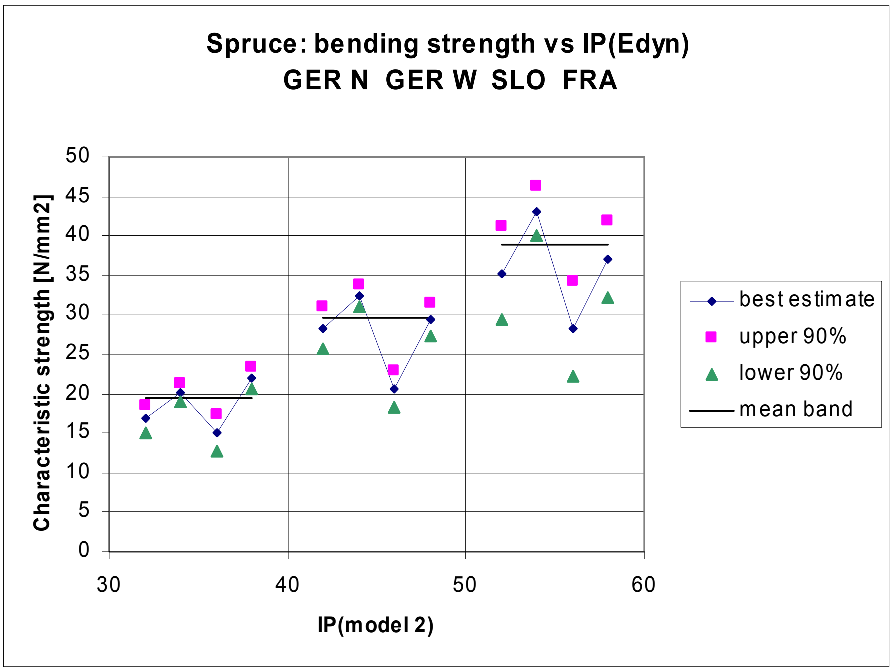

Figure 16. Comparison between CE- regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 2.

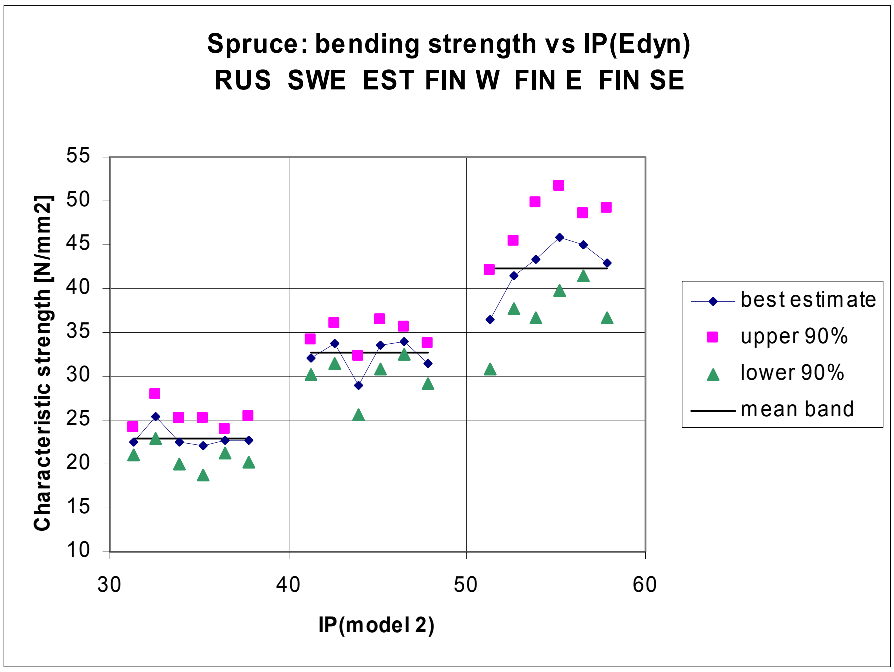

Figure 17. Comparison between Nordic regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 2.

For country comparison, German ($N = 1\ 920$) and Finnish ($N = 1\ 380$) results are analyzed. The averages are shown in Table 36. Fig. 18 illustrates difference in the values. The strength of the Finnish spruce is 2–4 MPa higher than that of the same grade in Germany.

Table 36. Averages of German and Finnish results for Model 2.

Range of	Weighted averages							Average	Upper	Lower
f_{model} N/mm^2	$f_{adj,mean}$ N/mm^2	*COV* %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	*COV* %	ρ_{mean} kg/m3	$\rho_{0.05}$ kg/m3	*N*	$f_{adj,0,05}$ N/mm^2	$f_{adj,0,05}$ N/mm^2
–10				11 297.0	0.0	431.0	431.0	1.0		
10–20	19.6	3.9		4 026.3	13.1	335.2	304.5	1.5		
20–30	23.5	33.2	10.6	7 007.7	20.1	376.1	325.9	138.0	12.13	9.16
30–40	35.2	25.6	20.4	10 105.7	14.8	414.2	360.6	664.5	21.37	19.37
40–50	47.4	19.7	32.0	13 157.4	11.3	454.1	403.0	673.5	33.21	30.80
50–60	58.6	16.9	42.3	16 216.0	9.6	501.7	452.0	159.0	45.07	39.47
60–70	64.1	15.4	47.8	18 807.7	7.9	551.4	507.1	12.5	58.10	37.45
70–	81.2			24 227.7		674.1		0.5		
all		32.0			24.3	436.8	120.2	1 650.0	0.00	0.00

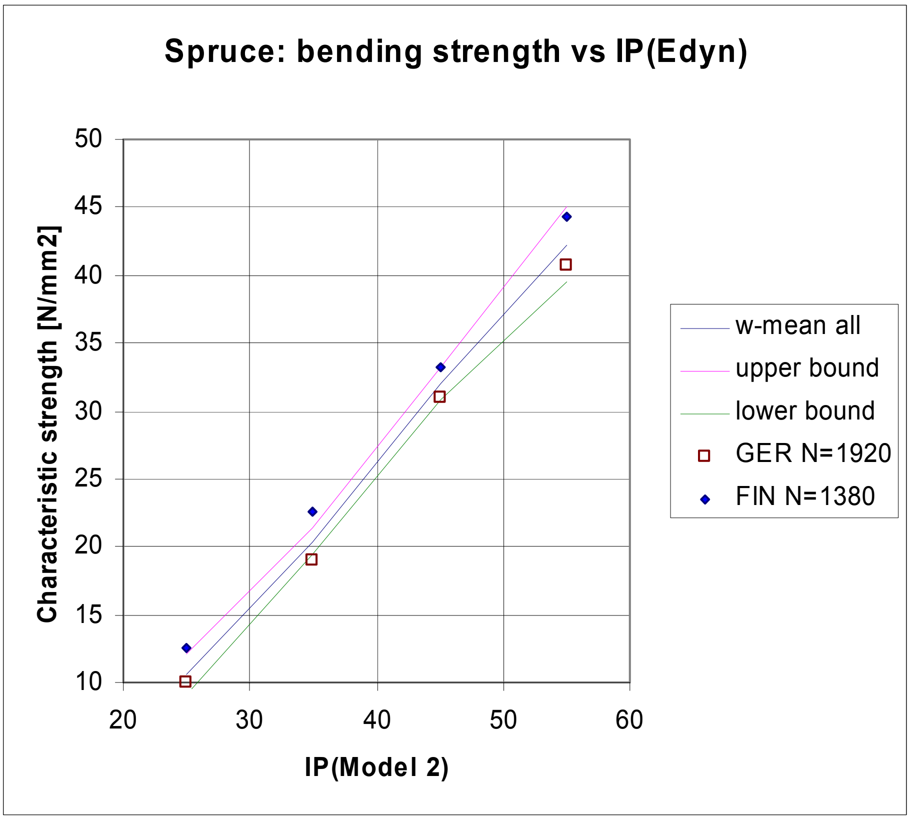

Figure 18. Comparison between countries, characteristic strength values with average confidence limits. Spruce in bending, Model 2.

Model 5

Model 5 has a ratio of the static *E* and density as variable. This model was chosen because it is analogous to commercially used grading methods measuring natural frequency of vibration and using constant value for density in calculation of E_{dyn}. When static and dynamic moduli are the same, this would simulate these common grading methods. Practically the same data was available here as for Model 1, total 13 547 specimens.

The Nordic results are based on 3 Finnish, 4 Swedish, Russian, Estonian and Latvian samples. 20% of values are outside the 90% confidence limits (Fig. 19). The average for the characteristic strength values for the highest grade $IP > 50$ is 38 N/mm^2, and the yield is 23%.

From Central Europe we have data from three regions in Germany, North ($N = 456$), West ($N = 1\ 437$), East ($N = 1\ 645$) and a combined sample from France ($N = 1\ 739$). Results are shown in Fig. 20. The results are nearly within the confidence limits, 2 of 12 are slightly outside. The average for the characteristic strength values for the highest grade $IP > 50$ is 38 N/mm^2, and yield is 24%.

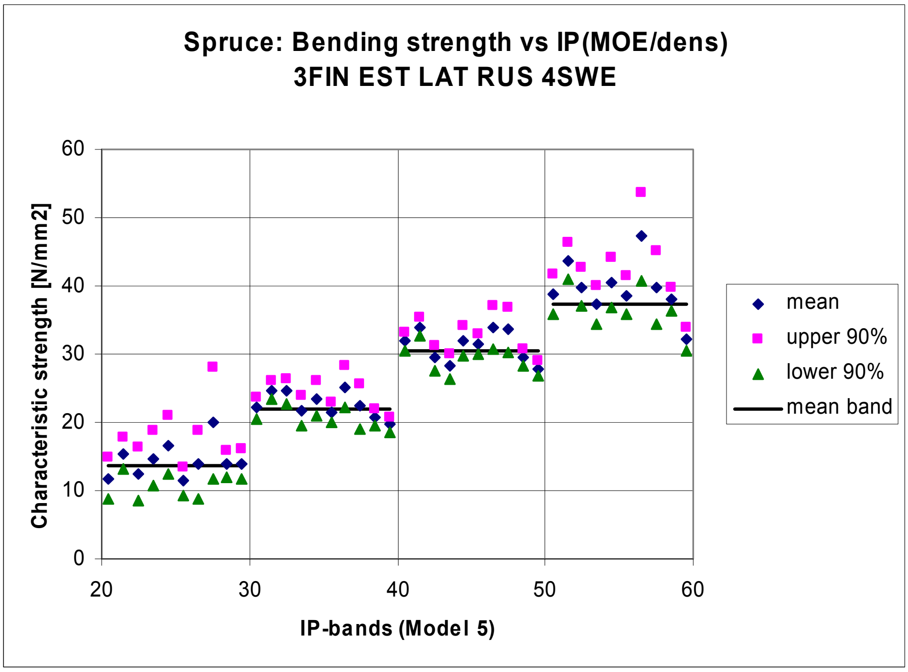

Figure 19. Comparison between Nordic regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 5.

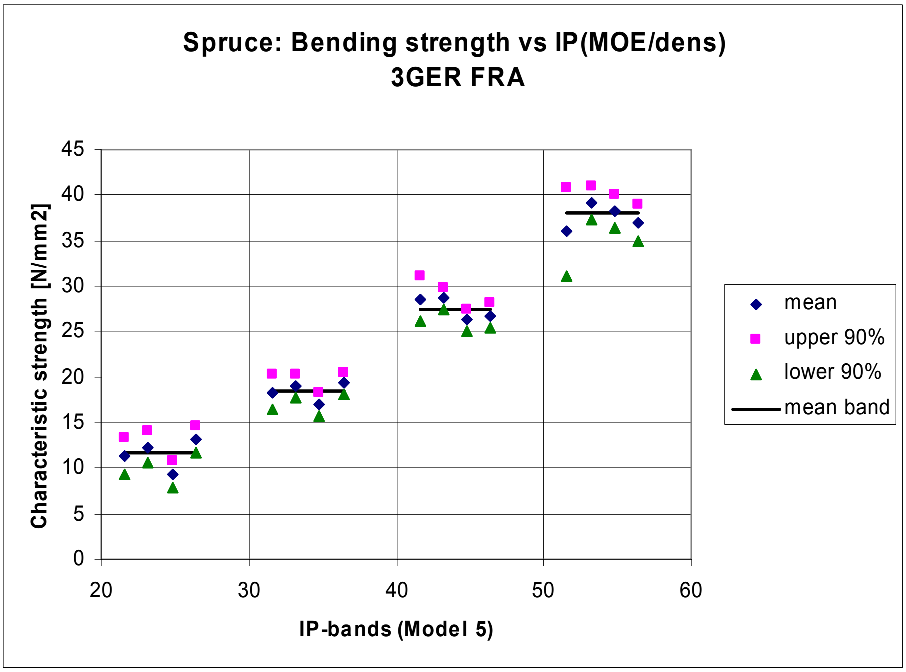

Figure 20. Comparison between CE-regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 5.

Averages of national results are given in Table 37 and graphical comparison of the results in Fig. 21. Nordic results are in general a little higher than Central European, with the exception of the highest grade.

Table 37. Averages of combined national results for Model 5.

Range of f_{model} N/mm²	Weighted averages						Upper	Lower
	$f_{adj,mean}$ N/mm²	COV %	$f_{adj,0,05}$ N/mm²	E_{mean} N/mm²	COV %	N	$f_{adj,0,05}$ N/mm²	$f_{adj,0,05}$ N/mm²
–10	9.7	36.7		2 586	32.1	2		
10–20	17.8	35.0	7.5	5 224	10.1	27	9.95	4.96
20–30	26.3	31.9	12.5	7 607	11.5	197	13.90	11.10
30–40	35.6	25.7	20.6	10 065	11.2	760	21.50	19.60
40–50	45.5	21.5	29.4	12 588	10.7	1 113	30.31	28.43
50–60	54.9	19.3	37.5	15 177	9.8	533	39.01	35.91
60–70	59.9	21.4	38.9	17 167	10.9	70	43.81	33.94
70–	60.6	23.1	31.8	18 098	12.5	9	43.71	19.81
all		30.7			18.0	2 709		

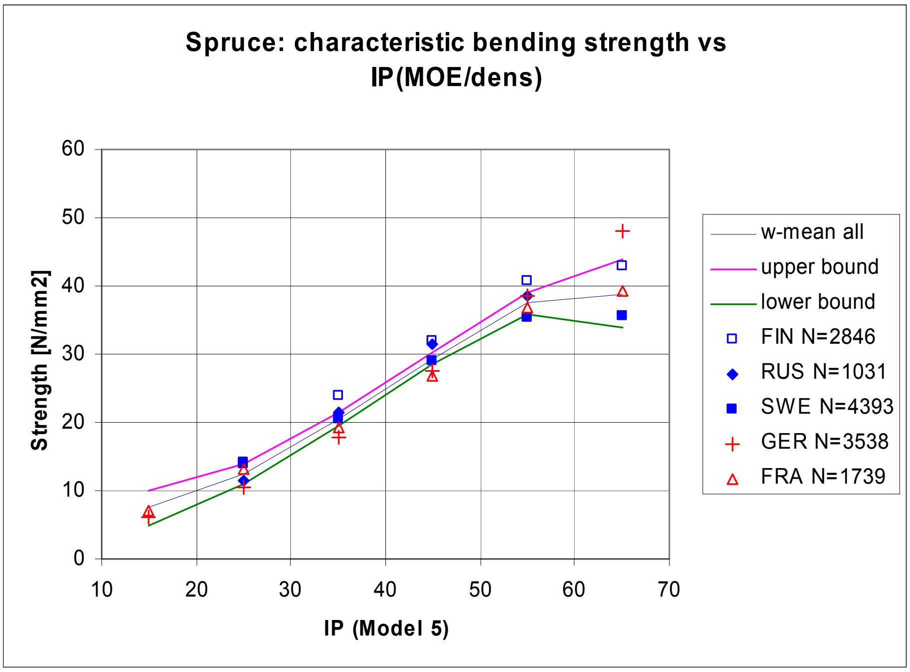

Figure 21. Comparison between countries, characteristic strength values with average confidence limits. Spruce in bending, Model 5.

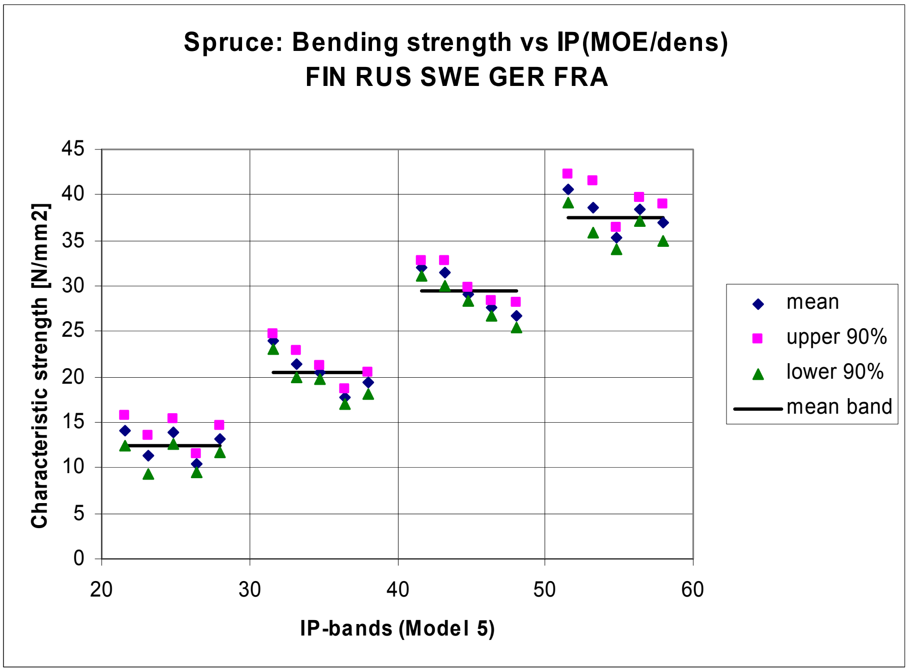

Figure 22. Comparison between countries, characteristic strength values with individual confidence limits. Spruce in bending, Model 5.

Model 14

Model 14 has E_{dyn}, *KAR*, density and sizes as variables, same as model 12 but here the dynamic modulus of elasticity replaces the static MoE. The sample sizes for this model are smaller and therefore all data the available was included in country comparison: Germany (N = 1 920), Finland (N = 645), Russia (N = 368) and Sweden (N = 350), in total 3 283 test results. Table 38 summarizes obtained mean values. Figs. 23 and 24 illustrate characteristic values of strength of each grade. German strength values are significantly higher than Nordic values for most grades. This result is at odds with that Model 12 but in line with model 2 which uses almost the same data large extent the same data.

Table 38. Averages of European results based on 3 283 results. Spruce, Model 14.

Range of f_{model} N/mm^2	Weighted averages $f_{adj,mean}$ N/mm^2	COV %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	COV %	Average N	Upper $f_{adj,0,05}$ N/mm^2	Lower $f_{adj,0,05}$ N/mm^2
–10						7		
10–20	21.1	29.3		6 856	18.4	40		
20–30	29.5	25.7	17.0	9 022	14.4	151	18.76	15.23
30–40	38.8	21.5	25.1	11 101	12.5	259	26.75	23.43
40–50	47.5	17.4	33.8	12 993	9.9	249	35.67	31.99
50–60	56.4	15.2	42.2	15 014	8.6	100	45.39	39.04
60–70	62.2	13.7	48.2	17 042	8.8	15	56.56	39.82
70–	67.7			18 026	1.3	1		
all		30.6			23.0	821		

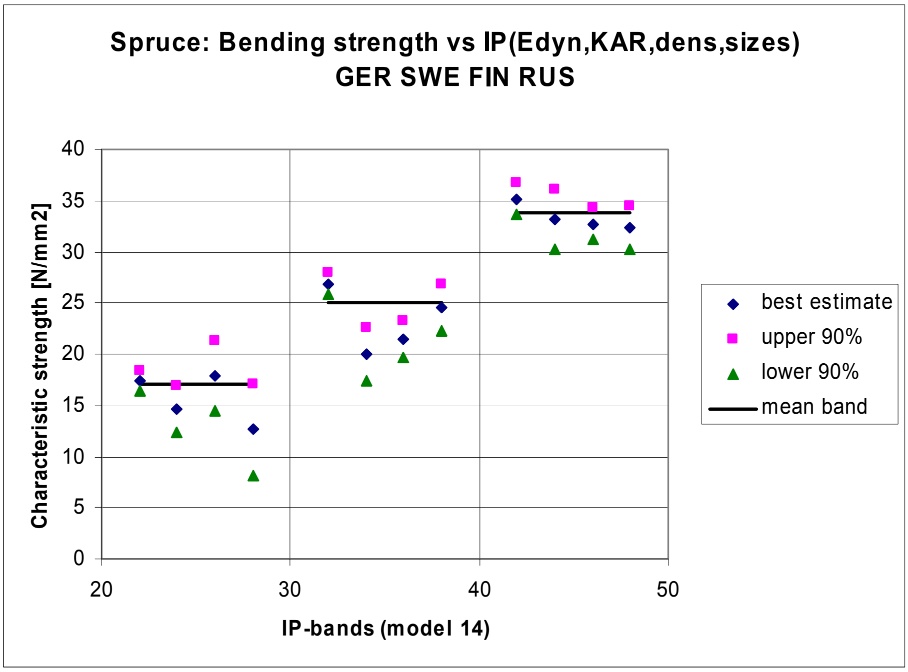

Figure 23. Comparison between countries, characteristic strength values with individual confidence limits. Spruce in bending, Model 14.

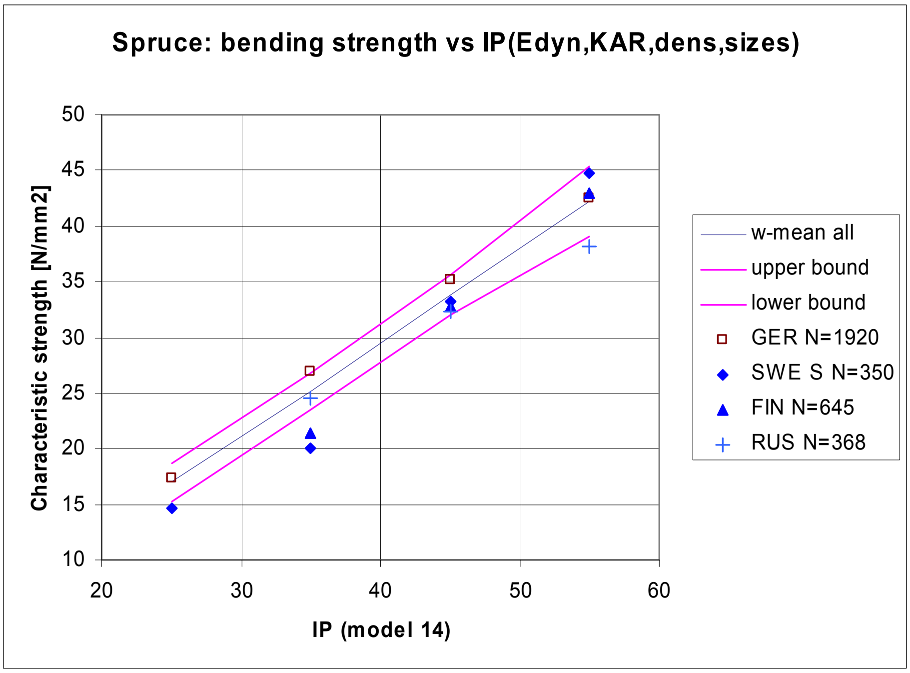

Figure 24. Comparison between countries, characteristic strength values with average confidence limits. Spruce in bending, Model 14.

4.1.2.3 Models with *KAR* as primary variable

Model 4 is based on *KAR*. From the Nordic countries there are 3 samples from Finland, in total 1 214 data points. The results are shown in Fig. 25. All the strength values are within the confidence limits.

For Central Europe we have three regions in Germany, North ($N = 456$), West ($N = 1\ 437$), East ($N = 1\ 645$) and a combined sample from France ($N = 1\ 647$). Results are shown in Fig. 26. 3 of 9 German values fall outside the confidence limits.

Model 9 uses *KAR* and density as variable, and the r^2 improves from 0.34 to 0.48. Nordic results are based on the same 3 samples from Finland, one sample from North West Russia ($N = 368$) and one sample from South Sweden ($N = 350$). 3 of 20 strength values are outside the confidence limits (see Appendix C).

Central European results are based on the same sample as in case of Model 4. Now 5 of 12 German strength values are outside the confidence limits (see Appendix C).

The difference between results based on models 4 and 9 is that yields for the highest grade $IP > 50$ are 21% for model 9 as opposed to 14% for model 4 in Central Europe and the characteristic strength rises from 34.2 to 35.8 N/mm^2. In Nordic countries the yield is 23% for both models, and strength increases from 36 to 38.3 N/mm^2 when using model 9.

Comparison between countries concerning Model 4 is based on results from Germany ($N = 3\ 538$), France ($N = 2\ 647$) and Finland ($N = 1\ 214$). The average values are shown in Table 39. Fig. 27 shows that the same knot criteria would lead to different strength values in Central Europe and Nordic countries. Results also show that higher grades than C30 are not feasible when using only knot size based grading, and *COV* of strength and *E* are as high for graded timber as for un-graded timber. The comparison between countries concerning Model 9 includes the same data sets as in case of Model 4. The averages are shown in Table 40, and results are illustrated in Appendix C. The results show that the Finnish results are above the confidence limit for this mainly Central Europe based model, and the German and French results are within the limits.

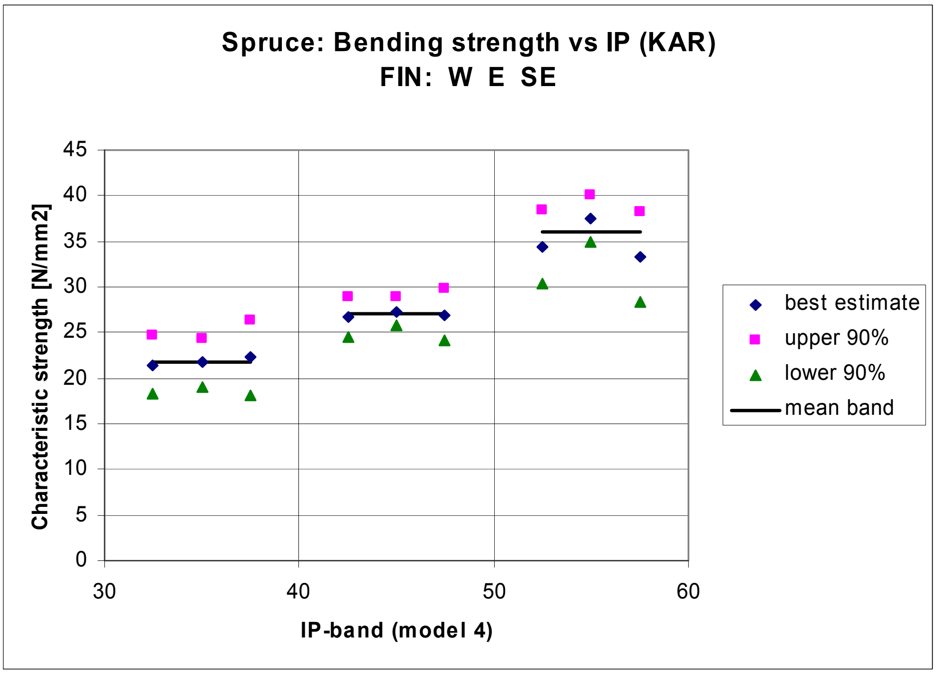

Figure 25. Comparison between Finnish regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 4.

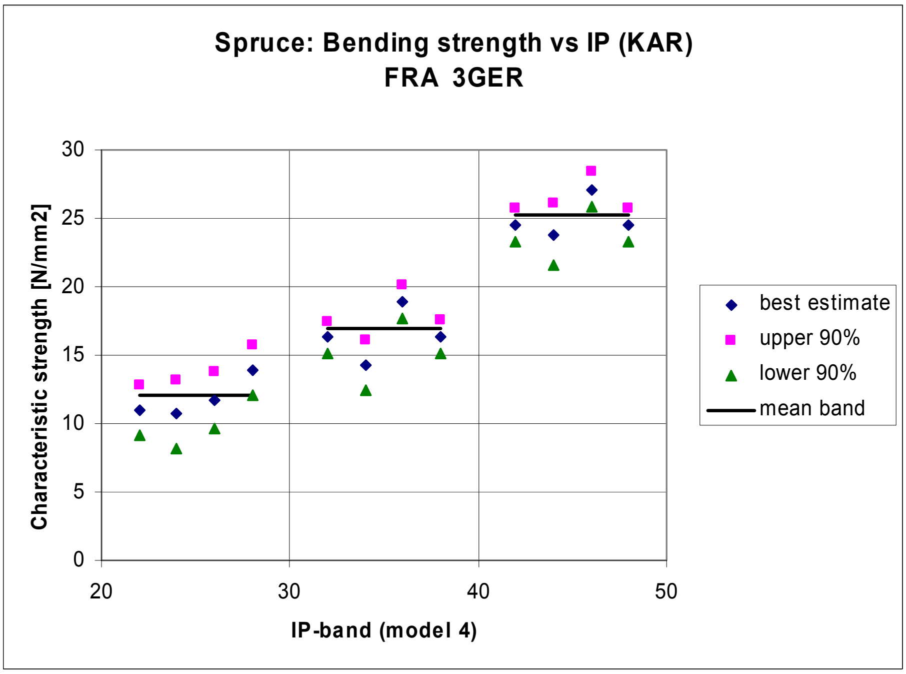

Figure 26. Comparison between CE-regions, characteristic strength values with individual confidence limits. Spruce in bending, Model 4.

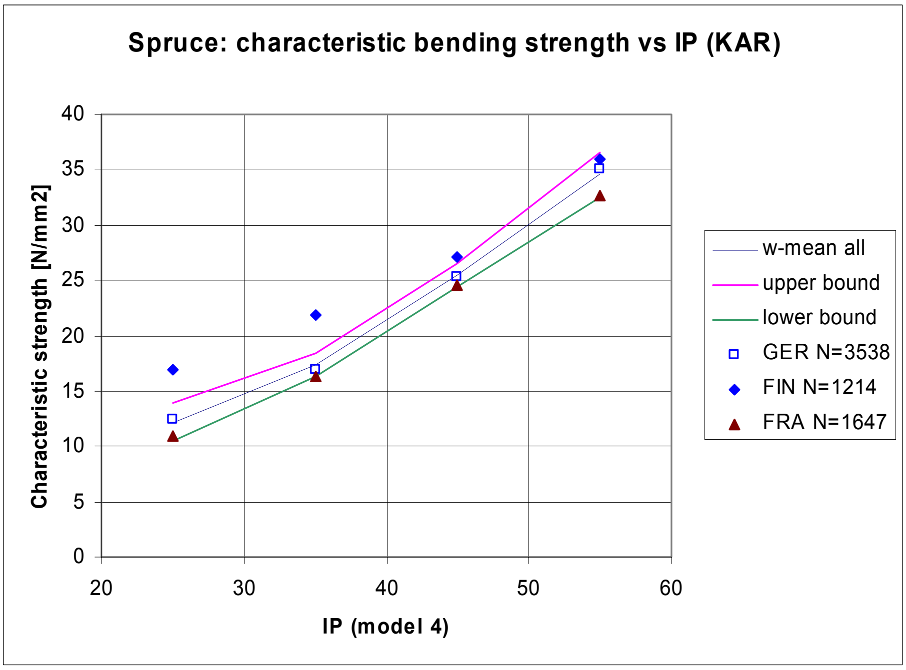

Figure 27. Comparison between countries, characteristic strength values with average confidence limits. Spruce in bending, Model 4.

Table 39. Averages of German, French and Finnish results for Model 4.

Range of f_{model} N/mm²	Weighted averages $f_{adj,mean}$ N/mm²	COV %	$f_{adj,0,05}$ N/mm²	E_{mean} N/mm²	COV %	Average N	Upper $f_{adj,0,05}$ N/mm²	Lower $f_{adj,0,05}$ N/mm²
–10	16.5	33.5		5 397	22.5	2		
10–20	21.4	34.2		7 623	19.1	24		
20–30	27.2	33.5	12.2	8 997	19.5	134	13.94	10.44
30–40	34.9	30.5	17.4	10 843	16.9	597	18.43	16.28
40–50	45.4	26.5	25.5	12 854	15.6	1 042	26.56	24.49
50–60	53.8	21.6	34.6	13 634	13.9	334	36.62	32.57
60–70						0		
70–								
all		31.4			15.4	2 133		

Table 40. Averages of German, French and Finnish results for Model 9.

Range of f_{model} N/mm²	Weighted averages $f_{adj,mean}$ N/mm²	COV %	$f_{adj,0,05}$ N/mm²	E_{mean} N/mm²	COV %	Average N	Upper $f_{adj,0,05}$ N/mm²	Lower $f_{adj,0,05}$ N/mm²
–10	21.5	32.9		6 525	15.9	4		
10–20	22.3	30.9	11.0	7 285	16.5	31	14.01	7.94
20–30	26.2	31.9	12.4	8 431	17.6	194	13.82	11.01
30–40	35.0	26.9	19.5	10 586	13.4	613	20.50	18.41
40–50	45.2	23.4	27.7	12 741	12.0	841	28.85	26.64
50–60	54.6	20.1	36.5	14 730	11.9	405	38.29	34.68
60–70	62.0	18.7	43.0	16 755	12.3	45	48.98	37.09
70–	75.1	4.5	69.7	20 301	2.0	1	85.22	54.18
all		31.4			15.4	2 133		

4.2 Tension of spruce

4.2.1 European regression models

14 regression equations are used in the analysis. Regression equations are given Eqn. (1) and coefficients for tension of spruce in Table 41. The table also includes the coefficient of determination (r^2), the total sample size and countries from where timber was harvested.

From single variable models highest the coefficient of determination r^2 = 0.65 is obtained when static tension modulus of elasticity is the variable, and second highest r^2 = 0.61 for $E_{dyn.}$ Also all other coefficients of determination are slightly higher than in the case of bending. These results are based on 3 000–5 000 test values.

Contrary to the bending results, tension E_{dyn} has a higher r^2 than E/ρ. Knot area ratio (*KAR*) alone has a r^2 = 0.35, and when combined to density (Model 9) the r^2 = 0.55. Addition of cross-section dimensions the model increase coefficient of determination only marginally and it remains r^2 = 0.55.

Strength values used in the analysis are adjusted to European reference size h = 150 mm and length l = 2 000 mm according to EN 1194 (CEN 1999), and this seems to be an adequate adjustment for spruce in tension. Other models in the table have the same conclusion drawn with regard to size effect.

When combining other variables for E in modeling the conclusions are:

1. density with or without dimensions does not improve the model (r^2 = 0.66). As for bending, an increase in the density gives a lower strength in the case of many of the models.
2. *KAR* improves the model to r^2 = 0.72 which is the highest value obtained. Adding the density and dimensions to the models does not improve the coefficient of determination.
3. E_{dyn} in combination with *KAR* and density gives r^2 = 0.69 which is slightly lower than that obtained by combining static E and *KAR*.

Table 41. Summary table of European regression models for tension of spruce.

Model	Coefficient of variable								r^2	N	Data included
	1	b mm	h mm	ρ kg/m^3	E N/mm^2	*KAR*	E_{dyn} N/mm^2	$E[N/mm^2]/\rho\ [kg/m^3]$			
1	-11.76				0.003658				0.65	4 879	GER, AT, SWE, NOR, FIN, RUS
2	-16.82						0.003770		0.61	3 134	GER, FIN, RUS
3	-22.95			0.12037					0.28	4 879	GER, AT, SWE, NOR, FIN, RUS
4	46.71					-59.05			0.35	3 096	GER, FIN, RUS
5	-22.20							2.041	0.53	4 879	GER, AT, SWE, NOR, FIN, RUS
6	-9.43	0.1210	-0.0012	-0.02630	0.004042				0.66	4 879	GER, AT, SWE, NOR, FIN, RUS
7	-4.67			-0.02531	0.004019				0.66	4 879	GER, AT, SWE, NOR, FIN, RUS
8	-4.16	0.0347	-0.0018	0.10393		-47.21			0.55	3 096	GER, FIN, RUS
9	-2.97			0.10402		-47.07			0.55	3 096	GER, FIN, RUS
10	0.02	0.0163	-0.0120		0.003272	-21.77			0.72	3 096	GER, FIN, RUS
11	-1.32				0.003269	-20.03			0.72	3 096	GER, FIN, RUS
12	5.17	0.0114	-0.0139	-0.02122	0.003649	-20.04			0.72	3 096	GER, FIN, RUS
13	2.55			-0.01786	0.003586	-18.30			0.72	3 096	GER, FIN, RUS
14	6.85	-0.0078	-0.0057	-0.02858		-29.67	0.003648		0.69	3 096	GER, FIN, RUS

4.2.2 Growth area analysis

European regression equations (Table 41) are used as strength indicating properties (*IP*) and test material held by participants is graded simultaneously to several grades by using *IP* = 10, 20, 30 etc as settings. Comparison of the 5^{th} percentile values of each grade of the wood grown in different regions is the main result of this analysis.

For tension, data available is considerably less than in bending, and an evaluation of variation in properties within Nordic region can only be made in the case of model 1, and for the evaluation between countries a sample of only 1 000 specimens was available.

Based on the degrees of determination and applicability as grading method the following models were used in the analysis: Model 1 (*E*), Model 11 (*E* + *KAR*), Model 2 (E_{dyn}), Model 14 (E_{dyn} + *KAR* + density), Model 4 (*KAR*), and Model 9 (*KAR* + density).

4.2.2.1 Models with *E* as primary variable

Model 1 based results

For Model 1 there are 2 000 Nordic and 3 000 Central European specimens, mainly German. Yields to the high grade *IP* > 40 are about 15%; being slightly lower in Central Europe than for the Nordic data (14 vs. 17%). A best estimate of 5^{th} percentile value of strength is about 29 N/mm^2 in both cases. In the other grades the strength of Nordic and Central European timber is practically the same.

Nordic growth area results are shown in Appendix C. 90% of the results for the 8 samples in three main bandwidths are within the confidence limits based on individual values of sample size and *COV*. Accordingly, it can be stated that for tension the results are less variable within Nordic countries than for bending.

Results of seven samples of Central European data based on Model 1 are shown in Appendix C. All values are within the confidence limits and thus less variable than bending results.

The hypothesis that all European data would belong to same growth area is studied by using combined samples of Finland (*N* = 611), Sweden (905), Norway (351), Russia (186), Germany (1 253), Austria (311) and Czech Republic (373). As shown in Figs. 28 and 29, all the 5^{th} percentile values for strength are within the confidence limits indicating that all these regions may belong to the same growth area.

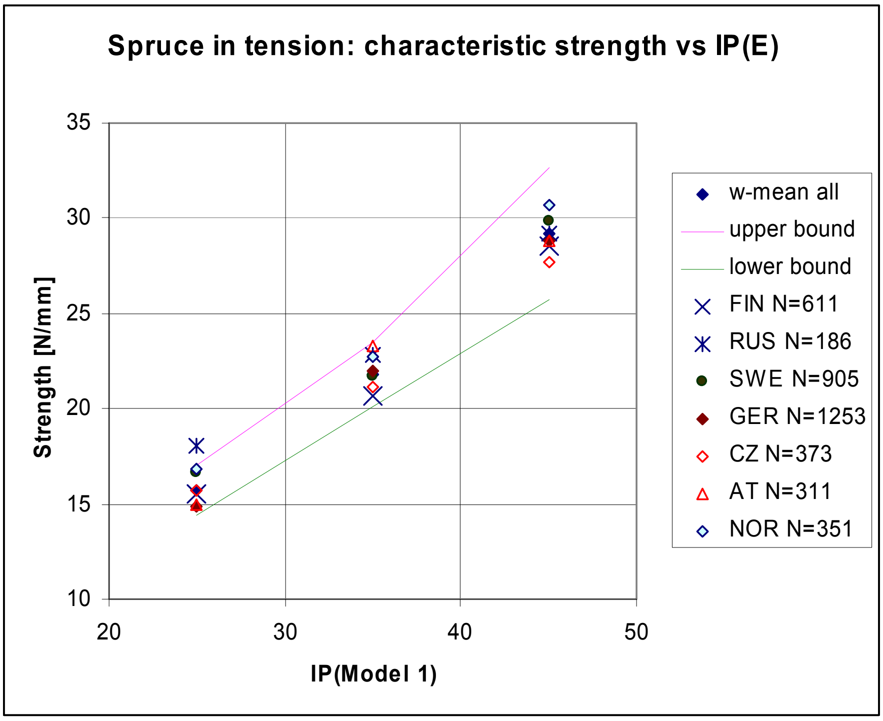

Figure 28. Comparison between countries, characteristic strength values with average confidence limits. Spruce in tension, Model 1.

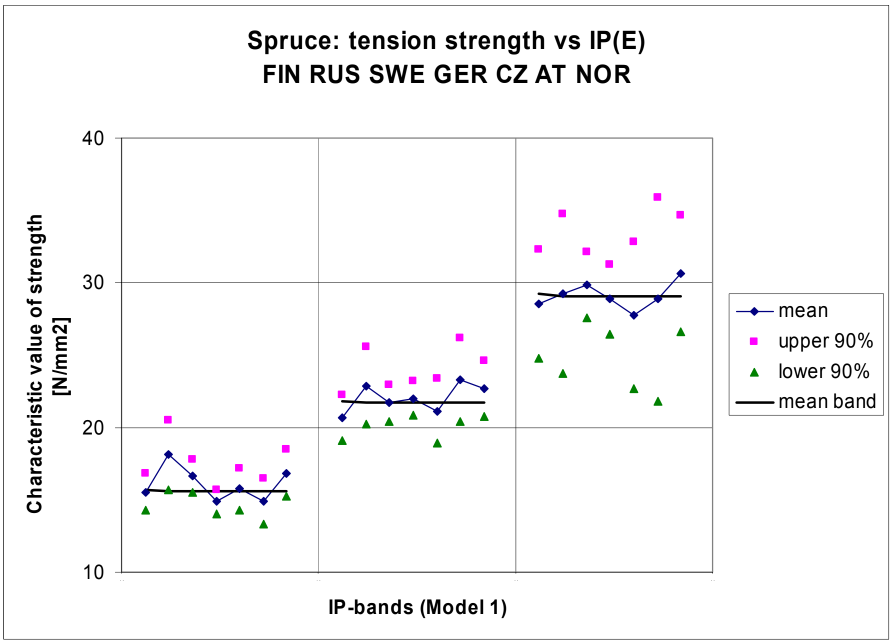

Figure 29. Comparison between countries, characteristic strength values with individual confidence limits. Spruce in tension, Model 1, based on same data as Fig. 28.

Table 42. Combined results of 7 countries for spruce in tension, Model 1. Weighted averages of mean values, 5 percentiles and COV's and means of sample sizes per country and band, and upper and lower confidence limits of 5 percentiles obtained by using average COV's and sample sizes.

Range of	Weighted averages					Average	Upper	Lower
f_{model} N/mm^2	$f_{adj,mean}$ N/mm^2	*COV* %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	*COV* %	*N*	$f_{adj,0,05}$ N/mm^2	$f_{adj,0,05}$ N/mm^2
–10						3		
10–20	17.1	25.3	10.0	7 782	8.3	61	11.62	8.41
20–30	25.4	23.7	15.7	10 182	7.3	207	17.01	14.44
30–40	34.1	22.4	21.8	12 662	6.0	208	23.49	20.14
40–50	44.4	21.1	29.2	15 197	4.9	77	32.68	25.72
50–60	55.1	20.2		17 03	3.9	14		
60–70						2		
70–								
all		35.6			20.5	570		

Model 11 based results

In Model 11 *E* and *KAR* are the variables. Adding *KAR* increases the r^2 from 0.65 to 0.72. At the same time the sample size available decreases from nearly 5 000 to 3 000. Especially for the Nordic data (Finland N = 246, Russia N = 172). Because of limited data the analysis is only for combination of all 7 samples as illustrated in Figure 30. All results are within the confidence limits. The results are similar to those of Model 1. In the case of Model 11 the strength values are marginally higher.

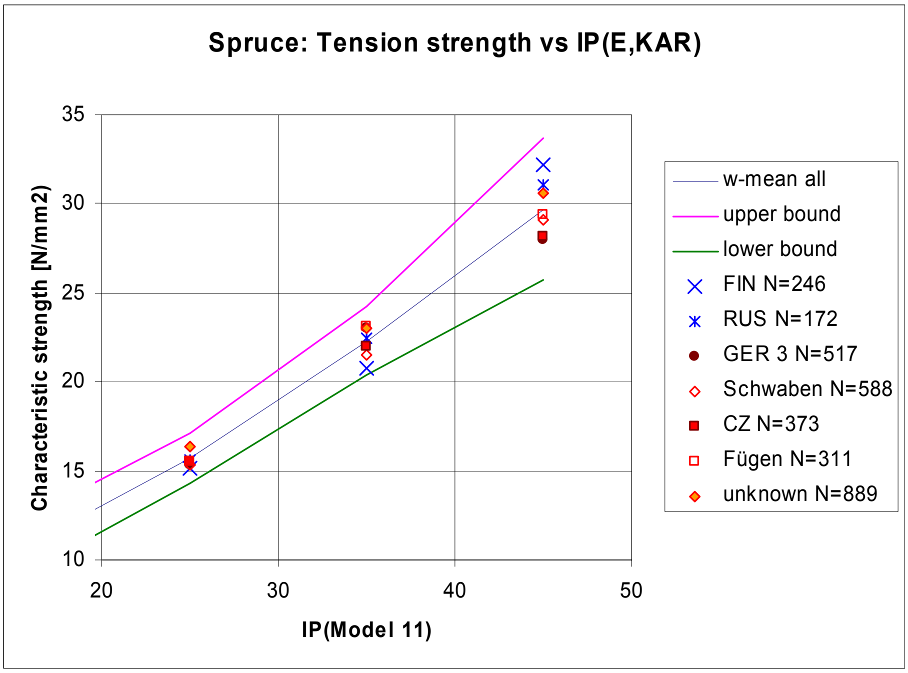

Figure 30. Comparison between countries, characteristic strength values with average confidence limits. Spruce in tension, Model 11.

4.2.2.2 Models with E_{dyn} as primary variable

Model 2 based results

For Model 2 we have only 450 Nordic and 2 700 Central European, mainly German, test results. Yields to the high grade *IP* > 40 is about 16%. A best estimate of the 5th percentile value of strength is clearly higher for Nordic than for Central European timber which is different to that of Model 1. The averages for the 5th percentiles are lower than in the case of Model 1, 27 N/mm^2 for the high grade *IP* > 40.

All results are shown in Figs. 31 and 32. 75% of the results of 7 samples in three main bandwidths are inside the confidence limits based on individual values for sample size and *COV*. Accordingly, nearly all Nordic values are outside the confidence limits. This result is opposite to that of Model 1, which is surprising, and further efforts are needed to find the reasons for this difference.

Table 43. Combined results of 5 countries for spruce in tension, model 2. Weighted averages of mean values, 5 percentiles and COV's and means of sample sizes per country and band, and upper and lower confidence limits of 5 percentiles obtained by using average COV's and sample sizes.

Range of	Weighted Averages						Upper	Lower
f_{model} N/mm^2	$f_{adj,mean}$ N/mm^2	*COV* %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	*COV* %	*N*	$f_{adj,0,05}$ N/mm^2	$f_{adj,0,05}$ N/mm^2
–10						2		
10–20	17.5	27.5	9.6	7 948	12.5	58	11.32	7.88
20–30	25.2	26.0	14.4	10 073	11.7	176	15.82	13.02
30–40	34.0	23.5	20.8	12 426	9.3	149	22.79	18.81
40–50	43.8	23.5	26.8	14 864	8.1	54	31.08	22.56
50–60	54.8	20.5		13 245	5.3	9		
60–70						2		
70–						0		
all		30.5			17.4	448		

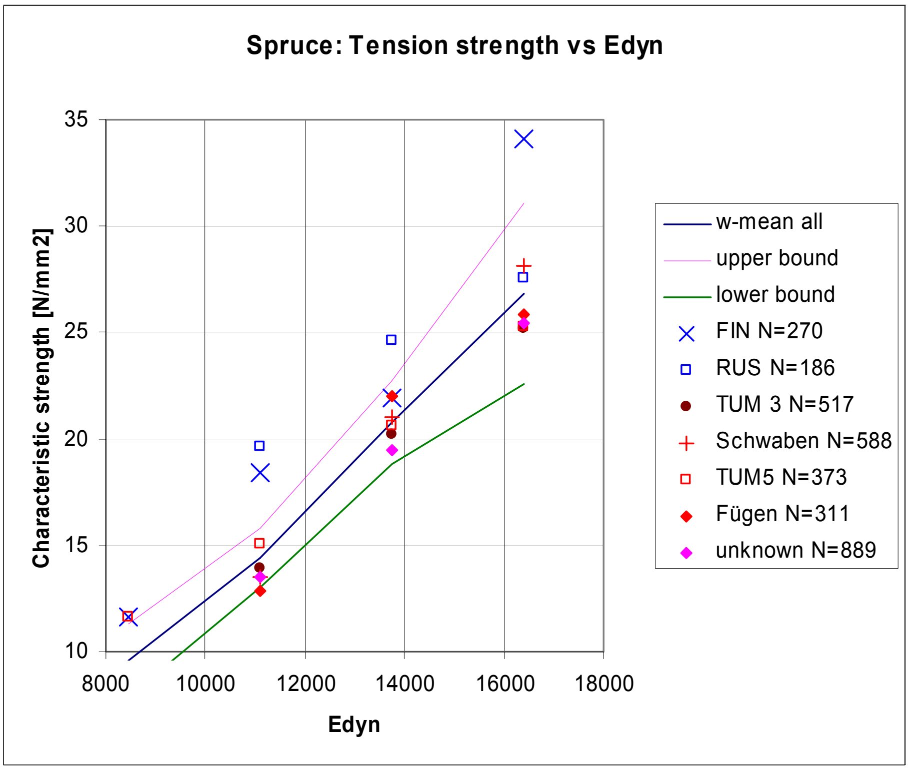

Figure 31. Comparison between regions, characteristic strength values with average confidence limits. Spruce in tension, Model 2.

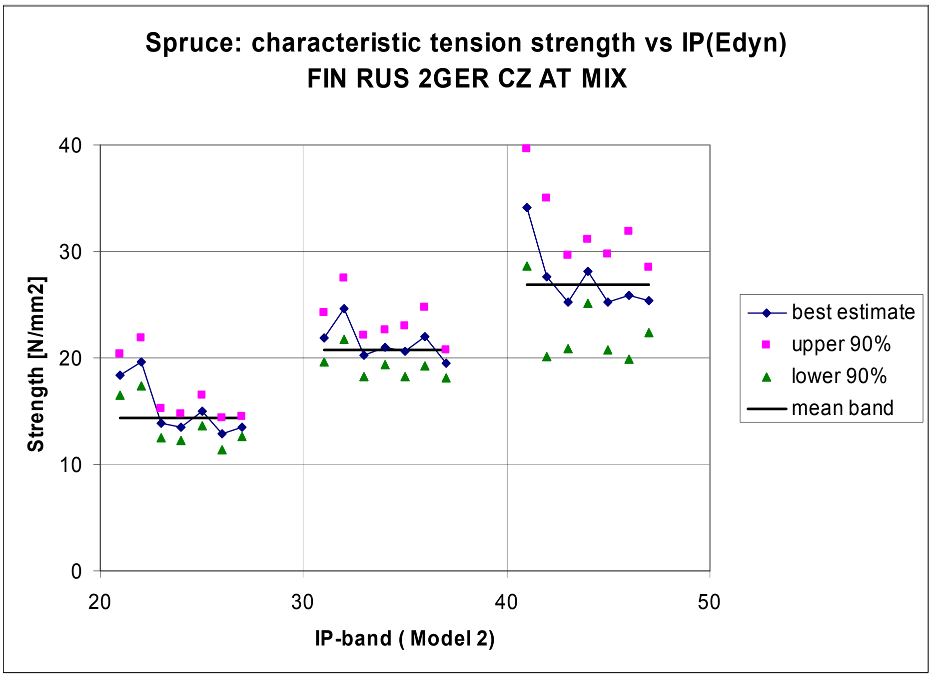

Figure 32. Comparison between regions, characteristic strength values with individual confidence limits. Spruce in tension, Model 2, based in same data as Fig. 31.

Model 14 based results

Model 14 includes E_{dyn}, *KAR* and density as variables. There is about the same amount of data for model Model 2: two regions from Germany (517 + 588), Check republic (373), Austria (311), unspecified area in Central Europe (889), Finland (246), and Russia (172). On average, the yield to *IP* > 40 is 15% and the 5th percentile of tension strength is 29 N/mm^2.

When all 7 samples are analyzed simultaneously, all the values are within the confidence limits (Fig. 34). This is clearly different from the case in Model 2.

Table 44. Combined results of 5 countries for spruce in tension, model 14. Weighted averages of mean values, 5 percentiles and COV's and means of sample sizes per country and band, and upper and lower confidence limits of 5 percentiles obtained by using average COV's and sample sizes.

Range of	Weighted averages						Upper	Lower
f_{model} N/mm²	$f_{adj,mean}$ N/mm²	*COV* %	$f_{adj,0,05}$ N/mm²	E_{mean} N/mm²	*COV* %	*N*	$f_{adj,0,05}$ N/mm²	$f_{adj,0,05}$ N/mm²
–10	12.6	25.3		6 995	19.7	5		
10–20	17.1	24.1	10.3	8 088	12.5	61	11.91	8.75
20–30	24.9	23.7	15.2	10 087	12.1	160	16.56	13.76
30–40	33.9	21.8	21.7	12 353	9.9	150	23.61	19.77
40–50	44.6	21.0	29.1	14 748	8.5	56	33.19	25.08
50–60	56.0	20.3	36.3	17 410	5.6	10	48.06	24.62
60–70						1		
70–						0		
all		30.9			17.6	442		

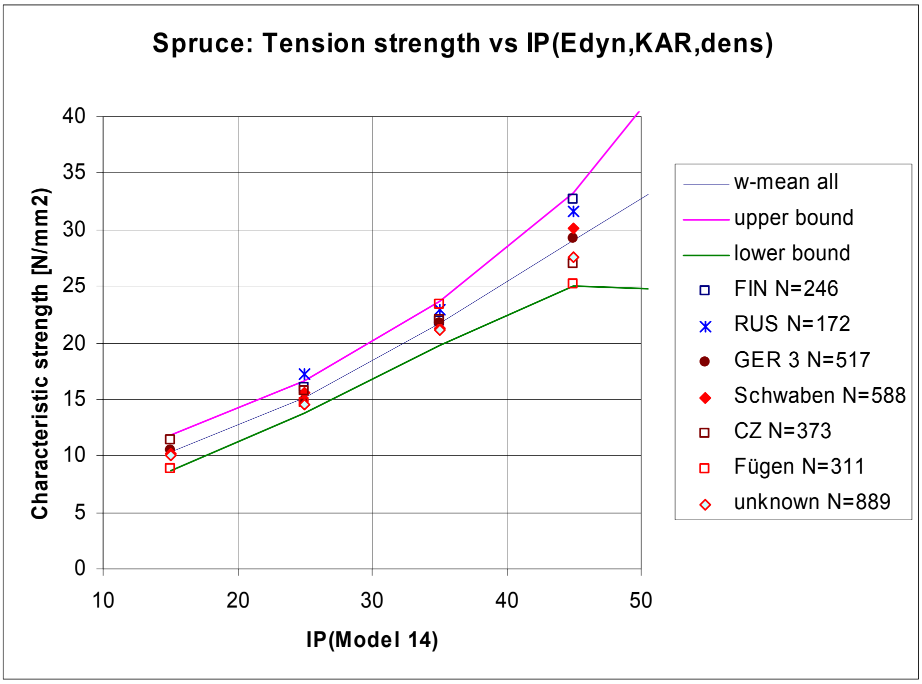

Figure 33. Comparison between regions, characteristic strength values with average confidence limits. Spruce in tension, Model 14.

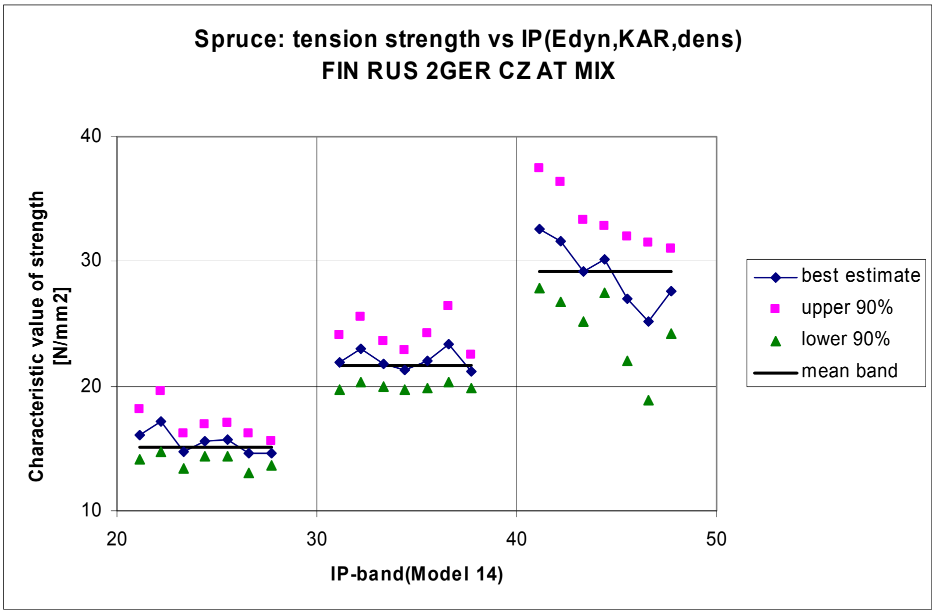

Figure 34. Comparison between regions, characteristic strength values with individual confidence limits. Spruce in tension, Model 14, based in same data as Fig. 33.

4.2.2.3 Models with *KAR* as primary variable

Model 4 based results

For Model 4 there are only 420 Nordic and 2 700 Central European, mainly German, test results. On average, the yield to the high grade $IP > 40$ is about 6%. The averages for the 5th percentiles are lower than for the other calculated models, 21 N/mm^2 for the high grade $IP > 40$.

All results are shown in Figs. 35 and 36. 60% of the results of 7 samples are in two main bandwidths and inside the confidence limits based on individual values of sample size and *COV*. If the Nordic values are excluded, only 50% of Central European values are inside the confidence limits. This indicates that knot-size based grading is less accurate than any other model calculated.

Table 45. Combined results of 5 countries for spruce in tension, model 4. Weighted averages of mean values, 5 percentiles and COV's and means of sample sizes per country and band, and upper and lower confidence limits of 5 percentiles obtained by using average COV's and sample sizes.

Range of	Weighted Averages						Upper	Lower
f_{model} N/mm^2	$f_{adj,mean}$ N/mm^2	*COV* %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	*COV* %	*N*	$f_{adj,0,05}$ N/mm^2	$f_{adj,0,05}$ N/mm^2
–10	15.7			7 887		3		
10–20	18.7	32.4		8 742	20.3	30		
20–30	24.8	31.2	12.1	10 315	19.4	178	13.49	10.69
30–40	34.6	31.1	16.8	12 325	18.6	205	18.65	15.03
40–50	43.3	30.8	20.8	13 322	19.2	27	26.91	14.71
50–60						0		
60–70						0		
70–						0		
all		30.9			17.6	442		

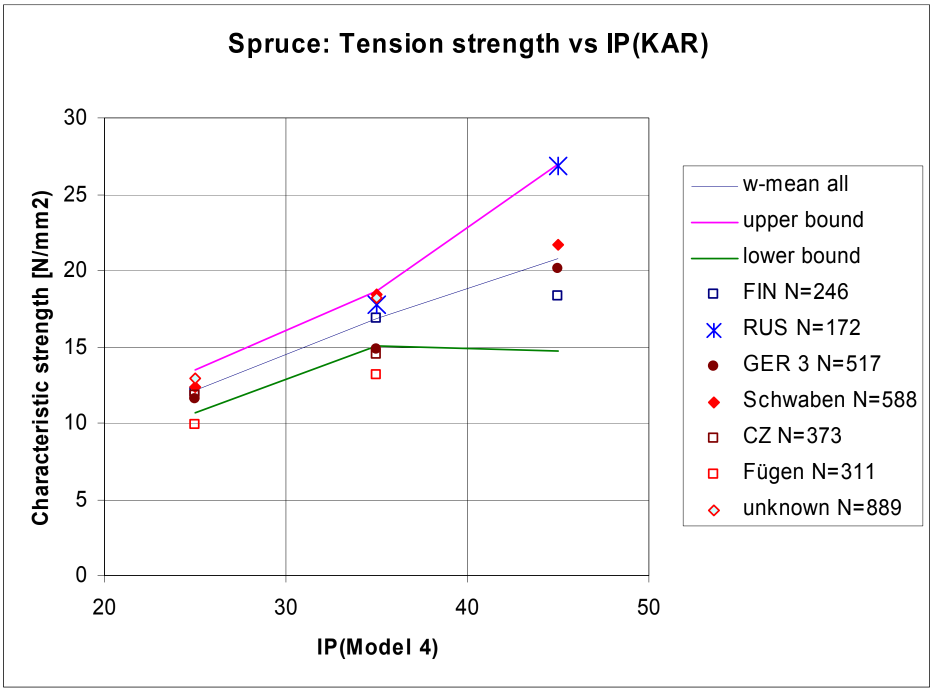

Figure 35. Comparison between regions, characteristic strength values with average confidence limits. Spruce in tension, Model 4.

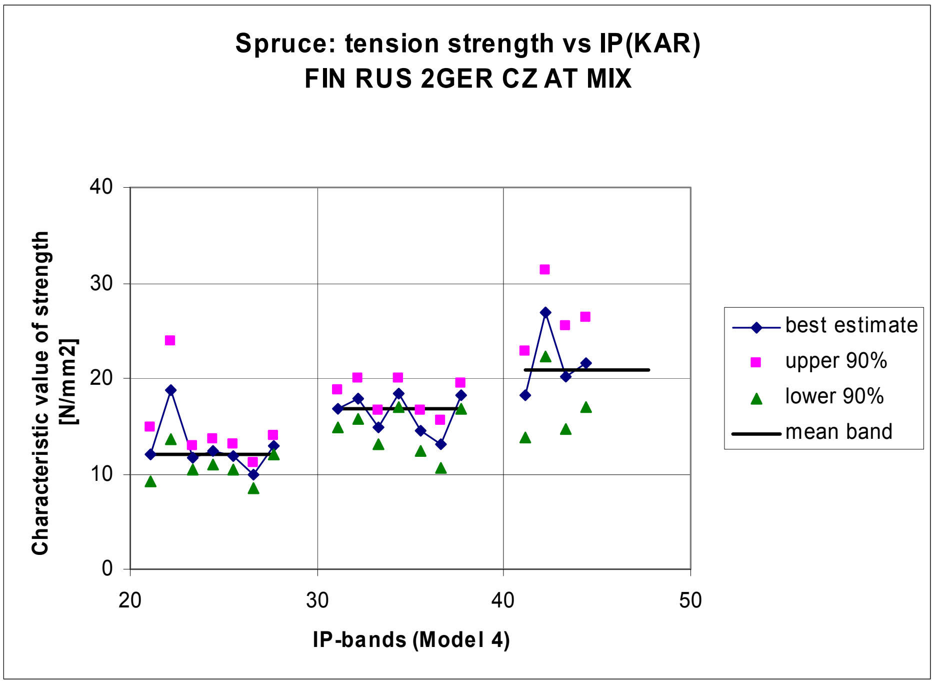

Figure 36. Comparison between regions, characteristic strength values with individual confidence limits. Spruce in tension, Model 4, based in same data as Fig. 35.

Model 9 based results

In Model 9 density is used as variable besides *KAR*, and r^2 increases from 0.35 to 0.55. The same test material is available in both cases. On average, yield to high the grade $IP > 40$ is about 12% instead of 6% as in case of Model 4. The averages for the 5th percentiles have increased, 26 N/mm^2 in the high grade $IP > 40$.

All the results are shown in Figs. 37 and 38. 95% of the results for the 7 samples in three main bandwidths are inside the confidence limits, based on individual values of sample size and *COV*. This indicates that knot-size combined with density is a better grading method than knot size alone.

Table 46. Combined results of 5 countries for spruce in tension, model 9. Weighted averages of mean values, 5 percentiles and COV's and means of sample sizes per country and band, and upper and lower confidence limits of 5 percentiles obtained by using average COV's and sample sizes.

Range of	Weighted averages						Upper	Lower
f_{model} N/mm^2	$f_{adj,mean}$ N/mm^2	COV %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	COV %	N	$f_{adj,0,05}$ N/mm^2	$f_{adj,0,05}$ N/mm^2
–10	14.1	25.4		7 048	12.9	4		
10–20	17.8	25.7		8 207	14.5	49		
20–30	24.6	26.7	13.8	10 026	14.5	167	15.19	12.37
30–40	34.3	26.1	19.5	12 407	12.8	171	21.44	17.59
40–50	45.1	26.0	25.8	14 914	12.9	48	30.62	21.00
50–60	57.3	33.8		17 871	16.1	4		
60–70						1		
70–						0		
all		30.9			17.6	442		

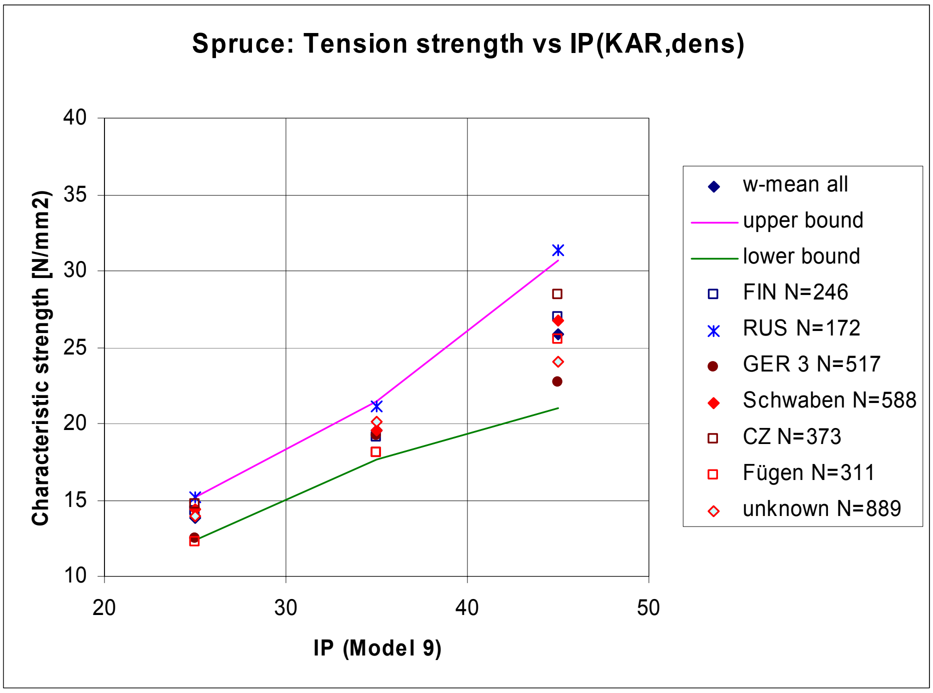

Figure 37. Comparison between regions, characteristic strength values with average confidence limits. Spruce in tension, Model 9.

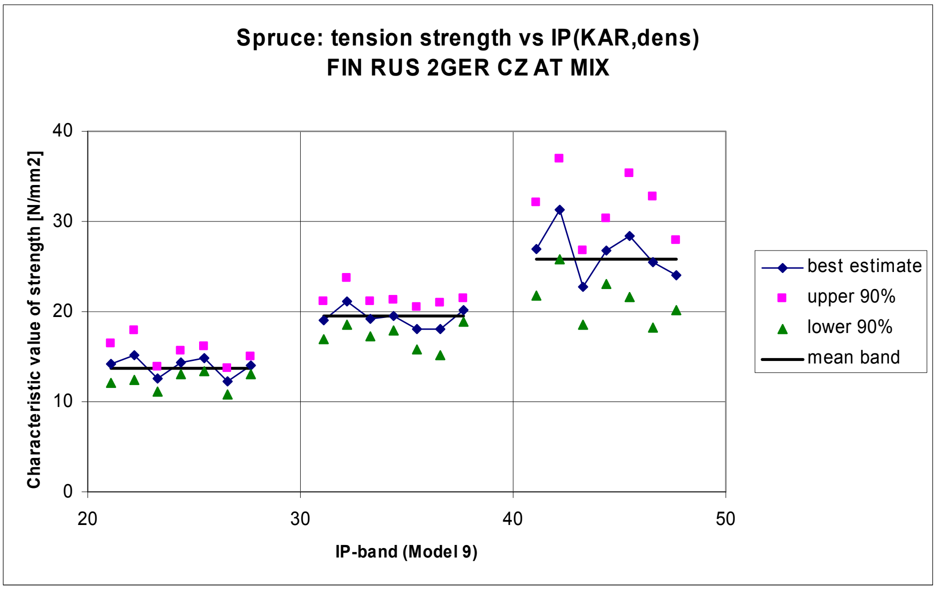

Figure 38. Comparison between regions, characteristic strength values with individual confidence limits. Spruce in tension, Model 9, based in same data as Fig. 37.

4.3 Strength profiles

4.3.1 *E*-strength relation

Relations of bending strength, tension strength, static and dynamic modulus of elasticity and density are analyzed. The first values obtained for the bandwidths when the bending of spruce results are graded by using Model 1 (edgewise *E*). Results are illustrated in Fig. 39. The relation of the 5th percentile for strength and mean values of *E* are evaluated by using the total samples of Sweden, Russia, Finland, Germany and France, total 13 500 values. *E* is 1 000–2 000 MPa higher for Central European timber than for Nordic timber when *E*-based grading results to the same strength. When comparing average strength vs. average *E*-results, the difference is similar but smaller (Fig. 40).

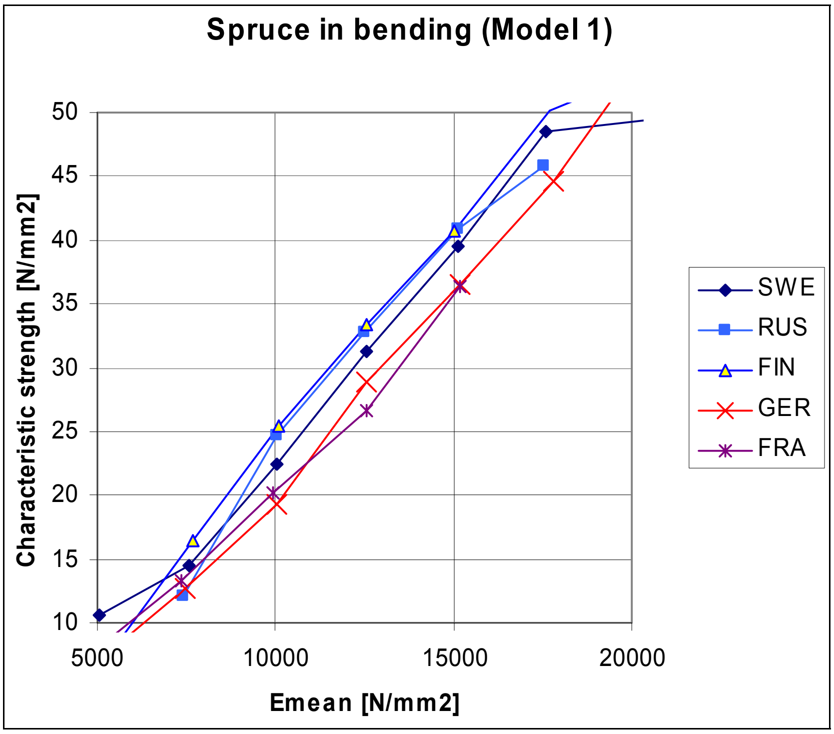

Figure 39. Characteristic bending strength of Swedish, Russian, Finnish, German and French grown spruce vs. average modulus of elasticity when graded on base of static E.

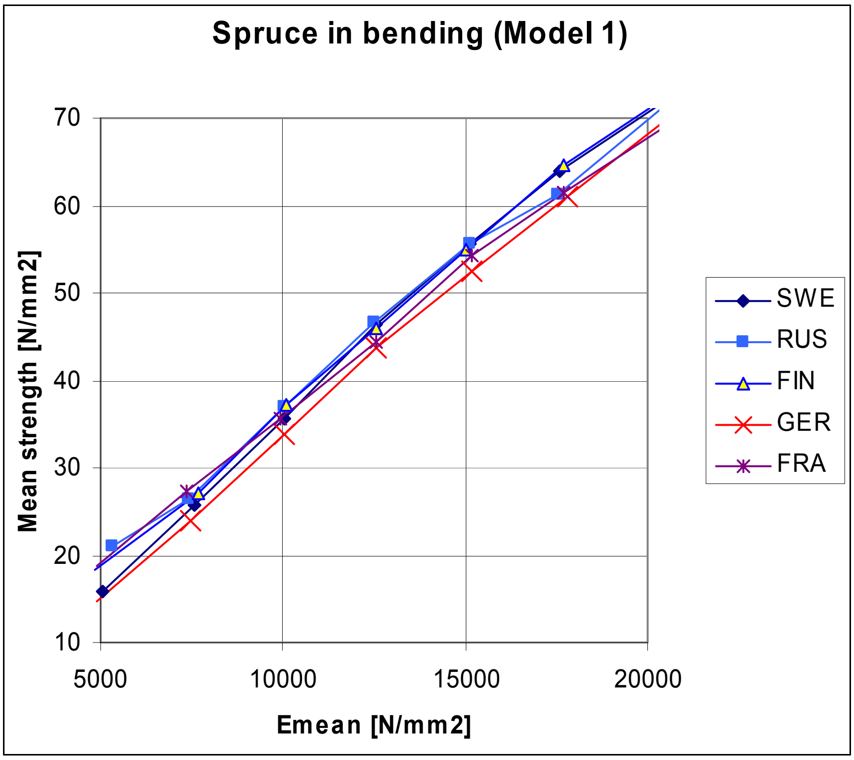

Figure 40. Average bending strength of Swedish, Russian, Finnish, German and French grown spruce vs. average modulus of elasticity when graded on base of static E.

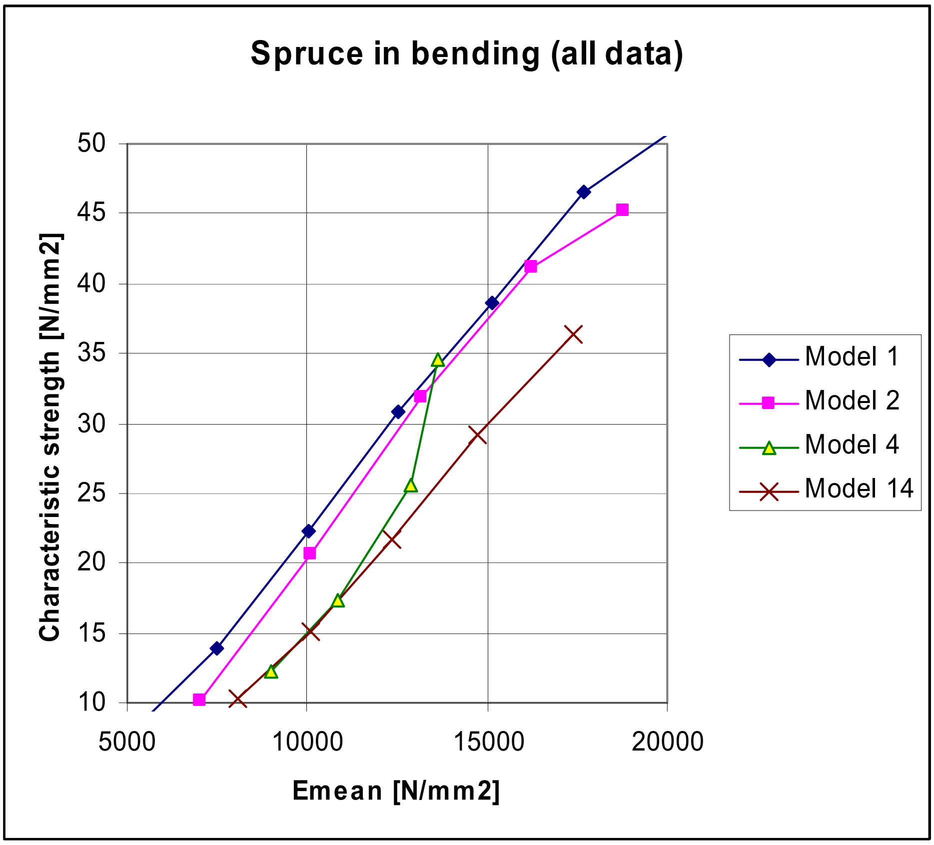

Figure 41. Characteristic bending strength vs. average E. Average of all European spruce data when grading is based on Models 1, 2, 4 and 14.

The dependence of strength-*E* relation as a grading method is studied by applying Models 1(*E*), 2(E_{dyn}), 4(*KAR*) and 14(E_{dyn}, *KAR*, density). Results are shown in Fig. 41, above, these indicate that grading based on E_{dyn} gives practically the same relation (E_{dyn} data is more Central European based than Model 1 data). Models 4 and 14 which include *KAR* result in higher *E* values for a given strength, the difference being 2 000 MPa to Models 1 and 2.

In tension the f_t-*E* relation is shown in Fig. 42, below. All data that was available has been used consisting primarily of German results. Models 1 (*E*), 9 (*KAR* + density) and 14 are applied. The results are close to each other, except for method 9 which gives 1 000 MPa higher *E* values for the same strength.

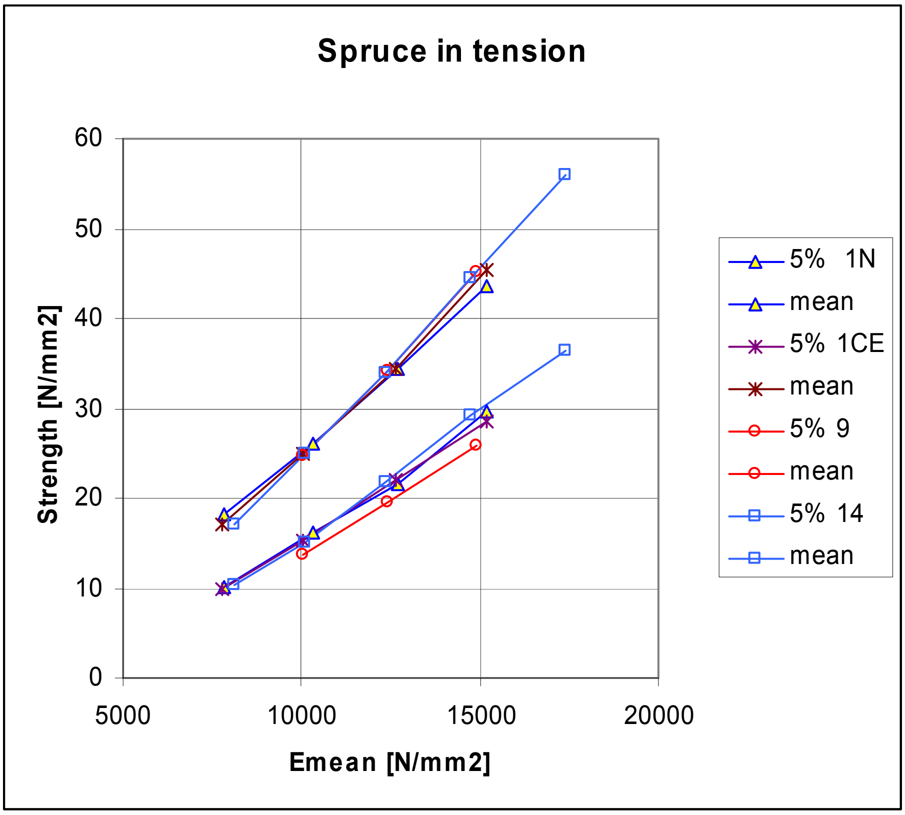

Figure 42. Tension strength of spruce vs. mean modulus of elasticity in tension. Nordic and Central European results of Model 1, combined European results of Models 9 and 14. Upper curves are mean values, lower curves characteristic values of strength.

4.3.2 Density-strength relation

Density and strength values are evaluated in bending for spruce, both by using combined national samples when using Model 1, and all data averages of characteristic values by using Model 2 (Fig. 43). Model 1 results show that for a given strength density is higher in Germany than in Nordic countries, the difference being 20 to 50 kg/m^3. When E_{dyn} is used as grading method, densities are marginally higher than in German data when using static modulus of elasticity. As most of the data in Model 2 is German, the difference between static and dynamic E is small. The results for mean values of strength are shown in Fig. 44.

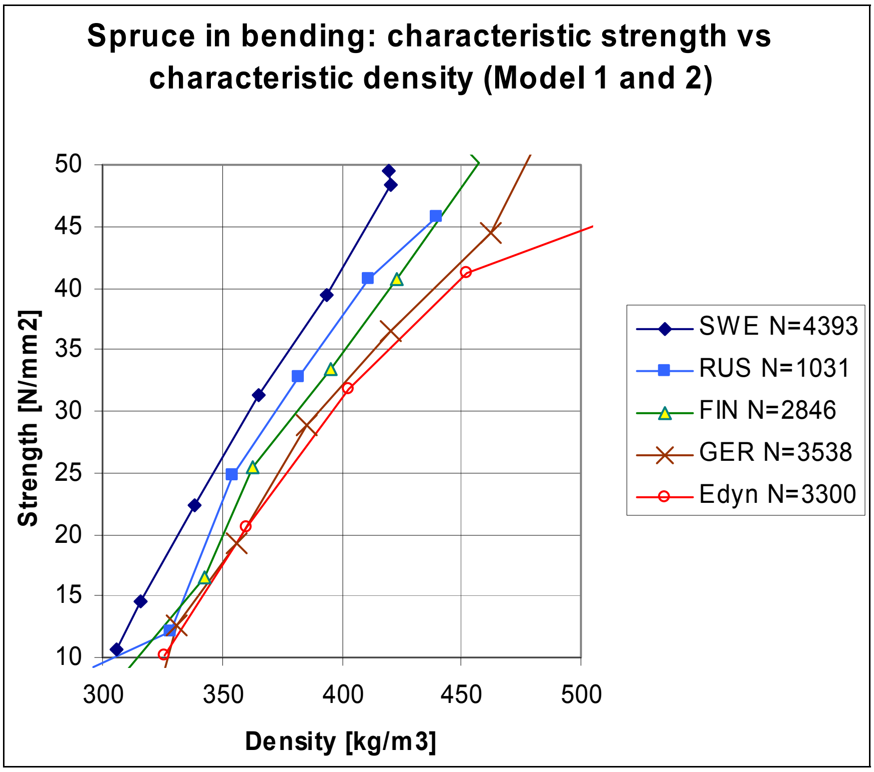

Figure 43. Characteristic bending strength of spruce vs. density when grading is based on static E (results separately for Swedish, Russian, Finnish, and German data) and dynamic E (combined data).

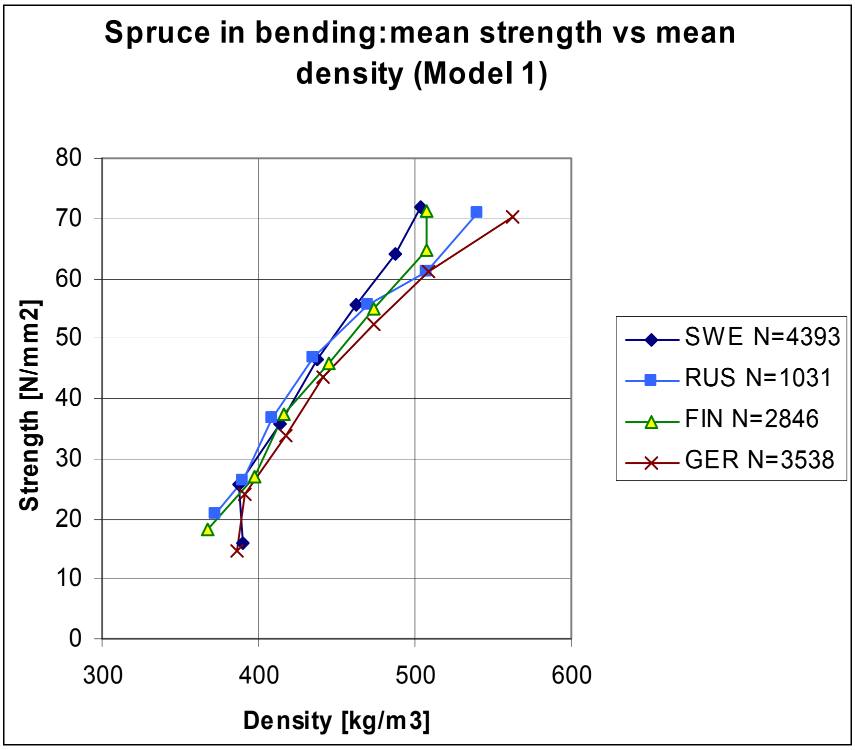

Figure 44. Average bending strength of spruce vs. density when grading is based on static E (results separately for Swedish, Russian, Finnish, and German data).

4.3.3 Bending vs. tension strength

Bending and tension strengths are compared by using Model 2 results, and by calculating both tension and bending strength values as function of E_{dyn}. Results are shown separately for German and Finnish results in Fig. 45. Based on linear regression lines shown in the Fig. 45, the ratio of tension and bending strength is calculated. When E_{dyn} is between 8 and 17 GPa, the ratio of tension and bending strength is quite constant, between 0.70 and 0.72 for Finnish spruce and between 0.66 and 0.73 for German spruce.

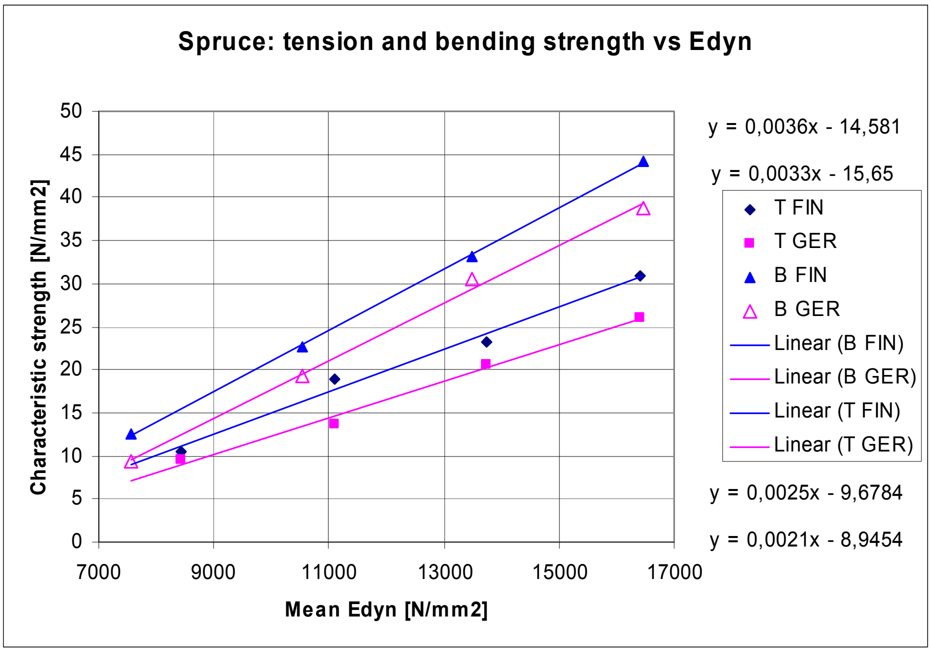

Figure 45. Illustration of bending (B) and tension (T) strength when grading is based on dynamic modulus of elasticity.

4.4 Conclusions for spruce

Results of **bending** of spruce show that variation in characteristic strength inside present growth areas is often larger than the applied confidence limits would suggest. Generally 80 to 90% of samples give values which are within the 90% confidence limits both in Germany and Nordic region. Results are different for different grading methods. In Germany, *E* based methods give upto 100% fit to the confidence limits, whereas *KAR* based methods give only 60 to 70%. In Nordic region, *E* and E_{dyn} based methods give normally 80%, and *KAR* based 90 to 100%.

When combining the samples from Central and Northern Europe, and calculating the 90% confidence limits for the joint area, often 50% of the samples are outside the confidence limits. Even when the values are within the confidence limits, normally the Nordic values are higher. The difference is however not big in all cases.

Results of **tension** of spruce show less variation within and between Nordic and Central Europe than bending results. Within Nordic countries 90% of tension samples for Model 1 are inside the confidence limits, and in Central Europe 100%, whereas the numbers in bending are 70 and 75%, respectively. When combining all national results of Model 1 in tension, only 10% are outside the confidence limits, whereas in the case of bending 60% are outside.

When grading is based on dynamic modulus of elasticity, Central European tension strength values show surprisingly marked variation. There may be an error in the data. When model 14, based on E_{dyn}, *KAR* and density is used, results of all seven samples representing Germany, Czech Republic, Austria, Russia and Finland are within the confidence limits, suggesting that these regions may belong to the same growth area.

When grading is based on *KAR* only, results are poor in terms of yields for the better grades, strength values and variability between regions. When grading is based on Model 9 combining *KAR* and density, the results are much better: 95% of tension strength values are within the confidence limits, when all available results are combined, the 5$^{\mathrm{th}}$ percentile for strength for the best grade is 26 N/mm^2 and the yield 12%.

Ratio of tension and bending strength was studied based on bandwidths obtained by the use of E_{dyn} as grading method. A fairly constant ratio of 0.7 was obtained for German and Finnish spruce.

The efficiency of grading methods is compared in terms of yield to the high grade and characteristic strength obtained. A summary of results is given in Tables 47 and 48.

Table 47. Yield to highest grade IP > 50 and 5 percentile of strength in bending of spruce.

Model	**Yield [%]**	**Strength [N/mm^2]**	**Regions included**
1	24	40	N
2	12	42	N
1	27	33	CE
2	10	39	CE
4	23	36	N
4	14	34	GER
5	23	38	N
5	24	38	CE
9	23	38	N
9	21	36	GER
11	24	43	N
11	26	39	CE
12	23	43	N
12	27	39	CE
14	24	42	N
14	8	43	CE

Table 48. Yield to highest grade IP > 40 and 5 percentile of strength in tension of spruce.

Model	Yield [%]	Strength [N/mm^2]	Regions included
1	17	30	N
2	11	32	N
1	14	29	CE
2	15	26	CE
4	19	21	N
4	4	20	GER
9	15	29	N
9	11	25	GER
11	20	32	N
11	14	30	CE
14	17	33	N
14	16	28	CE

5. Results for Scots pine in bending

5.1 European regression models

Pine results were available from more than one country only for bending. 14 regression equations are used in the analysis. Regression equations are given Eqn. (1) and coefficients for bending of spruce in Table 49. Table also includes coefficient of determination (r^2), total sample size and countries from where timber was harvested.

From single variable models the highest coefficient of determination was r^2 = 0.58, obtained when dynamic modulus of elasticity is the variable, and second highest of r^2 = 0.53 is obtained when static E is the variable and only r^2 = 0.29 when density is the variable. These values are based on 3 000 to 6 500 test values.

Knot area ratio (*KAR*) alone gives r^2 = 0.41, and when combined with density (Model 9) gives r^2 = 0.55. The addition of cross-sectional dimensions to the model increase coefficient of determination only marginally to r^2 = 0.56. Strength values used in the analysis had already been adjusted to European reference size h = 150 mm, and this seems to be an adequate adjustment for pine in bending. Other models in table give similar conclusion on size effect.

When combining other variables to E in modelling, the conclusions are:

1. addition of density does not improve the model, and addition of density and dimensions improves the model marginally (r^2 = 0.59)
2. addition of *KAR* improves the model to r^2 = 0.67. Adding also density and dimensions does not improve the model any more.

E_{dyn} gives marginally higher r^2 than E also when combined with other variables.

Table 49. Summary table of European regression models for bending of Scots pine.

Model	Coefficient of variable								r^2	N	Data included
	1	b mm	h mm	ρ kg/m³	E N/mm²	*KAR*	E_{dyn} N/mm²	E[N/mm²] / ρ [kg/m³]			
1	-1.31				0.003469				0.53	6 504	FRA, GER, FIN, RUS, SWE, UK
2	-14.78						0.004719		0.58	3 089	GER, FIN, RUS, SWE
3	-26.56			0.13172					0.29	6 504	FRA, GER, FIN, RUS, SWE, UK
4	61.28					-85.65			0.41	5 192	FRA, GER, FIN, RUS
5	-2.47							1.817	0.35	6 504	FRA, GER, FIN, RUS, SWE, UK
6	-3.37	0.0042	-0.0132	0.00588	0.003614				0.59	5 994	FRA, GER, FIN, RUS, SWE, UK
7	-13.47			0.03377	0.003050				0.54	6 504	FRA, GER, FIN, RUS, SWE, UK
8	18.86	-0.0453	-0.05363	0.09695		-72.96			0.56	5 192	FRA, GER, FIN, RUS
9	6.06			0.09943		-70.54			0.55	5 192	FRA, GER, FIN, RUS
10	27.92	-0.0821	-0.0506		0.003036	-46.59			0.69	5 192	FRA, GER, FIN, RUS
11	14.47				0.003069	-44.14			0.67	5 192	FRA, GER, FIN, RUS
12	22.02	-0.0733	-0.0507	0.01621	0.002803	-47.27			0.69	5 192	FRA, GER, FIN, RUS
13	7.85			0.01982	0.002782	-45.01			0.68	5 192	FRA, GER, FIN, RUS
14	6.41	0.0203	-0.0182	-0.00066		-38.30	0.003796		0.70	2 874	GER, FIN, RUS

5.2 Growth area analysis

European regression equations (Table 49) are used as strength indicating properties (*IP*) and test material hold by participants is graded simultaneously to several grades by using *IP* = 10, 20, 30 etc as settings. In other terms we use 10 N/mm^2 as the bandwidth. Comparison of the 5th percentile values for each grade of the wood grown in different regions is the main result of this analysis.

First, variation of strength values within an established growth area as defined in standardization is illustrated in cases where results are available from more than two regions. Present growth areas which are larger than one country are the Nordic area and the German-Austrian area, which are used as reference. In this analysis also relatively small samples are utilized, starting from *N* = 200. Second, variation between countries is analyzed. In case of pine smaller sample sizes are accepted for this comparison than in the case of spruce, because sample sizes are generally smaller.

It is known from previous research that bending strength of timber is strongly correlated to *E*, and this correlation can be only marginally improved by adding other variables. As we have the largest sample size available for Model 1, this was the starting point, and results for Models 11 (*E* + *KAR*), and 12 (*E* + *KAR* + density) were benchmarked against it.

5.2.1 Models with *E* as primary variable

For Model 1 we have the largest number of test results available: 1 600 Nordic, 2 100 French, 850 German and 800 from UK. Nordic growth area results from Finland, Sweden and Russia are shown in Fig. 46. Most of the results are inside the confidence limits, which is different from the case of spruce in bending. The yield for the high grade *IP* > 50 is 14% and the characteristic bending strength obtained is 48 N/mm^2. Models 11 and 12 give similar results, yield to the highest grade being higher (25%) and strength 42 N/mm^2.

Model 1 results for Central Europe including UK are shown in Appendix C. 70% of the values are not within the confidence limits. UK values are often below and German above the limits. When only French and German samples are combined, 30% of the values are outside the confidence limits, French values being generally lower. German-French combination gives an average characteristic value of 33 N/mm^2 and yield 23% for band *IP* > 50. Models 11 and 12 give qualitatively similar results, but a higher yield to the top grade 28%.

Data from all countries is presented in Fig. 47. The mean values for all reported characteristics for Model 1 are given for Nordic region in Table 50 and for Germany in Table 51.

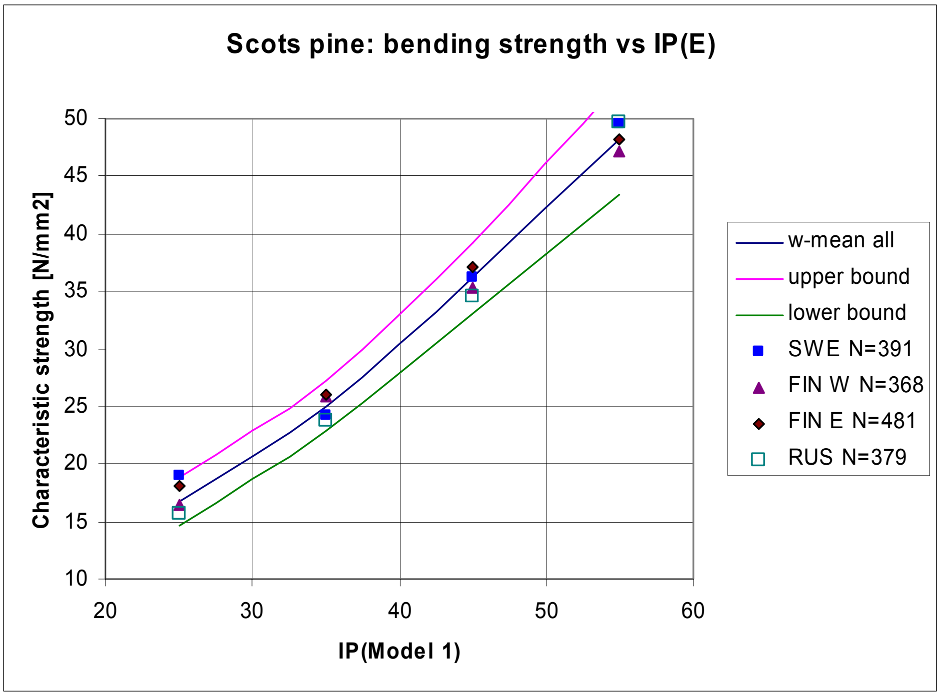

Figure 46. Comparison between Nordic regions, characteristic strength values with average confidence limits. Pine in bending, Model 1.

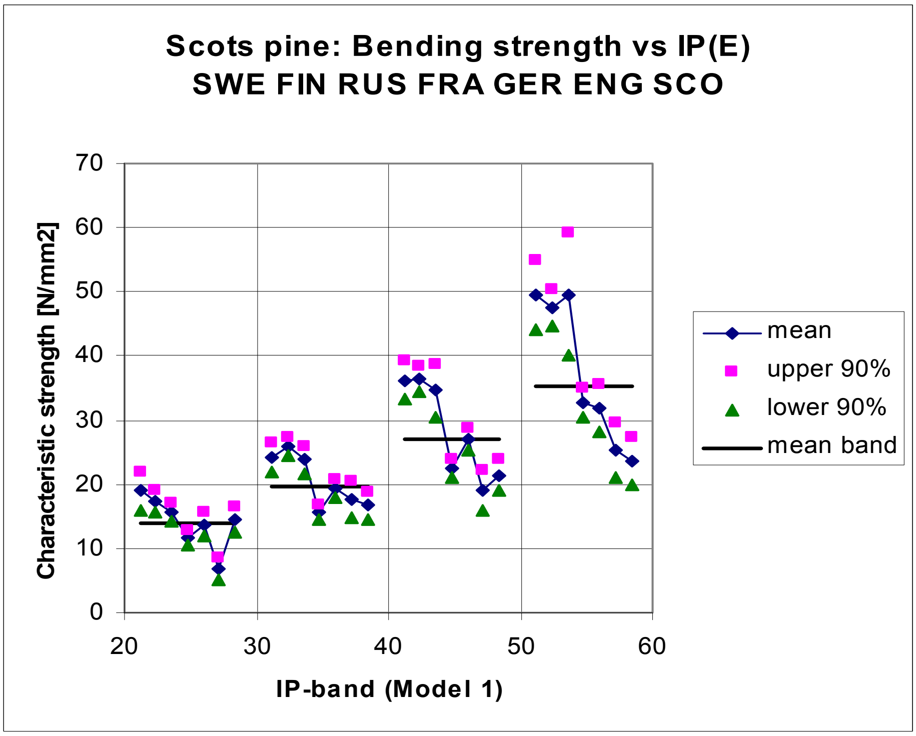

Figure 47. Comparison between countries, characteristic strength values with individual confidence limits. Pine in bending, Model 1.

Table 50. Combined Nordic results for pine in bending, Model 1. Weighted averages of mean values, 5 percentiles and COV's and means of sample sizes per country and band, and upper and lower confidence limits of 5 percentiles obtained by using average COV's and sample sizes.

Range of	Weighted averages							N	Upper	Lower
f_{model} N/mm²	$f_{adj,mean}$ N/mm²	COV %	$f_{adj,0,05}$ N/mm²	E_{mean} N/mm²	COV %	ρ_{mean} kg/m³	$\rho_{0.05}$ kg/m³	1 619	$f_{adj,0,05}$ N/mm²	$f_{adj,0,05}$ N/mm²
–10	8.2			3 085.0		423.0		1		
10–20	19.5	21.2		5 507.1	11.9	403.8	359.6	34		
20–30	27.7	23.8	16.8	7 903.9	9.9	426.3	376.4	358	18.90	14.71
30–40	38.4	21.1	25.0	10 402.6	8.0	461.3	405.9	562	27.23	22.81
40–50	51.2	17.8	36.2	13 240.5	6.1	508.0	434.1	441	39.20	33.13
50–60	63.7	14.6	48.3	15 952.6	5.0	556.2	489.5	202	53.19	43.36
60–70	75.7	9.5	63.4	18 468.4	4.2	585.6	538.9	21	76.44	50.44
70–								0		
all		32.5			23.9	477.9	389.5	1 619		

Table 51. German results for pine in bending, Model 1. Weighted averages of mean values, 5 percentiles and COV's and means of sample sizes per country and band, and upper and lower confidence limits of 5 percentiles obtained by using average COV's and sample sizes.

Range of	Weighted averages								Upper	Lower
f_{model} N/mm²	$f_{adj,mean}$ N/mm²	COV %	$f_{adj,0,05}$ N/mm²	E_{mean} N/mm²	COV %	ρ_{mean} kg/m³	$\rho_{0.05}$ kg/m³	N	$f_{adj,0,05}$ N/mm²	$f_{adj,0,05}$ N/mm²
–10	7.0			2 838.9		425.1		1		
10–20	13.1			5 312.0		430.2	405.6	8	11.5	5.1
20–30	25.4	27.8	13.2	8 183.7	9.0	463.5	397.3	112	15.5	11.9
30–40	33.2	25.2	20.4	10 492.8	7.6	487.7	422.2	336	20.7	18.1
40–50	42.1	21.7	27.8	13 177.6	6.3	527.2	452.3	278	28.8	25.3
50–60	51.2	22.9	33.9	15 724.6	4.7	574.3	500.6	94	35.6	28.1
60–70	64.9	16.2	42.9	18 884.0	3.9	633.9	572.1	21	55.9	39.3
70–								0		
all		33.5			22.6			850		

5.2.2 Models with E_{dyn} as primary variable

Model 2 is based on E_{dyn}. Nordic sampling consists of 4 regions: North Western Russia (N = 379), Sweden (N = 191), Western Finland (N = 181), Eastern Finland (N = 481). Results are shown in Fig. 48 together with 2 German samples (N = 421 + 429). 25% of data points (mainly German) in Fig. 48 are outside the confidence limits. This combined data gives 16% yield to IP > 50 and characteristic strength 37 N/mm^2.

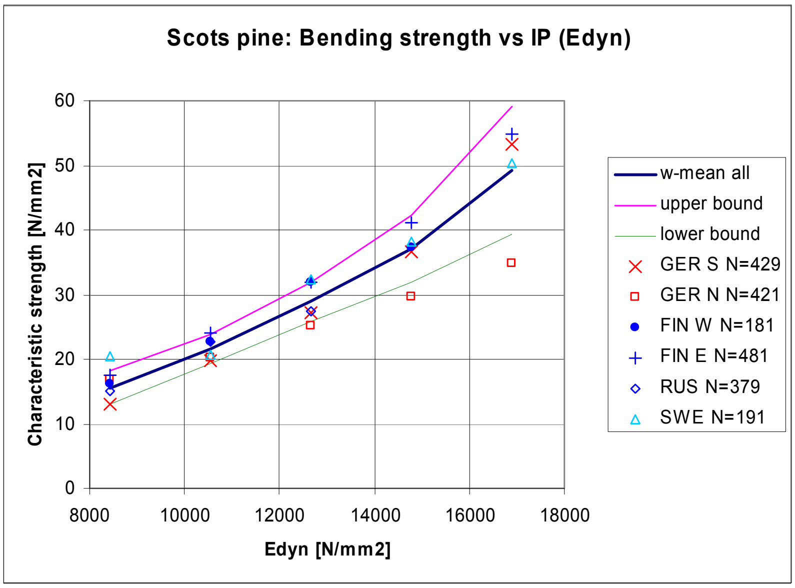

Figure 48. Comparison between regions, characteristic strength values with average confidence limits. Pine in bending, Model 2.

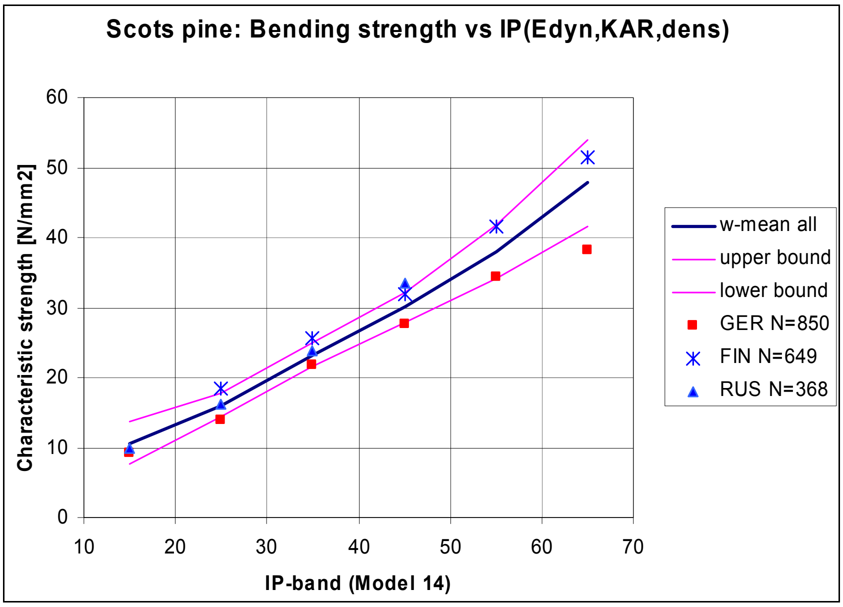

Figure 49. Comparison between countries, characteristic strength values with average confidence limits. Pine in bending, Model 14.

Results for Model 14 are shown in Fig. 49. Nordic values indicate 21% yield to $N > 50$ with characteristic strength 41 N/mm^2. German results give 15% yield with strength 35 N/mm^2. The averages of all Model 14 values are given in Table 52.

Table 52. Averages of all Model 14 values from Germany, Finland and Russia for Scots pine.

Range of	**Model 14 pine**		**Weighted averages**				**Upper**	**Lower**
f_{model} **N/mm²**	$f_{adj,mean}$ **N/mm²**	***COV*** **%**	$f_{adj,0,05}$ **N/mm²**	E_{mean} **N/mm²**	***COV*** **%**	***N*** **total**	$f_{adj,0,05}$ **N/mm²**	$f_{adj,0,05}$ **N/mm²**
–10	10.5			4 576		5		
10–20	20.4	28.3	10.6	6 662	18.1	75	13.61	7.66
20–30	26.9	23.7	16.0	8 510	14.3	360	17.69	14.28
30–40	34.8	20.9	23.2	10 384	13.0	628	24.87	21.56
40–50	43.5	18.3	30.0	12 453	11.5	459	32.24	27.84
50–60	54.1	18.4	38.0	14 421	10.5	251	41.81	34.25
60–70	63.4	13.6	47.8	16 452	7.6	81	54.01	41.59
70–	73.8			17 709		8		
all		32.9			24.0	1 867		

Model 5 is based on the same sample as Model 1. In this case the Nordic results are within the confidence limits. Highest grade has a10% yield and a 43 N/mm^2 characteristic bending strength. Central European values are lower, and qualitatively similar to models 2 and 14.

5.2.3 Models with *KAR* and density

Model 4 is based on *KAR*. From Nordic region we have 3 samples, 2 from Finland and one from Russia, in total 1 200 test values. Most Russian results are below the confidence limits. Finnish results give 37% yield at the grade $IP > 50$ and a characteristic strength 37 N/mm^2.

From Central Europe we have two regions in Germany, North ($N = 421$) and South ($N = 429$) and the combined French sample ($N = 2\ 133$). When these samples are analyzed, the North German sample falls outside the confidence limits. The yield to the $IP > 50$ is 20% and the strength is 30 N/mm^2.

All national results are combined in Fig. 50. In this analysis the Finnish results are above the confidence limits whereas Russian, German and French are nearly within the limits. The average results are given in Table 53.

Table 53. Averages of all Model 4 values from Germany, France, Finland and Russia for Scots pine.

Range of	Model 4 pine		Weighted averages				Upper	Lower
f_{model} N/mm^2	$f_{adj,mean}$ N/mm^2	*COV* %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	*COV* %	*N* total	$f_{adj,0,05}$ N/mm^2	$f_{adj,0,05}$ N/mm^2
–10	25.7	42.4		9 600	3.1	28		
10–20	24.0	40.3	8.1	8 728	7.1	121	10.98	5.14
20–30	28.2	33.4	12.6	9 813	8.3	537	14.37	10.78
30–40	35.1	30.2	17.4	10 985	10.3	1 278	18.90	15.99
40–50	43.9	28.1	23.3	12 555	10.5	1 269	25.10	21.46
50–60	56.8	25.8	32.4	14 337	9.5	774	35.40	29.44
60–70	69.2	22.6	42.6	15 392	6.2	185	49.58	35.59
70–						0		
all		35.8			18.1	4 185		

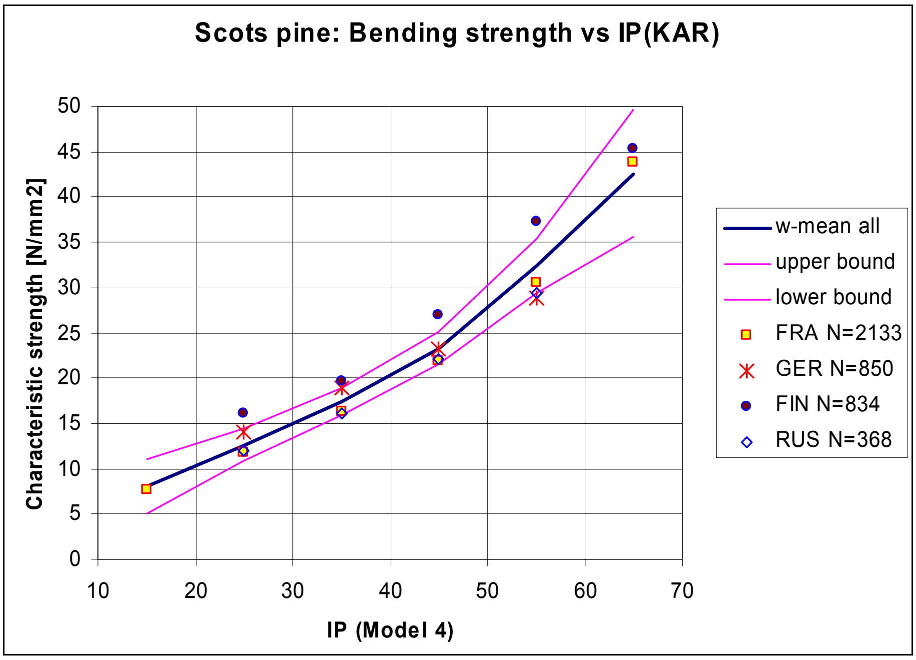

Figure 50. Comparison between countries, characteristic strength values with average confidence limits. Pine in bending, Model 4.

Model 3 uses density as the variable. This model was not applied to spruce data because of the low r^2 value obtained, but was applied for pine because the r^2 is a little higher (0.29). Nordic data consist of two Finnish and a Swedish and a Russian sample. Results in Appendix C show that 20% of Nordic values are outside the confidence limits. The yield to the IP > 50 is 6% and the strength is 43 N/mm^2.

Central European data consists of two German, one French, English and Scottish samples. Most of the values are outside confidence limits, French strength values being the lowest. This combined model gives 22% yield to the *IP* > 50 with a characteristic for of strength 23 N/mm^2.

All European results for Model 3 are illustrated in Fig. 51 which shows how different the values are and how weak density is as strength predictor.

Model 9 uses both *KAR* and density as variables. The r^2 improves to 0.55. Nordic results are based on the same 2 samples from Finland and one sample from North West Russia. 90% of strength values on main bandwidths are within the confidence limits. Grade *IP* > 50 reaches 21% yield and 41 N/mm^2 for characteristic strength.

Central European results are based on same sample as for Model 4. Nearly all values are outside the confidence limits. French values are lower except in the higher grades, and North German sample are different from South German (see Appendix C).

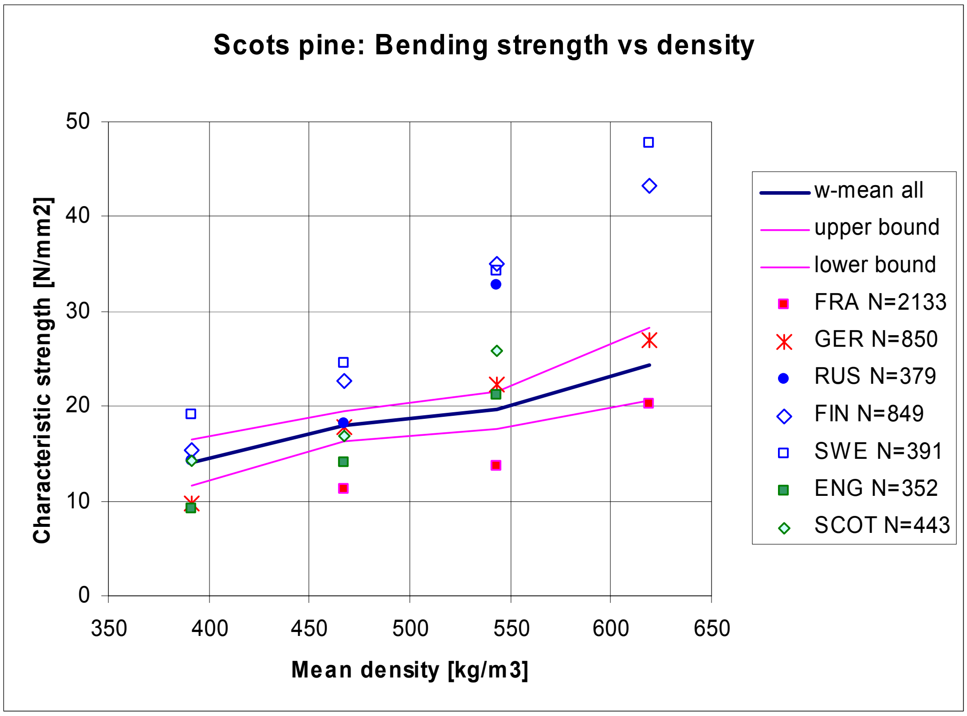

Figure 51. Comparison between countries, characteristic strength values with average confidence limits. Pine in bending, Model 3.

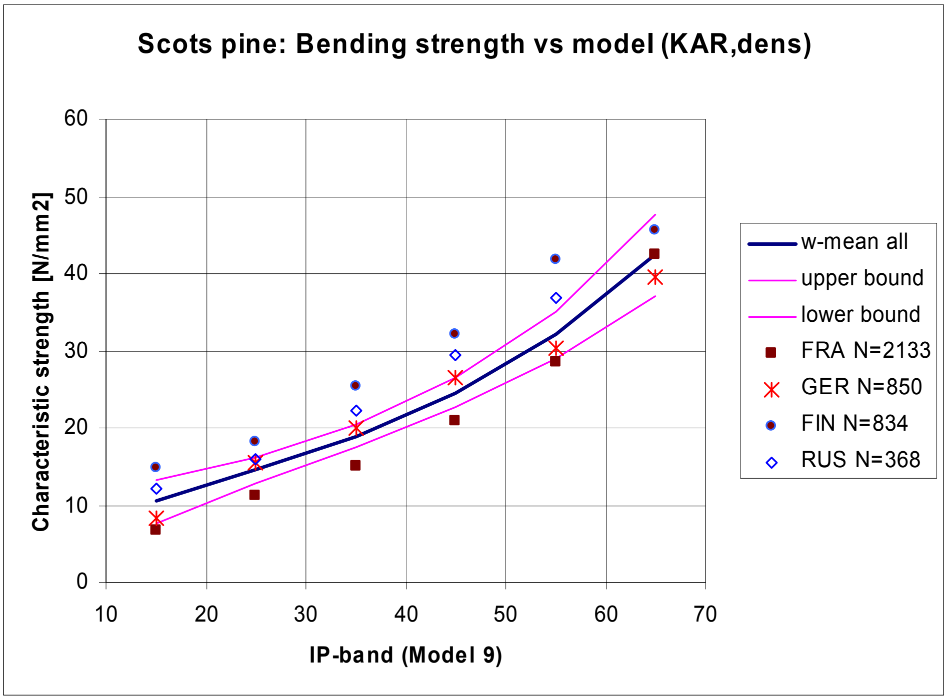

Figure 52. Comparison between countries, characteristic strength values with average confidence limits. Pine in bending, Model 9.

The averages obtained by the use of Model 9 are shown in Tables 54 and 55, and results are illustrated in Fig. 52 and in Appendix C.

Table 54. Averages of Model 9 values from Finland and Russia for Scots pine.

Range of	Weighted averages					Average	Upper	Lower
f_{model} N/mm²	$f_{adj,mean}$ N/mm²	*COV* %	$f_{adj,0,05}$ N/mm²	E_{mean} N/mm²	*COV* %	*N* 1 202	$f_{adj,0,05}$ N/mm²	$f_{adj,0,05}$ N/mm²
–10	26.9	30.5		7 971	13.2	4		
10–20	23.6	26.3	13.4	7 512	21.9	25	16.97	9.92
20–30	28.7	24.6	17.1	8 452	17.9	87	19.31	14.85
30–40	37.4	21.1	24.4	10 265	16.7	116	26.79	22.06
40–50	47.0	20.0	31.5	12 291	15.0	83	34.89	28.07
50–60	57.2	16.9	41.2	14 418	12.4	60	45.69	36.80
60–70	61.4	18.2	43.3	15 155	13.8	25	51.12	35.53
70–	63.1			12 778		0.3		
all		32.1			24.4	401		

Table 55. Averages of Model 9 values from France and Germany for Scots pine.

Range of	Weighted averages						Upper	Lower
f_{model} N/mm^2	$f_{adj,mean}$ N/mm^2	*COV* %	$f_{adj,0,05}$ N/mm^2	E_{mean} N/mm^2	*COV* %	*N* total	$f_{adj,0,05}$ N/mm^2	$f_{adj,0,05}$ N/mm^2
–10	19.3	53.9	2.3	7 633	7.4	9	5.85	-1.24
10–20	20.4	37.6	7.8	8 013	7.0	60	11.02	4.54
20–30	26.9	31.6	12.9	9 464	7.2	378	14.74	11.13
30–40	33.7	30.5	16.7	11 039	5.6	865	18.20	15.23
40–50	43.0	28.6	22.6	12 658	5.2	858	24.50	20.71
50–60	54.1	28.0	29.0	14 590	3.5	530	32.05	25.99
60–70	69.4	23.8	42.1	16 803	1.6	234	47.72	36.48
70–	80.4	22.2	51.0	19 307	0.6	78	62.01	40.06
all		32.9			10.5	2 983		

5.3 Strength profiles

Relations of the 5th percentile for strength, mean value of *E* and mean and the 5th percentile for density for the bandwidths related to Models 1, 2, 3 and 5 are compared. In Fig. 53 the characteristic strength is presented as a function of the average *E* for Nordic, German and French samples. Nordic strength values are highest and French lowest for all models. When the grading is based on the measurement of *E*, strength is highest. The variability of *E* to strength ratio is big. Models 1, 3 and 5 are compared in Fig. 53 because same samples were available for these models.

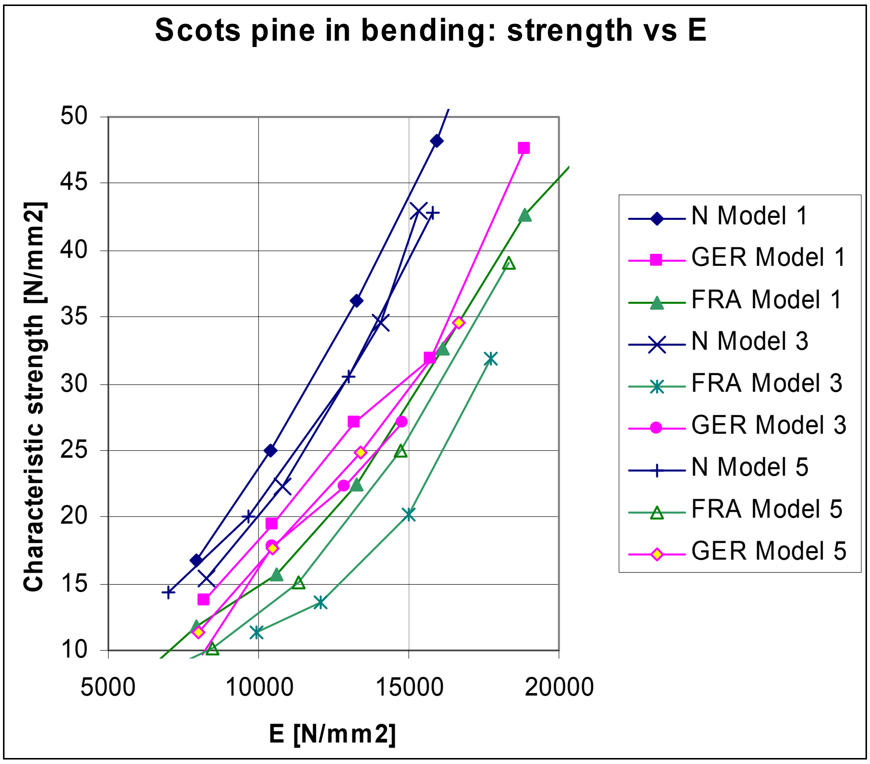

Figure 53. Characteristic strength vs. average of modulus of elasticity. Nordic, French and German values are compared for three different grading methods.

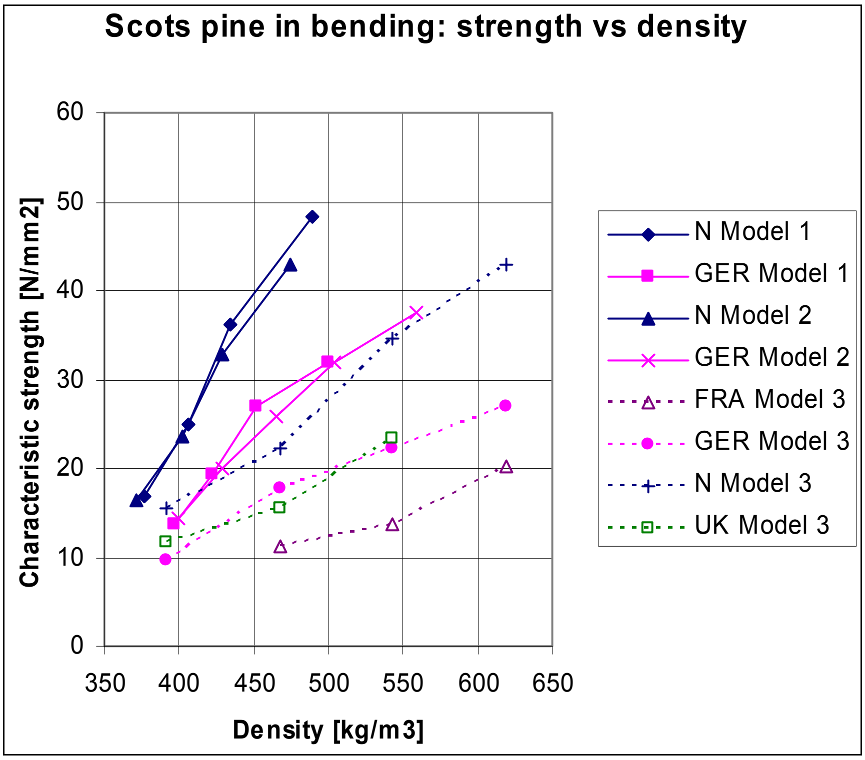

Figure 54. Characteristic strength vs. density. Solid lines refer to 5 percentile of density and dashed lines to average values.

In Fig. 54 strength-density relation is compared. Models 1 and 2 are used for the calculation of the 5th percentiles for density (solid lines), and Model 3 is used for the calculation of mean values (dashed lines). Nearly identical ratio(s) for characteristic values of strength and density are obtained by use of static and dynamic *E* as basis of the grading, both for Nordic and German material, even if the sample for dynamic *E* is different and smaller. Nordic strength values are 10 N/mm^2 higher than German values for the same density, or in other terms German densities are 50 kg/m^3 higher for the same strength. When grading is based on mean value of density (Model 3), German and UK relation is similar.

5.4 Conclusions for Scots pine

Results obtained for Scots pine are more variable and more growth region dependent than results for spruce. The *COV* for the un-graded population is larger, in Nordic countries the values are 27% for bending strength of spruce and 32% for pine. In Central Europe *COV* values are slightly larger but the difference between species is smaller. Variability of pine has also a positive consequence: yield to high grades is reasonably good. Some estimated yields are given in Table 56.

The hypothesis of having only one growth area in Europe is not supported by the results. Instead, the hypothesis of having a Nordic growth area is supported in all analyzed cases with the exception of *KAR* alone being used as basis of grading. Model 4 results obtained for North-Western Russia are below the confidence limits when combined with Finnish results. Similar discrepancy are observed between North and South Germany in *KAR*-based grading. Generally, results suggest that France, Germany and UK need their own settings in grading of pine for bending.

Table 56. Yield to highest grade IP > 50 and 5 percentile of strength in bending of pine.

Model	Yield [%]	Strength [N/mm^2]	Regions included
1	14	48	FIN, SWE, RUS
2	14	48	FIN, SWE, RUS
1	23	33	FRA, GER
2	16	32	GER
3	6	43	FIN, SWE, RUS
3	22	23	FRA, GER, UK
4	31	36	FIN, RUS
4	20	30	FRA, GER
9	21	41	FIN, RUS
11	24	42	FIN, RUS
12	25	42	FIN, RUS
14	21	41	FIN, RUS
11	27	34	GER, FRA
12	28	33	GER, FRA
14	15	35	GER

6. Results for Douglas fir in bending

6.1 European regression models

For Douglas-fir the results from more than one country were available only for bending. 14 regression equations are used in the analysis. Regression equations are given in Eqn. (1) and coefficients for bending of spruce in Table 57. The table also includes the coefficient of determination (r^2), total sample size and countries from where timber was harvested.

From single variable models the highest coefficient of determination was $r^2 = 0.58$, obtained when the dynamic modulus of elasticity is the variable, and second highest $r^2 = 0.54$ when static E is the variable and $r^2 = 0.32$ when density is the variable. These results are based on 2 000–6 500 test values.

Knot area ratio (*KAR*) alone gives a low coefficient of determination $r^2 = 0.24$, and when combined to density (Model 9) the result is $r^2 = 0.48$. The addition of cross-sectional dimensions to the model increase coefficient of determination only marginally to $r^2 = 0.50$. Strength values used in the analysis are already adjusted to the European reference size $h = 150$ mm, and this seems to be an adequate adjustment for bending. Other models in Table 57 give similar conclusion on size effect.

When combining other variables with E in modelling the conclusion is that the addition of density, *KAR* and dimensions improves the model marginally upto $r^2 = 0.61$.

E_{dyn} gives a little higher r^2 than E when combined with other variables and the highest value obtained being $r^2 = 0.66$.

Table 57. Summary table of European regression models for bending of Douglas-fir.

Model	Coefficient of variable								r^2	N	Data included
	1	b mm	h mm	ρ kg/m^3	E N/mm^2	*KAR*	E_{dyn} N/mm^2	E[N/mm^2]/ ρ [kg/m^3]			
1	-0.65				0.003213				0.54	6 562	FRA, GER, UK
2	-19.76						0.004870		0.58	2 107	GER, FRA
3	-42.14			0.16760					0.32	6 562	FRA, GER, UK
4	61.03					-60.98			0.24	2 867	FRA, GER, UK
5	-4.26							1.738	0.41	6 562	FRA, GER, UK
6	-20.57	0.0026	0.0516	0.01508	0.003587				0.55	5 654	FRA, GER
7	-24.31			0.05936	0.002725				0.54	5 654	FRA, GER
8	-14.71	-0.1629	0.08693	0.13356		-44.60			0.50	2 391	FRA, GER
9	-15.93			0.14560		-47.25			0.48	2 391	FRA, GER
10	15.88	-0.1838	0.0812		0.002590	-31.50			0.58	2 391	FRA, GER
11	16.39				0.002744	-32.76			0.56	2 391	FRA, GER
12	-5.65	-0.1624	0.0701	0.05748	0.002050	-31.48			0.61	2 391	FRA, GER
13	-8.00			0.06432	0.002114	-32.46			0.59	2 391	FRA, GER
14	1.38	-0.2083	0.0798	0.04649		-49.61	0.002565		0.66	1 207	GER

7. Results for Sitka spruce in bending

7.1 European regression models

For Sitka spruce the results from more than one country were available only for bending. 14 regression equations are used in the analysis. Regression equations are given Eqn. (1) and coefficients for bending of spruce in Table 58. Table includes also coefficient of determination (r^2), total sample size and countries from where timber was harvested.

From the single variable models the highest coefficient of determination $r^2 = 0.51$ is obtained when static modulus of elasticity is the variable, and second highest $r^2 = 0.37$ when the dynamic E is the variable and lowest $r^2 = 0.08$ when density is the variable. These results are based on 1 000 to 4 000 test values.

Knot area ratio (*KAR*) alone gives a low coefficient of determination $r^2 = 0.10$, and when combined with density (model 9) $r^2 = 0.34$. The addition of cross-sectional dimensions to the model increase the coefficient of determination only marginally to $r^2 = 0.35$. The strength values used in the analysis are already adjusted to European reference size $h = 150$ mm, and this seems to be an adequate adjustment for bending. Other models in table give similar conclusion on size effect.

When combining other variables to E in modelling the conclusion is that the addition of density, *KAR* and dimensions improves the model marginally upto $r^2 = 0.57$.

E_{dyn} gives a little lower r^2 than E when combined with other variables and the highest value obtained being $r^2 = 0.52$.

Table 58. Summary table of European regression models for bending of Sitka spruce.

Model	Coefficient of variable								r^2	N	Data included
	1	b mm	h mm	ρ kg/m^3	E N/mm^2	*KAR*	E_{dyn} N/mm^2	E[N/mm^2]/ ρ [kg/m^3]			
1	10.72				0.002327				0.51	4 201	UK, FRA, GER
2	1.47						0.003375		0.37	900	GER
3	5.61			0.06487					0.08	2 578	UK, FRA, GER
4	40.31					-24.26			0.10	2 971	FRA, GER, UK
5	14.13							0.823	0.32	2 578	FRA, GER, UK
6	-1.61	0.0026	0.0136	0.02077	0.002554				0.49	1 798	FRA, GER
7	-8.74			0.04579	0.002284				0.49	1 798	FRA, GER
8	15.59	-0.0843	0.0006	0.08318		-36.58			0.35	1 697	FRA, GER
9	9.07			0.08753		-35.28			0.34	1 697	FRA, GER
10	24.05	-0.0670	-0.0170		0.002195	-20.62			0.53	1 697	FRA, GER
11	16.71				0.002204	-16.81			0.51	1 697	FRA, GER
12	3.86	-0.0447	-0.0124	0.05083	0.001976	-21.57			0.57	1 697	FRA, GER
13	-2.97			0.05574	0.001960	-19.08			0.56	1 697	FRA, GER
14	2.79	-0.0231	0.0120	0.04541		-25.64	0.002028		0.52	900	GER

8. Summary

Strength data held by different participants has been jointly analyzed. Firstly, regression equations and coefficients of determination were determined for combined data. Second, selected regression equations were used as strength indicating function (*IP*) and averages and coefficients of variation of strength and modulus of elasticity were calculated for 10 MPa bandwidths of *IP* for sub-samples. Third, the 5^{th} percentile values for strength with 90% confidence limits were calculated for each bandwidth for each sub-sample, and fourth, growth area analysis was made based on hypothesis that sub-samples belong to the same growth area, if 90% of the 5 percentile values of bands are within the confidence limits.

The criterion of having 90% of observations within the confidence limits turned out to be quite tough and is not generally fulfilled within a country which has different growth conditions. Here the criterion was tested by applying it to sub-samples coming from different growth conditions in a country or a group of countries. Generally, the criterion is easier to fulfill when representative samples of countries are combined than when sub-samples of different growth regions of the same countries are jointly analyzed.

Calculated results are summarized in Table 59. In tension for spruce, based on our limited data, the hypothesis of same growth area is fulfilled among Nordic sub-samples and among Central European sub-samples. Criterion is fulfilled also for combination(s) of data representing Germany, Czech republic, Austria, Finland, Sweden, Norway and North West Russia (Model 1). The criterion is also fulfilled when regions of the Nordic countries and Central Europe are combined, when grading is based on Models 9 or 14, but not in the case of single variable Models 2 or 4.

In the case of spruce in bending, our criterion for the same growth area was strictly fulfilled only for a few combinations of samples:

1. combination(s) of three German samples and French country sample for most *E*-based models
2. combination of three Finnish and a Swedish, Estonian and Russian sample for Model 2 , and
3. combination of three Finnish samples for Model 4.

For pine in bending, the criterion for the same growth area was fulfilled for combinations of existing Nordic data for *E*- and E_{dyn}-based models and for Model 9.

The results in Table 59 show that the criterion applied is generally tougher than is the practice in standardisation when new settings are approved for EN 14081-4. In cases the result in Table 59 is “no”, the violence of the criterion was minor in some cases, and it is not suggested that countries or established regions should not be considered as one growth area. But when this criterion is fulfilled, it is a strong recommendation that regions can be considered as one growth area.

In the analysis larger sample sizes are available for static than for dynamic modulus of elasticity. Therefore an important question is, if the results obtained by using models with E as the variable can be extended to apply to E_{dyn} and other grading methods. There are some differences of r^2 values obtained for Models 1 and 2 which are not understood, but nevertheless the ratio of strength and modulus of elasticity for graded timber is practically the same, if independently determined, as when dynamic or static modulus of elasticity is used as basis of grading, both for pine and spruce. In growth area analysis, the results are quite similar for Model 1 and for different combinations of E_{dyn}, *KAR* and density, even if Model 9 is based on a combination of *KAR* and density and does not include any direct measurement of stiffness.

When the same *IP* with the same settings is applied to Nordic and Central European timber, the characteristic strength for Nordic timber is higher, in most cases. Only in the case of applying Model 14 (E_{dyn}, *KAR*, density) to bending of spruce, German values were higher. Nordic and Central European values were similar for several models in the case of tension of spruce.

Single variable strength models based on static or dynamic modulus of elasticity can be slightly improved by adding *KAR* in the model. This improvement can mean higher yield(s) to better grades or higher strength or wider growth area. Combined model including both *KAR* and density as variables is considerably better than models including only a single variable, *KAR* or density.

Table 59. Summary of results where criterion "90% of the 5 percentile values of bands are within the confidence limits" is fulfilled.

Model	Criterion fulfilled	Regions analysed
Spruce in tension		
E-based models 1, 11	yes	7 countries (CE + N)
1	yes	8 Nordic regions
1	yes	7 CE regions
E_{dyn}-based models 2	no	7 regions (CE + N)
14	yes	7 regions (CE + N)
KAR-based models 4	no	7 regions (CE + N)
9	yes	7 regions (CE + N)
Spruce in bending		
E-based models 1, 5, 11, 12	no	GER, FRA, FIN, (SWE, RUS)
1, 5	no	11 Nordic regions
1	no	SWE, RUS, FIN
1, 5, 11, 12	yes	3GER, FRA
13	no	3GER, FRA
11, 12	no	3FIN, RUS, SWE
E_{dyn}-based models 2, 14	no	GER, FIN, (SWE, RUS)
2	yes	3FIN, SWE, EST, RUS
KAR-based models 4, 9	no	GER, FRA, FIN
4	yes	3FIN
4, 9	no	3GER
9	no	3FIN, RUS, SWE
Pine in bending		
E-based models 1, 5, 11, 12	no	4–7 countries (CE + N)
1, 5, 11, 12	yes	2FIN, (SWE), RUS
1, 11, 12	no	2GER, FRA
5	no	GER, FRA, ENG, SCOT
E_{dyn}-based models 2, 14	no	GER, (SWE), FIN, RUS
2, 14	yes	FIN, RUS
KAR-based models 4, 9	no	FRA, GER, FIN, RUS
4	no	2FIN, RUS
9	yes	2FIN, RUS
4, 9	no	2GER, FRA

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Appendix A: Statistical basics

The ratio between characteristic value and average COV's

1. Introduction

The ratio between *COV* for the average value of the sample and *COV* of the characteristic value (5^{th} percentile of the random variable) is sought. The value of *COV* of the average is very easy to obtain by the equation

$$\mathrm{COV}_{\mathrm{average}} = \frac{\mathrm{COV}_{strength}}{\sqrt{n}} \qquad \text{(A1)}$$

where n is the sample size. The distribution of k^{th} percentile is not so evident since it represents the j^{th} smallest value, thus the *COV* of the characteristic value is not easily obtained in closed form. Therefore, we've chosen the method of simulations to determine the *COV* of the characteristic value for different COV_{strength} and different sample sizes. In all cases the number of simulations was equal to 5 000. The analysis was performed by computer program Mathematica.

2. Normal distribution

In the case of normally distributed variables it turns out that the relationship between *COV* of the average and characteristic value depends on sample size and *COV* of the parent distribution (*COV* of individual measured strength).

The following two diagrams (Fig. A1 and A2) show this relationship. It seems that the relationship is linear, if the *COV* is fixed. In Fig. A1 the red line corresponds to $COV = 0.3$, purple to $COV = 0.25$, blue to $COV = 0.2$ and green to $COV = 0.1$.

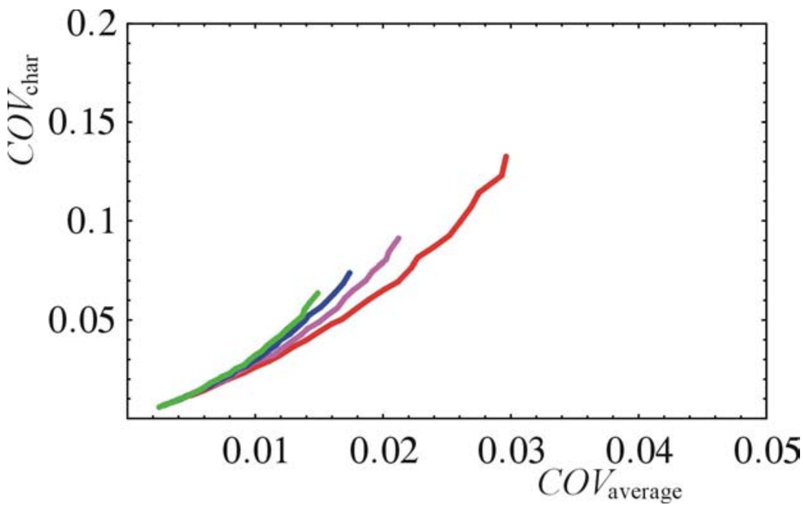


Figure A1. COV of characteristic value vs. COV of the average (COV of strength fixed).

The linear regression of these values reveals the following relationship between COV_{char} and $COV_{average}$:

$$COV_{char} = \beta\, COV_{average}$$

Table A1. The values of coefficient β.

***COV*strength**	**β**
0.10	2.45
0.20	3.05
0.25	3.55
0.30	4.13

The relationship is non-linear, if the sample size is fixed. In Fig. A2 the red line corresponds to sample size $n = 100$, purple to $n = 200$, blue to $n = 300$ and green to $n = 400$.

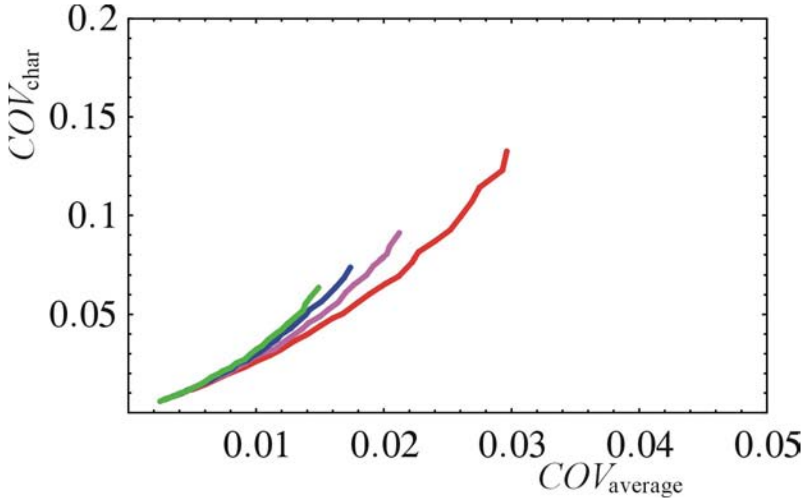


Figure A2. COV of characteristic value vs. COV of the average (sample size fixed).

3. Log-normal distribution

In the case of log-normally distributed variables it turns out that the relationship between COV_{char} and $COV_{average}$ is independent on sample size and the COV of strength. The next two diagrams confirm this statement.

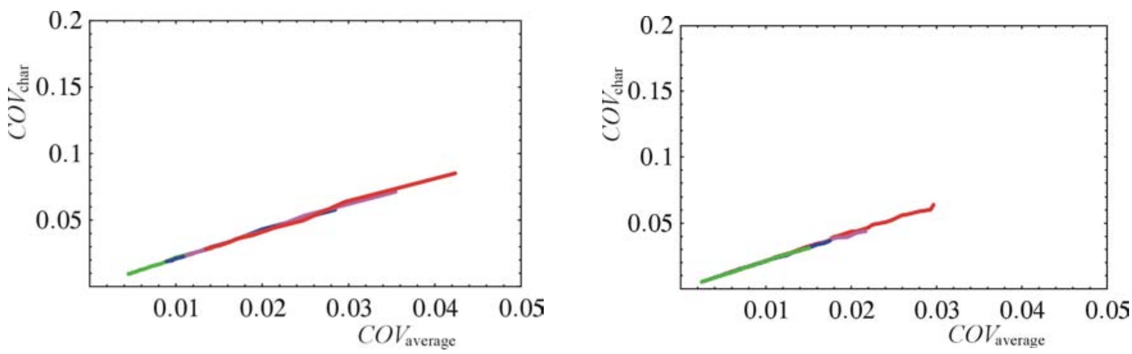


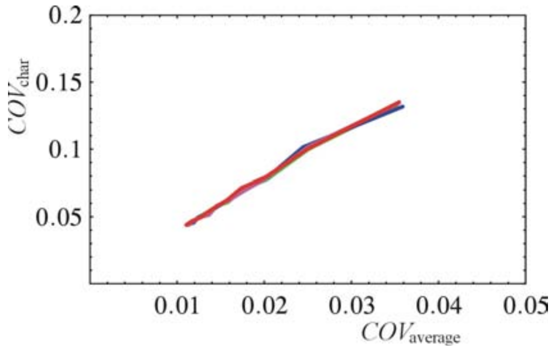
Figure A3. COV_{char} vs. $COV_{average}$ when COV of strength or sample size is fixed.

In this case the relationship between COV_{char} and $COV_{average}$ is uniform

$$COV_{char} = 2.0\ COV_{average}.$$

4. Weibull distribution

In the case of Weibull distribution variables the relationship between COV_{char} and $COV_{average}$ is slightly dependent on the COV of strength. The next two diagrams confirm this statement.



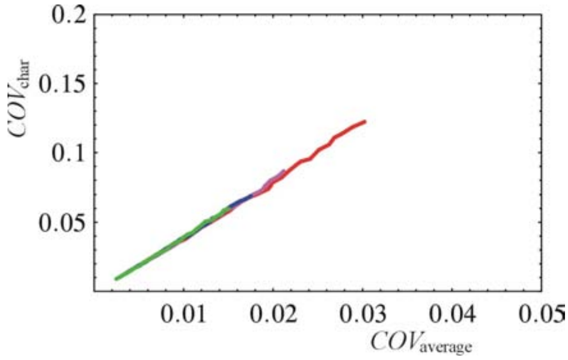


Figure A4. COV_{char} vs. $COV_{average}$ when COV of strength or sample size is fixed.

In this case the relationship between COV_{char} and $COV_{average}$ is almost uniform

$$COV_{char} \approx 4.0\ COV_{average}.$$

Appendix B: Definition of variables

Variables			Notes
Bending strength	$f_{m,adj}$	N/mm^2	Edgewise, tested acc. to EN408, adjusted to ref. size 150mm acc. to EN384. Tests made at high MC close to FSP will not be included
Tension strength	$f_{t,adj}$	N/mm^2	Tested acc. to EN408, adjusted to ref. width 150mm and length 2 000 mm acc. to EN1194.Tests made at high MC close to FSP will not be included
Modulus of elasticity	E	N/mm^2	Local modulus of elasticity in edgewise bending, adjusted to M.C. 12%. Can be inverted from global MOE. In case of tension, *E* is determined in tension test acc. to EN408
Dynamic modulus of elasticity	E_{dyn}	N/mm^2	Based on measurement of actual density by non-destructive or destructive means, adjusted to M.C. 12%
Density	ρ	kg/m^3	Based on destructive or non-destructive measurement, adjusted to M.C.12%
Knot area ratio	*KAR*	-	Ratio of area of knots in cross-section to total area. 150mm long area considered as one cross-section
depth/ width	h	mm	larger dimension of cross-section
thickness	b	mm	smaller dimension of cross-section

Appendix C: Figures of calculated results

Results are presented in order:

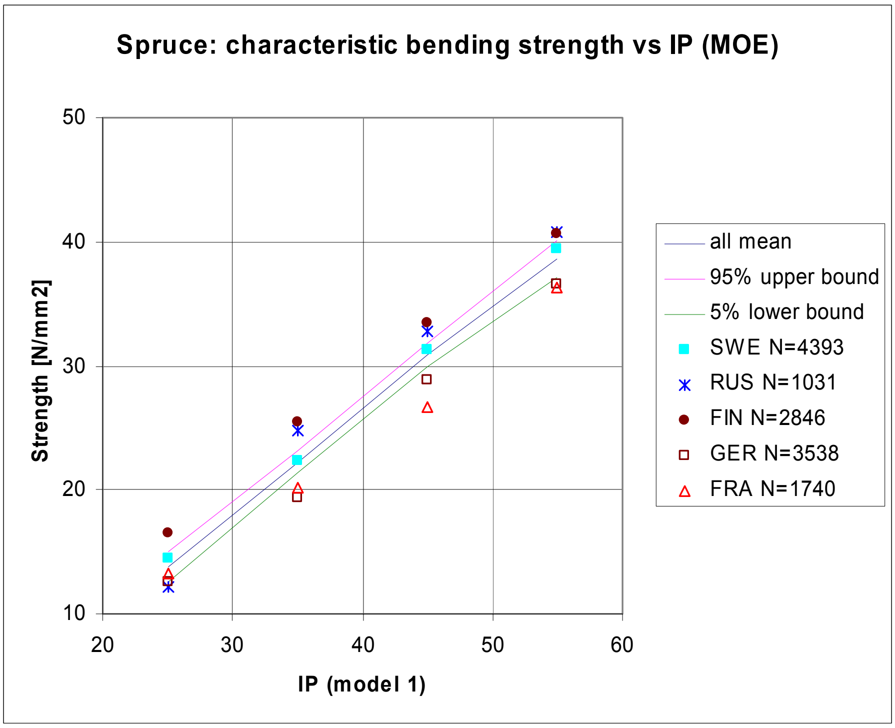
1. Spruce in bending, from Model 1 to Model 14
2. Spruce in tension, from Model 1 to Model 14
3. Scots pine in bending, from Model 1 to Model 14.

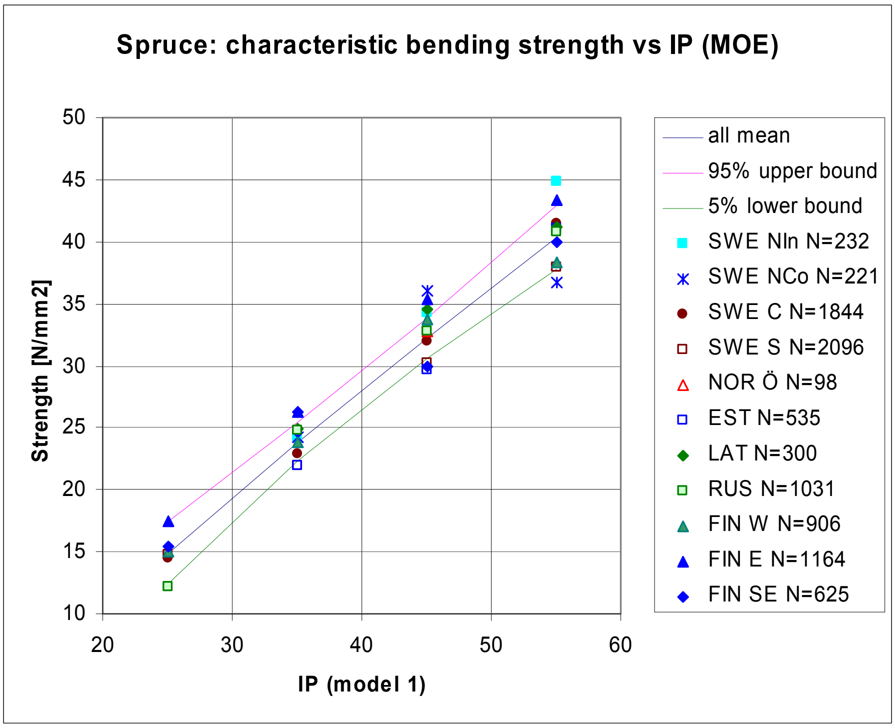
For each case, first comparison between results based on combined data of countries is presented followed by Nordic and Central European results based on regional samples when available.

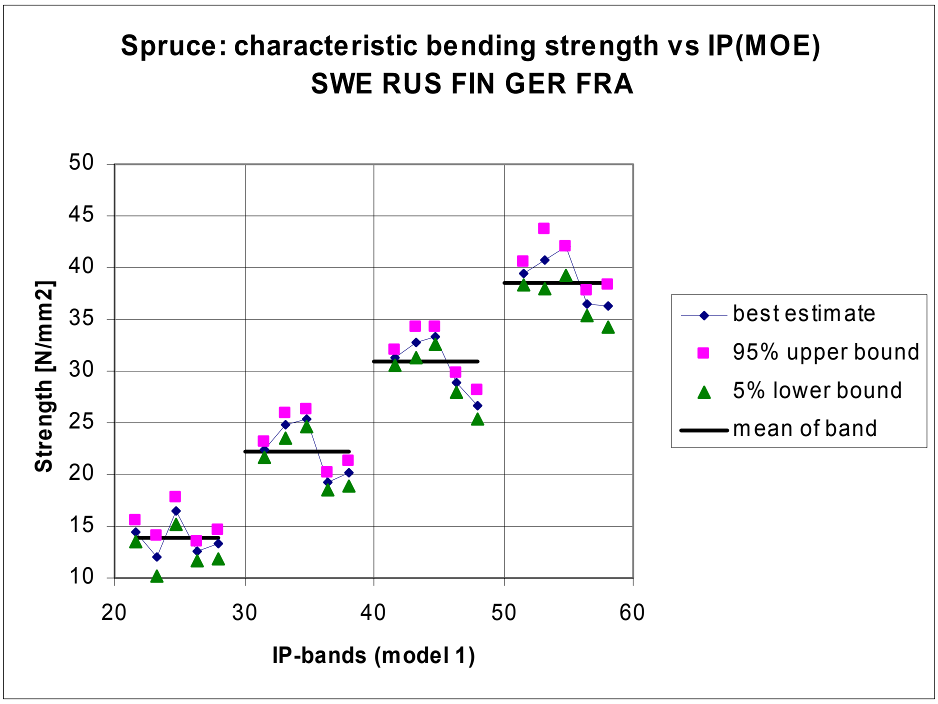
Each page contains two Figures, two different illustrations of the same data. Figures are without captions. Joint captions are below and identification of species, regions and Model is given in each Figure.

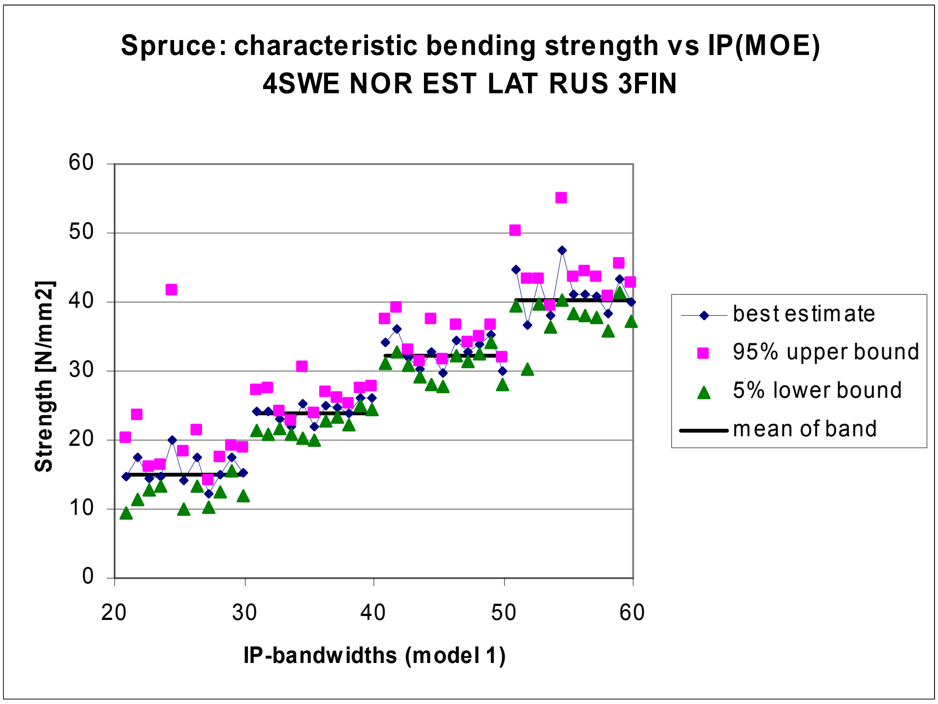
Upper Figure. Best estimates of characteristic strength of grades (bands) when grading is based on the strength model (IP) indicated in the figure. Bandwidth of IP is 10 MPa. 90% confidence limits are based on average sample size and COV of the grade.

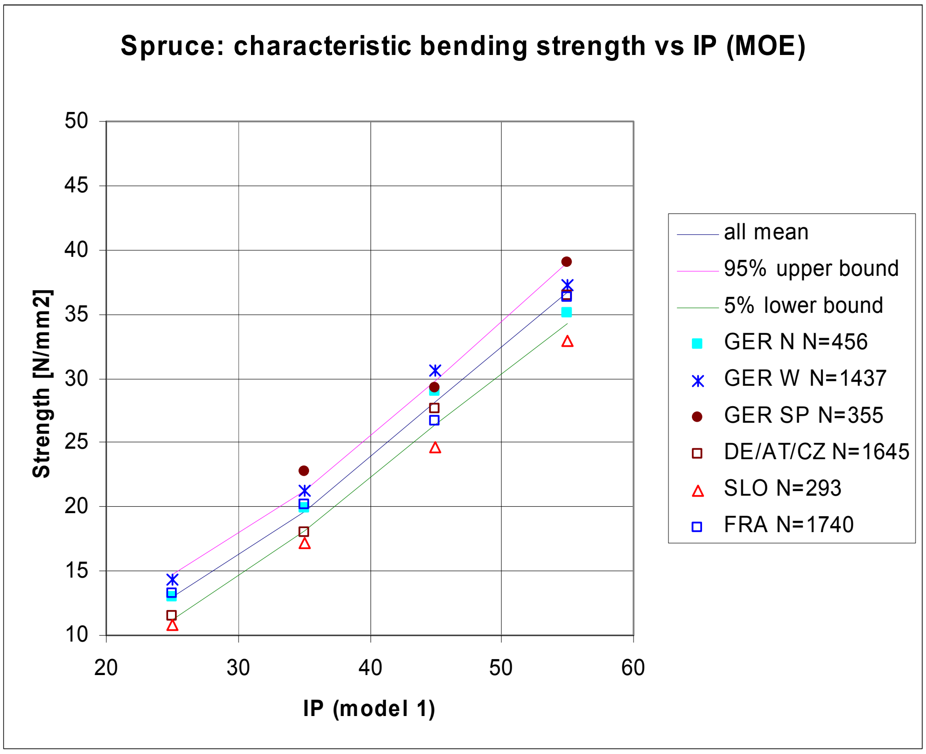
Lower Figure. Best estimates and confidence limits of characteristic strength values based on the actual sample size and COV of each band and region. Dots on each band are in same order as the test series are listed in Upper Figure. Please notice that in some figures the 90% confidence limits are expressed as upper and lower 90% confidence limit, in some others as upper 95% and lower 5% limit.

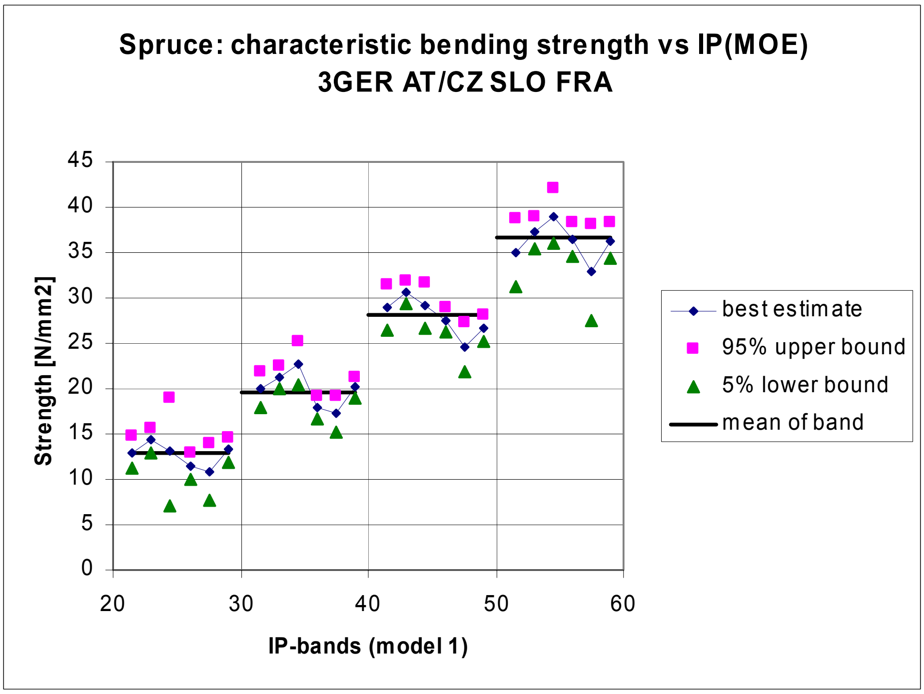

Spruce: characteristic bending strength vs IP (MOE)
Strength [N/mm2]
IP (model 1)
50
40
30
20
10
20
30
40
50
60
all mean
95% upper bound
5% lower bound
SWE N=4393
RUS N=1031
FIN N=2846
GER N=3538
FRA N=1740

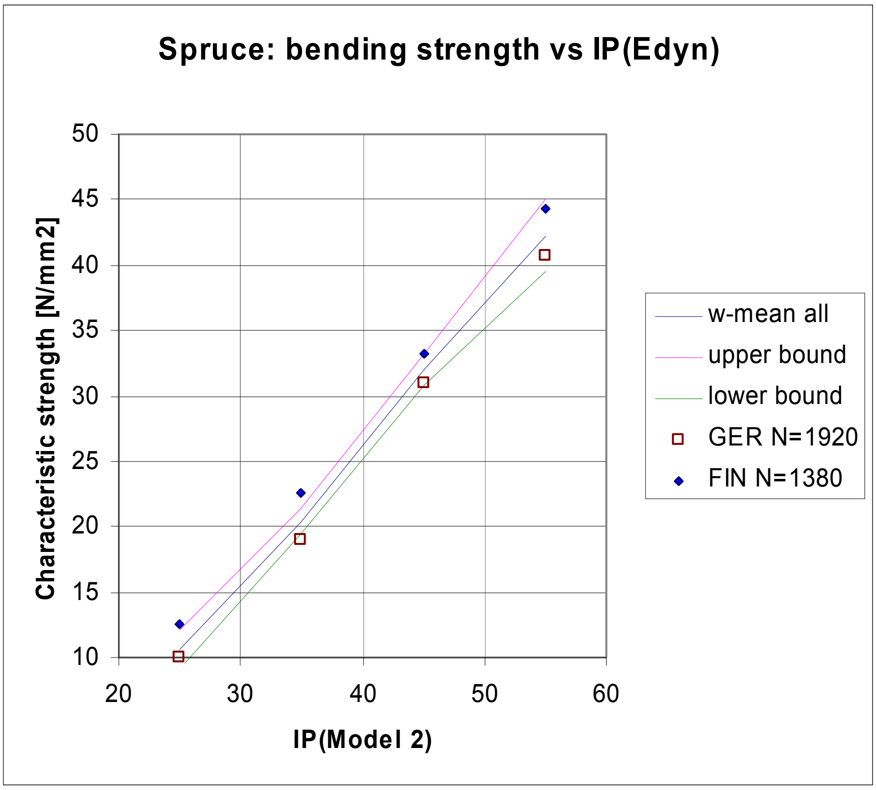

Spruce: characteristic bending strength vs IP (MOE)
Strength [N/mm2]
IP (model 1)
50
45
40
35
30
25
20
15
10
20
30
40
50
60
all mean
95% upper bound
5% lower bound
SWE NIn N=232
SWE NCo N=221
SWE C N=1844
SWE S N=2096
NOR Ö N=98
EST N=535
LAT N=300
RUS N=1031
FIN W N=906
FIN E N=1164
FIN SE N=625


Spruce: characteristic bending strength vs IP(MOE)
SWE RUS FIN GER FRA
Strength [N/mm2]
50
45
40
35
30
25
20
15
10
20
30
40
50
60
IP-bands (model 1)
best estimate
95% upper bound
5% lower bound
mean of band

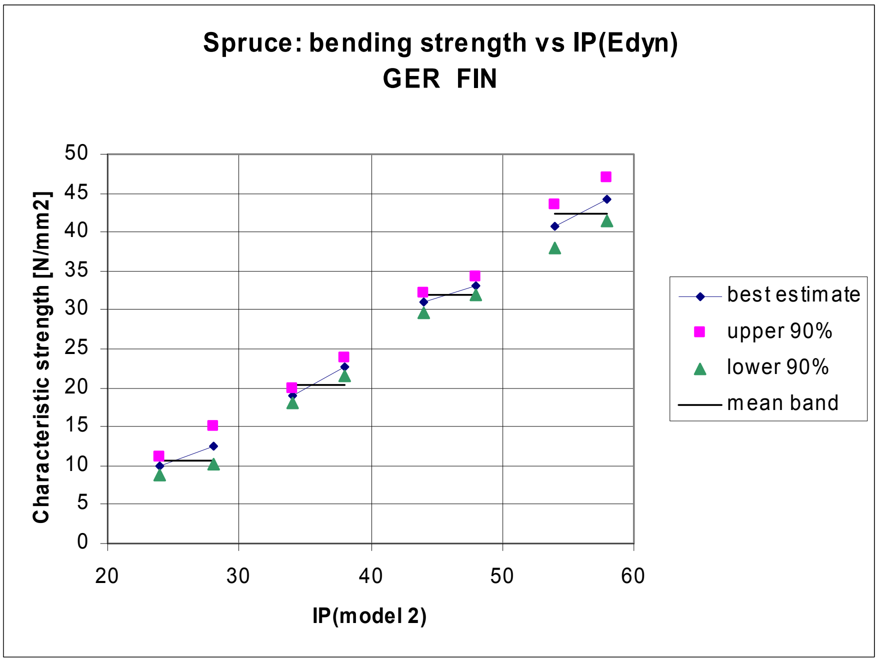

Spruce: characteristic bending strength vs IP(MOE)
4SWE NOR EST LAT RUS 3FIN
Strength [N/mm2]
60
50
40
30
20
10
0
20
30
40
50
60
IP-bandwidths (model 1)
best estimate
95% upper bound
5% lower bound
mean of band


Spruce: characteristic bending strength vs IP (MOE)
Strength [N/mm2]
IP (model 1)
50
45
40
35
30
25
20
15
10
20
30
40
50
60
all mean
95% upper bound
5% lower bound
GER N N=456
GER W N=1437
GER SP N=355
DE/AT/CZ N=1645
SLO N=293
FRA N=1740

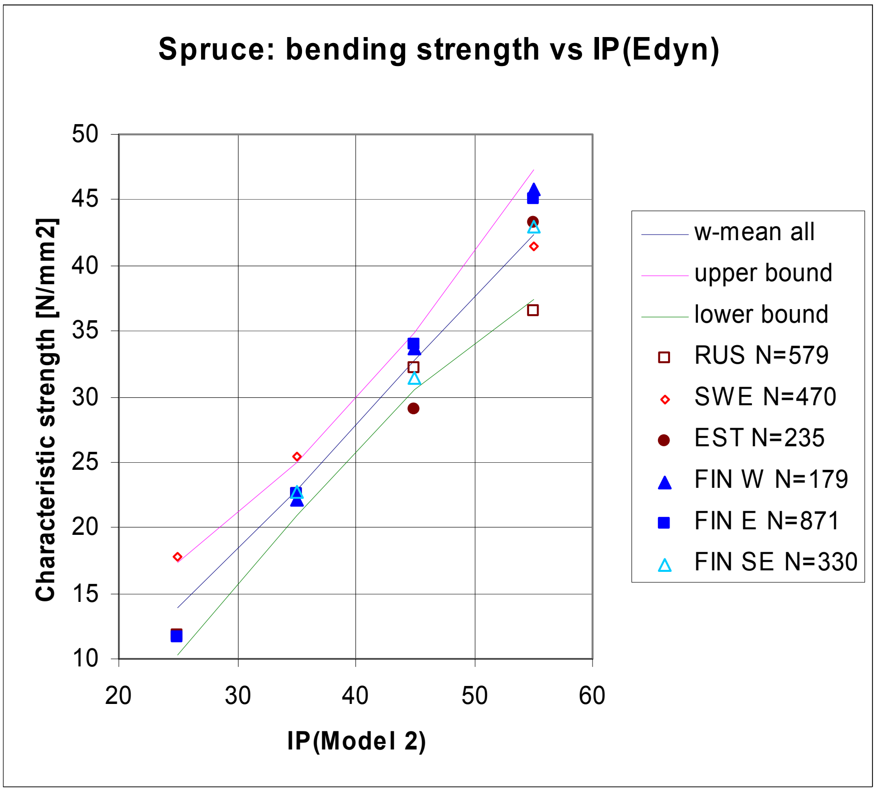

Spruce: characteristic bending strength vs IP(MOE)
3GER AT/CZ SLO FRA
Strength [N/mm2]
IP-bands (model 1)
45
40
35
30
25
20
15
10
5
0
20
30
40
50
60
best estimate
95% upper bound
5% lower bound
mean of band

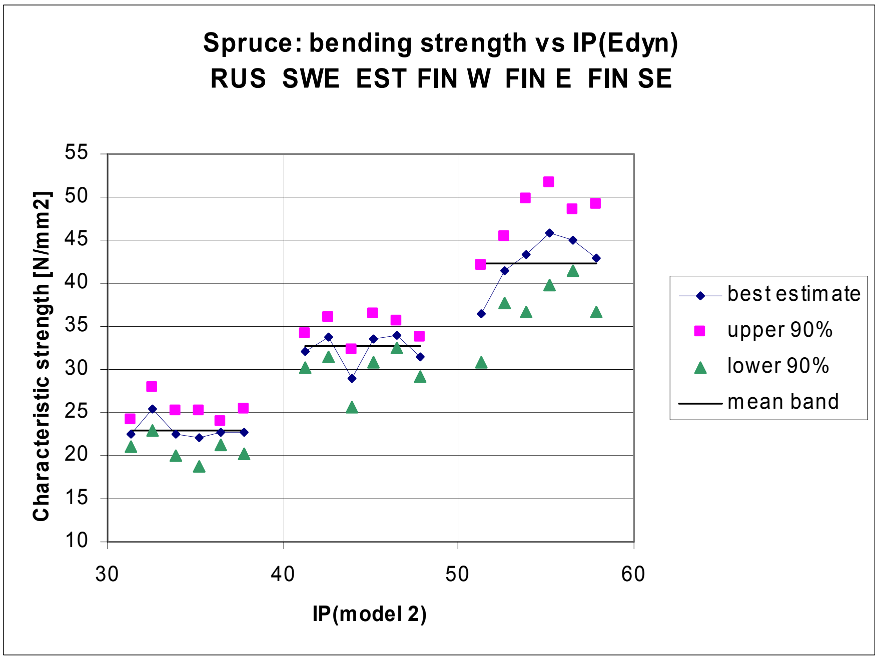


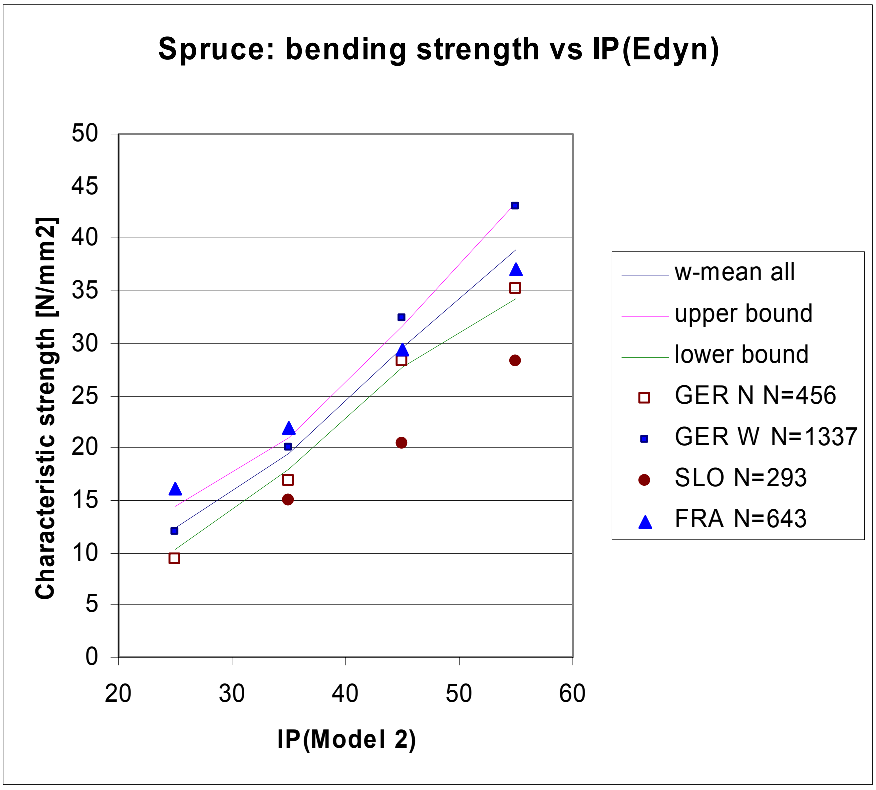
Spruce: bending strength vs IP(Edyn)
Characteristic strength [N/mm2]
IP(Model 2)
w-mean all
upper bound
lower bound
GER N=1920
FIN N=1380

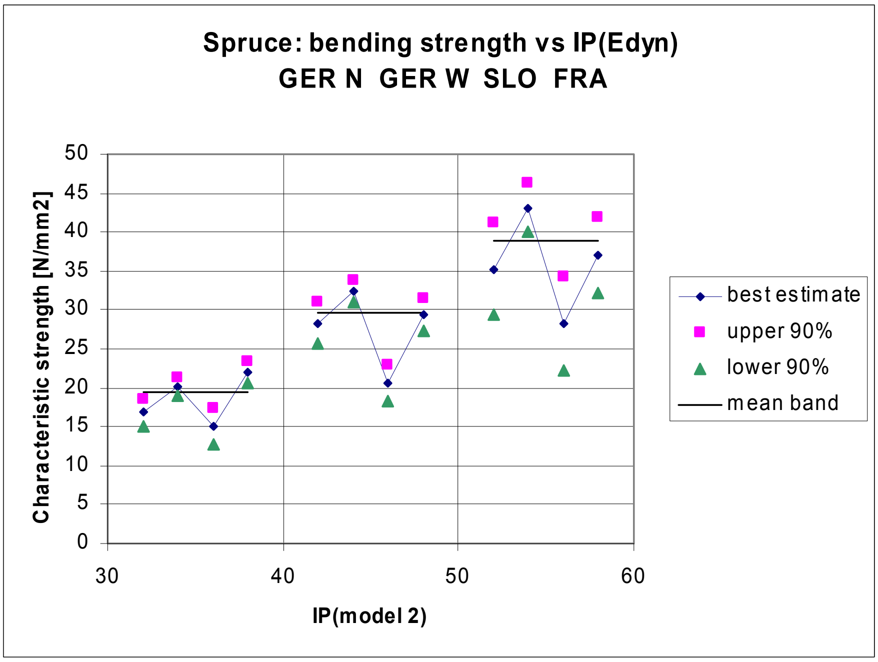


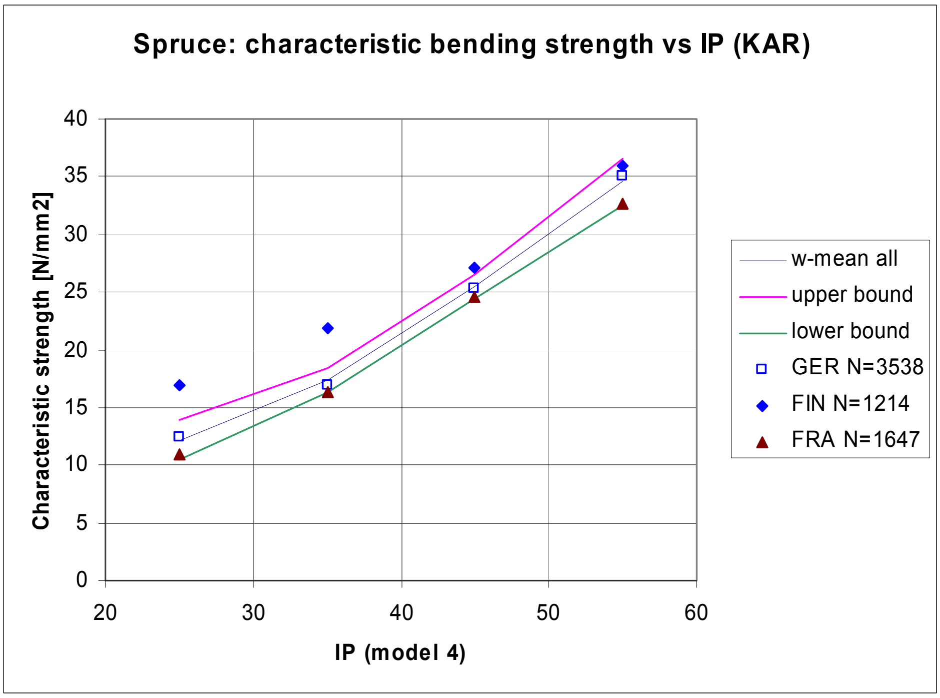
Spruce: bending strength vs IP(Edyn)
GER FIN
Characteristic strength [N/mm2]
IP(model 2)
best estimate
upper 90%
lower 90%
mean band

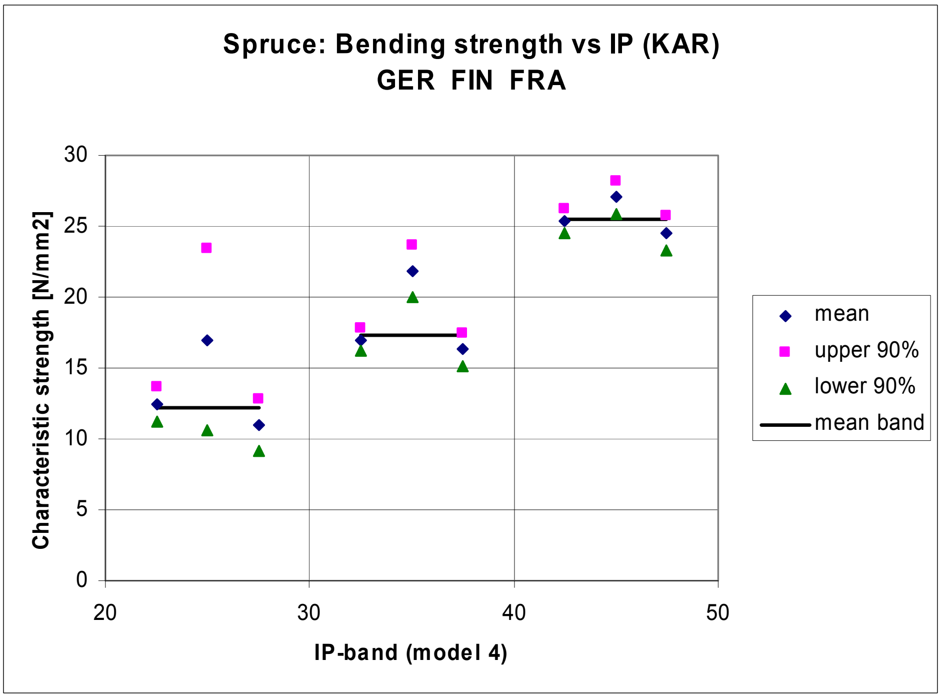

Spruce: bending strength vs IP(Edyn)
Characteristic strength [N/mm2]
IP(Model 2)
w-mean all
upper bound
lower bound
RUS N=579
SWE N=470
EST N=235
FIN W N=179
FIN E N=871
FIN SE N=330

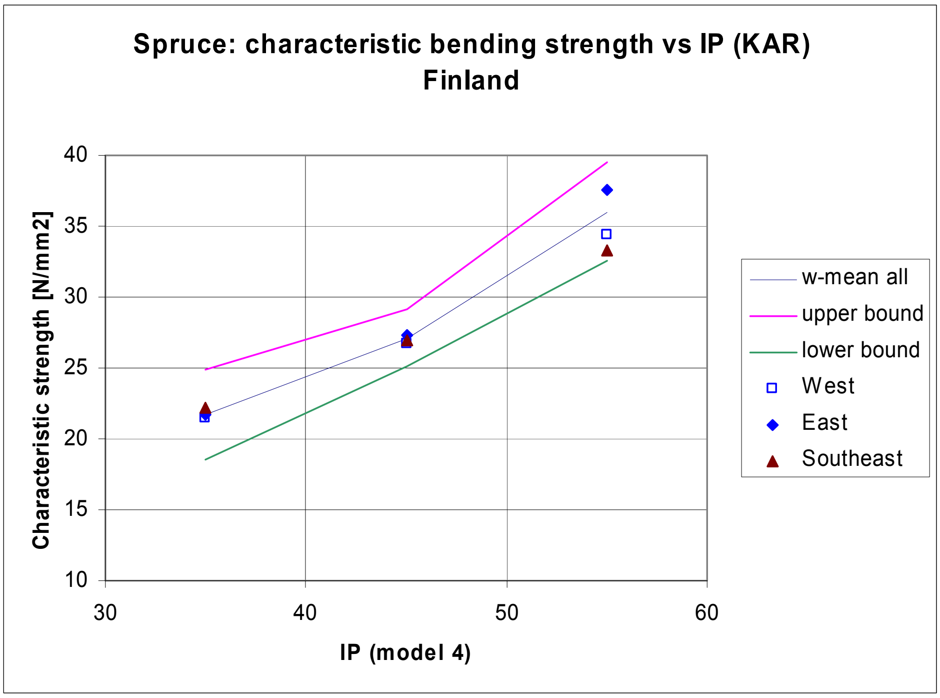

Spruce: bending strength vs IP(Edyn)
RUS SWE EST FIN W FIN E FIN SE
Characteristic strength [N/mm2]
IP(model 2)
best estimate
upper 90%
lower 90%
mean band

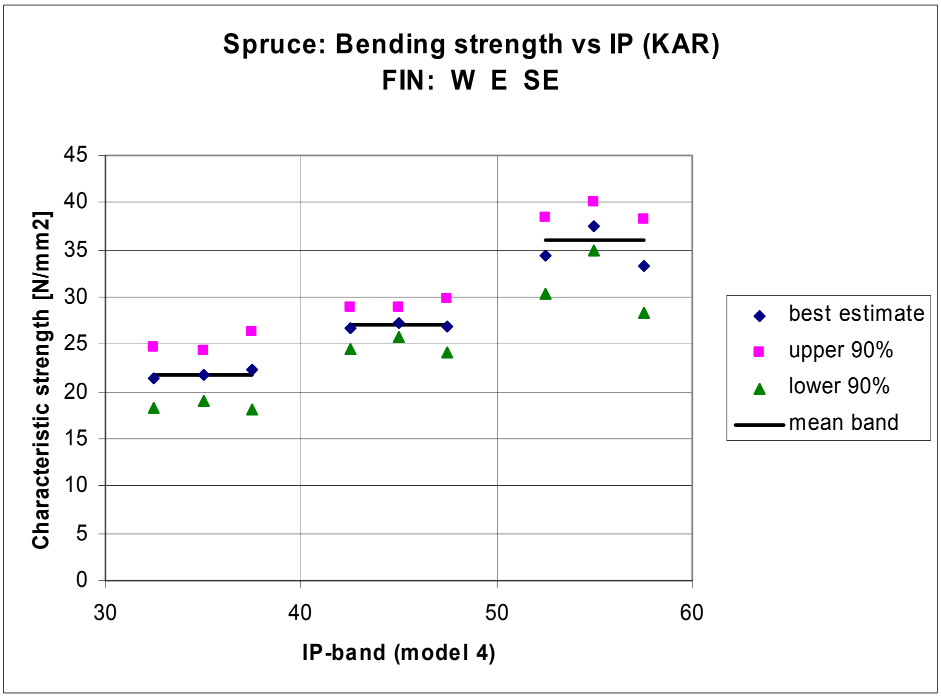

Spruce: bending strength vs IP(Edyn)
Characteristic strength [N/mm2]
IP(Model 2)
w-mean all
upper bound
lower bound
GER N N=456
GER W N=1337
SLO N=293
FRA N=643

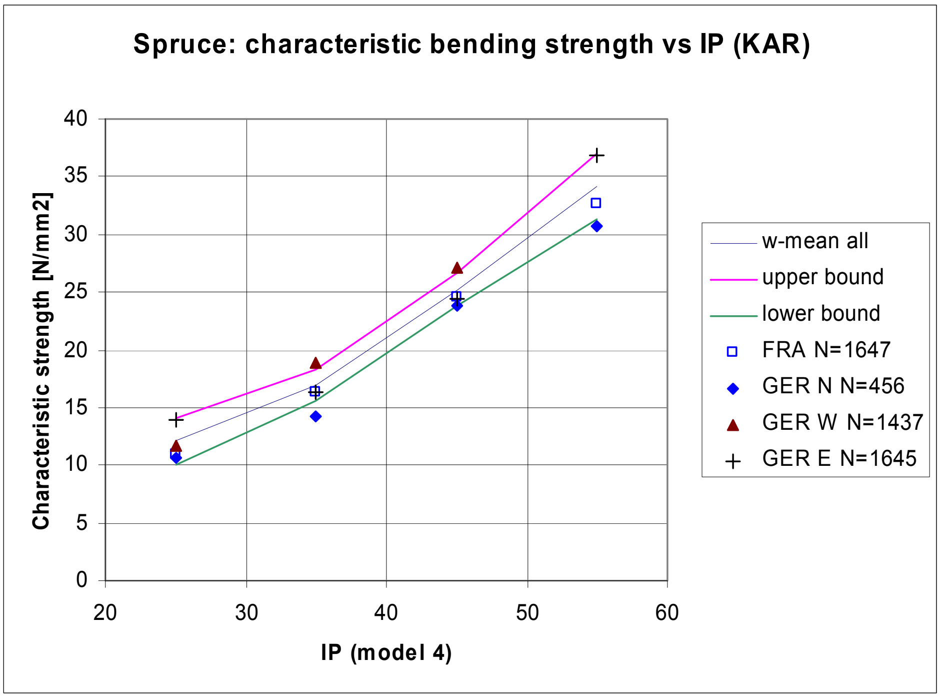

Spruce: bending strength vs IP(Edyn)
GER N GER W SLO FRA
Characteristic strength [N/mm2]
IP(model 2)
best estimate
upper 90%
lower 90%
mean band

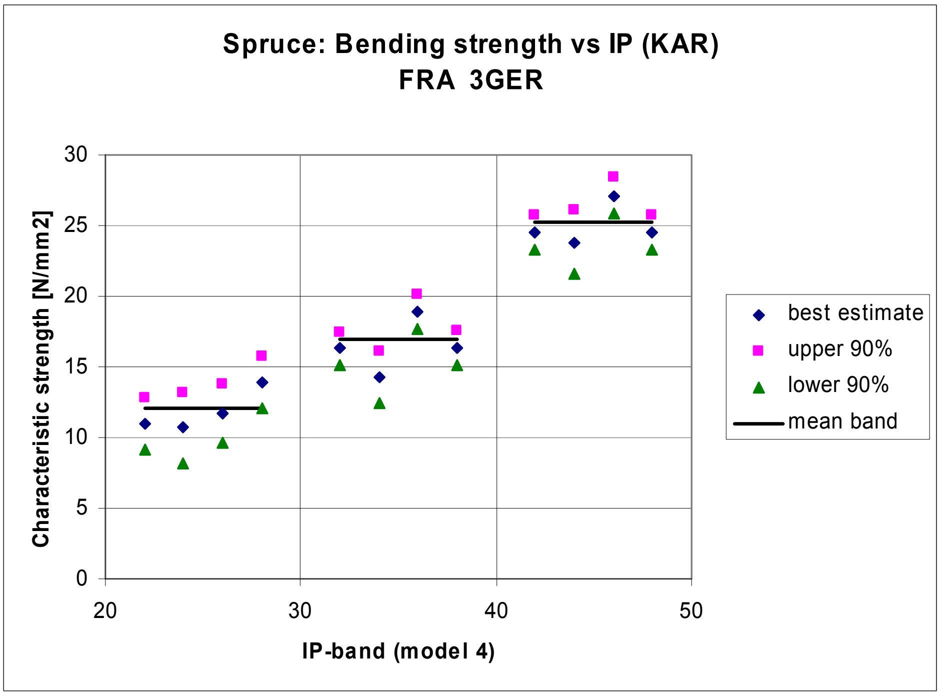

Spruce: characteristic bending strength vs IP (KAR)
Characteristic strength [N/mm2]
IP (model 4)
0
5
10
15
20
25
30
35
40
20
30
40
50
60
w-mean all
upper bound
lower bound
GER N=3538
FIN N=1214
FRA N=1647

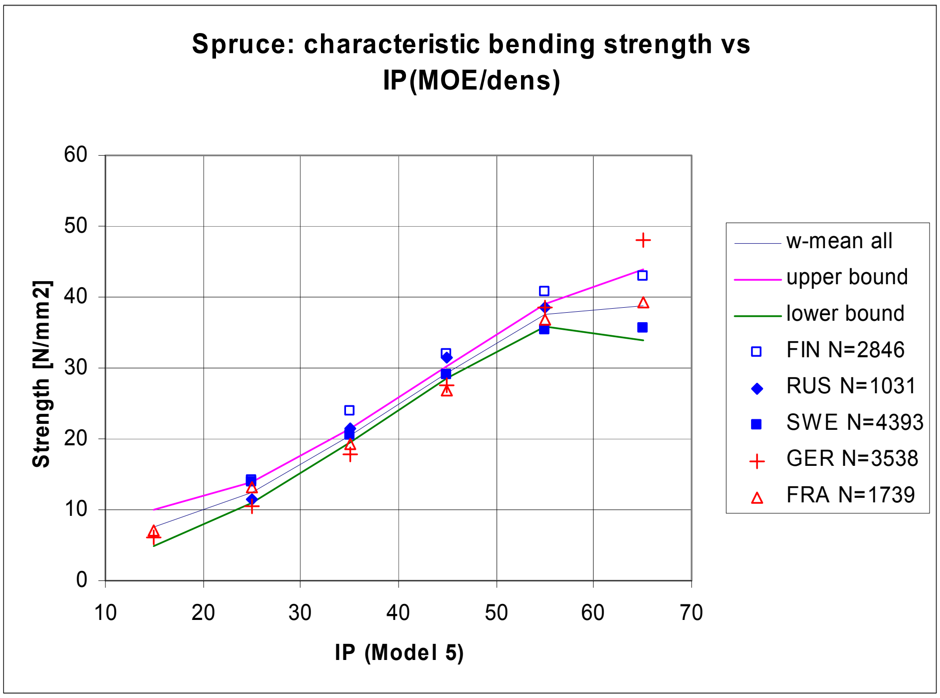

Spruce: Bending strength vs IP (KAR)
GER FIN FRA
Characteristic strength [N/mm2]
IP-band (model 4)
0
5
10
15
20
25
30
20
30
40
50
mean
upper 90%
lower 90%
mean band

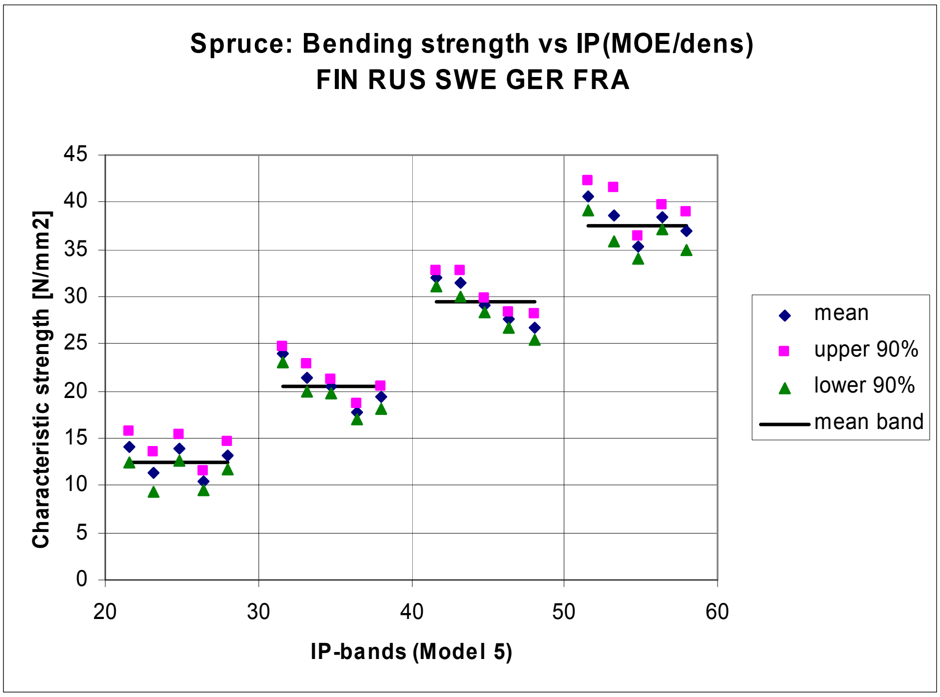

Spruce: characteristic bending strength vs IP (KAR)
Finland
Characteristic strength [N/mm2]
IP (model 4)
40
35
30
25
20
15
10
30
40
50
60
w-mean all
upper bound
lower bound
West
East
Southeast

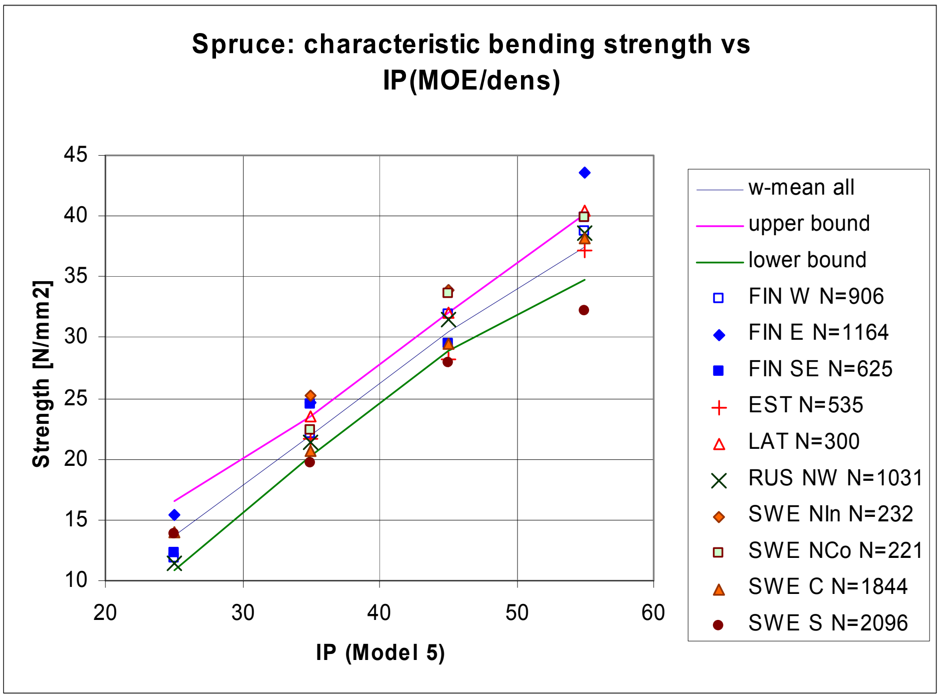

Spruce: Bending strength vs IP (KAR)
FIN: W E SE
Characteristic strength [N/mm2]
IP-band (model 4)
45
40
35
30
25
20
15
10
5
0
30
40
50
60
best estimate
upper 90%
lower 90%
mean band

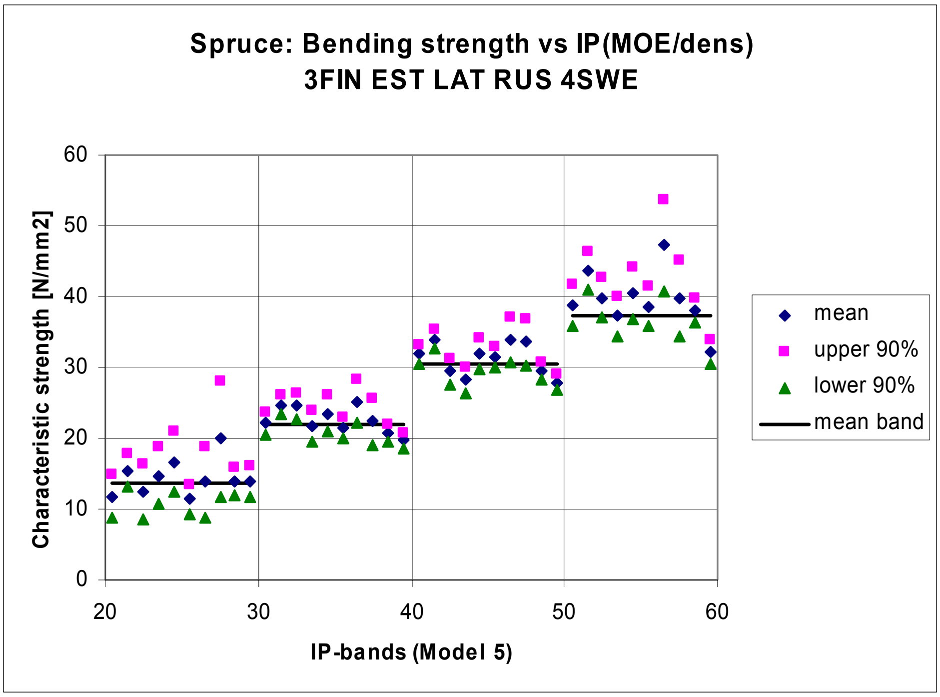

Spruce: characteristic bending strength vs IP (KAR)
Characteristic strength [N/mm2]
IP (model 4)
0
5
10
15
20
25
30
35
40
20
30
40
50
60
w-mean all
upper bound
lower bound
FRA N=1647
GER N N=456
GER W N=1437
GER E N=1645

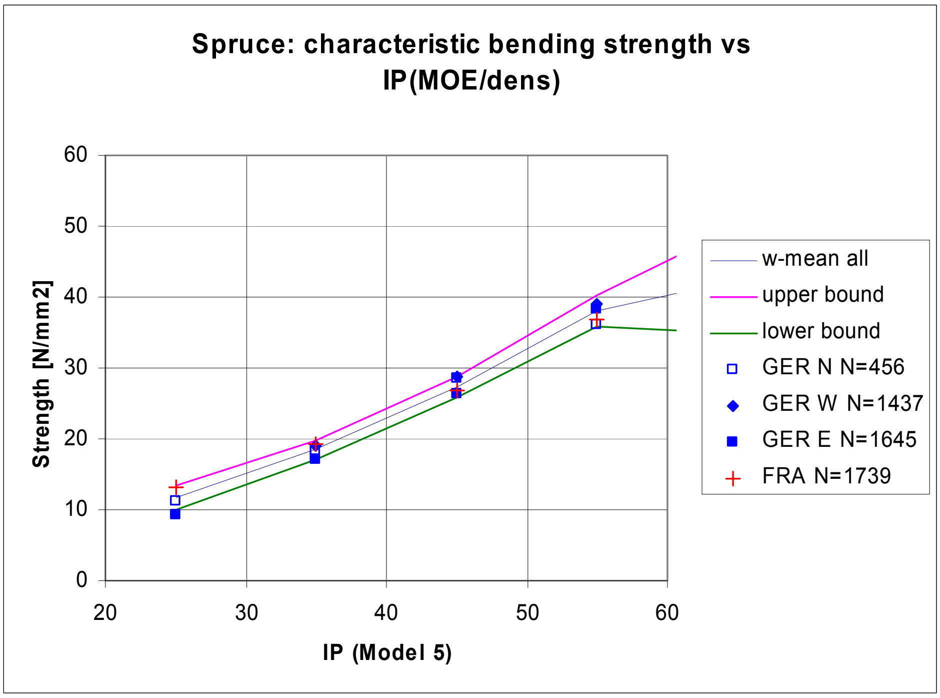

Spruce: Bending strength vs IP (KAR)
FRA 3GER
Characteristic strength [N/mm2]
IP-band (model 4)
0
5
10
15
20
25
30
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

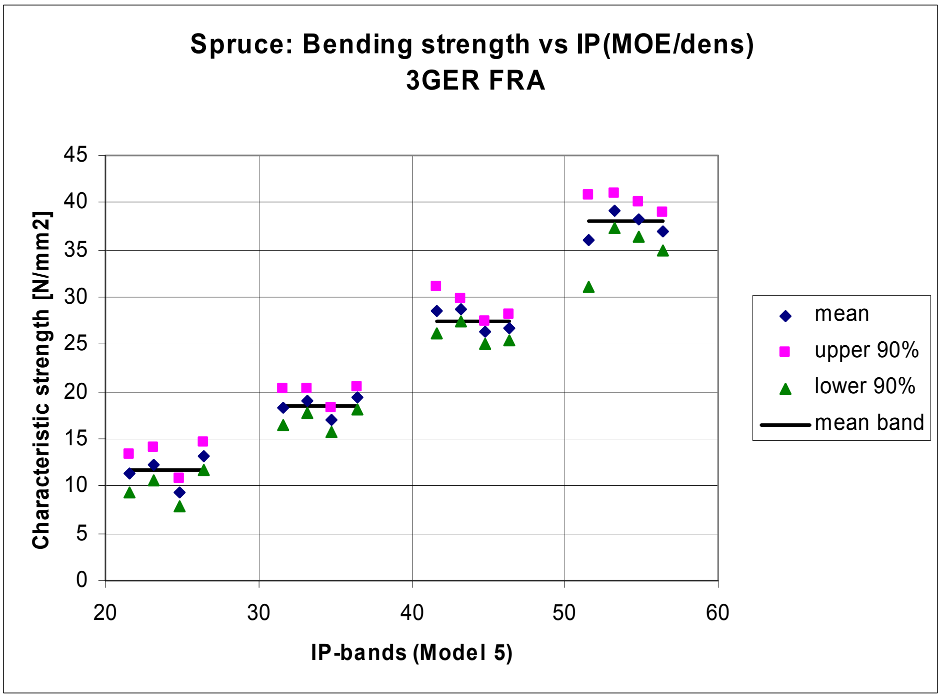

Spruce: characteristic bending strength vs IP(MOE/dens)
Strength [N/mm2]
IP (Model 5)
w-mean all
upper bound
lower bound
FIN N=2846
RUS N=1031
SWE N=4393
GER N=3538
FRA N=1739

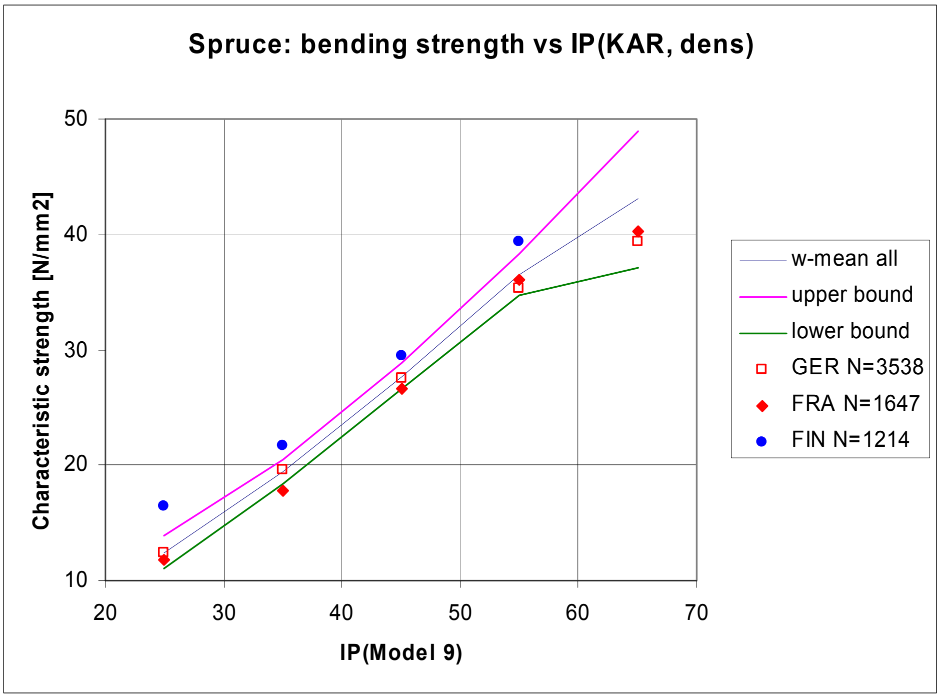

Spruce: Bending strength vs IP(MOE/dens)
FIN RUS SWE GER FRA
Characteristic strength [N/mm2]
IP-bands (Model 5)
mean
upper 90%
lower 90%
mean band

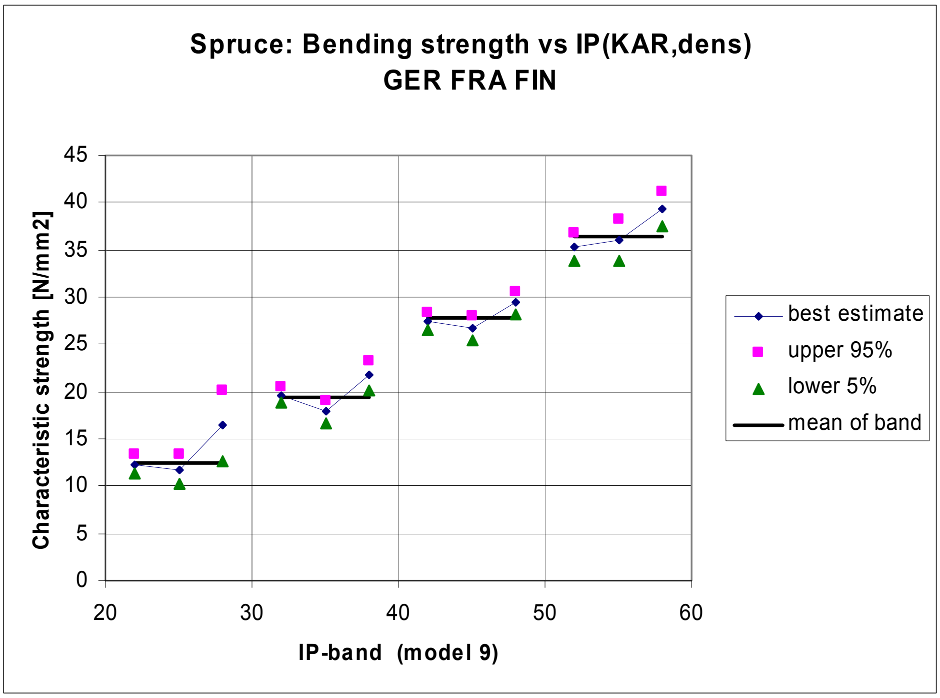

Spruce: characteristic bending strength vs IP(MOE/dens)
Strength [N/mm2]
IP (Model 5)
w-mean all
upper bound
lower bound
FIN W N=906
FIN E N=1164
FIN SE N=625
EST N=535
LAT N=300
RUS NW N=1031
SWE NIn N=232
SWE NCo N=221
SWE C N=1844
SWE S N=2096

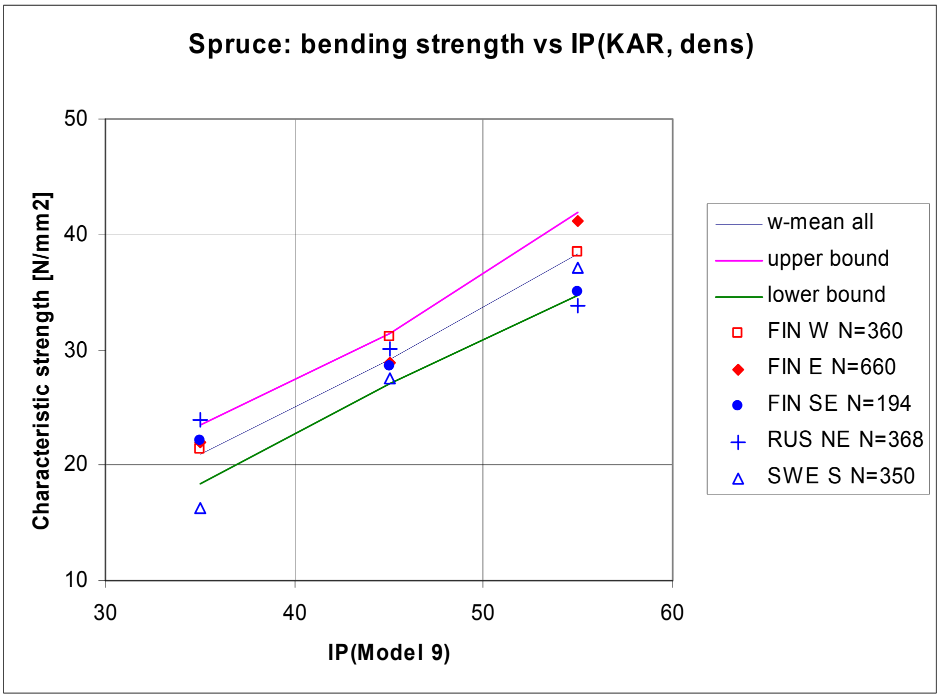

Spruce: Bending strength vs IP(MOE/dens)
3FIN EST LAT RUS 4SWE
Characteristic strength [N/mm2]
IP-bands (Model 5)
mean
upper 90%
lower 90%
mean band

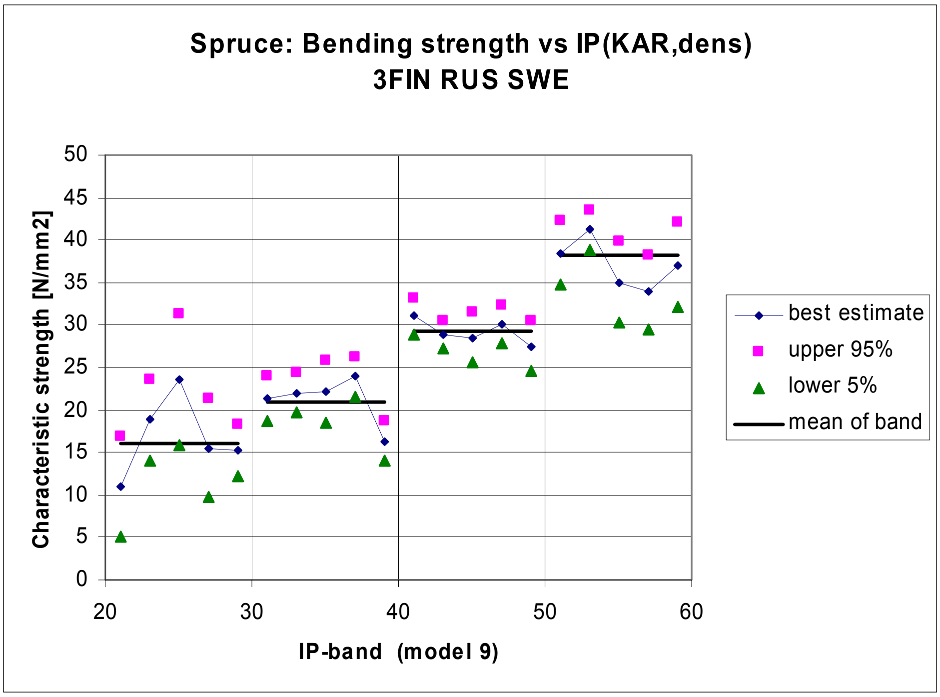

Spruce: characteristic bending strength vs IP(MOE/dens)
60
50
40
30
20
10
0
Strength [N/mm2]
20
30
40
50
60
IP (Model 5)
w-mean all
upper bound
lower bound
GER N N=456
GER W N=1437
GER E N=1645
FRA N=1739

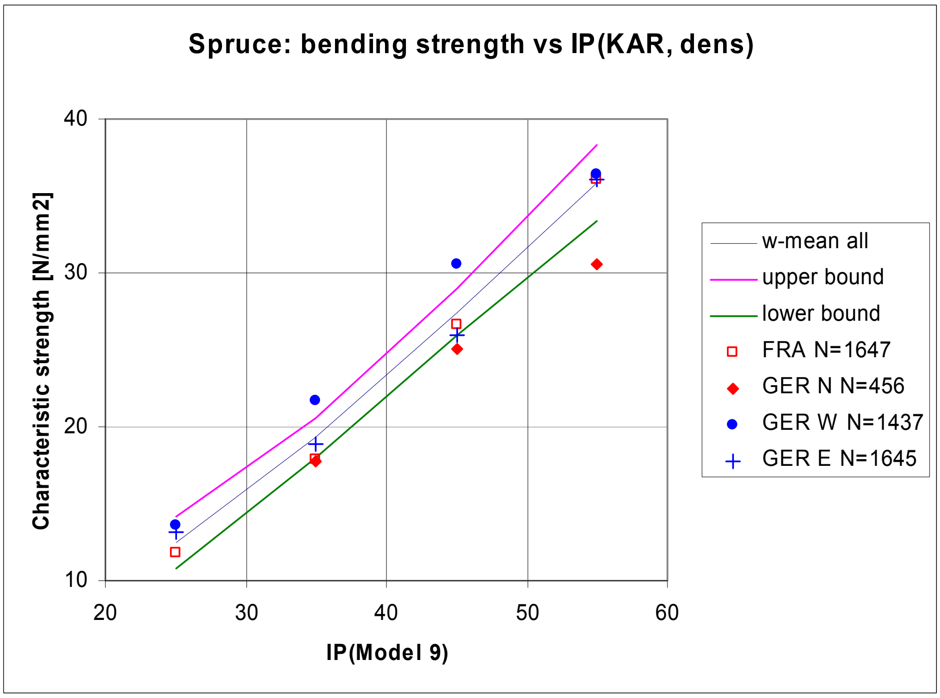

Spruce: Bending strength vs IP(MOE/dens) 3GER FRA
45
40
35
30
25
20
15
10
5
0
Characteristic strength [N/mm2]
20
30
40
50
60
IP-bands (Model 5)
mean
upper 90%
lower 90%
mean band

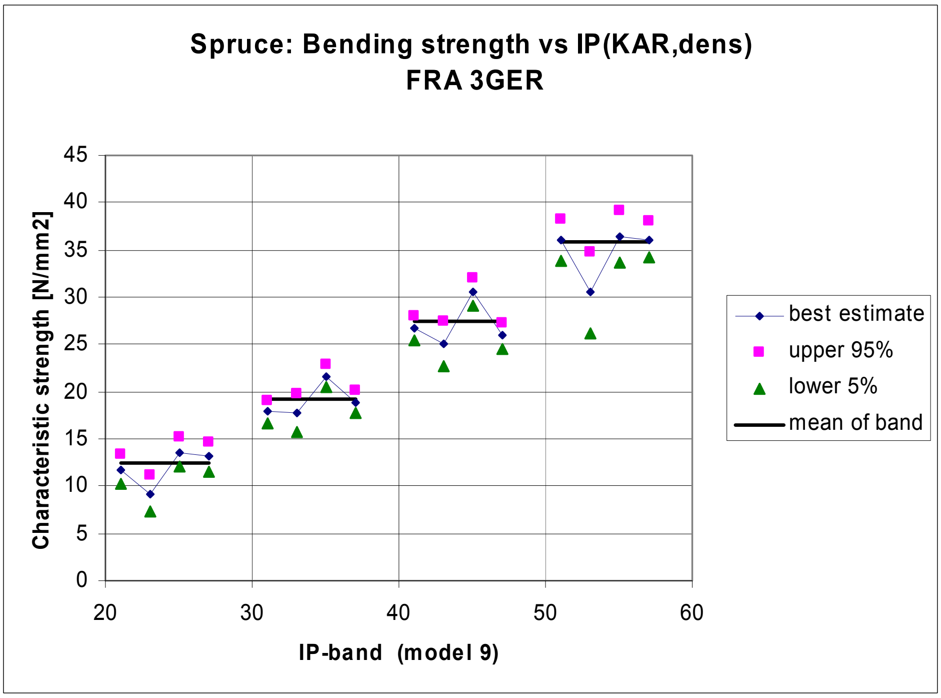

Spruce: bending strength vs IP(KAR, dens)
Characteristic strength [N/mm2]
IP(Model 9)
10
20
30
40
50
20
30
40
50
60
70
w-mean all
upper bound
lower bound
GER N=3538
FRA N=1647
FIN N=1214

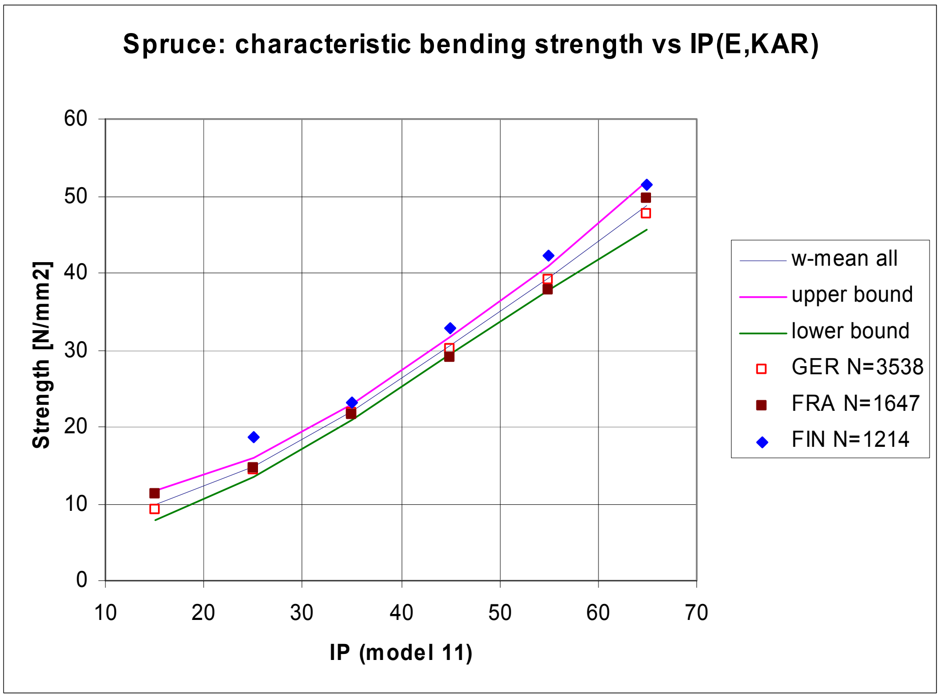

Spruce: Bending strength vs IP(KAR,dens)
GER FRA FIN
Characteristic strength [N/mm2]
IP-band (model 9)
0
5
10
15
20
25
30
35
40
45
20
30
40
50
60
best estimate
upper 95%
lower 5%
mean of band

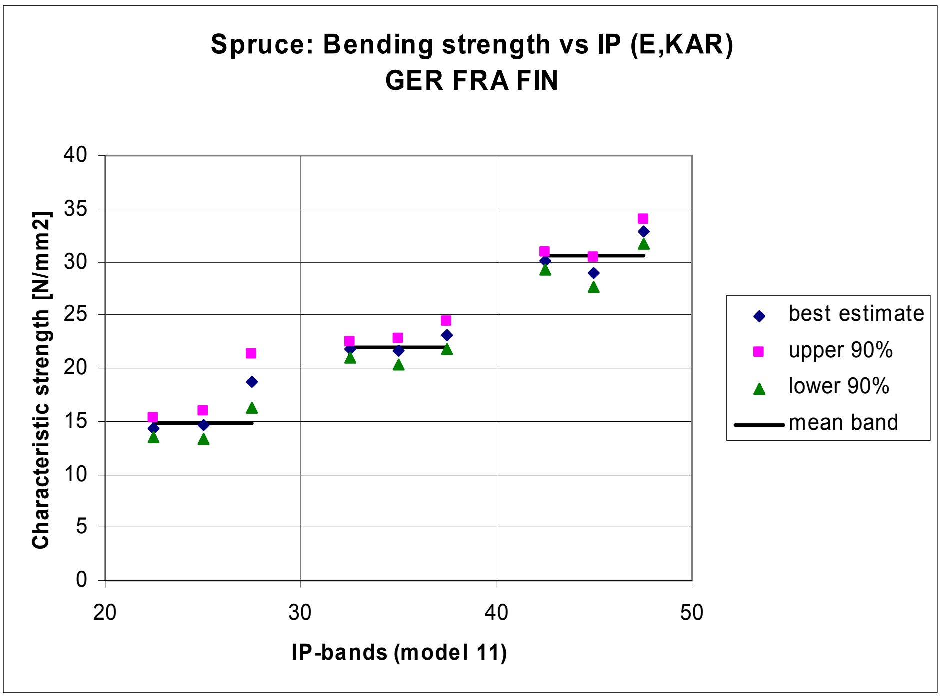

Spruce: bending strength vs IP(KAR, dens)
Characteristic strength [N/mm2]
IP(Model 9)
50
40
30
20
10
30
40
50
60
w-mean all
upper bound
lower bound
FIN W N=360
FIN E N=660
FIN SE N=194
RUS NE N=368
SWE S N=350

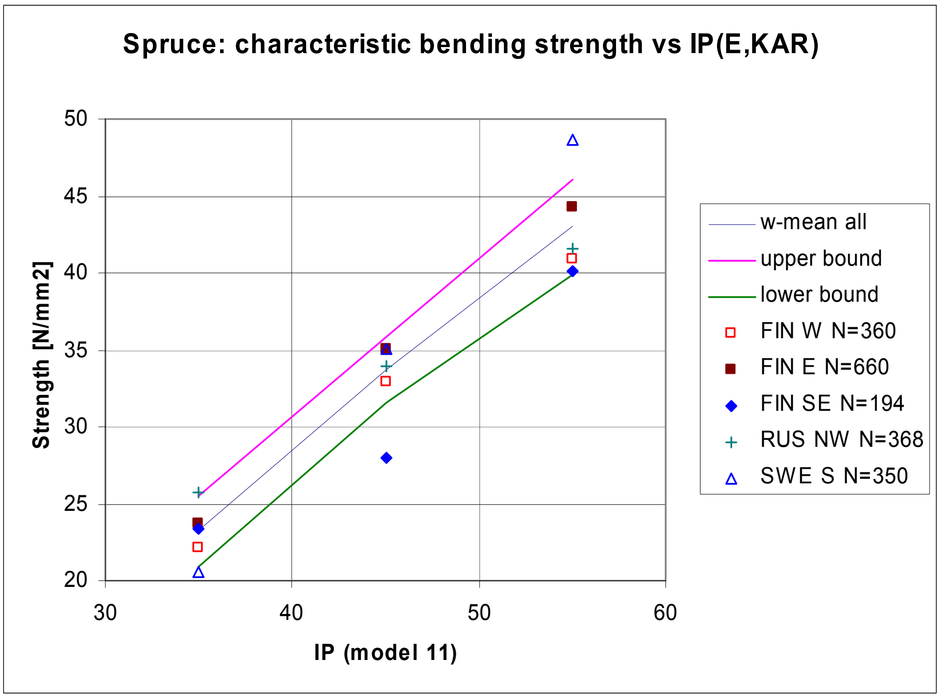

Spruce: Bending strength vs IP(KAR,dens)
3FIN RUS SWE
Characteristic strength [N/mm2]
IP-band (model 9)
50
45
40
35
30
25
20
15
10
5
0
20
30
40
50
60
best estimate
upper 95%
lower 5%
mean of band

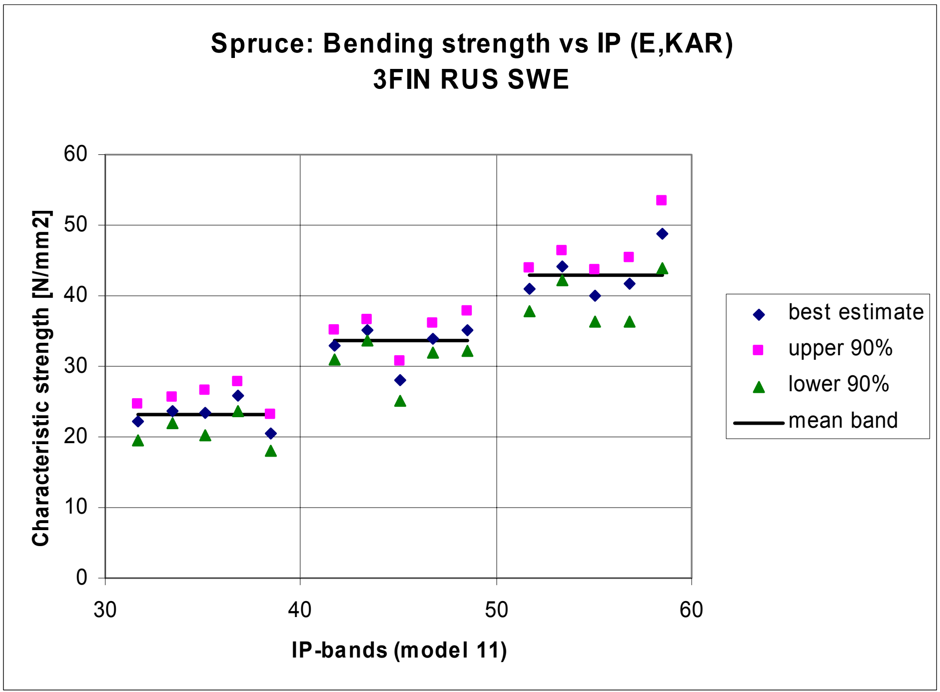

Spruce: bending strength vs IP(KAR, dens)
Characteristic strength [N/mm2]
IP(Model 9)
w-mean all
upper bound
lower bound
FRA N=1647
GER N N=456
GER W N=1437
GER E N=1645
40
30
20
10
20
30
40
50
60

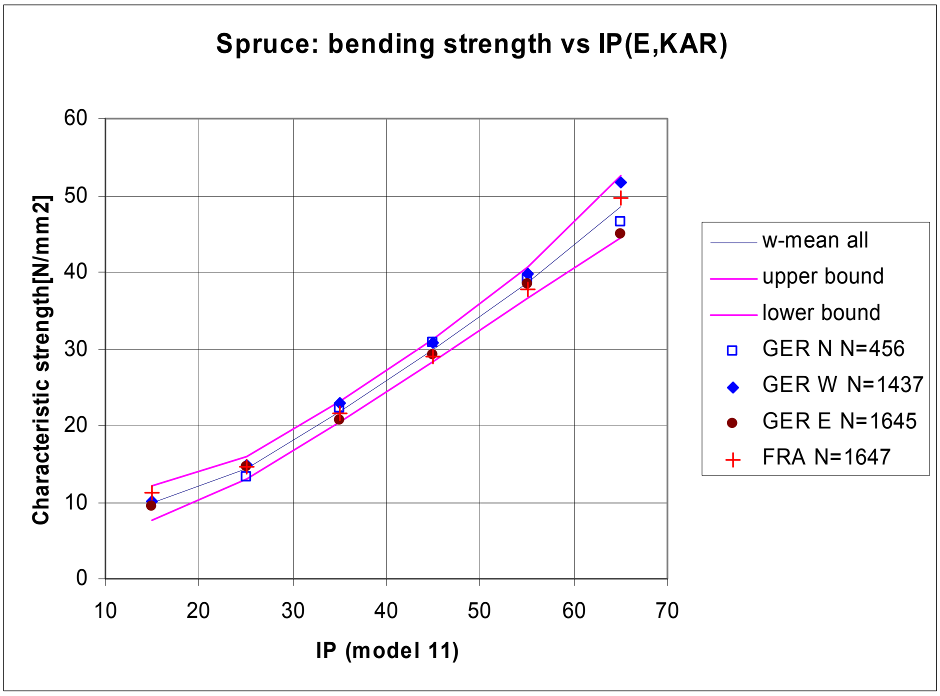

Spruce: Bending strength vs IP(KAR,dens)
FRA 3GER
Characteristic strength [N/mm2]
IP-band (model 9)
best estimate
upper 95%
lower 5%
mean of band
45
40
35
30
25
20
15
10
5
0
20
30
40
50
60

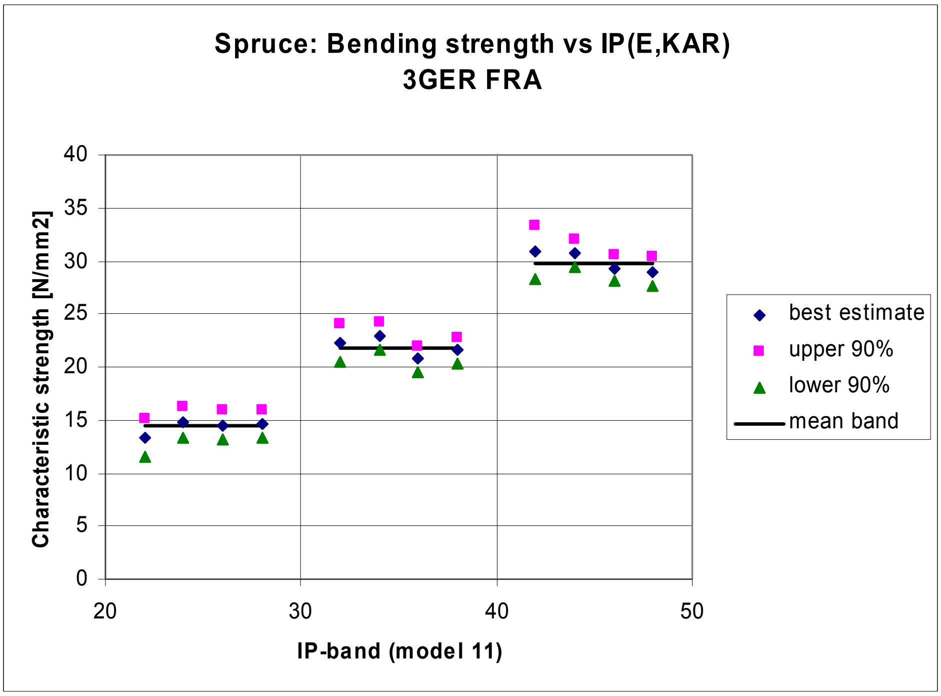

Spruce: characteristic bending strength vs IP(E,KAR)
Strength [N/mm2]
IP (model 11)
60
50
40
30
20
10
0
10
20
30
40
50
60
70
w-mean all
upper bound
lower bound
GER N=3538
FRA N=1647
FIN N=1214

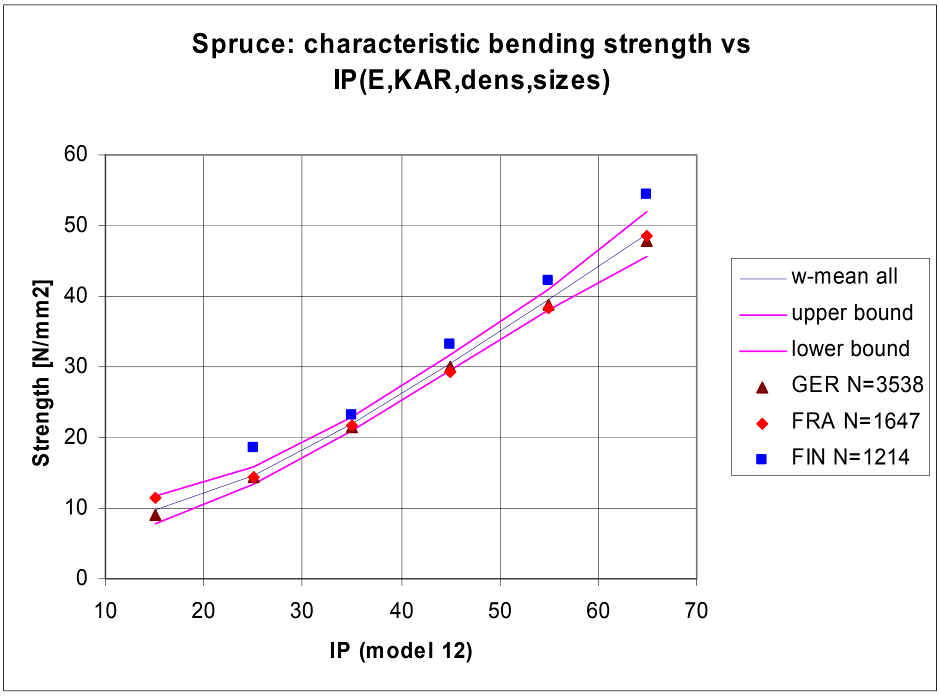

Spruce: Bending strength vs IP (E,KAR)
GER FRA FIN
Characteristic strength [N/mm2]
IP-bands (model 11)
40
35
30
25
20
15
10
5
0
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

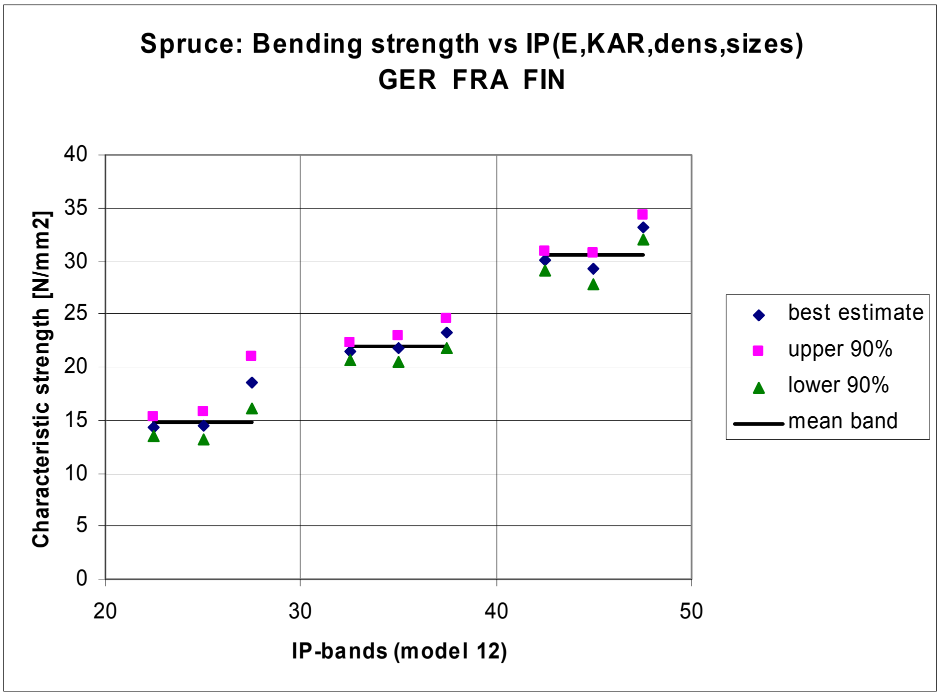

Spruce: characteristic bending strength vs IP(E,KAR)
Strength [N/mm2]
IP (model 11)
50
45
40
35
30
25
20
30
40
50
60
w-mean all
upper bound
lower bound
FIN W N=360
FIN E N=660
FIN SE N=194
RUS NW N=368
SWE S N=350

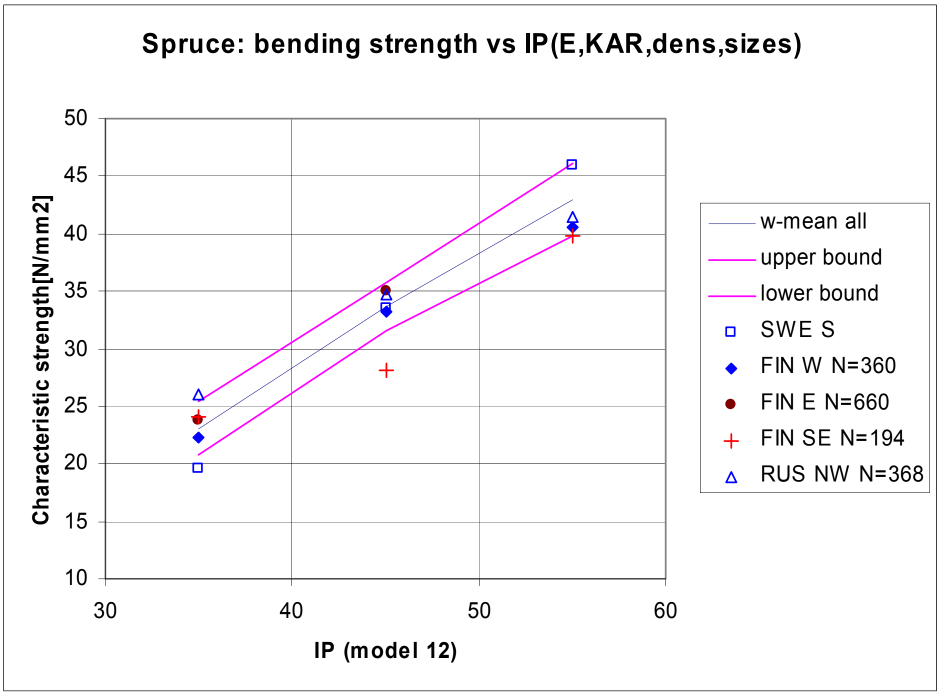

Spruce: Bending strength vs IP (E,KAR)
3FIN RUS SWE
Characteristic strength [N/mm2]
IP-bands (model 11)
60
50
40
30
20
10
0
30
40
50
60
best estimate
upper 90%
lower 90%
mean band

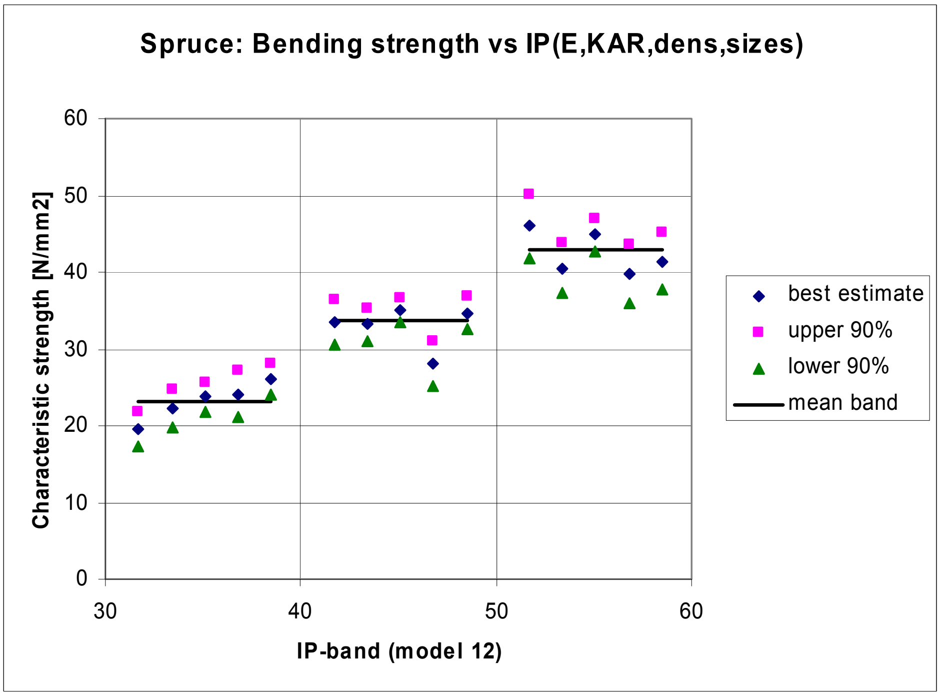

Spruce: bending strength vs IP(E,KAR)
Characteristic strength[N/mm2]
IP (model 11)
0
10
20
30
40
50
60
10
20
30
40
50
60
70
w-mean all
upper bound
lower bound
GER N N=456
GER W N=1437
GER E N=1645
FRA N=1647

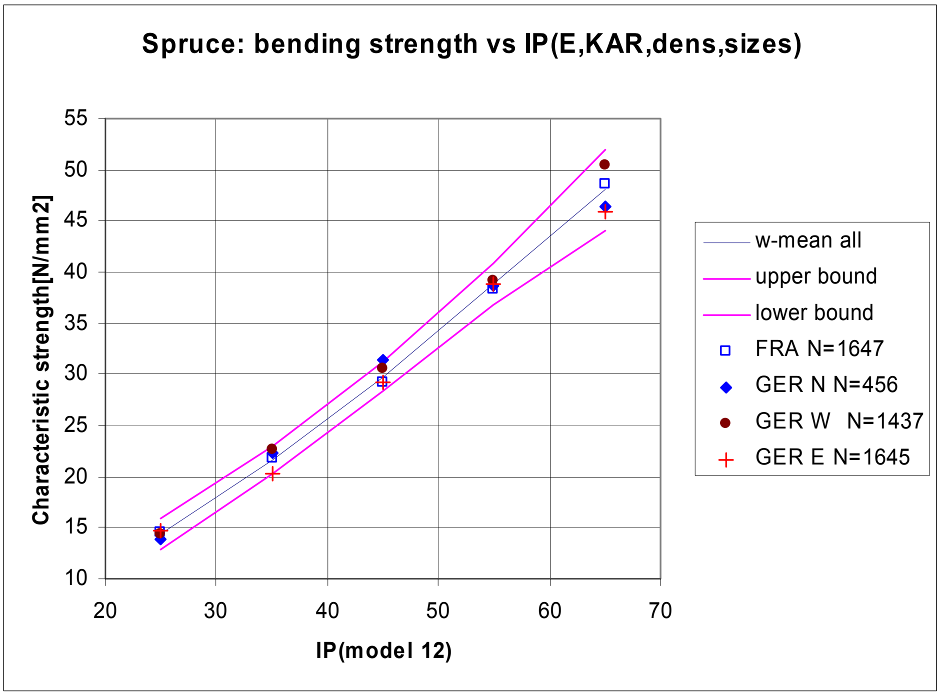

Spruce: Bending strength vs IP(E,KAR)
3GER FRA
Characteristic strength [N/mm2]
IP-band (model 11)
0
5
10
15
20
25
30
35
40
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

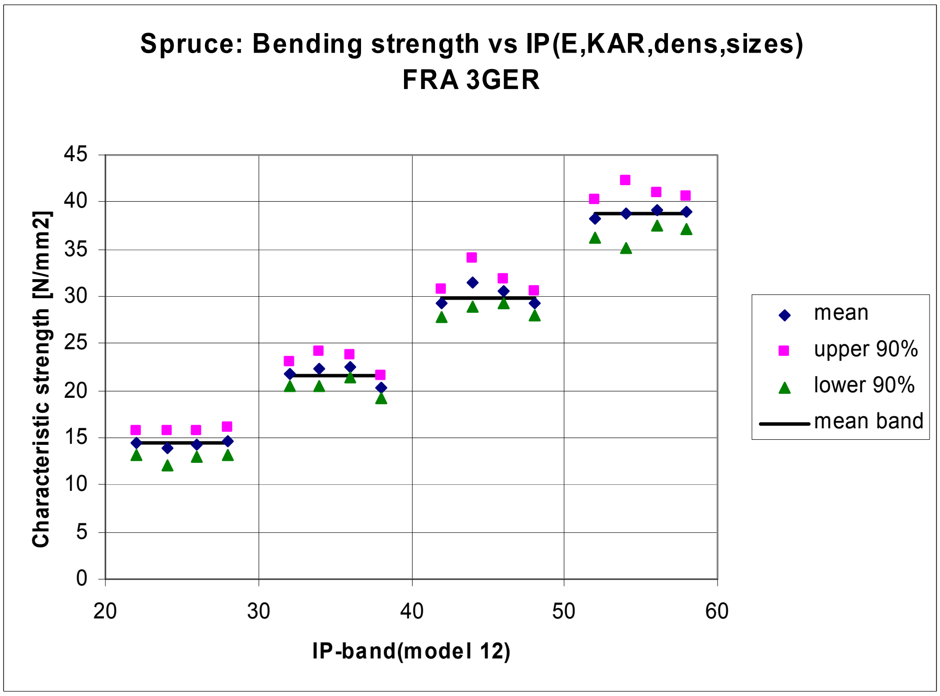

Spruce: characteristic bending strength vs IP(E,KAR,dens,sizes)
Strength [N/mm2]
IP (model 12)
0
10
20
30
40
50
60
10
20
30
40
50
60
70
w-mean all
upper bound
lower bound
GER N=3538
FRA N=1647
FIN N=1214

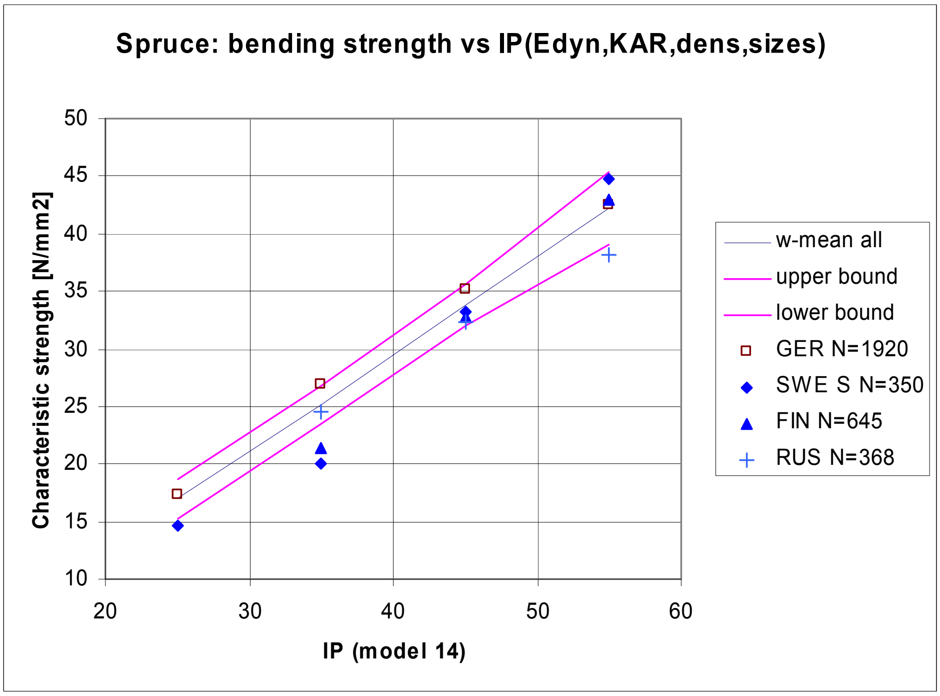

Spruce: Bending strength vs IP(E,KAR,dens,sizes)
GER FRA FIN
Characteristic strength [N/mm2]
IP-bands (model 12)
0
5
10
15
20
25
30
35
40
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

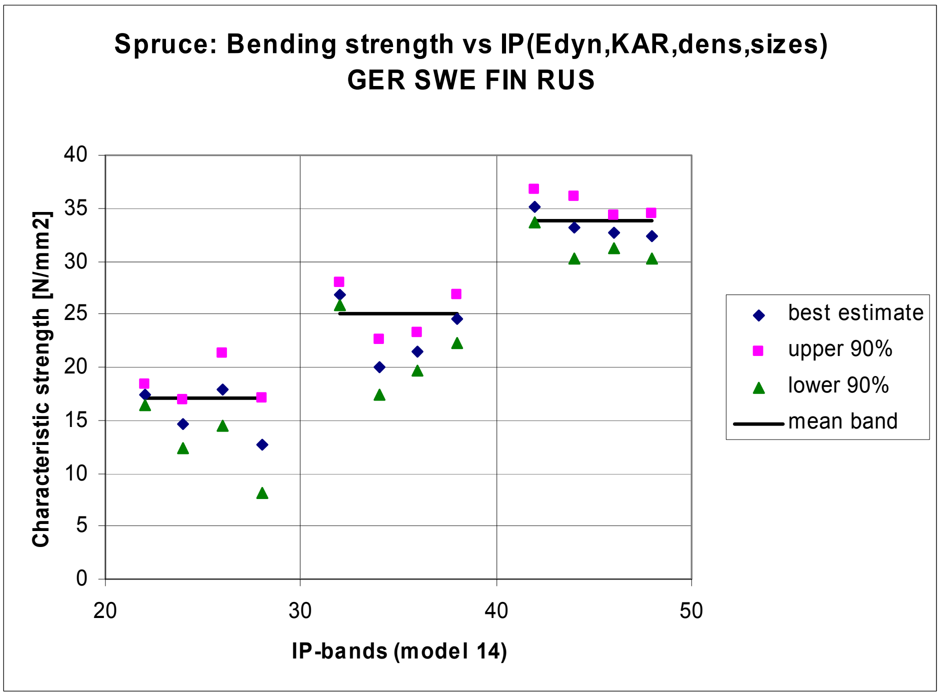

Spruce: bending strength vs IP(E,KAR,dens,sizes)
Characteristic strength[N/mm2]
IP (model 12)
50
45
40
35
30
25
20
15
10
30
40
50
60
w-mean all
upper bound
lower bound
SWE S
FIN W N=360
FIN E N=660
FIN SE N=194
RUS NW N=368

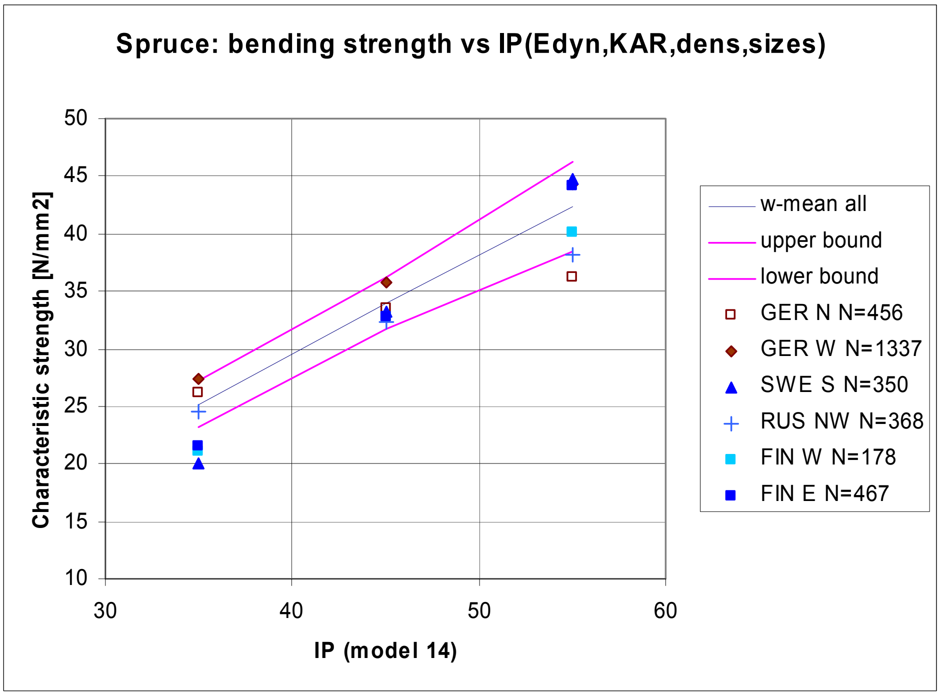

Spruce: Bending strength vs IP(E,KAR,dens,sizes)
Characteristic strength [N/mm2]
IP-band (model 12)
60
50
40
30
20
10
0
30
40
50
60
best estimate
upper 90%
lower 90%
mean band

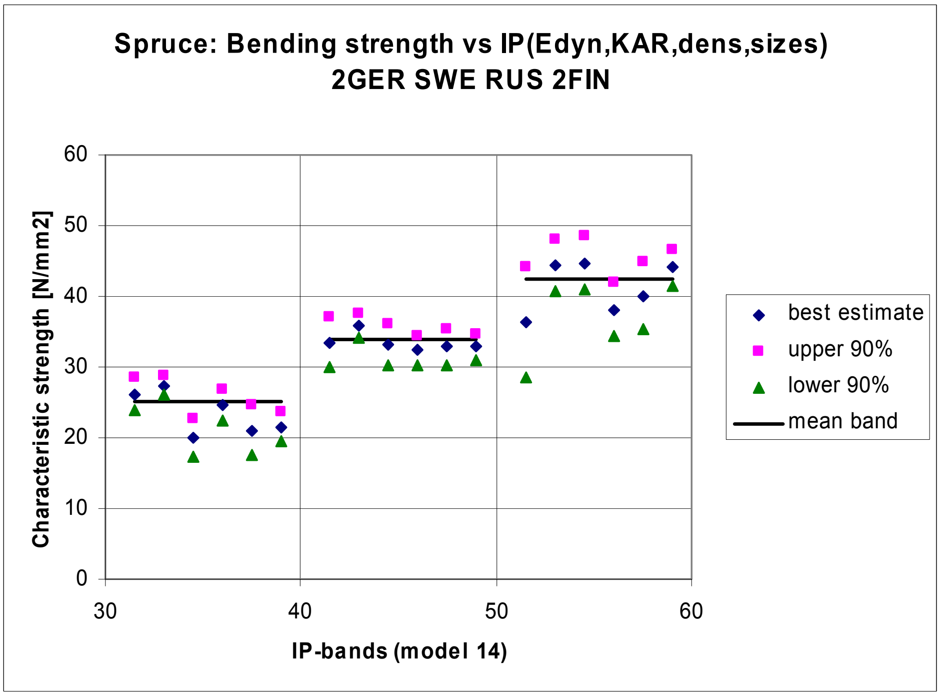

Spruce: bending strength vs IP(E,KAR,dens,sizes)
Characteristic strength[N/mm2]
IP(model 12)
55
50
45
40
35
30
25
20
15
10
20
30
40
50
60
70
w-mean all
upper bound
lower bound
FRA N=1647
GER N N=456
GER W N=1437
GER E N=1645

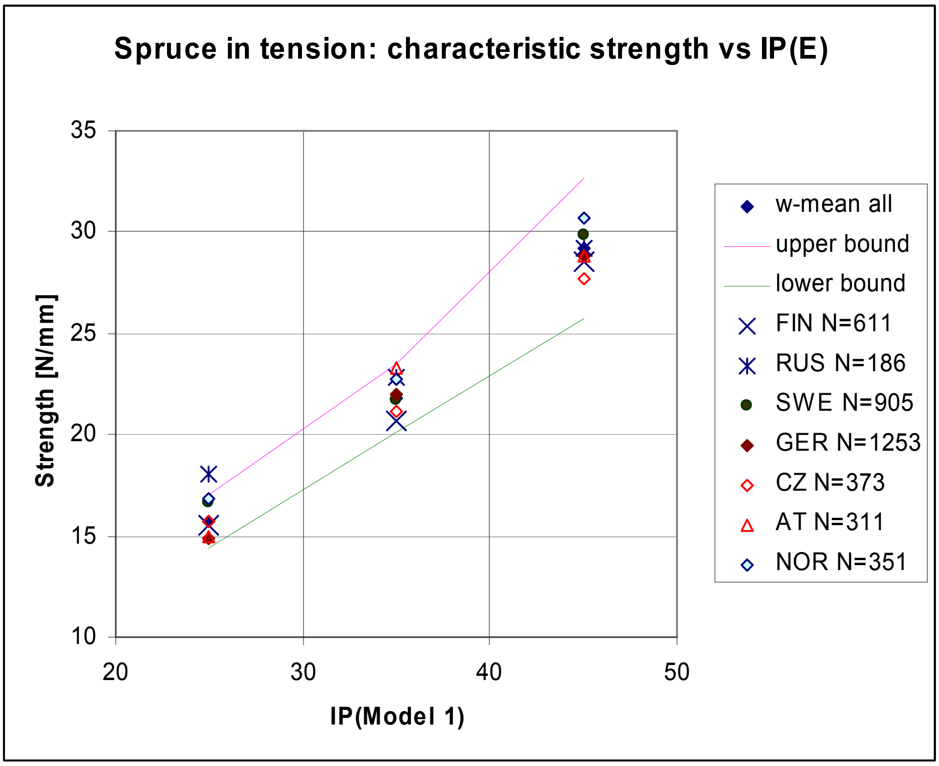

Spruce: Bending strength vs IP(E,KAR,dens,sizes)
FRA 3GER
Characteristic strength [N/mm2]
IP-band(model 12)
45
40
35
30
25
20
15
10
5
0
20
30
40
50
60
mean
upper 90%
lower 90%
mean band

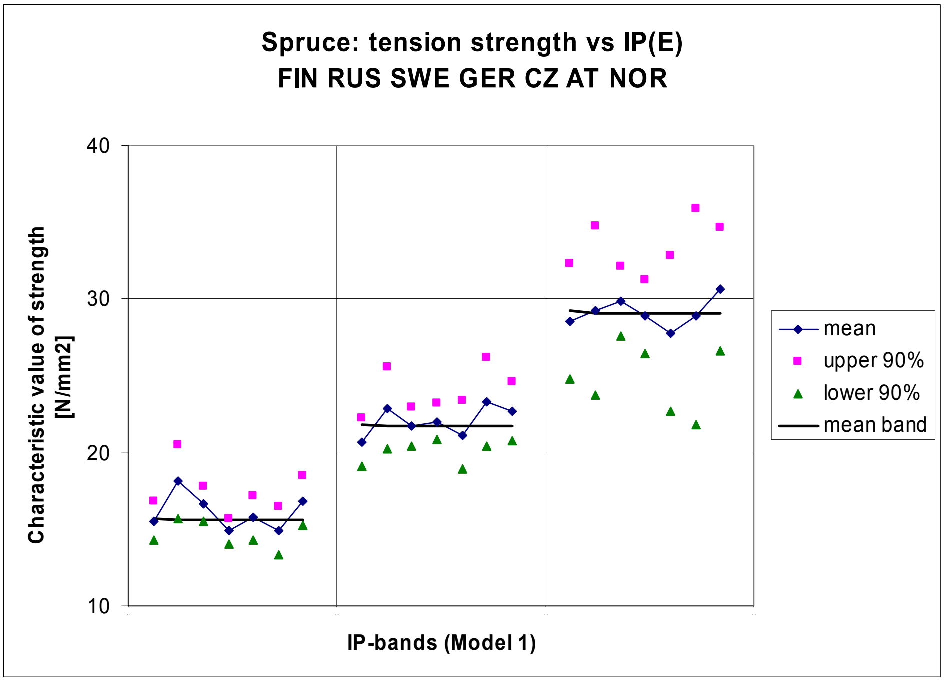

Spruce: bending strength vs IP(Edyn,KAR,dens,sizes)
Characteristic strength [N/mm2]
50
45
40
35
30
25
20
15
10
20
30
40
50
60
IP (model 14)
w-mean all
upper bound
lower bound
GER N=1920
SWE S N=350
FIN N=645
RUS N=368

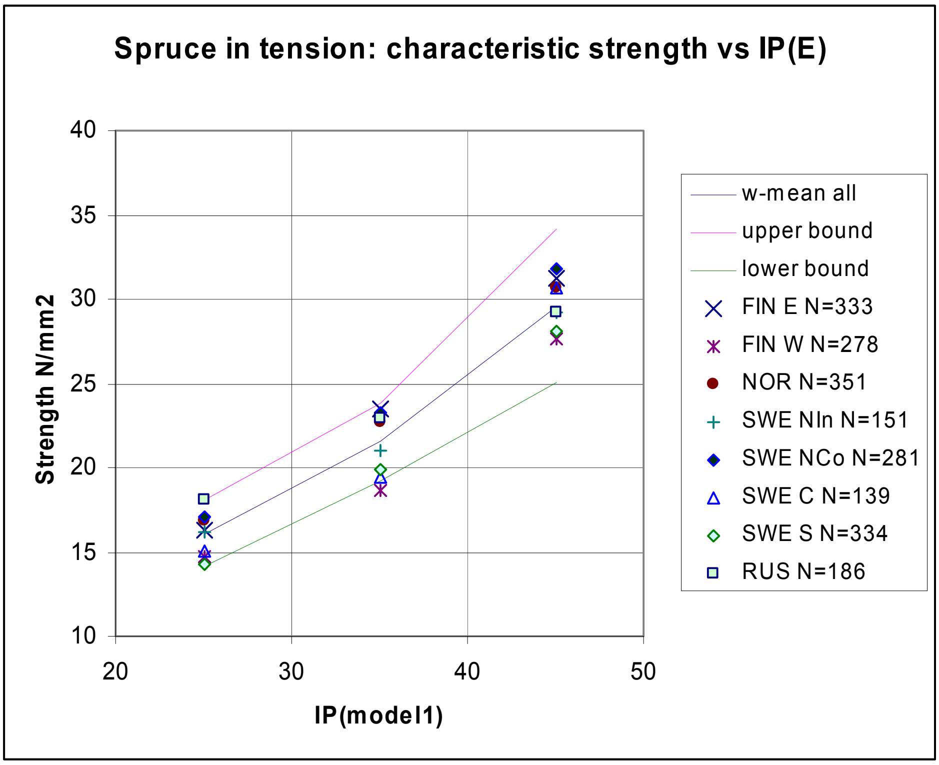

Spruce: Bending strength vs IP(Edyn,KAR,dens,sizes)
GER SWE FIN RUS
Characteristic strength [N/mm2]
40
35
30
25
20
15
10
5
0
20
30
40
50
IP-bands (model 14)
best estimate
upper 90%
lower 90%
mean band

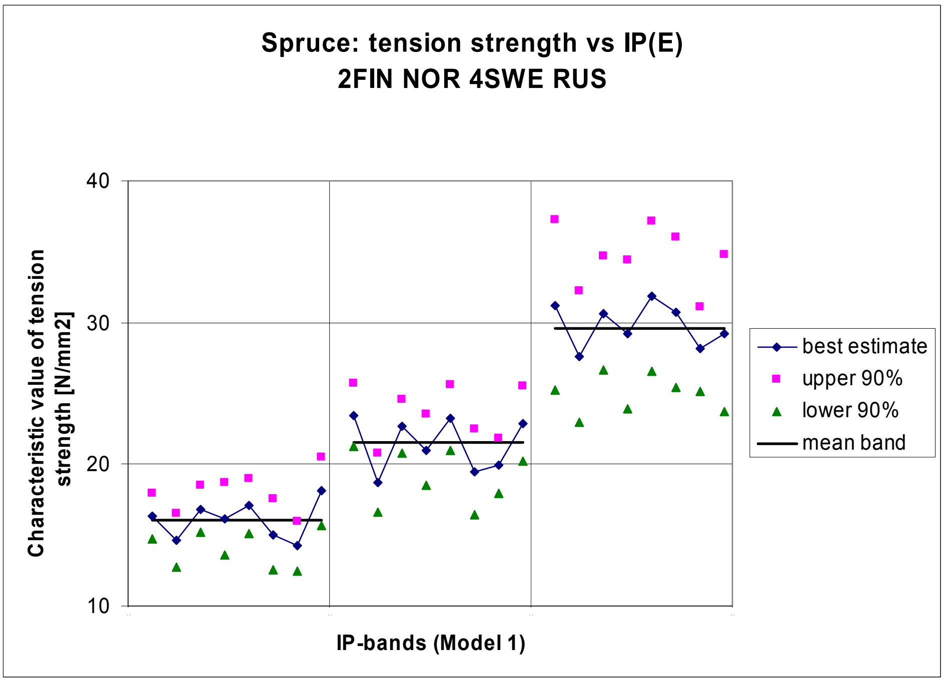

Spruce: bending strength vs IP(Edyn,KAR,dens,sizes)
Characteristic strength [N/mm2]
IP (model 14)
50
45
40
35
30
25
20
15
10
30
40
50
60
w-mean all
upper bound
lower bound
GER N N=456
GER W N=1337
SWE S N=350
RUS NW N=368
FIN W N=178
FIN E N=467

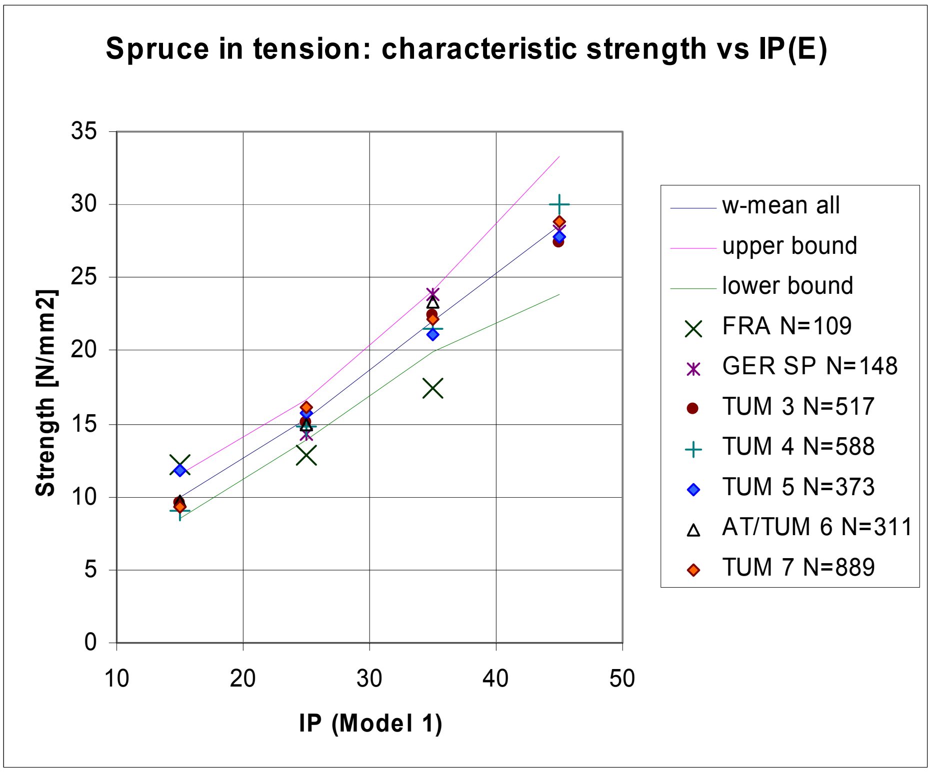

Spruce: Bending strength vs IP(Edyn,KAR,dens,sizes)
2GER SWE RUS 2FIN
Characteristic strength [N/mm2]
IP-bands (model 14)
60
50
40
30
20
10
0
30
40
50
60
best estimate
upper 90%
lower 90%
mean band


Spruce in tension: characteristic strength vs IP(E)
Strength [N/mm]
35
30
25
20
15
10
20
30
40
50
IP(Model 1)
w-mean all
upper bound
lower bound
FIN N=611
RUS N=186
SWE N=905
GER N=1253
CZ N=373
AT N=311
NOR N=351

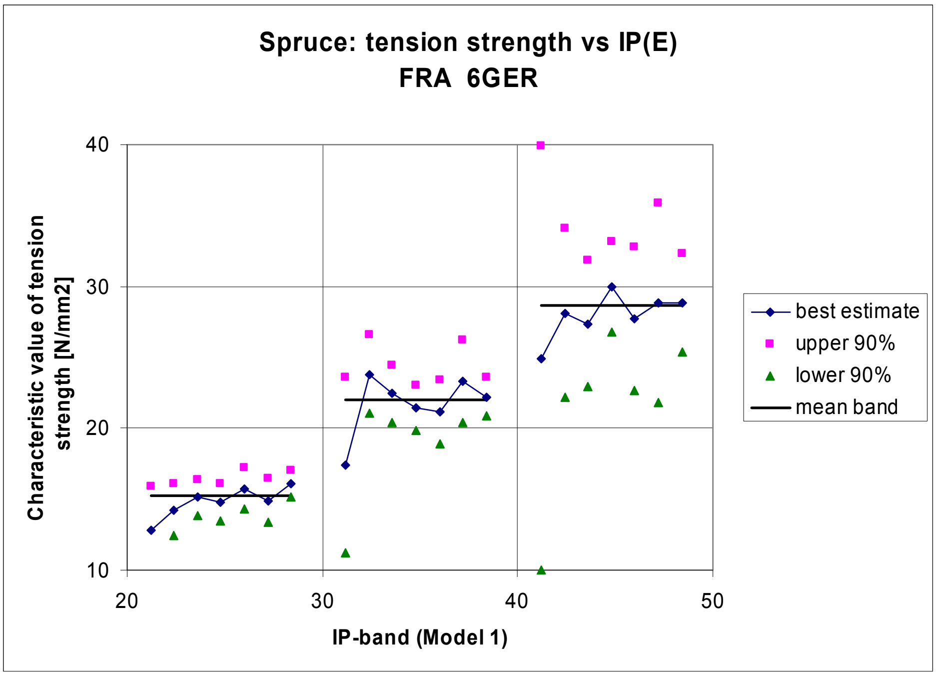

Spruce: tension strength vs IP(E)
FIN RUS SWE GER CZ AT NOR
Characteristic value of strength [N/mm2]
40
30
20
10
IP-bands (Model 1)
mean
upper 90%
lower 90%
mean band


Spruce in tension: characteristic strength vs IP(E)
Strength N/mm2
40
35
30
25
20
15
10
20
30
40
50
IP(model1)
w-mean all
upper bound
lower bound
FIN E N=333
FIN W N=278
NOR N=351
SWE NIn N=151
SWE NCo N=281
SWE C N=139
SWE S N=334
RUS N=186

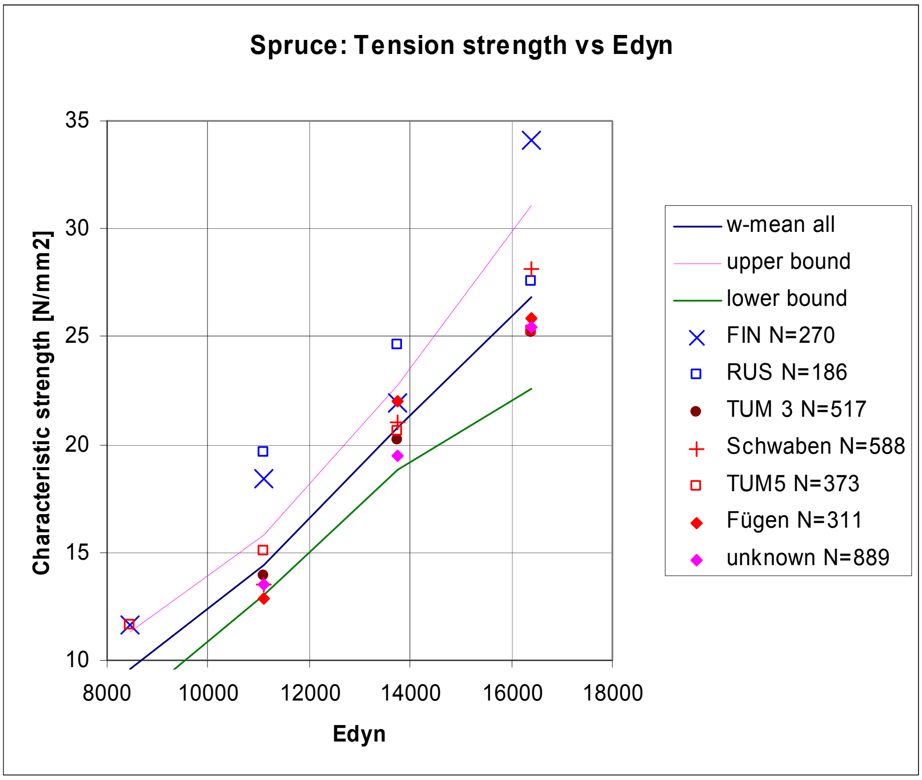

Spruce: tension strength vs IP(E)
2FIN NOR 4SWE RUS
Characteristic value of tension strength [N/mm2]
40
30
20
10
IP-bands (Model 1)
best estimate
upper 90%
lower 90%
mean band

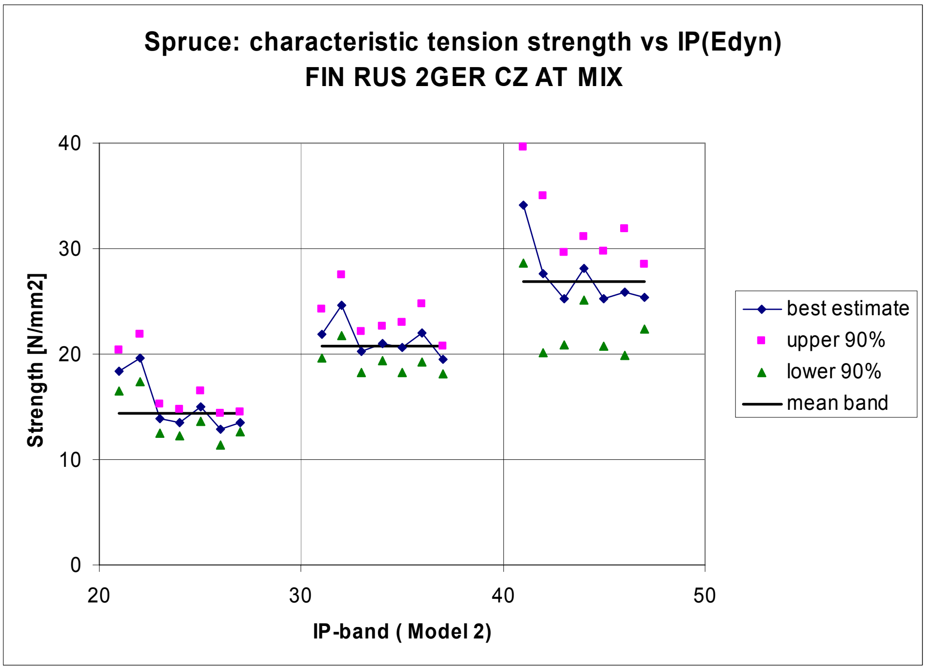


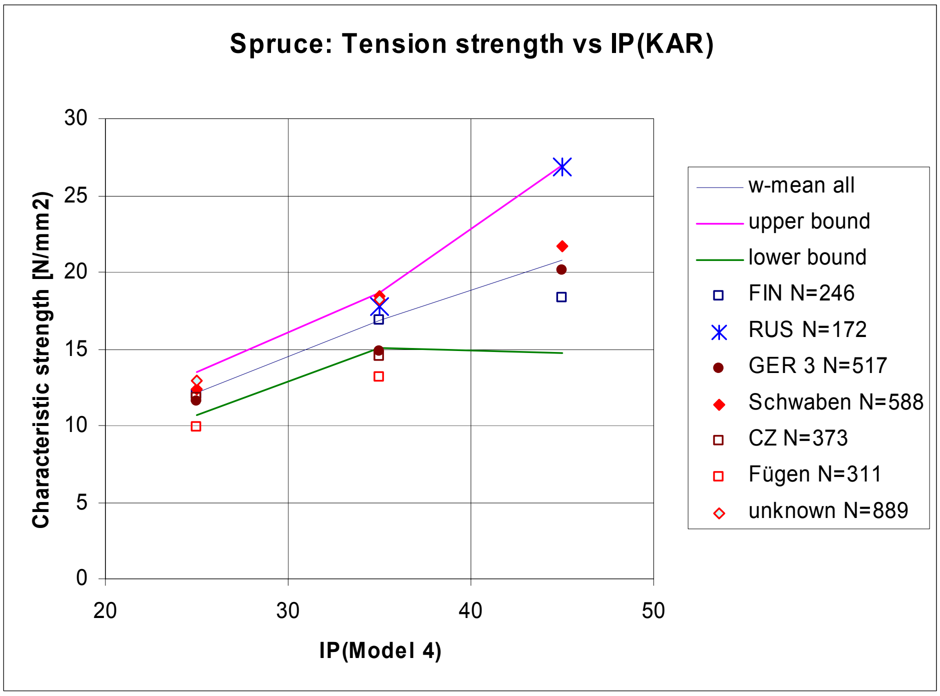
Spruce in tension: characteristic strength vs IP(E)
Strength [N/mm2]
IP (Model 1)
35
30
25
20
15
10
5
0
10
20
30
40
50
w-mean all
upper bound
lower bound
FRA N=109
GER SP N=148
TUM 3 N=517
TUM 4 N=588
TUM 5 N=373
AT/TUM 6 N=311
TUM 7 N=889

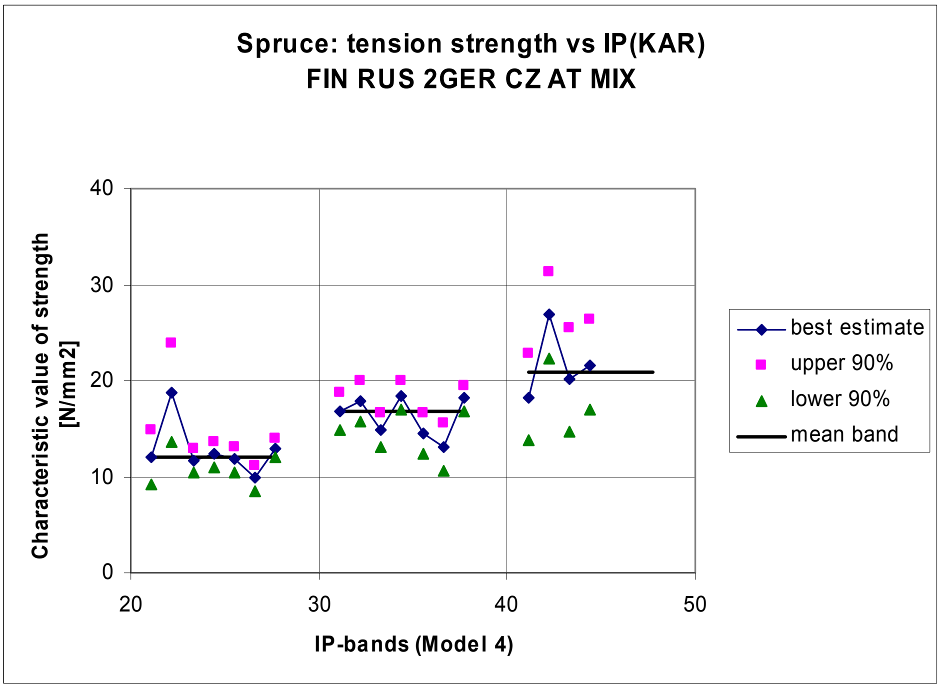


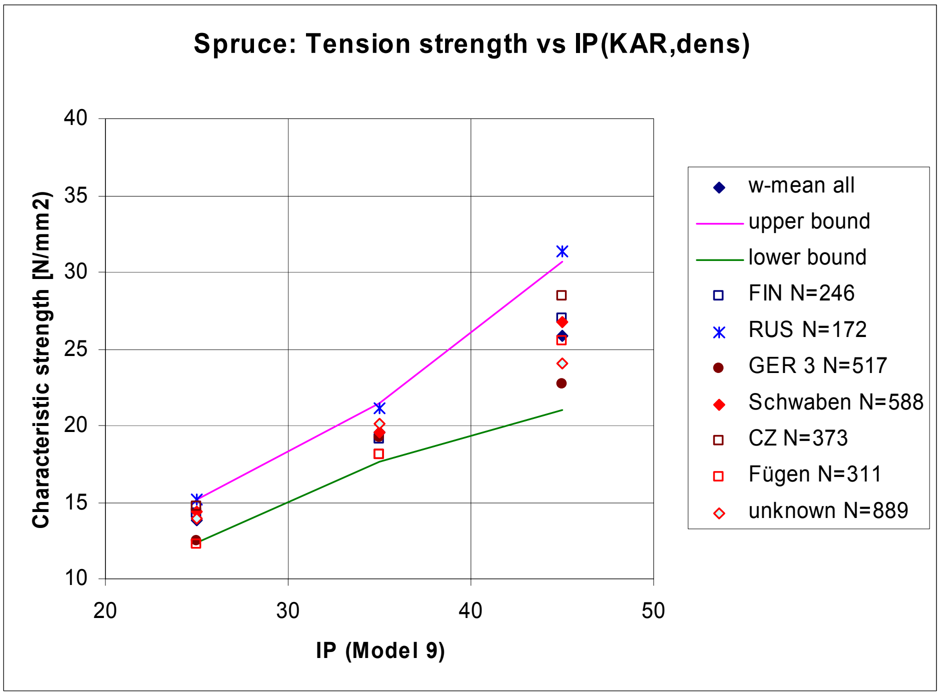
Spruce: tension strength vs IP(E)
FRA 6GER
Characteristic value of tension strength [N/mm2]
IP-band (Model 1)
40
30
20
10
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

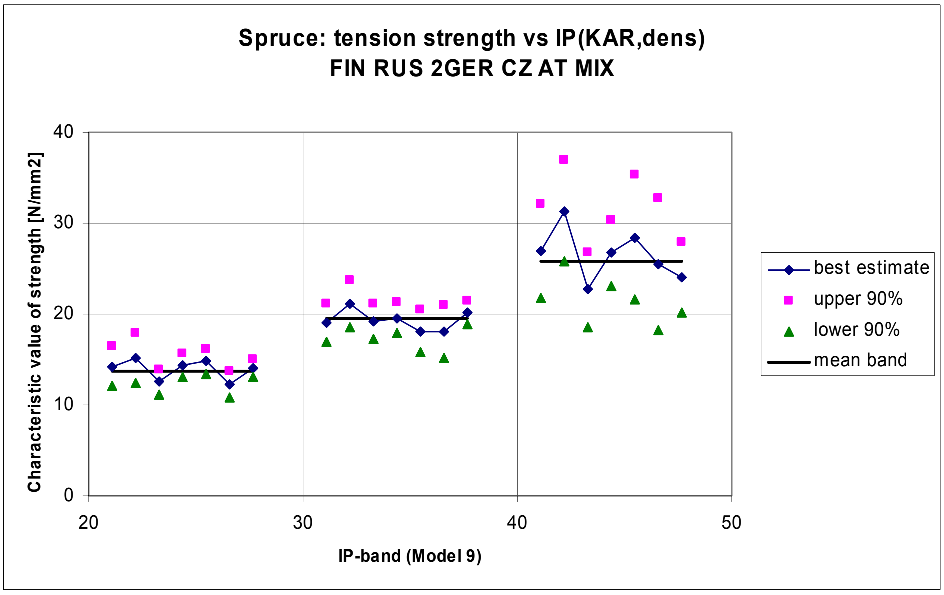

Spruce: Tension strength vs Edyn
Characteristic strength [N/mm2]
35
30
25
20
15
10
8000
10000
12000
14000
16000
18000
Edyn
w-mean all
upper bound
lower bound
FIN N=270
RUS N=186
TUM 3 N=517
Schwaben N=588
TUM5 N=373
Fügen N=311
unknown N=889

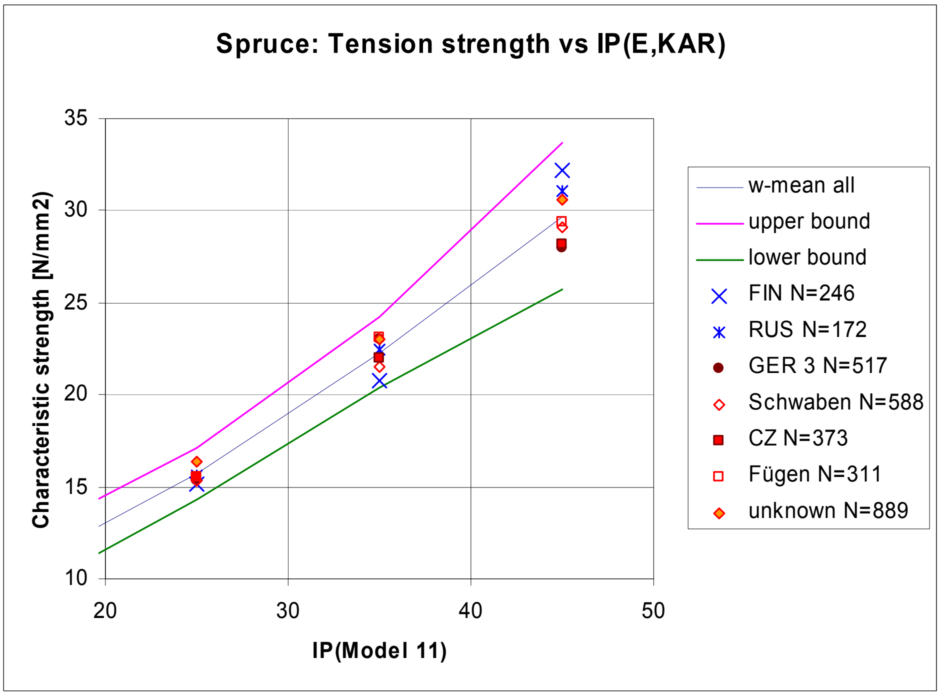

Spruce: characteristic tension strength vs IP(Edyn)
FIN RUS 2GER CZ AT MIX
Strength [N/mm2]
40
30
20
10
0
20
30
40
50
IP-band (Model 2)
best estimate
upper 90%
lower 90%
mean band

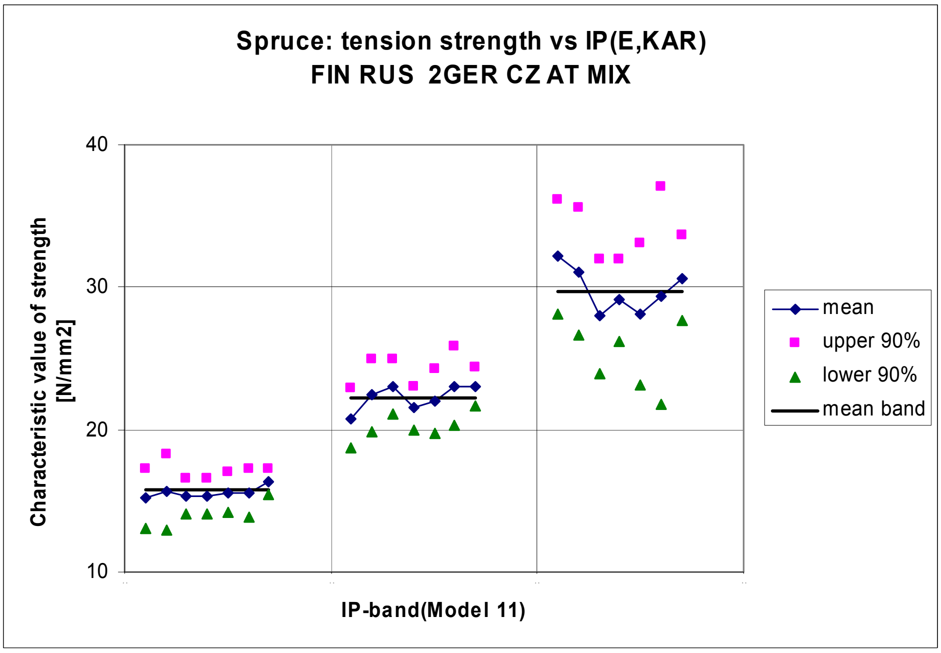

Spruce: Tension strength vs IP(KAR)
Characteristic strength [N/mm2]
IP(Model 4)
30
25
20
15
10
5
0
20
30
40
50
w-mean all
upper bound
lower bound
FIN N=246
RUS N=172
GER 3 N=517
Schwaben N=588
CZ N=373
Fügen N=311
unknown N=889

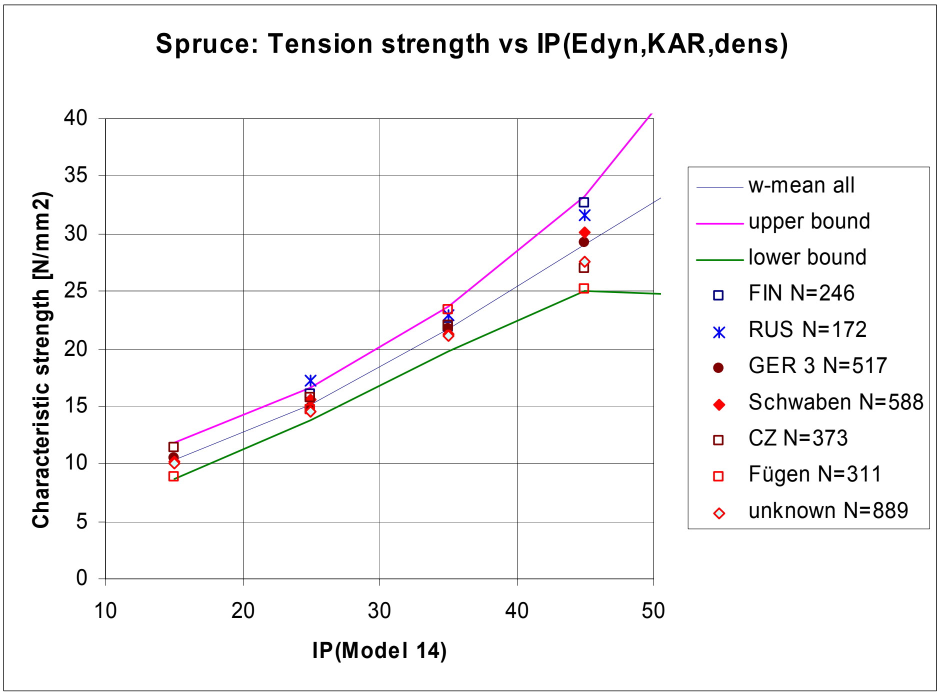

Spruce: tension strength vs IP(KAR)
FIN RUS 2GER CZ AT MIX
Characteristic value of strength [N/mm2]
IP-bands (Model 4)
40
30
20
10
0
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

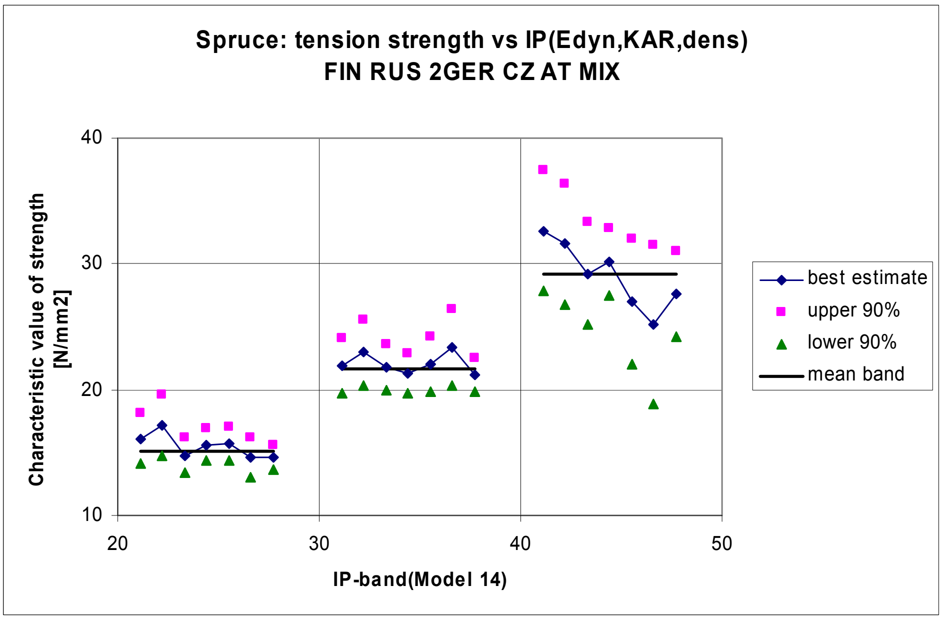

Spruce: Tension strength vs IP(KAR,dens)
Characteristic strength [N/mm2]
40
35
30
25
20
15
10
20
30
40
50
IP (Model 9)
w-mean all
upper bound
lower bound
FIN N=246
RUS N=172
GER 3 N=517
Schwaben N=588
CZ N=373
Fügen N=311
unknown N=889

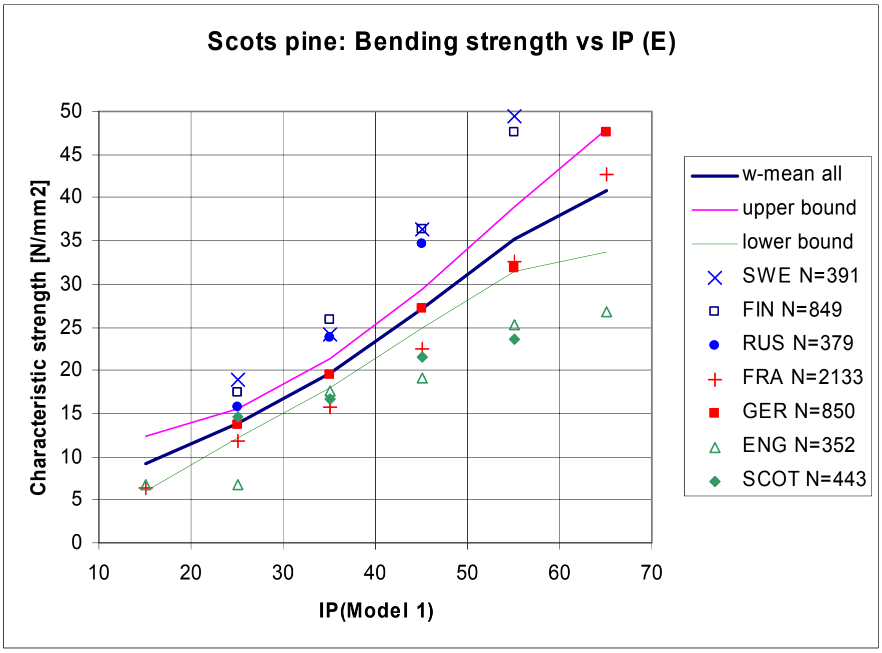

Spruce: tension strength vs IP(KAR,dens)
FIN RUS 2GER CZ AT MIX
Characteristic value of strength [N/mm2]
40
30
20
10
0
20
30
40
50
IP-band (Model 9)
best estimate
upper 90%
lower 90%
mean band

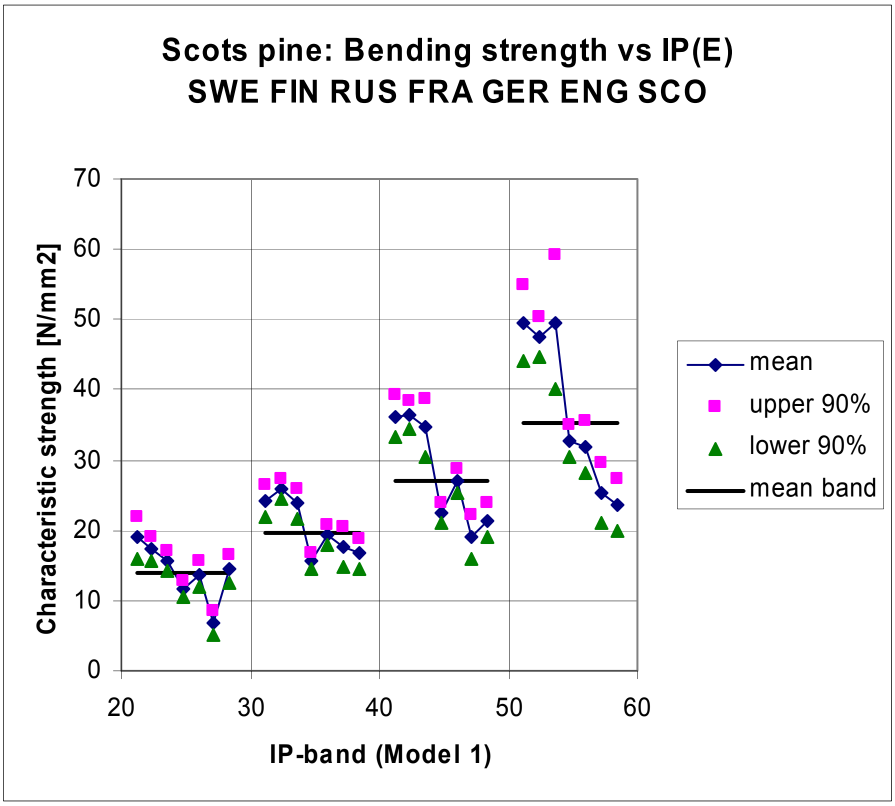

Spruce: Tension strength vs IP(E,KAR)
Characteristic strength [N/mm2)
IP(Model 11)
35
30
25
20
15
10
20
30
40
50
w-mean all
upper bound
lower bound
FIN N=246
RUS N=172
GER 3 N=517
Schwaben N=588
CZ N=373
Fügen N=311
unknown N=889

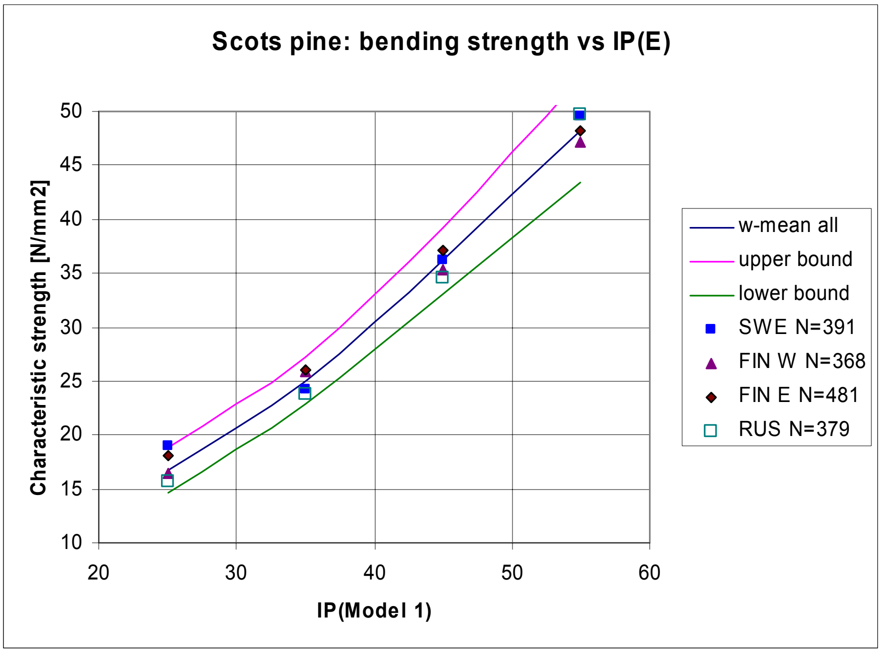

Spruce: tension strength vs IP(E,KAR)
FIN RUS 2GER CZ AT MIX
Characteristic value of strength [N/mm2]
IP-band(Model 11)
40
30
20
10
mean
upper 90%
lower 90%
mean band

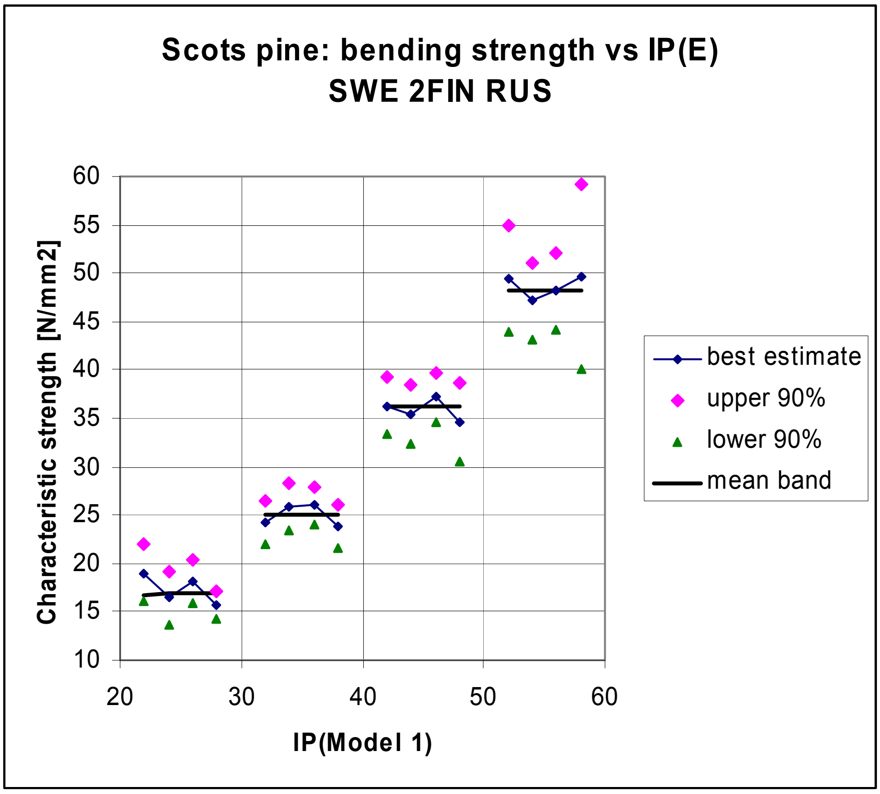

Spruce: Tension strength vs IP(Edyn,KAR,dens)
Characteristic strength [N/mm2]
0
5
10
15
20
25
30
35
40
10
20
30
40
50
IP(Model 14)
w-mean all
upper bound
lower bound
FIN N=246
RUS N=172
GER 3 N=517
Schwaben N=588
CZ N=373
Fügen N=311
unknown N=889

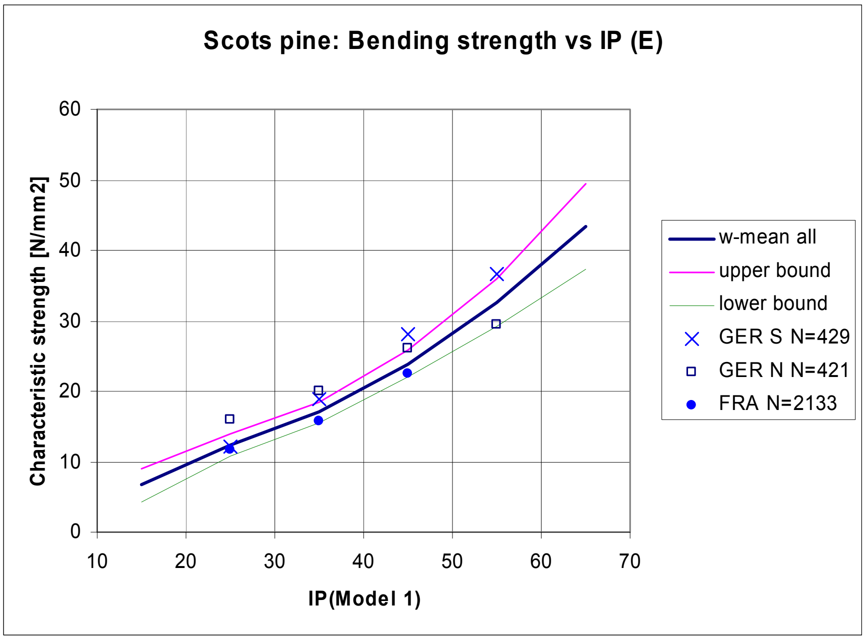

Spruce: tension strength vs IP(Edyn,KAR,dens)
FIN RUS 2GER CZ AT MIX
Characteristic value of strength [N/mm2]
10
20
30
40
20
30
40
50
IP-band(Model 14)
best estimate
upper 90%
lower 90%
mean band

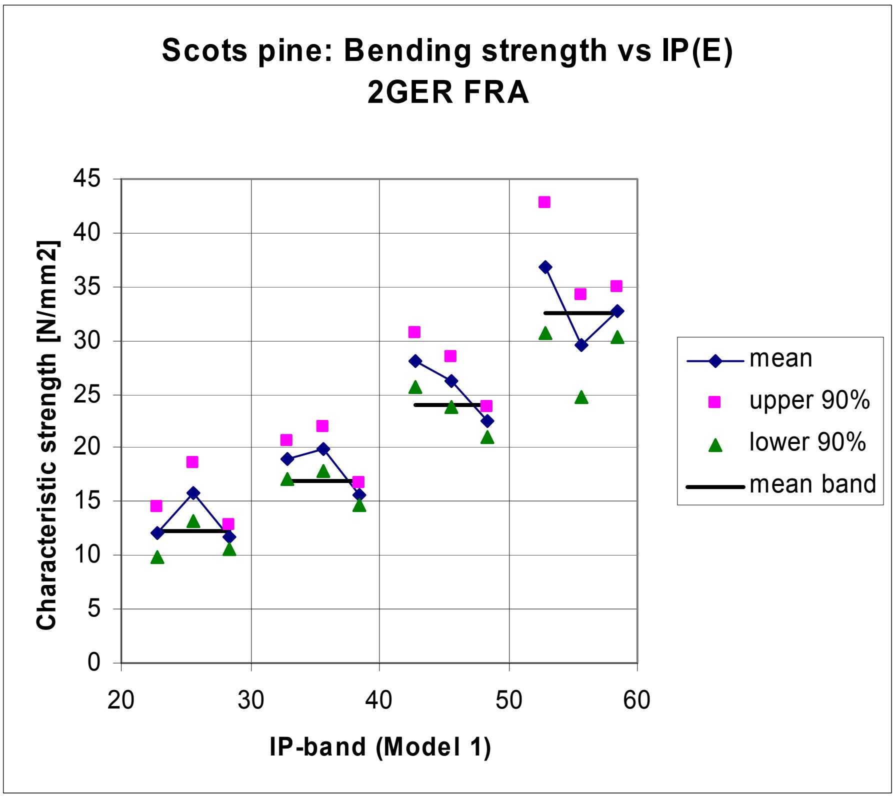

Scots pine: Bending strength vs IP (E)
Characteristic strength [N/mm2]
IP(Model 1)
w-mean all
upper bound
lower bound
SWE N=391
FIN N=849
RUS N=379
FRA N=2133
GER N=850
ENG N=352
SCOT N=443

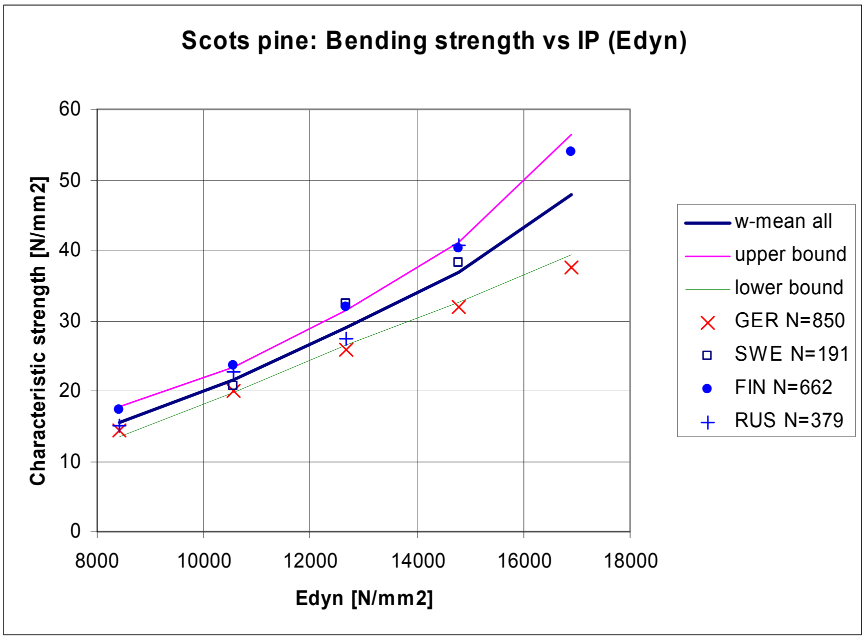

Scots pine: Bending strength vs IP(E)
SWE FIN RUS FRA GER ENG SCO
Characteristic strength [N/mm2]
IP-band (Model 1)
mean
upper 90%
lower 90%
mean band


Scots pine: bending strength vs IP(E)
Characteristic strength [N/mm2]
IP(Model 1)
w-mean all
upper bound
lower bound
SWE N=391
FIN W N=368
FIN E N=481
RUS N=379
50
45
40
35
30
25
20
15
10
20
30
40
50
60

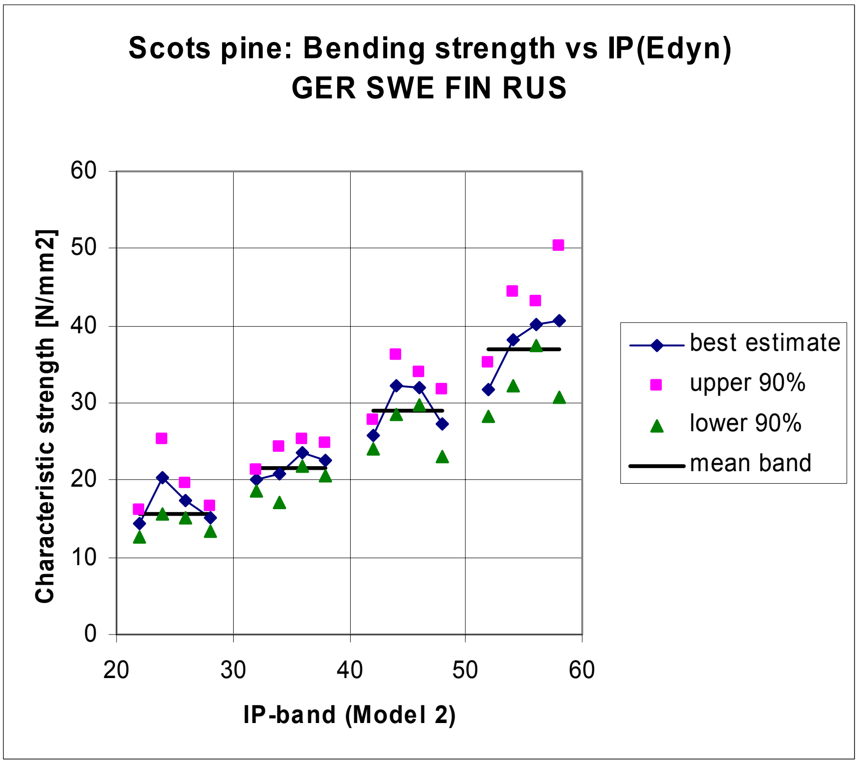

Scots pine: bending strength vs IP(E)
SWE 2FIN RUS
Characteristic strength [N/mm2]
IP(Model 1)
best estimate
upper 90%
lower 90%
mean band
60
55
50
45
40
35
30
25
20
15
10
20
30
40
50
60


Scots pine: Bending strength vs IP (E)
Characteristic strength [N/mm2]
IP(Model 1)
0
10
20
30
40
50
60
10
20
30
40
50
60
70
w-mean all
upper bound
lower bound
GER S N=429
GER N N=421
FRA N=2133

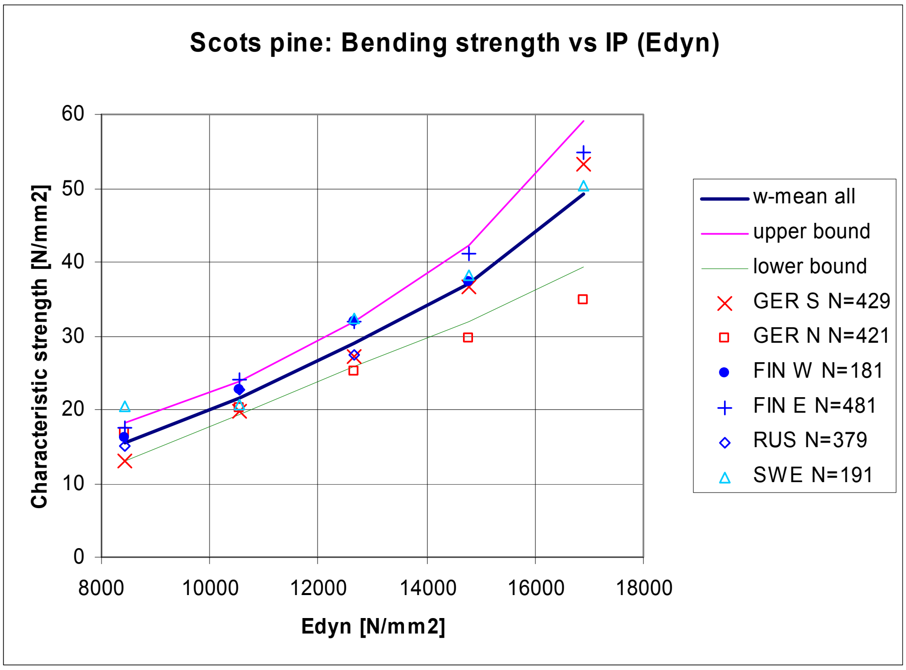

Scots pine: Bending strength vs IP(E)
2GER FRA
Characteristic strength [N/mm2]
IP-band (Model 1)
0
5
10
15
20
25
30
35
40
45
20
30
40
50
60
mean
upper 90%
lower 90%
mean band

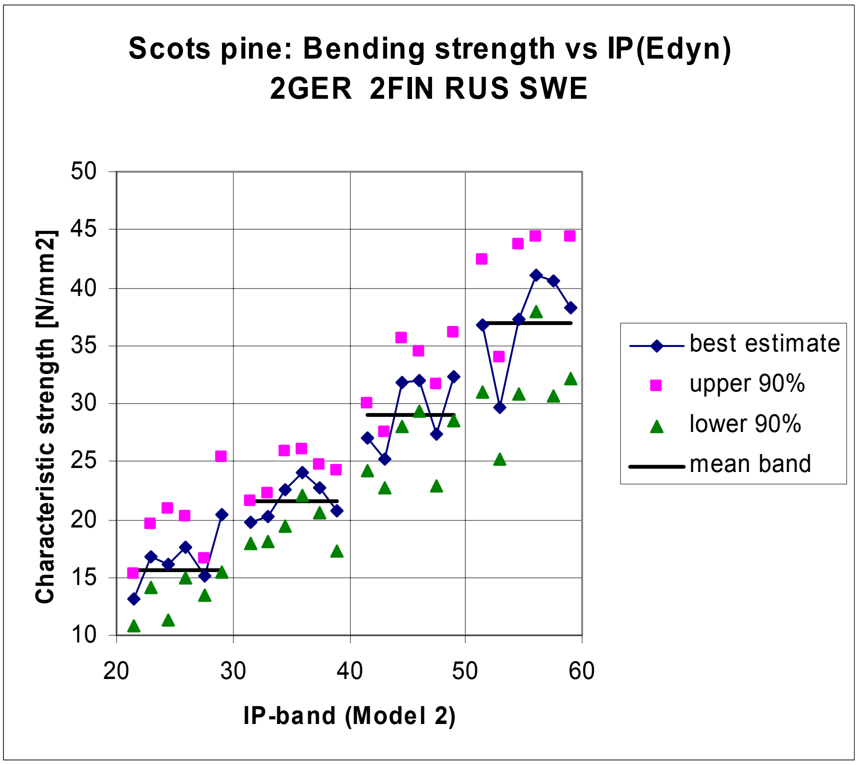


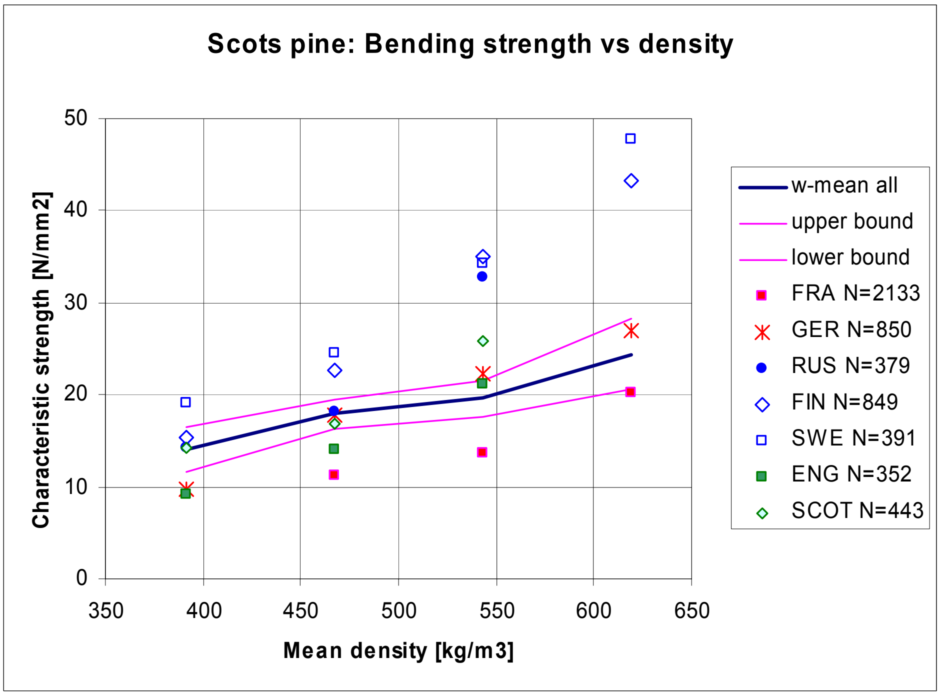
Scots pine: Bending strength vs IP (Edyn)
Characteristic strength [N/mm2]
0
10
20
30
40
50
60
8000
10000
12000
14000
16000
18000
Edyn [N/mm2]
w-mean all
upper bound
lower bound
GER N=850
SWE N=191
FIN N=662
RUS N=379

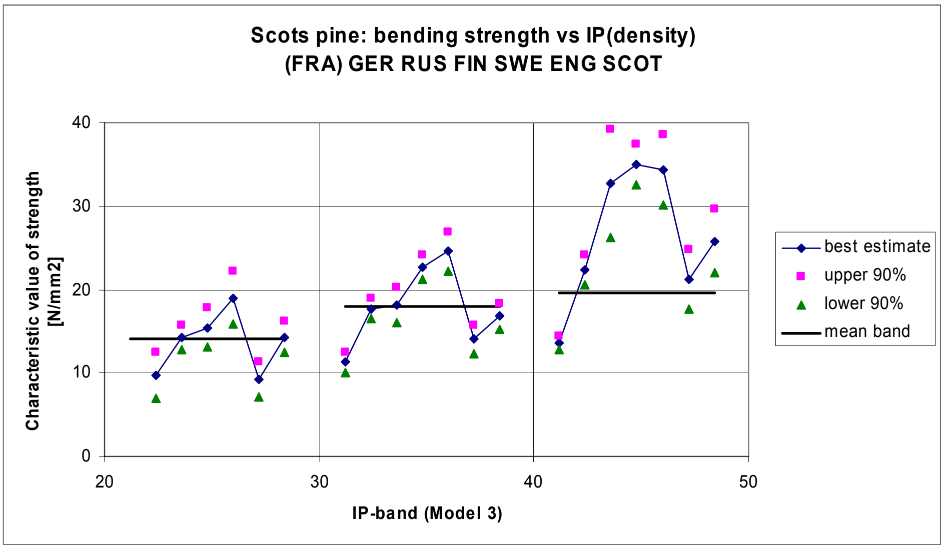


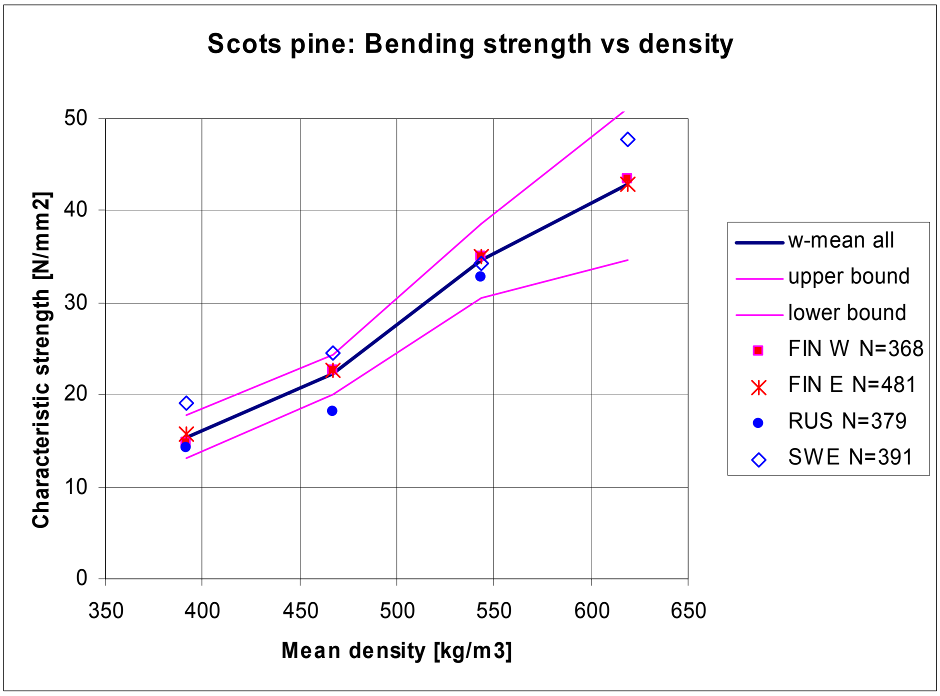
Scots pine: Bending strength vs IP(Edyn)
GER SWE FIN RUS
Characteristic strength [N/mm2]
0
10
20
30
40
50
60
20
30
40
50
60
IP-band (Model 2)
best estimate
upper 90%
lower 90%
mean band

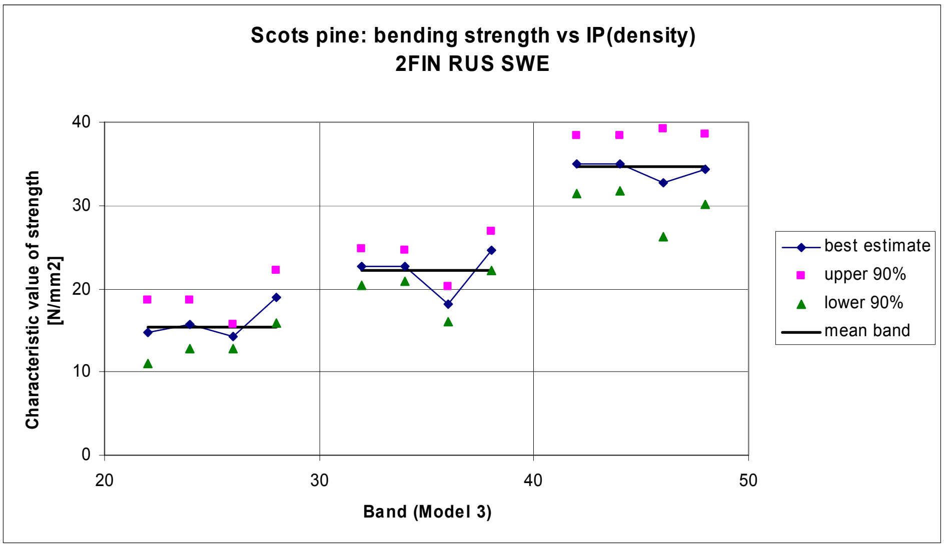

Scots pine: Bending strength vs IP (Edyn)
Characteristic strength [N/mm2]
Edyn [N/mm2]
0
10
20
30
40
50
60
8000
10000
12000
14000
16000
18000
w-mean all
upper bound
lower bound
GER S N=429
GER N N=421
FIN W N=181
FIN E N=481
RUS N=379
SWE N=191

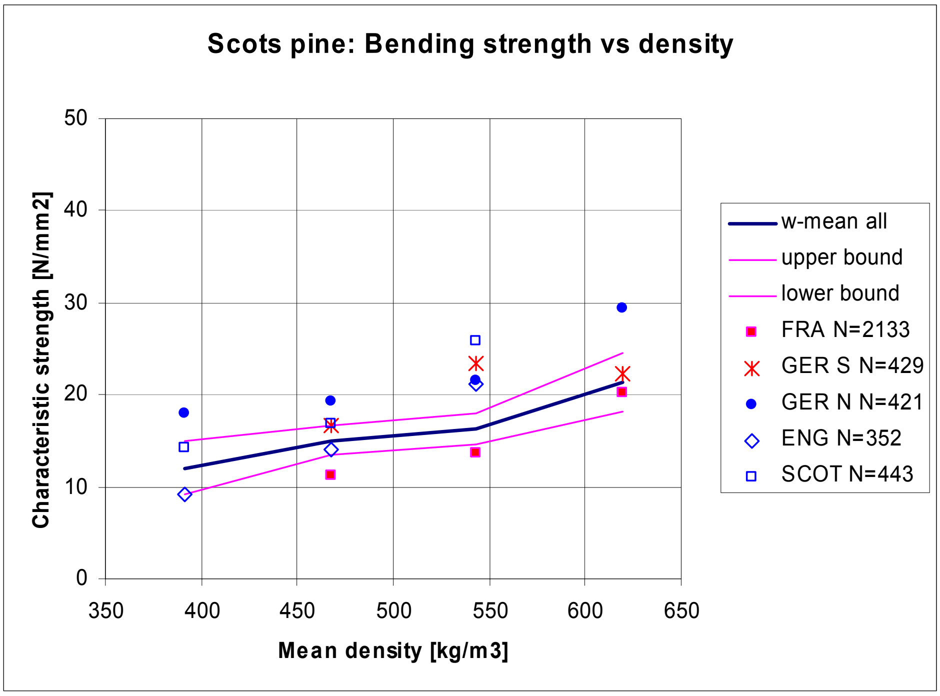

Scots pine: Bending strength vs IP(Edyn)
2GER 2FIN RUS SWE
Characteristic strength [N/mm2]
IP-band (Model 2)
10
15
20
25
30
35
40
45
50
20
30
40
50
60
best estimate
upper 90%
lower 90%
mean band

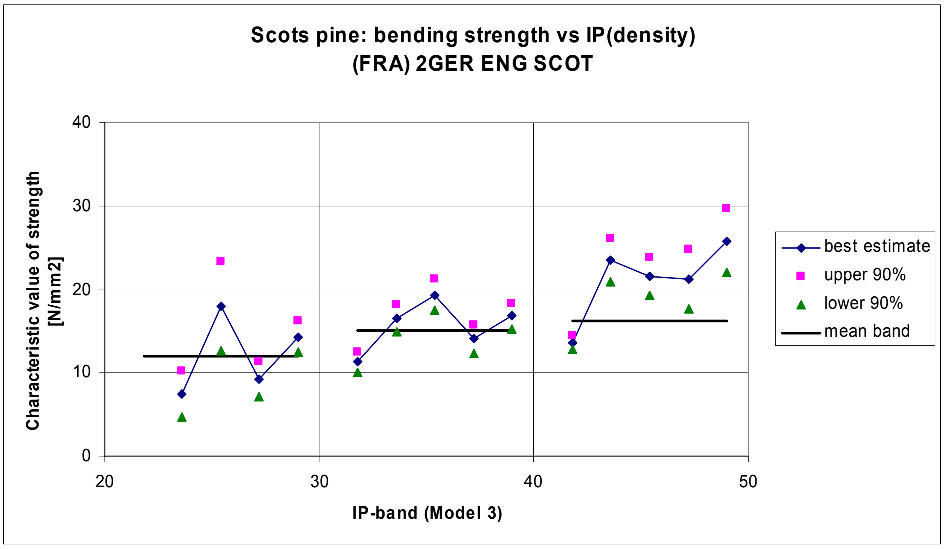

Scots pine: Bending strength vs density
Characteristic strength [N/mm2]
Mean density [kg/m3]
0
10
20
30
40
50
350
400
450
500
550
600
650
w-mean all
upper bound
lower bound
FRA N=2133
GER N=850
RUS N=379
FIN N=849
SWE N=391
ENG N=352
SCOT N=443

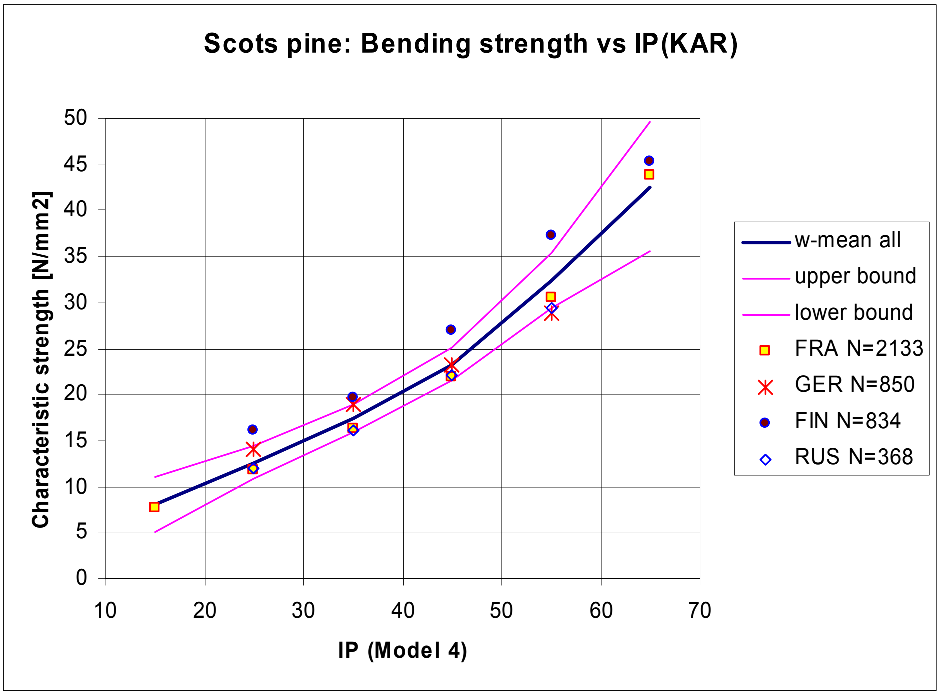

Scots pine: bending strength vs IP(density)
(FRA) GER RUS FIN SWE ENG SCOT
Characteristic value of strength [N/mm2]
IP-band (Model 3)
0
10
20
30
40
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

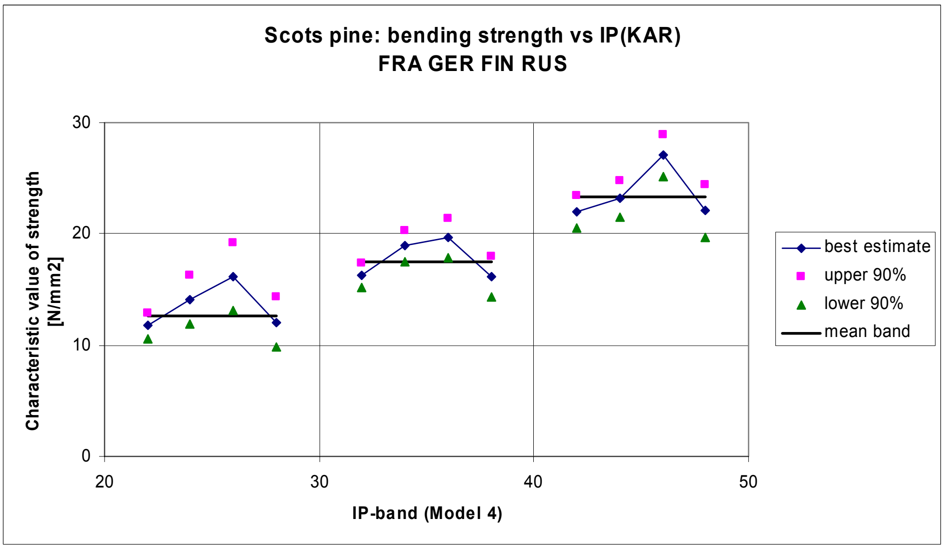

Scots pine: Bending strength vs density
Characteristic strength [N/mm2]
Mean density [kg/m3]
0
10
20
30
40
50
350
400
450
500
550
600
650
w-mean all
upper bound
lower bound
FIN W N=368
FIN E N=481
RUS N=379
SWE N=391

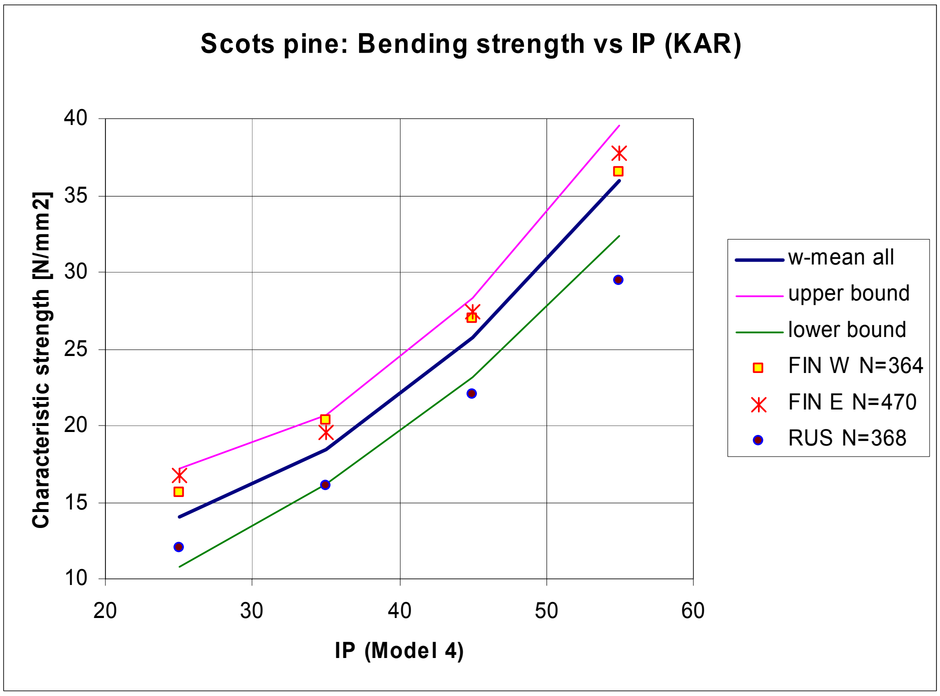

Scots pine: bending strength vs IP(density)
2FIN RUS SWE
Characteristic value of strength [N/mm2]
Band (Model 3)
0
10
20
30
40
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

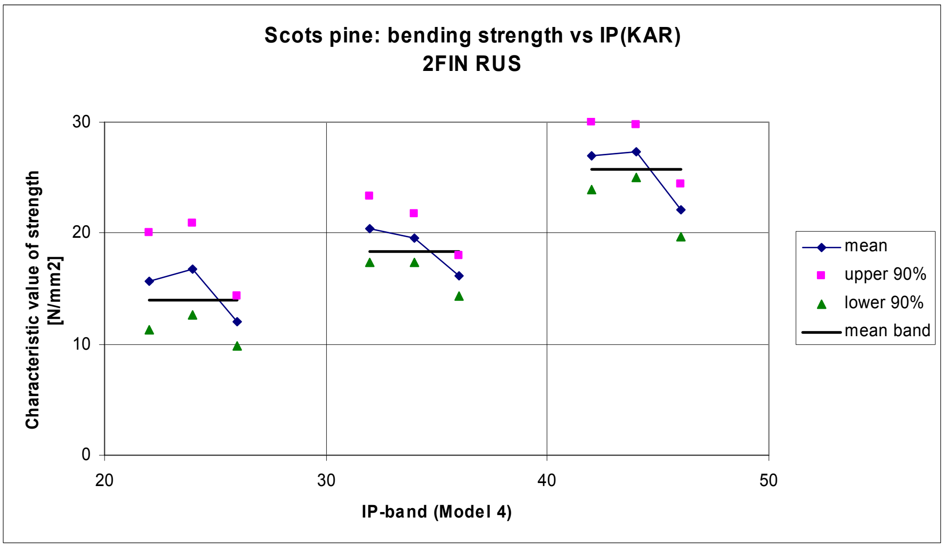

Scots pine: Bending strength vs density
Characteristic strength [N/mm2]
Mean density [kg/m3]
0
10
20
30
40
50
350
400
450
500
550
600
650
w-mean all
upper bound
lower bound
FRA N=2133
GER S N=429
GER N N=421
ENG N=352
SCOT N=443

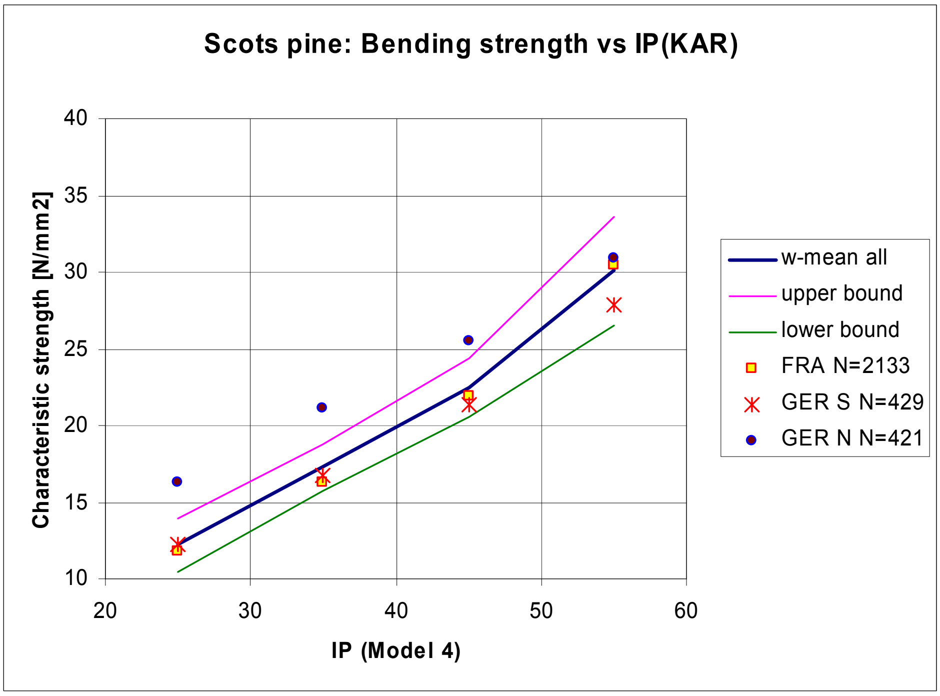

Scots pine: bending strength vs IP(density)
(FRA) 2GER ENG SCOT
Characteristic value of strength [N/mm2]
IP-band (Model 3)
0
10
20
30
40
20
30
40
50
best estimate
upper 90%
lower 90%
mean band


Scots pine: Bending strength vs IP(KAR)
Characteristic strength [N/mm2]
IP (Model 4)
w-mean all
upper bound
lower bound
FRA N=2133
GER N=850
FIN N=834
RUS N=368

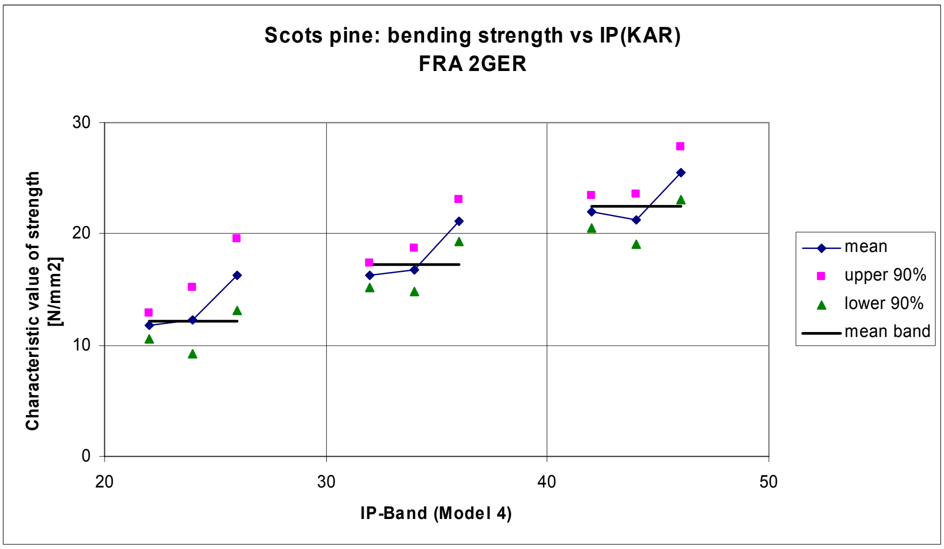

Scots pine: bending strength vs IP(KAR)
FRA GER FIN RUS
Characteristic value of strength [N/mm2]
IP-band (Model 4)
best estimate
upper 90%
lower 90%
mean band


Scots pine: Bending strength vs IP (KAR)
Characteristic strength [N/mm2]
IP (Model 4)
40
35
30
25
20
15
10
20
30
40
50
60
w-mean all
upper bound
lower bound
FIN W N=364
FIN E N=470
RUS N=368

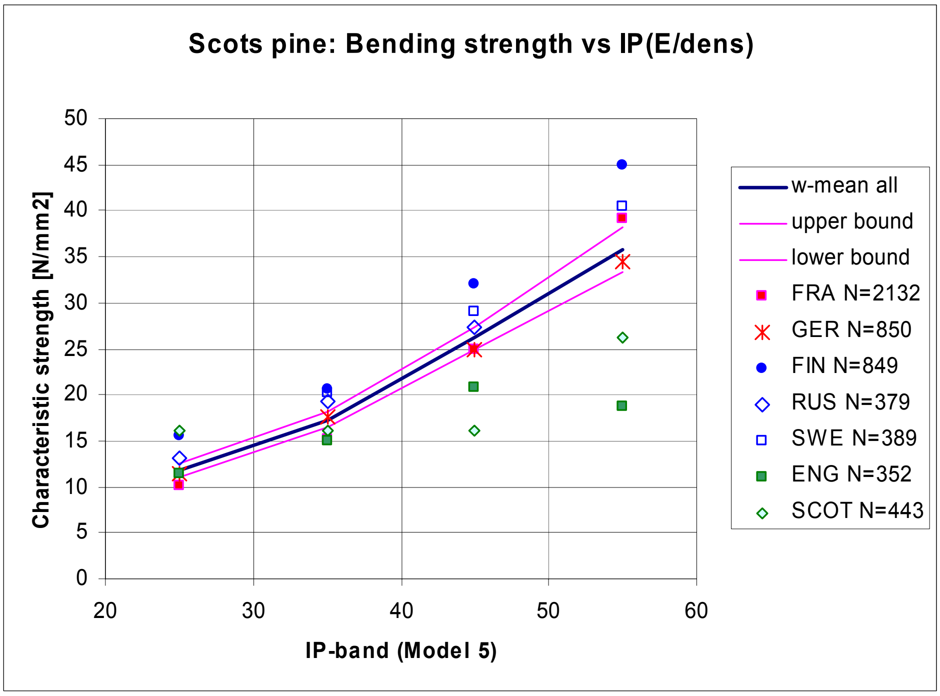

Scots pine: bending strength vs IP(KAR)
2FIN RUS
Characteristic value of strength [N/mm2]
IP-band (Model 4)
30
20
10
0
20
30
40
50
mean
upper 90%
lower 90%
mean band

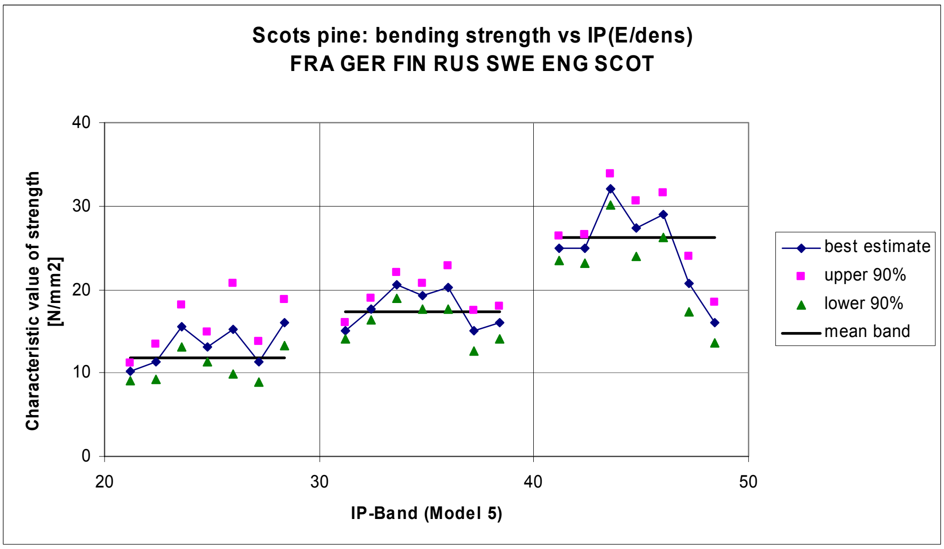


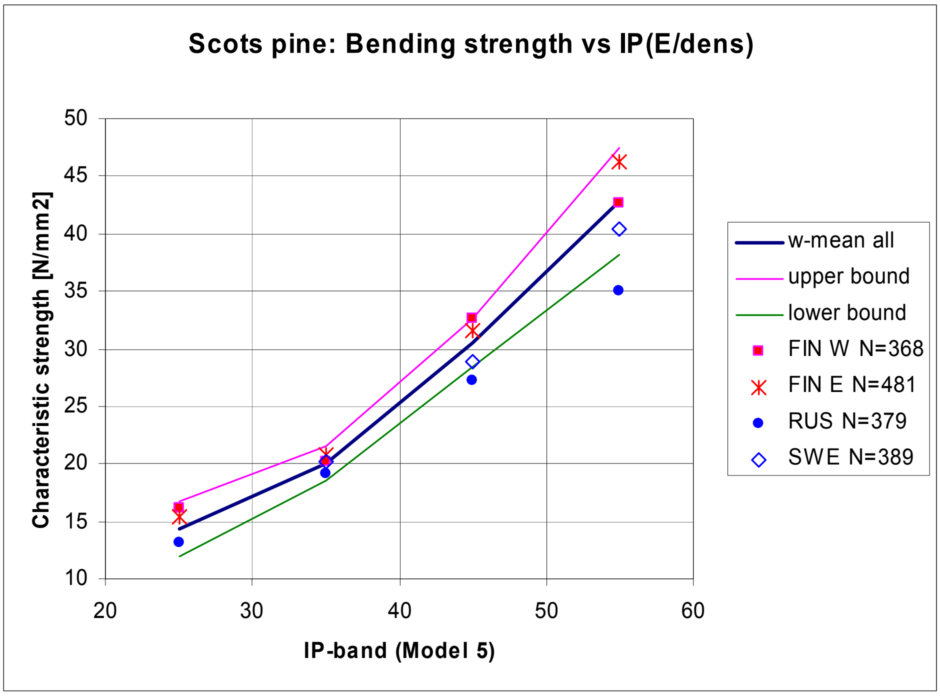
Scots pine: Bending strength vs IP(KAR)
Characteristic strength [N/mm2]
IP (Model 4)
40
35
30
25
20
15
10
20
30
40
50
60
w-mean all
upper bound
lower bound
FRA N=2133
GER S N=429
GER N N=421



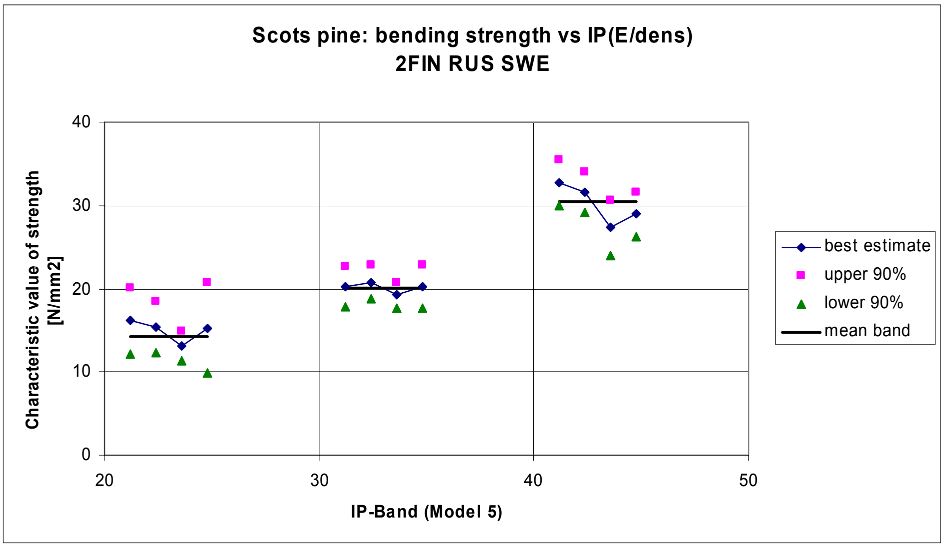
Scots pine: bending strength vs IP(KAR)
FRA 2GER
Characteristic value of strength [N/mm2]
IP-Band (Model 4)
30
20
10
0
20
30
40
50
mean
upper 90%
lower 90%
mean band


Scots pine: Bending strength vs IP(E/dens)
Characteristic strength [N/mm2]
IP-band (Model 5)
0
5
10
15
20
25
30
35
40
45
50
20
30
40
50
60
w-mean all
upper bound
lower bound
FRA N=2132
GER N=850
FIN N=849
RUS N=379
SWE N=389
ENG N=352
SCOT N=443

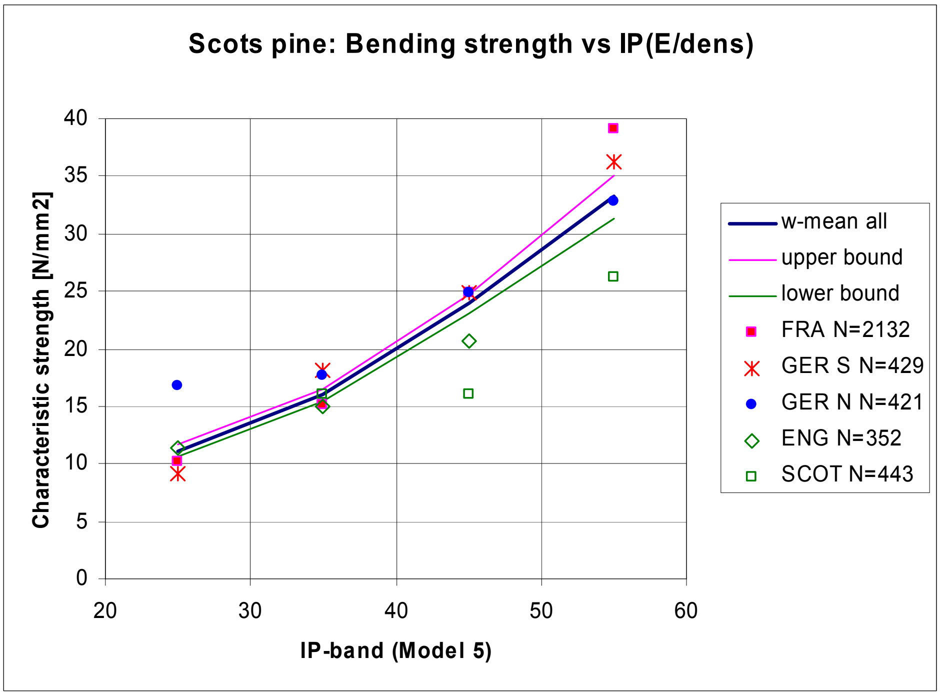

Scots pine: bending strength vs IP(E/dens)
FRA GER FIN RUS SWE ENG SCOT
Characteristic value of strength [N/mm2]
IP-Band (Model 5)
0
10
20
30
40
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

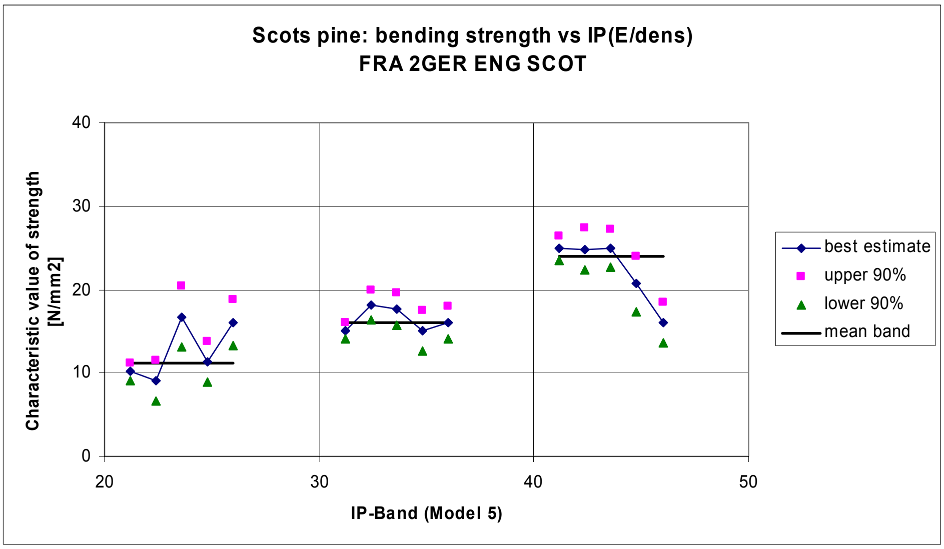


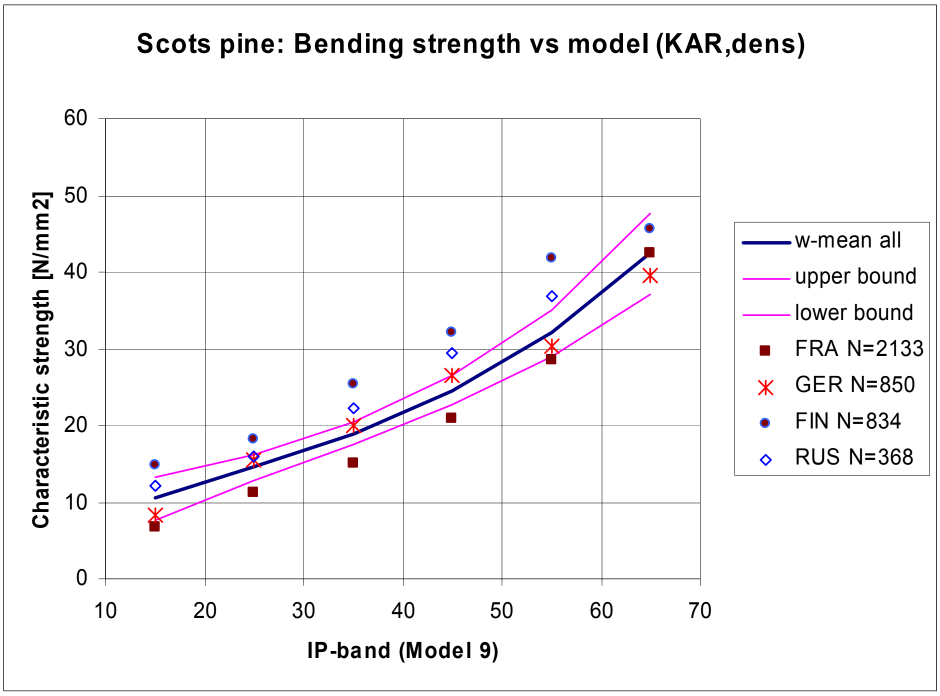
Scots pine: Bending strength vs IP(E/dens)
Characteristic strength [N/mm2]
IP-band (Model 5)
50
45
40
35
30
25
20
15
10
20
30
40
50
60
w-mean all
upper bound
lower bound
FIN W N=368
FIN E N=481
RUS N=379
SWE N=389

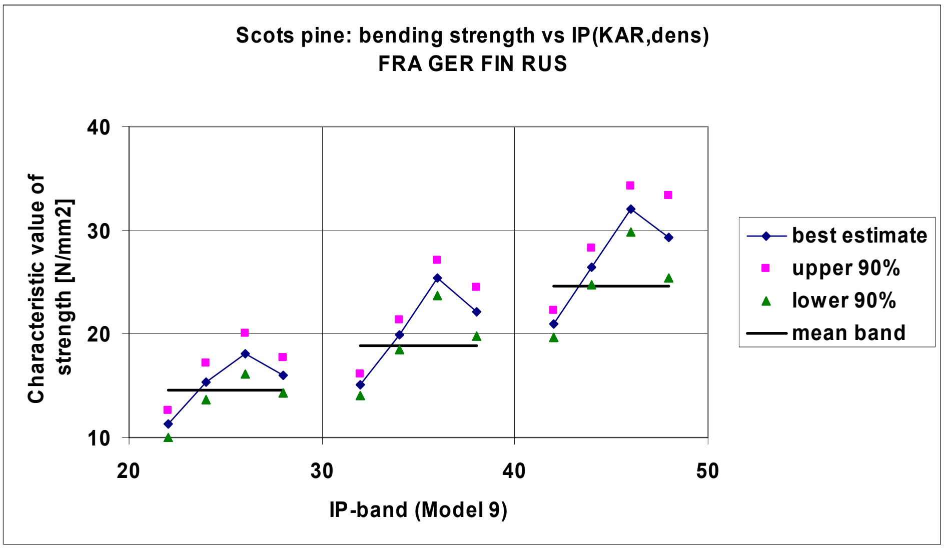


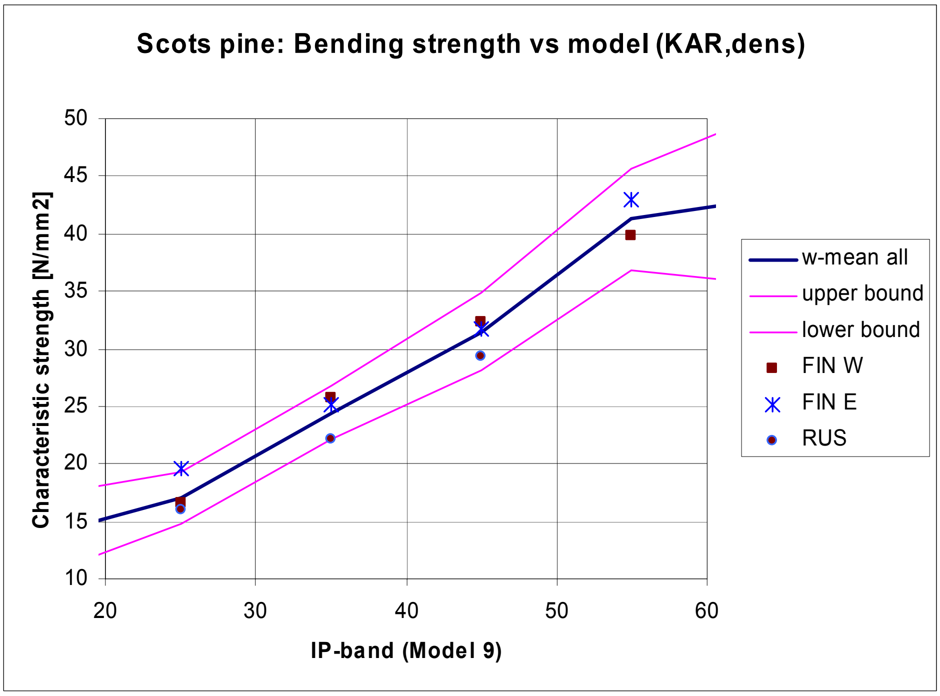
Scots pine: bending strength vs IP(E/dens)
2FIN RUS SWE
Characteristic value of strength [N/mm2]
IP-Band (Model 5)
40
30
20
10
0
20
30
40
50
best estimate
upper 90%
lower 90%
mean band


Scots pine: Bending strength vs IP(E/dens)
Characteristic strength [N/mm2]
IP-band (Model 5)
0
5
10
15
20
25
30
35
40
20
30
40
50
60
w-mean all
upper bound
lower bound
FRA N=2132
GER S N=429
GER N N=421
ENG N=352
SCOT N=443

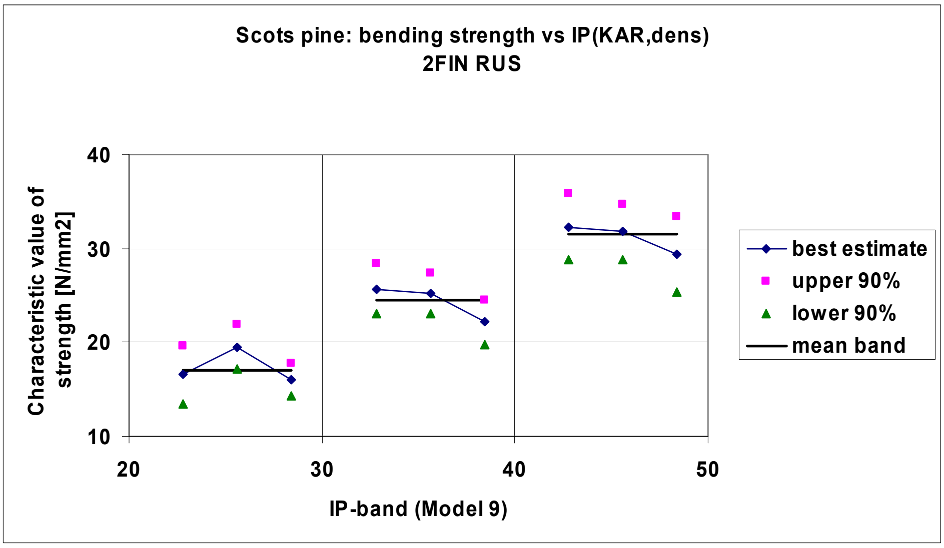

Scots pine: bending strength vs IP(E/dens)
FRA 2GER ENG SCOT
Characteristic value of strength [N/mm2]
IP-Band (Model 5)
0
10
20
30
40
20
30
40
50
best estimate
upper 90%
lower 90%
mean band


Scots pine: Bending strength vs model (KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 9)
w-mean all
upper bound
lower bound
FRA N=2133
GER N=850
FIN N=834
RUS N=368
0
10
20
30
40
50
60
10
20
30
40
50
60
70

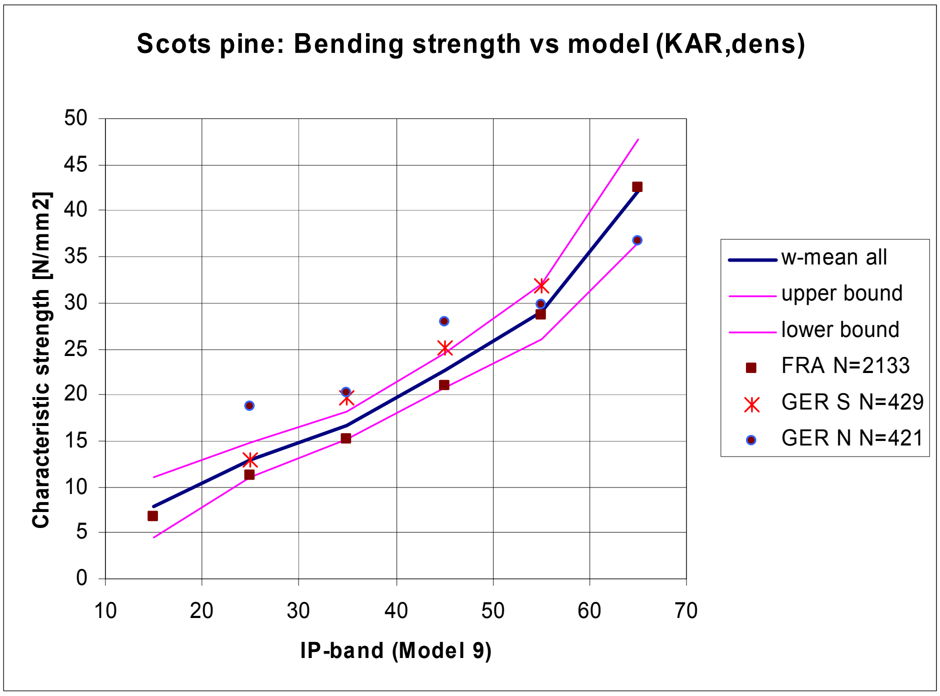

Scots pine: bending strength vs IP(KAR,dens)
FRA GER FIN RUS
Characteristic value of strength [N/mm2]
IP-band (Model 9)
best estimate
upper 90%
lower 90%
mean band
10
20
30
40
20
30
40
50

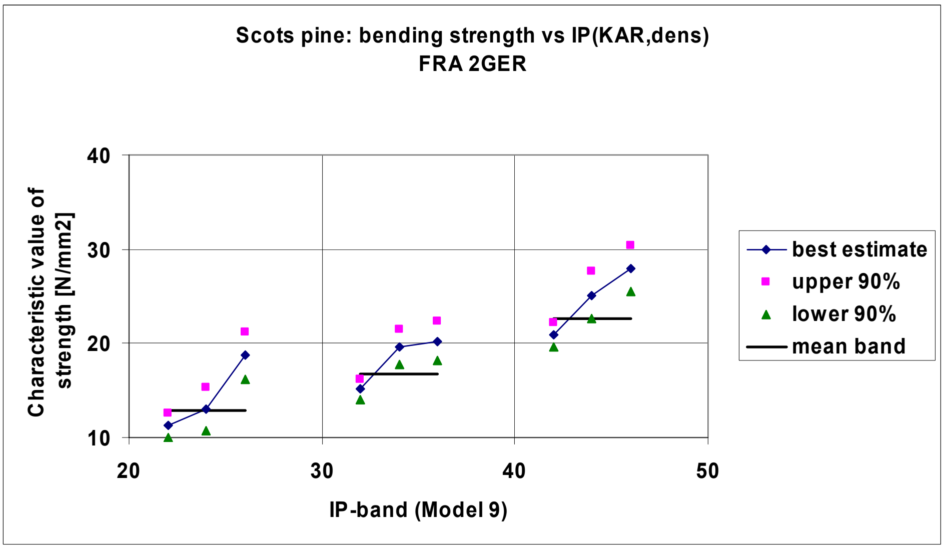


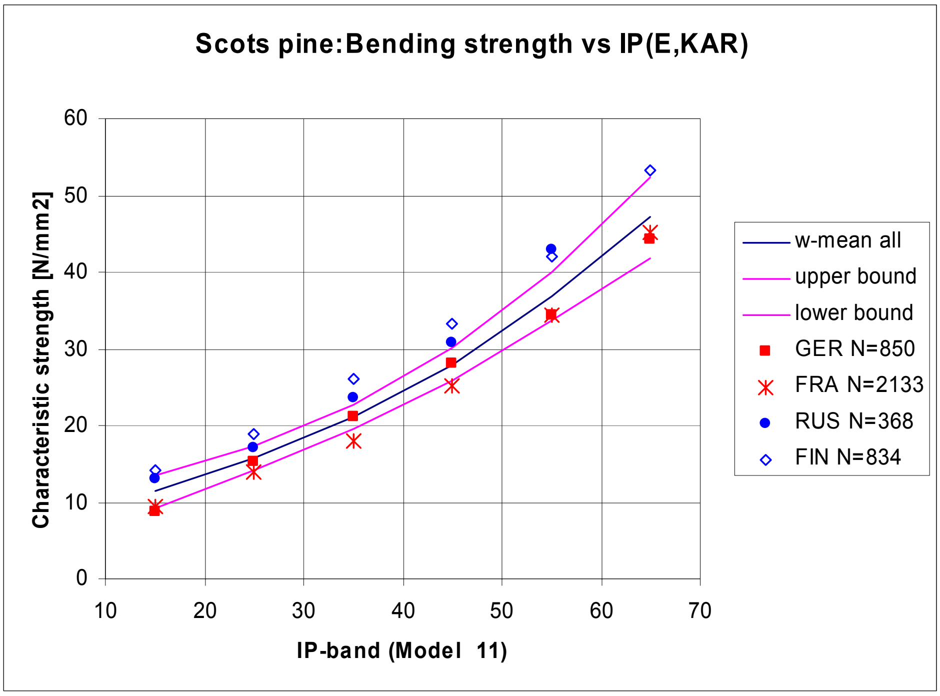
Scots pine: Bending strength vs model (KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 9)
50
45
40
35
30
25
20
15
10
20
30
40
50
60
w-mean all
upper bound
lower bound
FIN W
FIN E
RUS

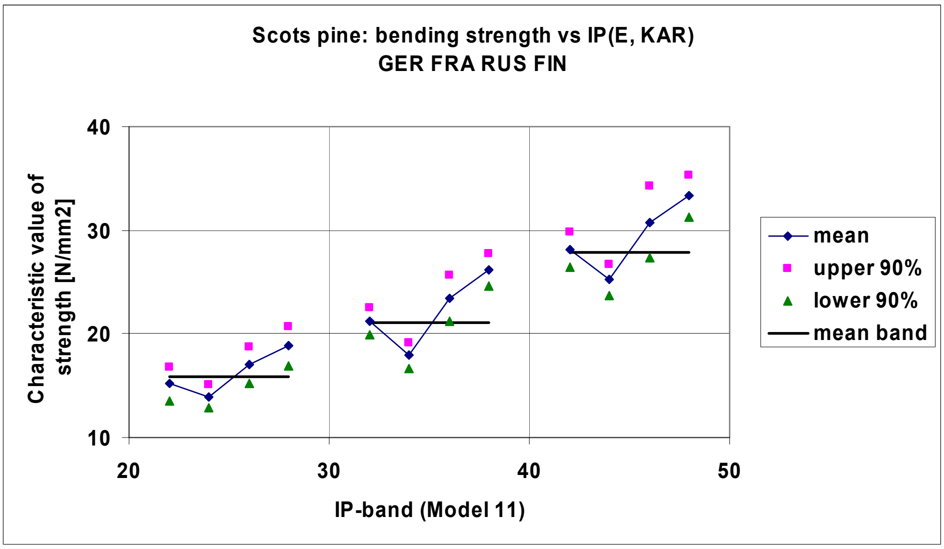


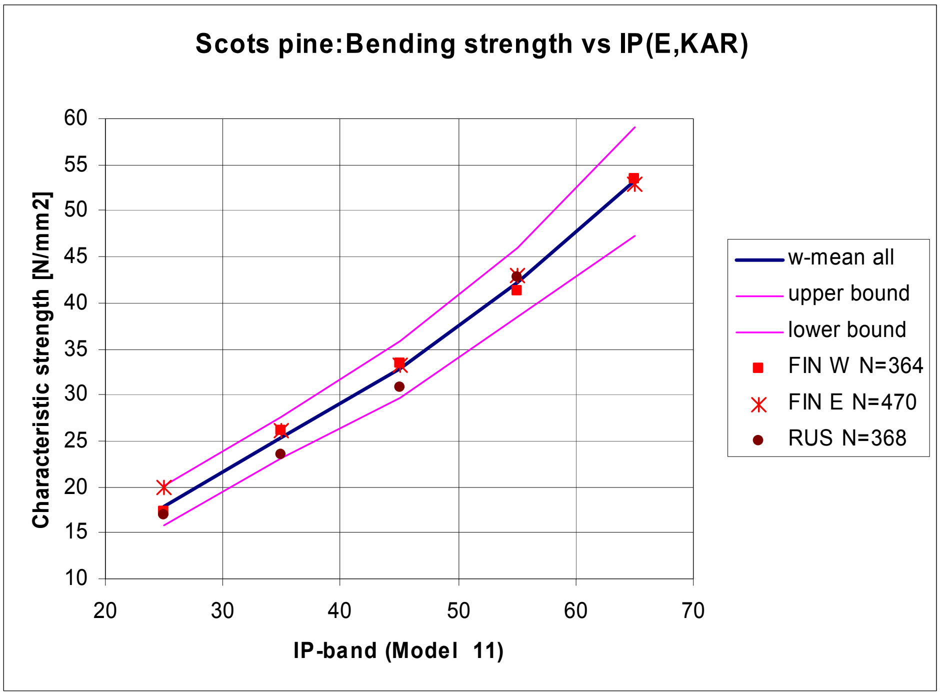
Scots pine: bending strength vs IP(KAR,dens)
2FIN RUS
Characteristic value of strength [N/mm2]
IP-band (Model 9)
40
30
20
10
20
30
40
50
best estimate
upper 90%
lower 90%
mean band

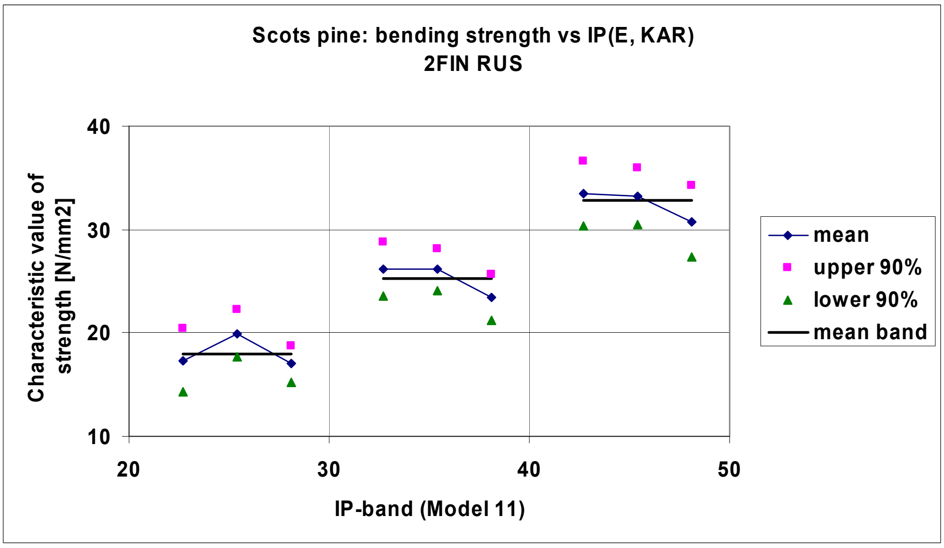

Scots pine: Bending strength vs model (KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 9)
w-mean all
upper bound
lower bound
FRA N=2133
GER S N=429
GER N N=421

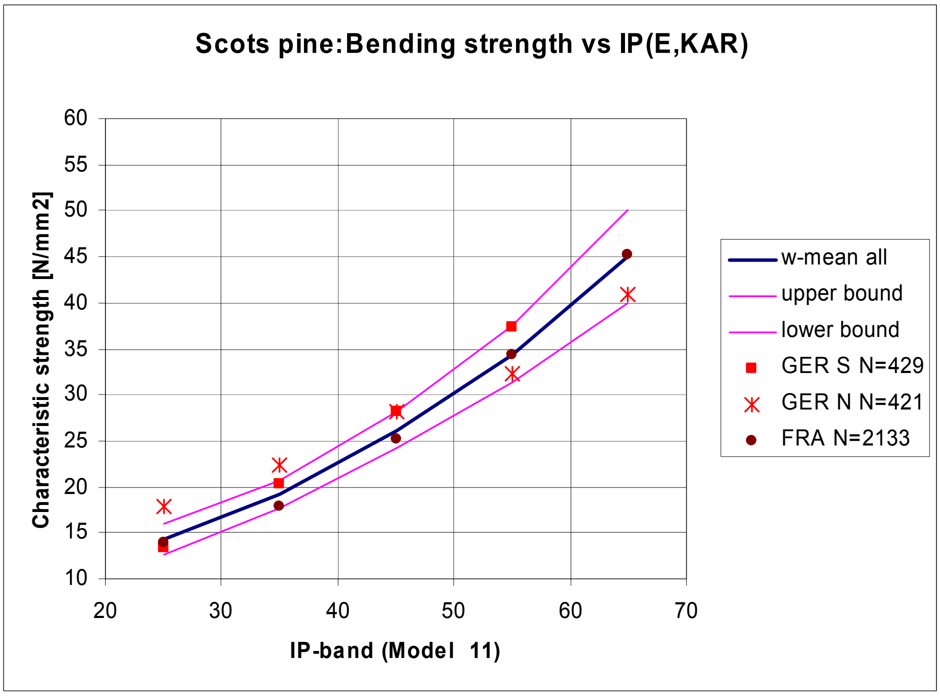

Scots pine: bending strength vs IP(KAR,dens)
FRA 2GER
Characteristic value of strength [N/mm2]
IP-band (Model 9)
best estimate
upper 90%
lower 90%
mean band

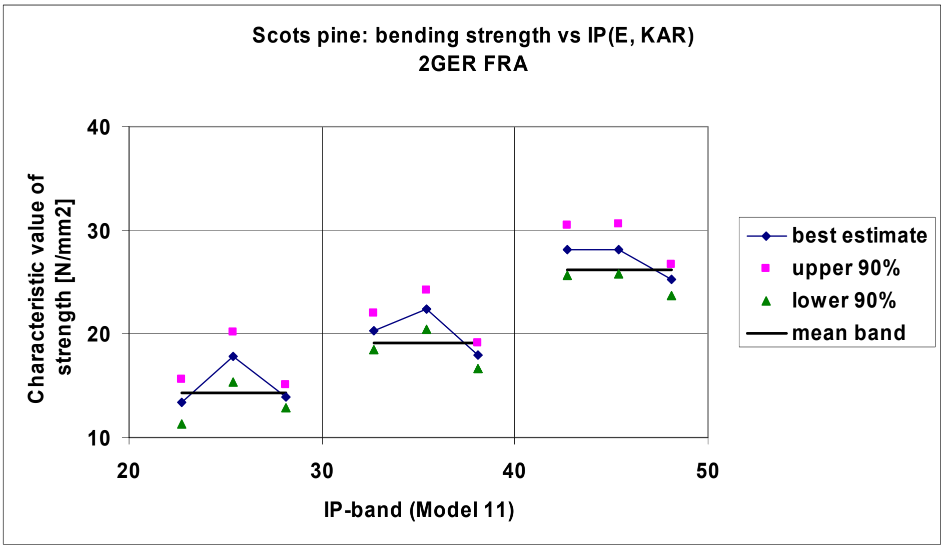

Scots pine:Bending strength vs IP(E,KAR)
Characteristic strength [N/mm2]
IP-band (Model 11)
w-mean all
upper bound
lower bound
GER N=850
FRA N=2133
RUS N=368
FIN N=834
0
10
20
30
40
50
60
10
20
30
40
50
60
70

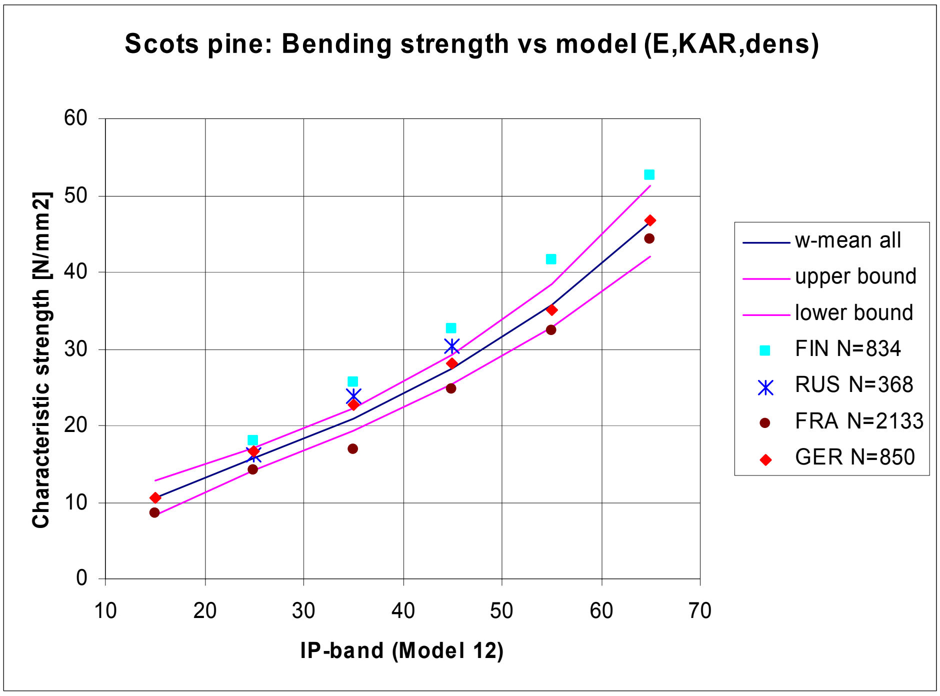

Scots pine: bending strength vs IP(E, KAR)
GER FRA RUS FIN
Characteristic value of strength [N/mm2]
IP-band (Model 11)
mean
upper 90%
lower 90%
mean band
10
20
30
40
20
30
40
50

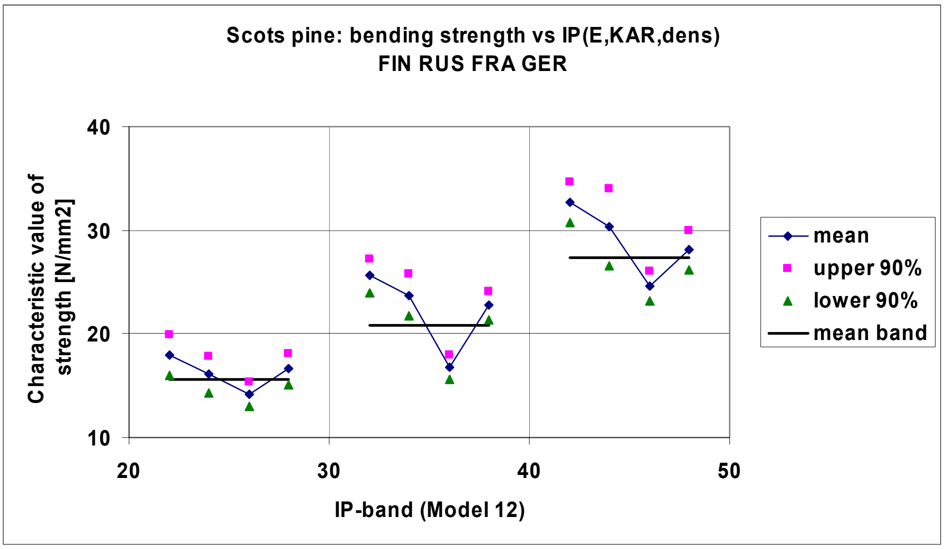

Scots pine:Bending strength vs IP(E,KAR)
Characteristic strength [N/mm2]
60
55
50
45
40
35
30
25
20
15
10
20
30
40
50
60
70
IP-band (Model 11)
w-mean all
upper bound
lower bound
FIN W N=364
FIN E N=470
RUS N=368

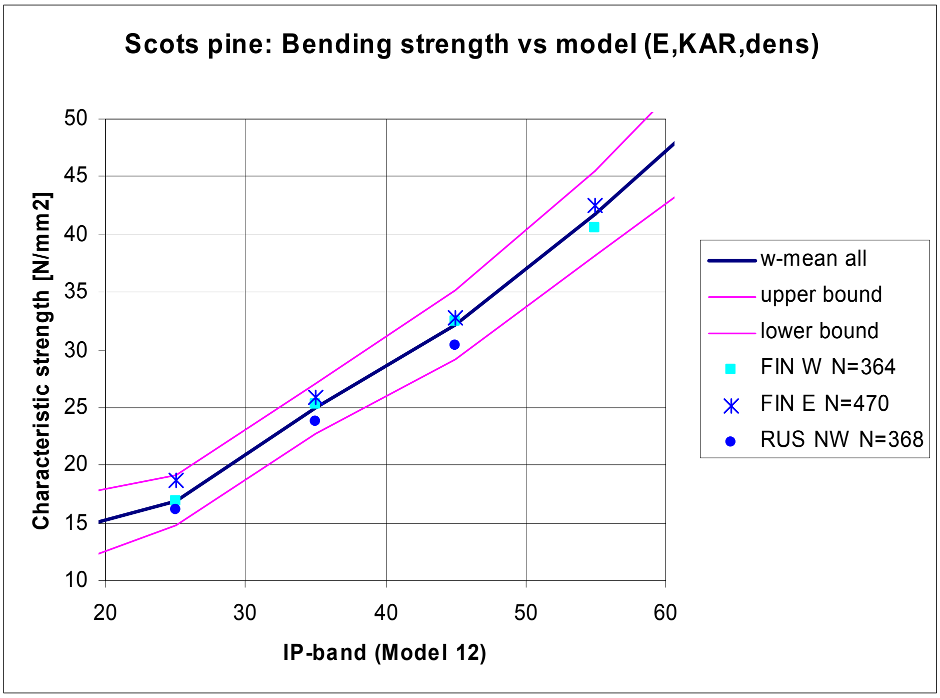

Scots pine: bending strength vs IP(E, KAR)
2FIN RUS
Characteristic value of strength [N/mm2]
40
30
20
10
20
30
40
50
IP-band (Model 11)
mean
upper 90%
lower 90%
mean band


Scots pine:Bending strength vs IP(E,KAR)
Characteristic strength [N/mm2]
IP-band (Model 11)
w-mean all
upper bound
lower bound
GER S N=429
GER N N=421
FRA N=2133
60
55
50
45
40
35
30
25
20
15
10
20
30
40
50
60
70


Scots pine: bending strength vs IP(E, KAR)
2GER FRA
Characteristic value of strength [N/mm2]
IP-band (Model 11)
best estimate
upper 90%
lower 90%
mean band
40
30
20
10
20
30
40
50


Scots pine: Bending strength vs model (E,KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 12)
60
50
40
30
20
10
0
10
20
30
40
50
60
70
w-mean all
upper bound
lower bound
FIN N=834
RUS N=368
FRA N=2133
GER N=850


Scots pine: bending strength vs IP(E,KAR,dens)
FIN RUS FRA GER
Characteristic value of strength [N/mm2]
IP-band (Model 12)
40
30
20
10
20
30
40
50
mean
upper 90%
lower 90%
mean band


Scots pine: Bending strength vs model (E,KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 12)
w-mean all
upper bound
lower bound
FIN W N=364
FIN E N=470
RUS NW N=368
50
45
40
35
30
25
20
15
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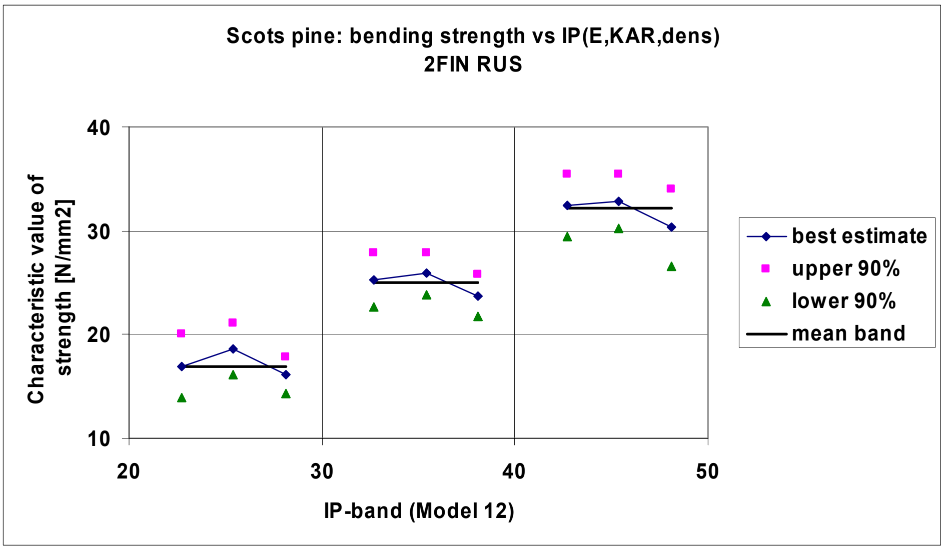
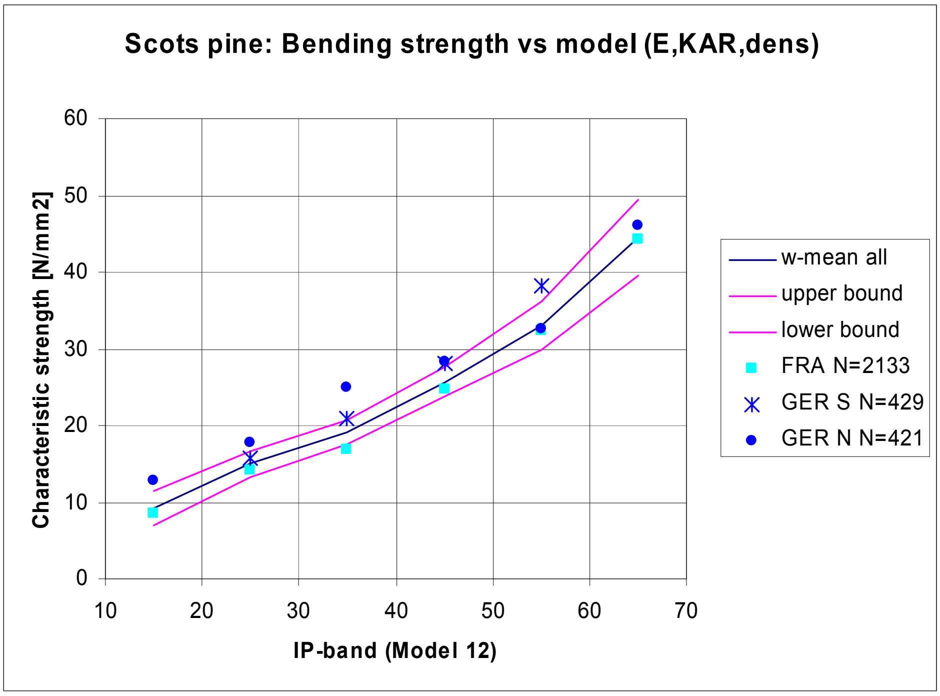
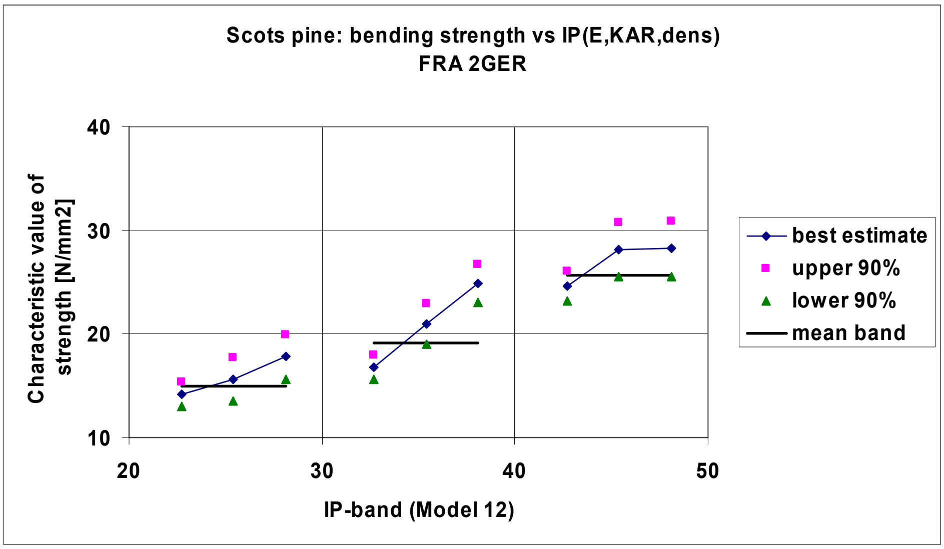
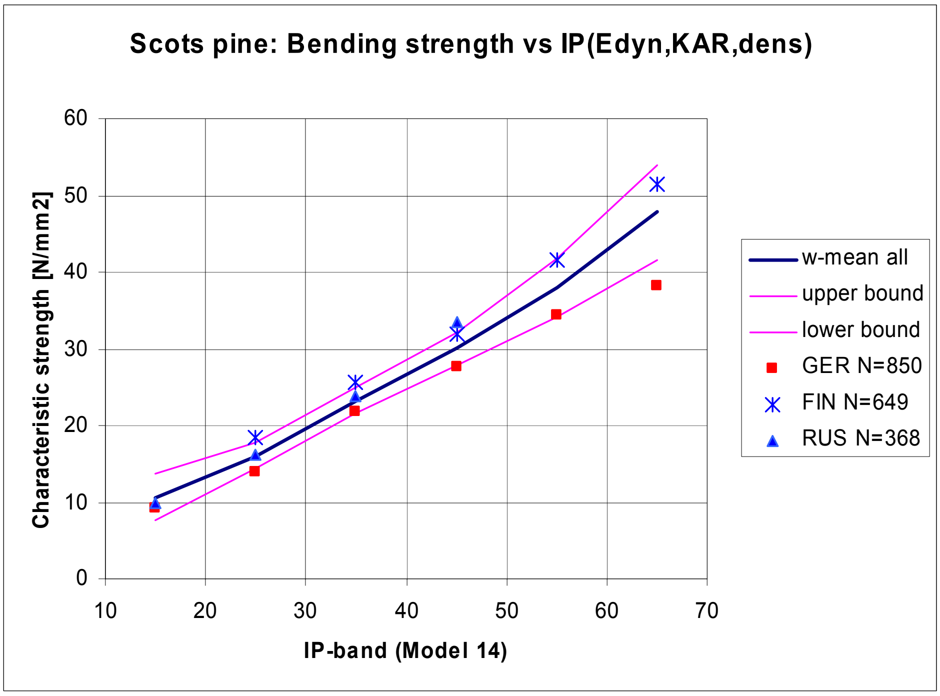
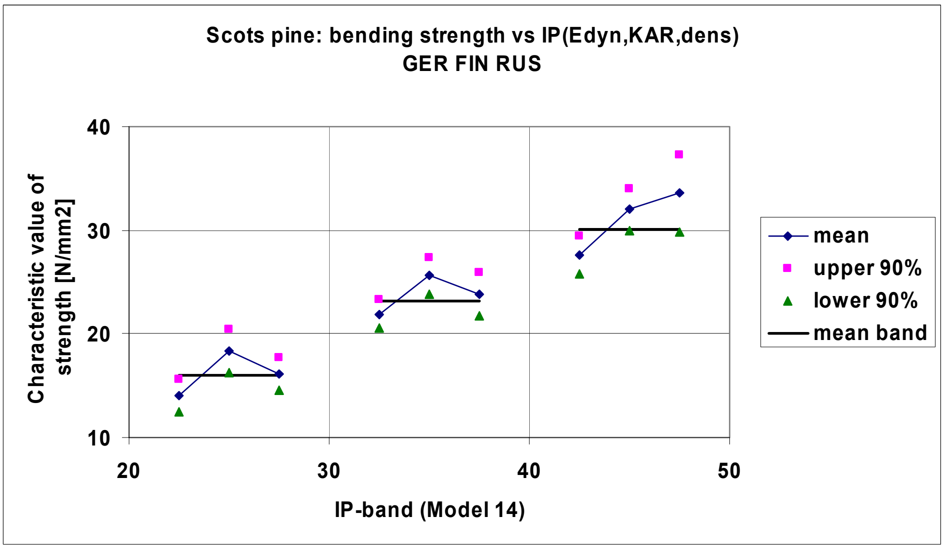
20
30
40
50
60

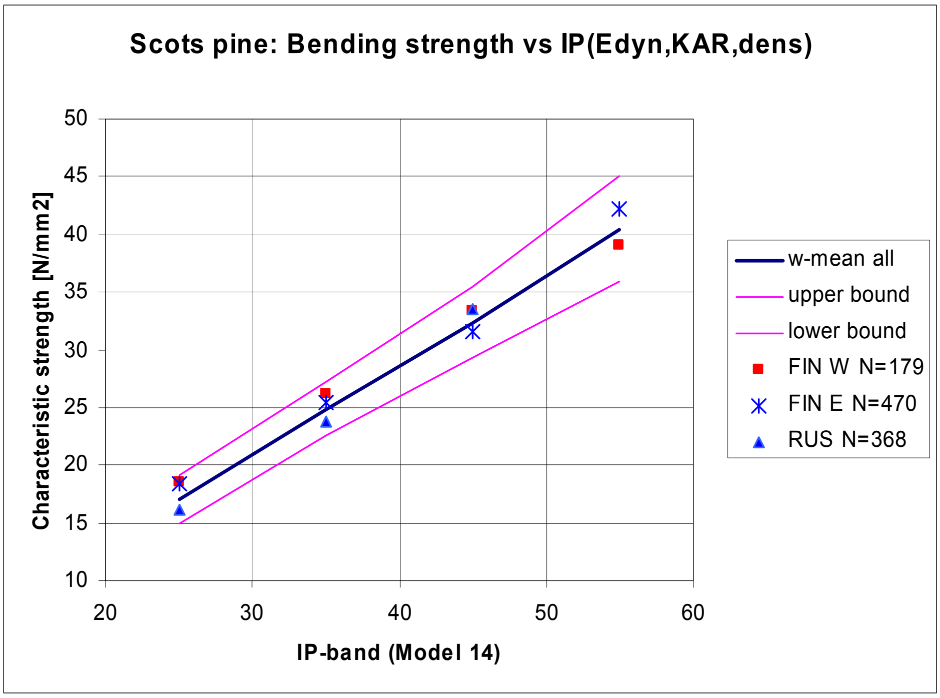

Scots pine: bending strength vs IP(E,KAR,dens)
2FIN RUS
Characteristic value of strength [N/mm2]
IP-band (Model 12)
best estimate
upper 90%
lower 90%
mean band
40
30
20
10
20
30
40
50

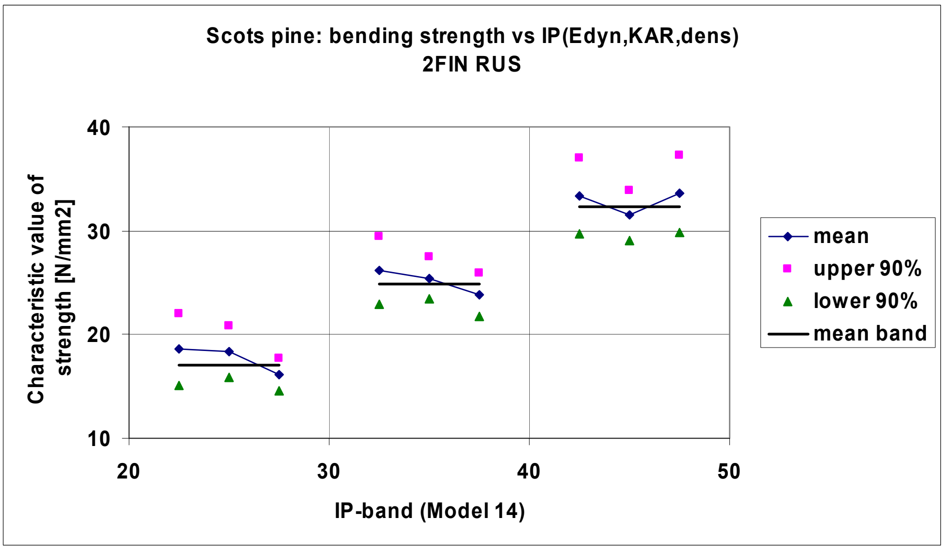

Scots pine: Bending strength vs model (E,KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 12)
w-mean all
upper bound
lower bound
FRA N=2133
GER S N=429
GER N N=421

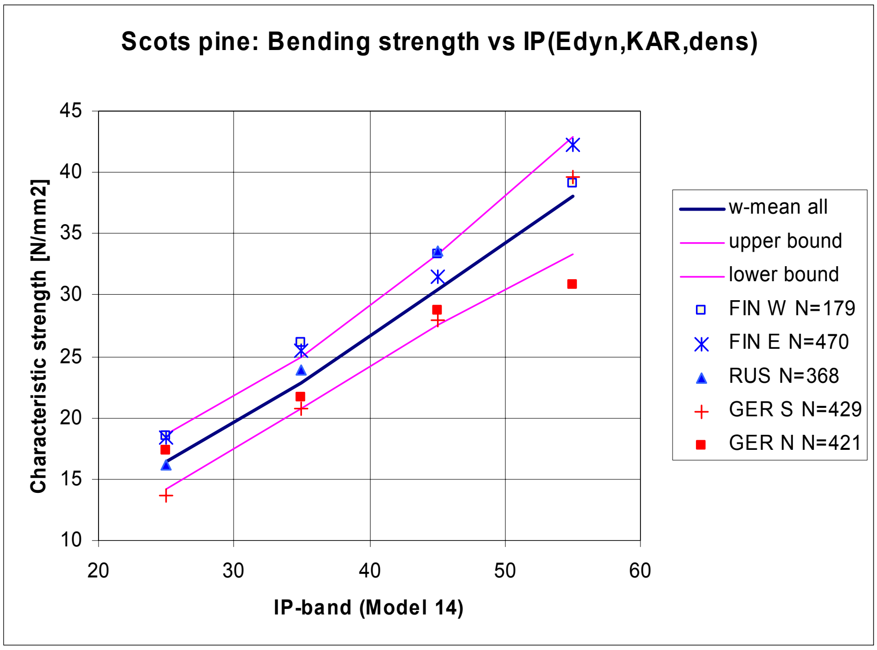

Scots pine: bending strength vs IP(E,KAR,dens)
FRA 2GER
Characteristic value of strength [N/mm2]
IP-band (Model 12)
best estimate
upper 90%
lower 90%
mean band

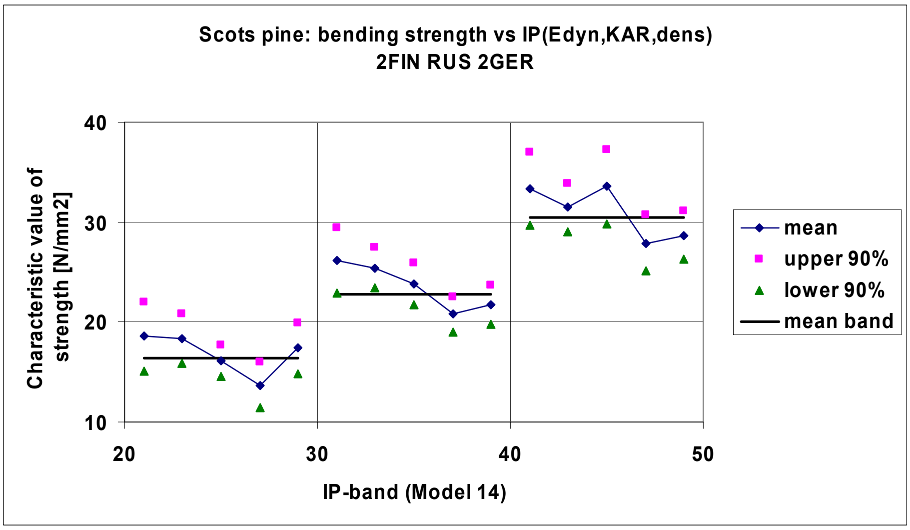

Scots pine: Bending strength vs IP(Edyn,KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 14)
0
10
20
30
40
50
60
10
20
30
40
50
60
70
w-mean all
upper bound
lower bound
GER N=850
FIN N=649
RUS N=368


Scots pine: bending strength vs IP(Edyn,KAR,dens)
GER FIN RUS
Characteristic value of strength [N/mm2]
IP-band (Model 14)
10
20
30
40
20
30
40
50
mean
upper 90%
lower 90%
mean band


Scots pine: Bending strength vs IP(Edyn,KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 14)
w-mean all
upper bound
lower bound
FIN W N=179
FIN E N=470
RUS N=368


Scots pine: bending strength vs IP(Edyn,KAR,dens)
2FIN RUS
Characteristic value of strength [N/mm2]
IP-band (Model 14)
mean
upper 90%
lower 90%
mean band


Scots pine: Bending strength vs IP(Edyn,KAR,dens)
Characteristic strength [N/mm2]
IP-band (Model 14)
w-mean all
upper bound
lower bound
FIN W N=179
FIN E N=470
RUS N=368
GER S N=429
GER N N=421


Scots pine: bending strength vs IP(Edyn,KAR,dens)
2FIN RUS 2GER
Characteristic value of strength [N/mm2]
IP-band (Model 14)
mean
upper 90%
lower 90%
mean band

Series title, number and report code of publication

VTT Publications 706
VTT-PUBS-706

Author(s)
Alpo Ranta-Maunus (ed.)

Title

Strength of European timber

Part 1. Analysis of growth areas based on existing test results

Abstract

Joint analysis of existing strength data for major commercial European timber species is presented in this report. The work has been carried out as a co-operative venture between 6 research institutes from 6 countries. The main objective of the work was the analysis of growth area issue for European grading standard: in which regions common grading machines settings can be used.

This research is mainly based on laboratory measurements of grade indicating properties: static and dynamic modulus of elasticity, knot area ratio (*KAR*), density, tension and bending strength. Results for thousands of test specimens from Central and Northern Europe are analyzed.

The results indicate that it is reasonable to determine different settings for Central and Northern Europe. In the case of grading spruce for glued laminated timber where tension strength is determined, differences between Central and Northern Europe are small and it may be possible and economically feasible to use the same settings for a large area when advanced grading methods based on measurement of stiffness and knot size related properties are used. When grading Scots pine for bending properties it is obvious that different settings are needed for Germany, France and UK, whereas the Nordic countries may use the same settings.

After the analysis of existing data the project continues with a new experimental programme after which more definitive conclusions can be expected.

ISBN
978-951-38-7337-0 (URL: http://www.vtt.fi/publications/index.jsp)

Series title and ISSN	Project number
VTT Publications 1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)	17542

Date	Language	Pages
April 2009	English, Finnish abstr.	105 p. + app. 63 p.

Name of project	Commissioned by
Gradewood	Tekes, CEI-Bois

Keywords	Publisher
timber, spruce, Scots pine, Douglas fir, strength, grading, growth area	VTT Technical Research Centre of Finland P.O. Box 1000, FI-02044 VTT, Finland Phone internat. +358 20 722 4520 Fax +358 20 722 4374

Julkaisun sarja, numero ja raporttikoodi

VTT Publications 706
VTT-PUBS-706

Tekijä(t)
Alpo Ranta-Maunus (toim.)

Nimeke

Eurooppalaisen rakennepuutavaran lujuus
Osa 1. Kasvualueiden vaikutuksen analyysi olemassa olevien testitulosten perusteella

Tiivistelmä

Tämä tutkimus perustuu olemassa olevan puun lujuuden testausdatan koordinoituun analysointiin. Työhön osallistui kuusi tutkimuslaitosta Pohjois- ja Keski-Euroopasta. Tutkimuksella pyritään vastaamaan kysymykseen, millä alueilla voidaan käyttää samoja asetusarvoja kuusi- ja mäntysahatavaran ja liimapuulamellien koneellisessa lujuuslajittelussa.

Tutkimuksessa käytetään lähinnä laboratorioissa mitattuja puun lujuuden mallinnuksessa tarvittavia suureita, kuten staattista ja dynaamista kimmokerrointa, oksa-alasuhdetta (*KAR*), tiheyttä ja rikkovissa kokeissa saatuja taivutus- ja vetolujuuden arvoja. Tutkijoilla oli käytettävissä useiden tuhansien koekappaleiden tulokset.

Tulokset vahvistavat käsitystä jonka mukaan Pohjoismaissa ja Keski-Euroopassa kasvaneelle kuuselle on syytä käyttää eri asetusarvoja. Kuitenkin vetolujuuden vaihtelu on vähäisempää kuin taivutuslujuuden, ja yhteisten asetusarvojen määritys liimapuulamelleille voisi olla mahdollista. Männyn ominaisuuksien vaihtelu on suurempaa kuin kuusen ja on ilmeistä että Iso-Britannia, Ranska ja Saksa tarvitsevat kukin omat asetusarvonsa. Pohjoismaiden kesken vaihtelu on pientä, ja nykyinen käytäntö pohjoismaisesta kasvualueesta on perusteltu.

Tämän olemassa olevien tulosten analysoinnin jälkeen projekti jatkuu uudella koeohjelmalla, minkä jälkeen tulokset tarkentuvat.

ISBN
978-951-38-7337-0 (URL: http://www.vtt.fi/publications/index.jsp)

Avainnimeke ja ISSN	Projektinumero
VTT Publications 1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)	17542

Julkaisuaika	Kieli	Sivuja
Huhtikuu 2009	Englanti, suom. tiiv.	105 s. + liitt. 63 s.

Projektin nimi	Toimeksiantaja(t)
Gradewood	Tekes, CEI-Bois

Avainsanat	Julkaisija
timber, spruce, Scots pine, Douglas fir, strength, grading, growth area	VTT PL 1000, 02044 VTT Puh. 020 722 4520 Faksi 020 722 4374

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