# Variability of strength of in-grade spruce timber

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## Abstract

Bending strength of machine strength graded spruce timber has been studied based on GoldenEye-706 grading machine data and simulated strength values. Data of nearly 200,000 boards has been available, from which 16 sub-samples of 2000 were selected to represent different dimensions and low and high ends of material properties. Grading is made according to European machine control method and standard settings. For comparison, results for knot size based grading are also shown.

Main objective of the work has been to determine a quantitative relation between the average properties of timber measured by grading machine and the characteristic strength of in-grade timber. The relation has been determined both based on average modelled strength of total population to be graded, and based on average for in-grade timber.

Results indicate that characteristic strength of in-grade timber strongly depends on quality of mother population when grading is made to one or two grades allowing very high yield to a grade (80%). When grading is made to three grades with maximum yield of 50% each, strength of in-grade timber is less dependent of quality of material to be graded, and deviation of strength is only in conservative direction for high quality material.

## 1 Introduction

Strength grading methods are not perfect, as is generally known. Accordingly, in-grade timber has higher strength when the initial unsorted population is of high quality and vice versa. Recently a new concept of adaptive settings for machine grading was proposed to react to occurring quality shifts (Sandomeer *et.al* 2007, 2008). Such quality shifts can be detected on several measured parameters simultaneously and can be quite dramatic (Figure 1). This kind of quality variation was first shown in COST E53 Conferences (Bacher 2008, 2009) with conclusion concerning settings used in grading: "For standard or high quality raw material these settings may be too conservative and for the low quality material still too optimistic. Adaptive thresholds have the potential to improve the overall yield for the producer and simultaneously also to increase the reliability in the product for the end user".

Further results on the quality variation have been published in recent papers (Ranta-Maunus & Denzler 2009, Ranta-Maunus 2009). This paper has the objective to quantify the influence of quality of the mother population to the strength of in-grade timber. European "machine control" method is studied.

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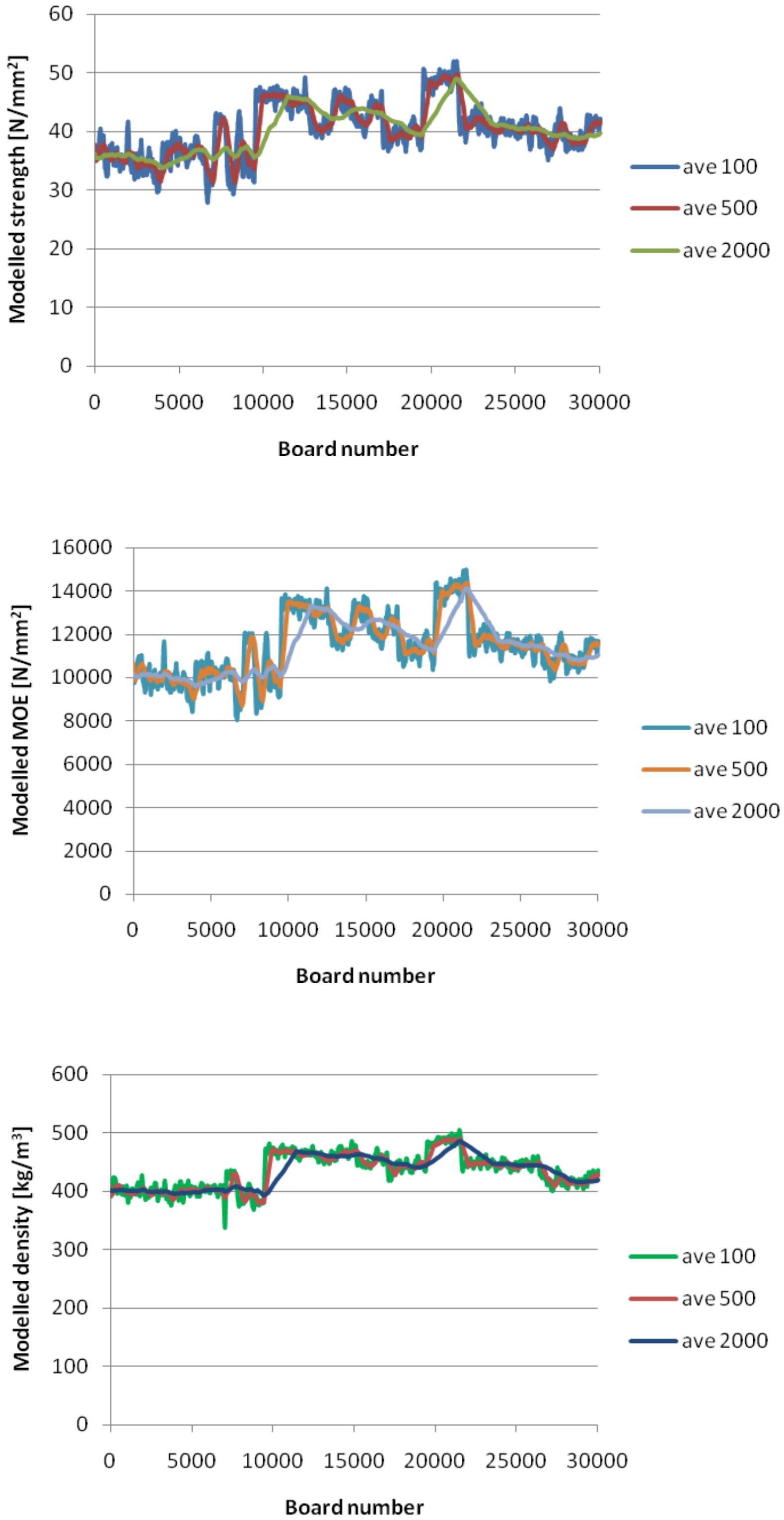


Figure 1: Variation of modelled strength, MOE and density of (partial) samples of FI 225, FI 175 and FI 150 in Table 1.

Modern computerized grading machines have made it possible to follow quality changes in a way which has not been possible until now. A way to illustrate quality variation in production of a sawmill has been to show the moving average of grade indicating properties of consecutive boards. Figure 1 shows the moving average of 100, 500 and 2000 boards of 3 grade indicating properties given by grading machine GoldenEye-706. These numbers are selected for illustration because

- 100 could be feasible as basis of dynamic settings in grading
- 500 has been used in previous paper as basis to find low and high quality samples
- 2000 will be used in this paper to find low and high quality samples

First 9000 boards in Figure 1 have width of 225 mm, next 8000 175 mm and rest 150 mm.

## 2 Material

This study is based on measured strength grading data of Nordic spruce (*Picea abies*) with addition of simulated bending strength values of each board. The readings of the strength grading equipment GoldenEye-706 at two Nordic saw mills since 2008 are analysed. In total results of nearly 200,000 boards were made available for this research. The dimensions varied between $w$ = 75 mm and $w$ = 225 mm in width and $t$ = 40 mm to $t$ = 50 mm in thickness. Sample sizes and average properties are given in Table 1.

The strength grading machine GoldenEye-706 uses X-Ray radiation to determine sizes, knots and density of a board via grey scale image, and combines this information to a frequency measurement to determine dynamic

Table 1: Average density and modelled strength of samples

| Sample | $n$ | $\rho_{mod,mean}$ kg/m³ | $f_{m,mod,mean}$ N/mm² |
|---|---|---|---|
| FI 75 | 17 334 | 461 | 43.4 |
| FI 100 | 53 473 | 460 | 42.6 |
| FI 125 | 13 829 | 449 | 41.7 |
| FI 150 | 42 609 | 447 | 42.3 |
| FI 175 | 7 867 | 461 | 43.8 |
| FI 200 | 22 900 | 423 | 39.2 |
| FI 225 | 16 065 | 401 | 35.6 |
| SE 100-200 | 22503 | 470 | 44.0 |
| all | 196570 | 449 | 41,6 |

modulus of elasticity $E_{dyn}$. Using this information the machine estimates the bending strength of each board by calculating its indicating property $f_{m,mod}$ for bending strength with an equation based on multi linear regression, as well as indicating properties $E_{m,mod}$ *and* $\rho_{mod}$.

An estimate of bending strength of each board is generated numerically ($f_{m,sim}$). Numerical simulation is made by adding to $f_{m,mod}$ an error term $\varepsilon$ which is a normally distributed variable having zero mean:

$$f_{m,sim} = f_{m,\mathrm{mod}} + \varepsilon \qquad \text{Equation 1}$$

$$\mathrm{var}\ f_{m,sim} = \mathrm{var}\ f_{m,\mathrm{mod}} + \mathrm{var}\ \varepsilon \qquad \text{Equation 2}$$

Standard deviation ($s$) of $\varepsilon$ can be estimated based on the fact that variance of a sum of two independent random variables equals the sum of variances (Equation 2). Standard deviation of $\varepsilon$ may not be the same for lower and higher grades. This has been studied in Gradewood project by comparing variation of strength of European spruce in different countries when various strength models were applied (Ranta-Maunus 2009). Result of a later analysis of that data is illustrated in Figure 2, where the dotted line (Equation 3) fits quite well to averages of European spruce bending data, and solid line (Equation 4) to the Nordic spruce with more advanced strength models. Equation 4 has been used in this paper.

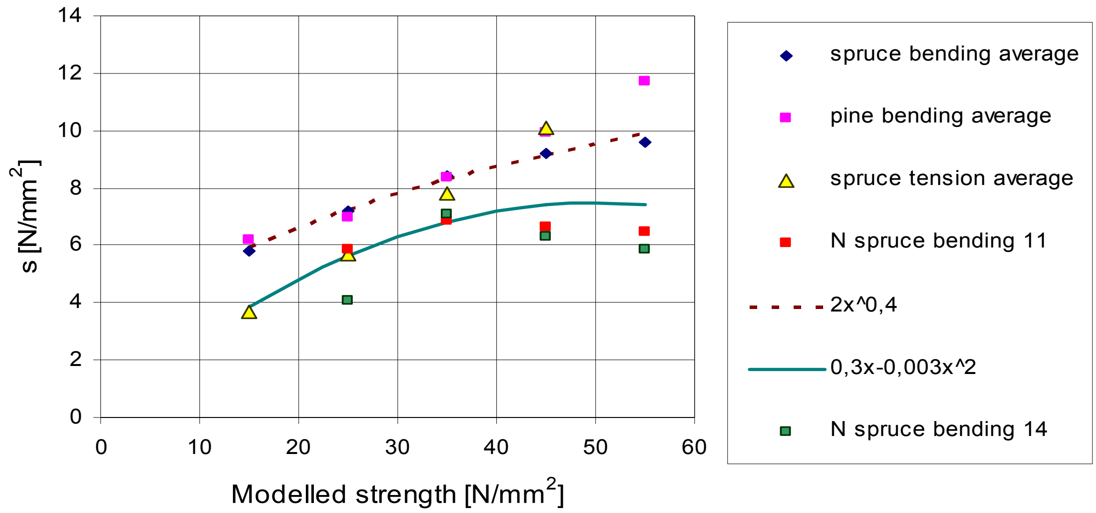


Figure 2: Average standard deviation of strength of European timber of 10 N/mm$^2$ wide bandwidths based on models 1, 2, 4, 9, 11 and 14 of Gradewood publication (Ranta-Maunus 2009) and separately for bending of Nordic spruce models 11 and 14.

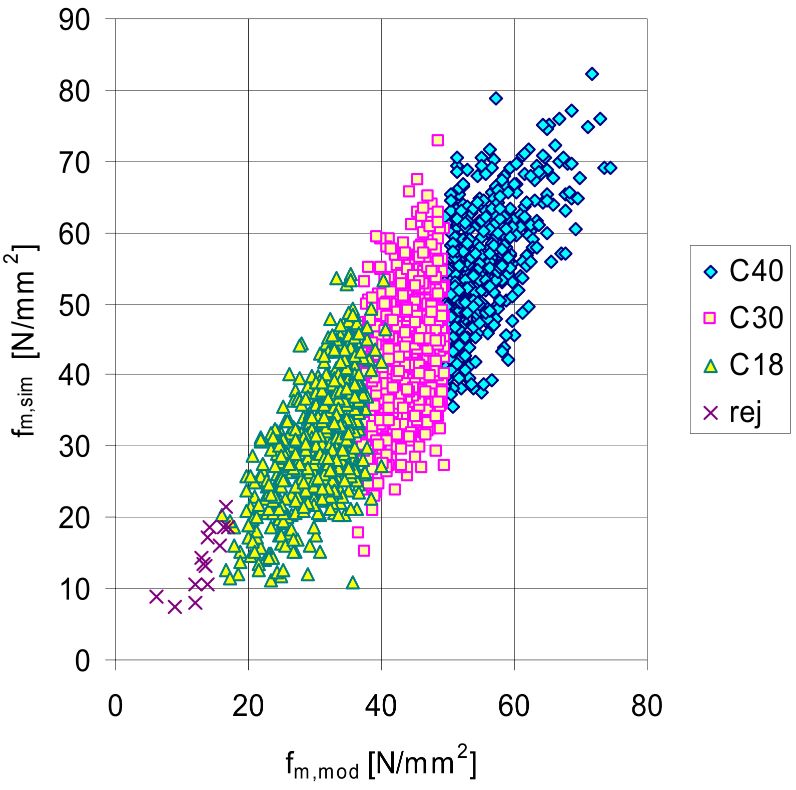


Figure 3: Example of simulated strength values, sub-sample SE 100-200 lower.

$$s = 2 f_{m,\mathrm{mod}}^{0.4}$$ Equation 3

$$s = -0.003 f_{m,\mathrm{mod}}^{2} + 0.3 f_{m,\mathrm{mod}}$$ Equation 4

In Equations 3 and 4 the modelled strength is given and *s* obtained in N/mm$^2$.

## 3 Analysis

Data of all 8 samples of Table 1 is utilised in such a way that two sub-samples of 2000 specimens each are selected from the samples (the values where moving average of $f_{m,mod}$ of 2000 consecutive timbers in the order they were graded, attains its maximum and minimum values). As a result we obtained 16 sub-samples of 2000 specimens with grading machine measured values and simulated strength values. One of the sub-samples is shown in Figure 3, the lower Swedish sub-sample, which is the median sample of all 16. This sub-sample has $r^2$=0.69 between simulated and modelled strength which is nearly same in the sub-samples.

All 16 sub-samples are graded according to EN 14081-4 settings for GoldenEye-706 and Nordic spruce in bending. Grading is made to three grade combinations:

1. C40-C30-C18-rej
2. C40-C24-rej
3. C27-rej

Standard settings for these grades are given in Table 2.

Table 2: Settings used in grading

| Grade | Grade combination | $f_{m,mod,th}$ | $E_{mod,th}$ | $\rho_{mod,th}$ |
|---|---|---|---|---|
| C40 | any | 49.6 | 12000 | 410 |
| C30 | C40-C30-C18 | 36.1 | 10000 | 370 |
| C18 | C40-C30-C18 | 15.3 | 5500 | 310 |
| C24 | C40-C24 | 15.3 | 5500 | 320 |
| C27 | C27 | 22.9 | 5500 | 320 |

Characteristic strength of each graded sub-sample will be compared to the quality of the timber. Quality is characterised by mean value of $f_{m,mod}$ of each total sub-sample, and separately by mean value of $f_{m,mod}$ of in-grade timber.

## 4 Results

### 4.1 Influence of quality of timber to be graded

Grading result is visualised by plotting characteristic strength of timber as function of average of IP ($f_{m,mod,mean}$) of sub-sample to be graded (Figure 4). We can conclude that average quality of timber has minor effect to the strength of graded timber when grading to combination C40-C30-C18, but a considerable effect when grading to a single grade (C27) or to C24 after C40. Regression lines for C27 (Equation 5) and C24 (Equation 6) are

$$f_{m,05} = 0.688 f_{m,\mathrm{mod},mean} - 3.88$$ Equation 5

$$f_{m,05} = 0.695 f_{m,\mathrm{mod},mean} - 6.74$$ Equation 6

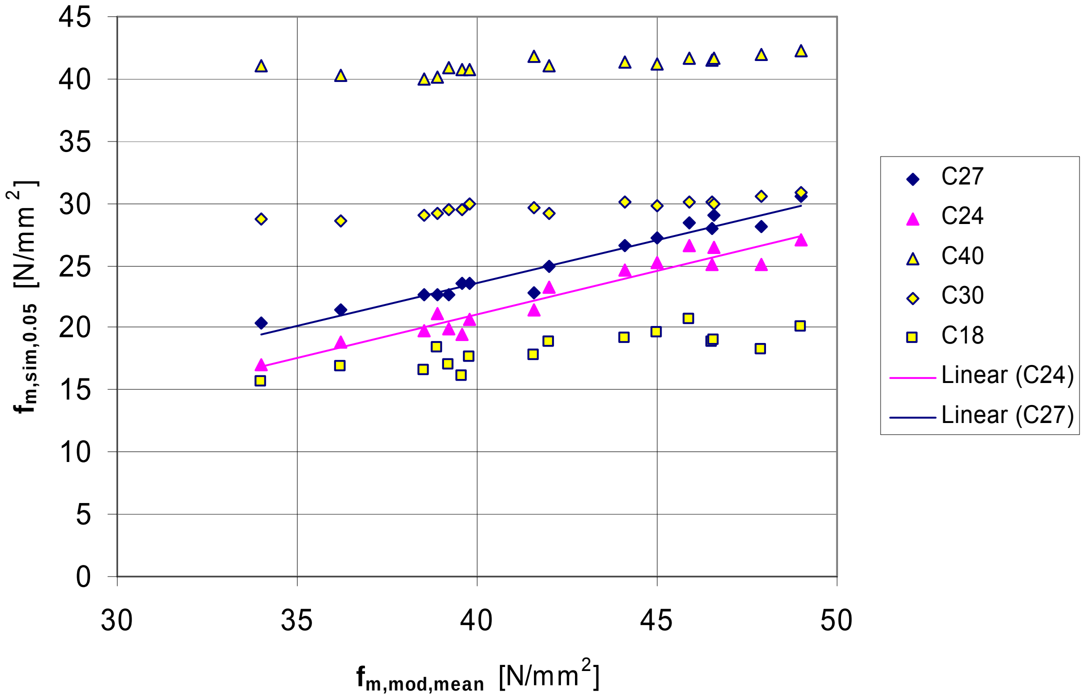


Figure 4: Strength of in-grade timber vs. average IP of ungraded timber

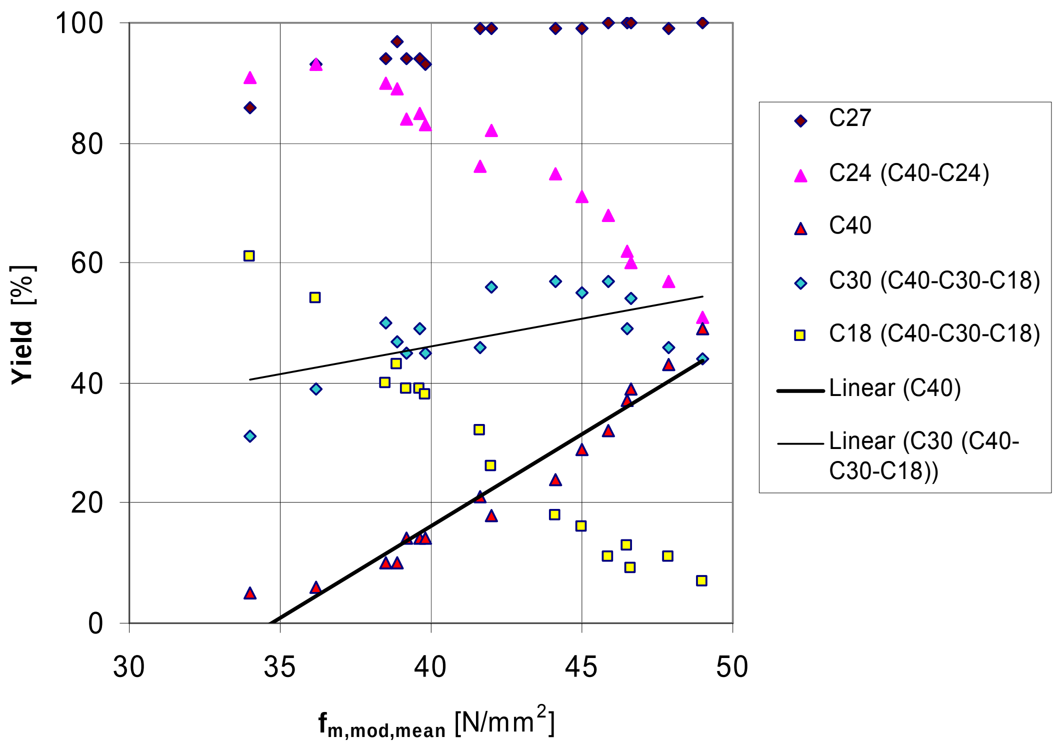


Figure 5: Yield vs. average IP of ungraded timber

Figure 5 shows the yields. Yield to C40 increases from 0 to 50% when mean IP increases from 35 to 50 N/mm$^2$. In all cases characteristic strength is adequate. The same time yield to C30 (C40-C30-C18 grading) has an increasing trend, too. Yield to C27 shows why this grade was selected for single-grade grading: yield is nearly 100%, and grading to lower single grade would not be sorting at all.

### 4.2 Influence of quality of in-grade timber

Characteristic strength of in-grade timber can be predicted by average of IP of the same in-grade timber as illustrated by Figure 6. Regression lines are shown for C30, C27 and C24 and equations for all grades are given: C40 (Equation 7), C30 (Equation 8), C27 (Equation 9), C24 (Equation 10) and C18 (Equation 11):

$$f_{m,05} = 0.56 f_{m,\mathrm{mod},mean} + 10.30$$ Equation 7

$$f_{m,05} = 0.85 f_{m,\mathrm{mod},mean} - 6.65$$ Equation 8

$$f_{m,05} = 0.75 f_{m,\mathrm{mod},mean} - 7.10$$ Equation 9

$$f_{m,05} = 1.15 f_{m,\mathrm{mod},mean} - 22.03$$ Equation 10

$$f_{m,05} = 1.25 f_{m,\mathrm{mod},mean} - 20.56$$ Equation 11

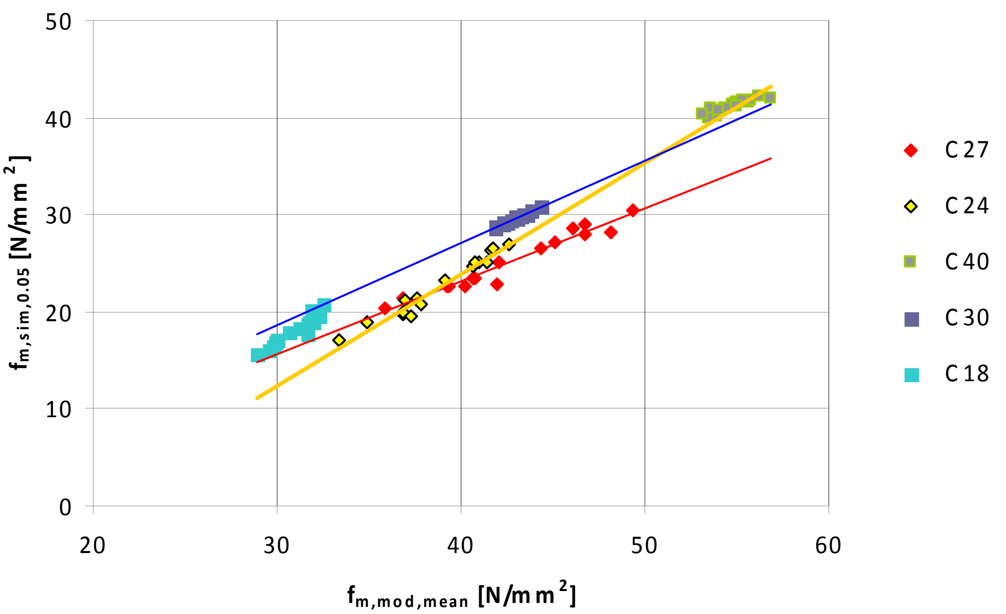


Figure 6: Strength of in-grade timber vs. average IP of in-grade timber

## 5 Comparison to knot size based grading

It is expected that characteristic strength of visually graded timber depends on quality of ungraded timber at least as much as strength of machine graded timber. Unfortunately we have no records of visually graded timber, similar to those of grading machines. As the grading machine GoldenEye-706 is calculating also a Machine Knot Parameter (*MKP*) based on X-ray, we study the selected three samples of those 16 presented in Figure 6: samples giving lowest, medium and highest IP-MOR. For the medium sample, three separate limits of *MKP* are set so that rate of rejects is 1%, 5% and 20%. These three thresholds of *MKP* are 5820, 4323 and 3153. Reject yields in these artificial grades are shown in Table 4.

Figure 7 shows characteristic values of simulated strength of knot size based grades determined in an identical way to Figure 6 for machine grades. Highest and lowest quality ungraded samples are the same in both cases. In case of machine grading (C24 and C27) the difference of characteristic strength of highest and lowest quality sample is 10 N/mm$^2$, and in case of "visual" X-ray grading 11...14 N/mm$^2$ depending on the grade. Results of strength, MOE and density are shown in Table 3.

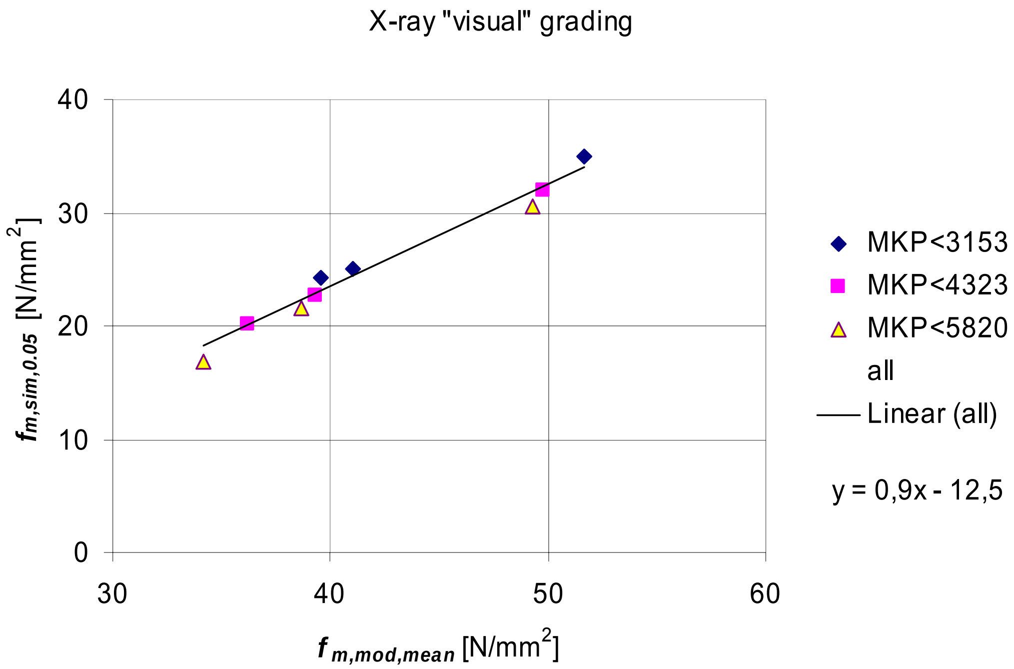


Figure 7: Strength of in-grade timber vs. average IP of in-grade timber, when grades are based on *MKP* given by X-ray.

Table 3: Characteristic values obtained for 3 samples in knot based grading

| Sample | *MKP* threshold | $f_{m,mod,mean}$ | $f_{m,sim,05}$ | $f_{m,sim,005}$ | $E_{mod,mean}$ | $\rho_{mod,05}$ |
|---|---|---|---|---|---|---|
| | | N/mm$^2$ | N/mm$^2$ | N/mm$^2$ | N/mm$^2$ | kg/m$^3$ |
| FI 225 lo | 5820 | 34.2 | 16.9 | 10 | 9700 | 343 |
| | 4323 | 36.2 | 20.2 | 13 | 10000 | 345 |
| | 3153 | 39.6 | 24.3 | 16 | 10700 | 351 |
| FI 75 lo | 5820 | 38.7 | 21.6 | 14 | 10800 | 373 |
| | 4323 | 39.3 | 22.7 | 15 | 10900 | 373 |
| | 3153 | 41.0 | 25.1 | 18 | 11200 | 378 |
| FI 150 hi | 5820 | 49.3 | 30.9 | 21 | 14200 | 419 |
| | 4323 | 49.8 | 32.0 | 23 | 14400 | 421 |
| | 3153 | 51.7 | 35.0 | 27 | 14700 | 427 |

Table 4: Yields to reject in knot size based grading

| Grade | Sample quality | | |
|---|---|---|---|
| | High | Medium | Low |
| *MKP*<5820 | 0.00 | 0.01 | 0.04 |
| *MKP*<4323 | 0.03 | 0.05 | 0.18 |
| *MKP*<3153 | 0.20 | 0.20 | 0.45 |

## 6 Discussion

Characteristic strength of in-grade timber is lower than required when yield to any grade is more than 80%, and the average quality of timber is lower than in the sample used for determination of settings. In these cases, strength is observed to be dependent of material to be sorted so that in the highest quality case of 16 analysed samples (n=2000) $f_{m,05}$ of C24 is 27 N/mm$^2$ and in the lowest 17 N/mm$^2$. For C27 the results are between $f_{m,05}$=20...30 N/mm$^2$. In knot size based grading, variation within a grade is still larger: $f_{m,05}$=17...31 N/mm$^2$ in the lowest artificial grade and $f_{m,05}$=24...35 N/mm$^2$ in the highest grade analysed. The used Machine Knot Parameter (*MKP*) has higher correlation to strength than visual *KAR*. *MKP* is the same as "*X-ray knot b*" in Table 16 of Combigrade project report which gives $r^2$= 0.40 whereas $r^2$= 0.20 for *TKAR* in bending of spruce (Hanhijärvi *et al* 2008).

In C40-C24 grading of the better half of material, strength of both grades is above requirement, and there would be potential to allow higher yield to C40.

When grading to three grades C40-C24-C18, yield to any grade is below 80%, and strength is generally above required value, for high quality material more than for low quality material. Obtained values are however closer to requirement than in case of grading to C40-C24 or to C27 alone.

More even strength values could be obtained if we would use dynamic settings adapting information of the previously graded timber collected by the grading machine. Based on Equations 7 to 11 we can conclude that one N/mm$^2$ higher mean of IP-MOR results in 0.6 to 1.2 N/mm$^2$ higher characteristic strength of in-grade timber. This information can be utilised in determination of dynamic settings and is the topic of a coming WCTE paper (Ranta-Maunus & Turk, 2010). It will further develop the approach described in COST E53 Lisbon paper (Ranta-Maunus, 2009). Basically the approach is to adjust settings for each board based on the mean of a number of previous boards:

$$f_{\mathrm{mod},th} = f_{\mathrm{mod},th,ini} + \alpha\left(f_{\mathrm{mod},mean,ref} - f_{\mathrm{mod},meanN}\right) \qquad \text{Equation 12}$$

where $f_{\mathrm{mod,th,ini}}$ are the initial settings based on reference sample which gives average IP for strength of in-grade timber: $f_{\mathrm{mod,mean,ref}}$. $f_{\mathrm{mod,meanN}}$ is mean of IP of previous N pieces graded to the grade according to initial settings. N and α are to be optimised to give maximum yield within the requirements for grades. Initially, based on Equations 7 to 11, we can select

$$\alpha = 1.75 - 0.03C \qquad \text{Equation 13}$$

where *C* means C-class (i.e. *C*=24 for C24). A method for determination initial settings is also presented in coming paper (Ranta-Maunus & Turk, 2010).

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