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TEST MACHINE EFFECT IN THE DETERMINATION OF MODULUS OF ELASTICITY FOR STRENGTH-GRADED TIMBER

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ABSTRACT: This paper investigates if the relationship between the global and local moduli of elasticity (MoE), measured in bending tests, is affected by the test machines employed, and how that may influence strength grading. The ultimate aim is to study the potential influence of those factors on the yields of graded timber in Europe, and improve the standards used. More than 2000 structural timber pieces of Douglas fir (*Pseudotsuga menziesii*), larch (*Larix* spp.) and spruce (*Picea sitchensis & P. abies*) grown in Ireland and the United Kingdom, were tested using two different test machines. The results are examined, and compared to the dynamic MoE measured using longitudinal vibration resonance.

Results found that there can be a sufficiently large systematic effect of the test machine on the measurement of MoE, to potentially be transferred to the grading process with important consequences in the yields of structural grade timber. Furthermore, adjustment factors for MoE, as used in the standards, may not be transferable between laboratories, even when the species and timber source are the same. Caution is therefore recommended when deriving or using these MoE adjustment equations, with due care to ensuring the timber is of similar characteristics and tested under as similar as possible setups. The extrapolation of models derived from other sources is best avoided, unless confirmed by cross-checking measurements.

KEYWORDS: Wood properties, Grading, Modulus of elasticity, Strength Classes, European standards

1 INTRODUCTION

Design values for structural timber are typically determined based on grades, in Europe called strength classes, that group pieces of timber according to quality. One of the key grade-determining properties is the modulus of elasticity (MoE) in bending, which is usually described by the required mean value of the graded population. This mean value and the lower fifth percentile of the strength and density properties are called the characteristic values of a (graded) population. Grading requires some destructive measurements to establish or confirm the grading rules. In Europe, the bending stiffness (along with bending strength) is established on the basis of four-point bending, according to the standards EN408 [1] and EN384 [2], with the latter standard requiring the worst defect to be placed in the centre of the test span. It is assumed that all bending test machines perform equally, so long as they are calibrated and follow the standard, but there are reasons to think that that may not be a correct assumption in the case of stiffness. The stiffness of the testing machine itself, the exact support conditions, the restrains to prevent lateral torsional buckling, the type of transducers (LVDTs, lasers displacement, draw-wires, etc.) and the exact arrangement of deflection transducers all have the potential to influence the measurement in ways that are small enough to not be immediately apparent, but large enough to make a meaningful difference in the grading calculation. This may be different from machine to machine, even though each is within the specification of the standards.

Specifically, the standards allow for two types of measurement of MoE: local (MoE_L), measured at the neutral axis in the middle of the board (pure bending part) and global (MoE_G), normally measured from the centre of the tension edge and that (by definition) includes the deformation due to shearing action between the supports and load points (Figure 1). Of the two, the latter is more widely used due to the ease of the measurement compared to MoE_L but in both cases the laboratory measurement setup sometimes varies slightly from the standard requirement for practical reasons, depending on what equipment there is available. For further grading calculation there is an empirical adjustment in EN384 for softwoods given here as Equation (1) that adjusts MoE_G to a “shear free” stiffness or pure bending (MoE_0), equivalent to the MoE_L measurement, which was the standard method before 2003.

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$$E_0 = E_{global} * 1.3 - 2690 \quad (\text{N/mm}^2) \tag{1}$$

This equation produces a negative value for very low (but sometimes measured) stiffness, and in addition it is not appropriate for all species and countries [3]. This was recognised in the 2016 revision of EN384 giving the option of using a different equation based on sufficient relevant data, at least 450 pieces.

Here we present a case study from the United Kingdom and Ireland, where the climate growing conditions are very similar. This explains in good part the comparable quality of the timber. In fact, it is common to sample and develop machine grading settings for use in both countries. However, specific adjustments developed in one laboratory to convert MoE_G to a "shear free" stiffness may not be transferable to other laboratory due to the different variables influencing the measurements mentioned above.

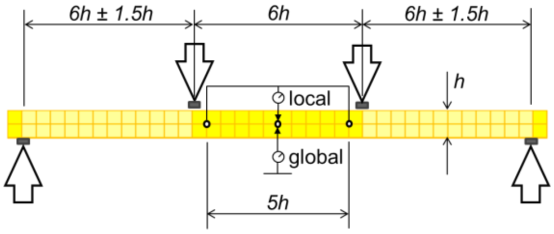

Figure 1. *EN408 test arrangement (for beam of depth h)*

These issues, while seemingly small at first inspection, could ultimately impact the grading of a timber population, depending on what limits that grading. Although strength was found to limit the grading of Douglas fir in Ireland and in the UK [4], MoE is the determining property that typically limits the grading of the most widely planted commercial timber species in these countries, the species combination "British spruce", a combination of Sitka spruce (*Picea sitchensis*) with a small amount of Norway spruce (*Picea abies*) [5,6]. That is to say, MoE is relatively lower than strength and density, compared to the profiles used for the strength classes. In these cases, the grading settings and yields are sensitive to small changes in stiffness and therefore it is important not to apply conversion equations that do not appropriately adjust the measured stiffness values for the machine, and populations, in use.

In this paper, we firstly examine the existence of a possible systematic effect by test machine affecting the measurement of MoE in bending. We do this using the non-destructive dynamic modulus of elasticity (MoE_{dyn}) as a reference. Secondly, how the effect translates into the grading process of stiffness for different quality stiffness requirement is examined.

2 MATERIALS AND METHODS

More than 2000 pieces from three different conifer species grown in the Republic of Ireland and the United Kingdom are used for this study: Douglas fir (*Pseudotsuga menziesii* - PSMN), larch (*Larix decidua, kaempferi and x eurolepis* - WLAD) and British spruce (WPCS). Table 1 summarises the distribution of tested specimens by laboratory. Part of the Douglas fir (277 specimens) and all the Sitka spruce tested in NUIG came from previous studies [7,8]. In order to normalise the dataset, and avoid the possible influence of different cross sections, the pieces covered here are a nominal cross section of roughly 50x100 mm^2, with widths from 87 mm to 107 mm, and thicknesses from 41 mm to 58 mm.

Table 1: *Source and laboratories of the specimens*

Species	Total	NUIG	ENU
Sitka spruce	976	473	503
Douglas fir	572	384	188
Larch	478	60	418
Total	2026	917	949

Prior to destructive testing, the dynamic modulus of elasticity (MoE_{dyn}) was measured. Most of the specimens (96%) used the MTG960 grading machine (Brookhuis Applied Technologies BV) that uses vibration resonance and density obtained from individual dimensions. In order to increase the Douglas fir tested at ENU seventy-five specimens of Douglas fir measured with a Viscan (MiCROTEC s.r.l. – GmbH) using the same principles are included. These are very replicable measurements when operating the same machine model, and the differences between the two machines are typically less than 1% and not systematic. It is considered that for this study this difference is neglectable, and therefore MoE_{dyn} can be used as a reference level for comparison. MoE_{dyn} was calculated for each specimen using the frequency of the vibration and the measured specimen density using the Equation (2):

$$MoE_{dyn} = \rho * (2 * L * f)^2 \quad \text{N/m}^2 \tag{2}$$

where ρ is the wood density (kg/m^3), and the velocity at which the stress wave propagates is calculated from the length of the specimen (L, m), and the first mode resonance frequency (f, Hz). Results were adjusted to a 12% moisture content (mc) using the adjustments given for MoE_{dyn} in EN14081-2 [9]. The average mc of the specimens was 14.0% at the time of measuring the MoE_{dyn} and 13.2% at the time of testing. When possible (60% of boards), it was calculated from the difference in mass at the time of measuring the MoE_{dyn} and at the time of testing, together with a sample obtained near the failure point and oven dried [10]. Otherwise it was measured using a hand-held wood moisture meter over a depth of at least 0.3 times the thickness [11]. Two testing machines were used for the MoE measurements. Figure 2 shows the Zwick/Roell 500 kN Servo Hydraulic testing machine installed in the structures laboratory of the National University of Ireland Galway (NUIG). Figure 3 shows the Zwick/Roell Z050 with capacity for 50 kN operated in Edinburgh Napier University (ENU). The tests and adjustments followed the requirements of the European standards EN 408 [1] (with span 18 times depth) and EN 384 [2]. The MoE_L was measured on the neutral axis using an almost identical set-up in both laboratories, except for Sitka spruce tested in NUIG that used a different setup in slight variance with EN408 but intended to measure the same deflection. EN408 allows measurement for MoE_G from the middle of the compression edge, middle of the tension edge, or either side on the neutral axis. In this study, except Sitka spruce in NUIG, the set ups measured at the centre of the bottom (tension) side, with a displacement laser sensor in NUIG and with a displacement transducer in ENU. Sitka spruce in NUIG measured MoE_G at the top (compression) side.

Figure 2. *Test machine in NUIG laboratory.*

The measured global and local moduli of elasticity were adjusted to 12% moisture content in accordance with EN 384 [2]. All the pieces had 8 % ≤ mc ≤ 18 % except one piece of larch that was above 18% and was adjusted as if it was at 18% mc (penalising therefore the stiffness performance). This is the same as the MoE_{dyn} adjustment to 12% mc in accordance with EN 14081-2 [10], except this covers the range 6 % ≤ mc ≤ 22 %. There was not any piece out of this range.

Figure 3. *Test machine in ENU laboratory.*

2.1 ANALYSIS

The statistical analysis was made using R software version 3.6.2 [12].

2.1.1 Timber characterisation

The study analysed, in the first place, the quality by species for further conclusions on the impact of the test machines. Following this, the strength of the relationships between the three MoE (MoE_L, MoE_G and MoE_{dyn}) were investigated.

MoE_G is more often measured for grading than MoE_L. Whether the relationship between MoE_{dyn} and MoE_G was affected by test machines was examined by conducting an analysis of variance (ANOVA) of the linear model of the form:

$$MoE_G = \alpha_0 + \alpha_1 MoE_{dyn} + \alpha_2 set + \alpha_3 MoE_{dyn} set + \\ + \alpha_4 Sp + \alpha_5 MoE_{dyn} Sp + \varepsilon \quad (3)$$

where α_0 is the regression coefficient of intercept, α_1 is the regression coefficient of slope, α_2 represents the additive effect of the machines studied (set), α_3 is the interaction term between MoE_{dyn} and machines, α_4 represents the additive effect of the species (Sp), α_5 is the interaction term between MoE_{dyn} and species and ε is the residual error not explained by the model. The ANOVA conducted was type III to account for the unbalanced number of specimens in each group.

The linear relationship between MoE_L and MoE_G for each laboratory was then examined, and following this, a paired t-test was used to compare the mean of MoE_L and MoE_G.

2.1.2 Influence of test machines on MoE grading

The implications of the effect of the test machine on the individual boards were examined at a population level using the Douglas fir and Sitka spruce datasets (as there was only a small number of larch boards for NUIG). Firstly, linear regressions were derived by species for each test machine to convert MoE_G to a “shear free” stiffness with MoE_L as the predicted variable. These equations, together with the Equation (1) given in EN384, were applied to the measured MoE_G to simulate stiffness grading and compare the suitability of the equations to the material assessed. The MoE_{dyn} worked as the indicating property (IP) to determine the quality, here understood as the mean MoE of the population graded.

3 RESULTS AND DISCUSSION

3.1 RELATION BETWEEN MoE_{dyn} AND STATIC MoE

The difference in the quality of the populations was investigated as the first step (Table 2). Direct comparison of species is not recommended here, as the material came from trees of different ages. The laboratory where the pieces were tested does not necessarily correspond with the country of origin of the material, and therefore results should not be used to conclude differences in the timber quality of the countries.

Table 2 shows that both tested populations of Sitka spruce are of lower stiffness than those of the other two species. This was anticipated, and it is considered not to influence the conclusions of our study. On the contrary, it allows to cover a broader range of MoE_{dyn} and static MoE values.

Table 2: *Characteristic values for each modulus of elasticity (kN/mm²). The datasets are not constructed so as to be representative of differences between species or countries.*

	NUIG			ENU		
	MoE_L	MoE_G	MoE_{dyn}	MoE_L	MoE_G	MoE_{dyn}
WPCS (Spruce)						
mean	8.05	7.11	8.43	7.52	7.64	9.32
CoV	0.27	0.22	0.18	0.29	0.22	0.22
PSMN (Douglas fir)						
Mean	11.1	11.2	13.3	9.16	9.10	10.8
CoV	0.30	0.24	0.22	0.25	0.20	0.22
WLAD (Larch)						
Mean	10.4	10.2	12.4	9.26	8.76	10.6
CoV	0.23	0.21	0.22	0.25	0.22	0.25

The relationships between the MoE_{dyn} and bending MoE properties are shown in Figure 4. This includes a difference ratio of species by laboratory, so the relevant difference is in the correlation rather than the means or variance. The figure shows that the MoE_{dyn} has a strong relationship with the static moduli of elasticity, stronger with MoE_G, which confirms the suitability of MoE_{dyn} to be used as a reference variable. The figure also shows that MoE_{dyn} values are consistently higher than static MoE. This is a well-known phenomenon reported in many studies [e.g. 13,14,15,16].

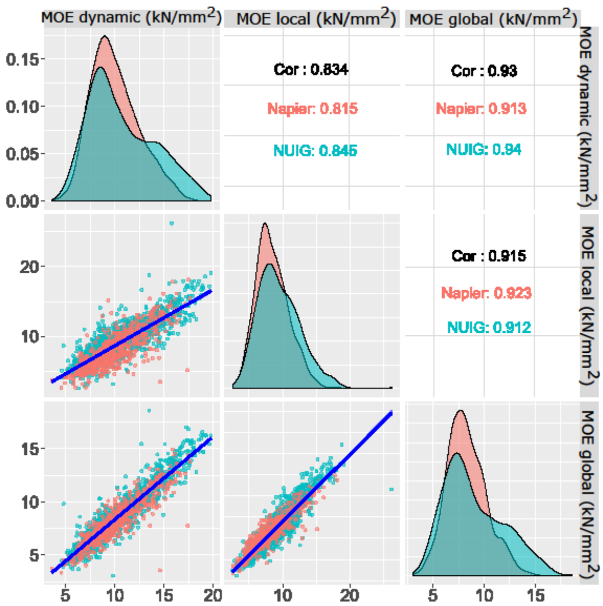

Figure 4: *Pearson correlations between MoE_L, MoE_G and MoE_{dyn} for pieces measured in the NUIG and ENU labs.*

The variation in the relationships between MoE_G and MoE_{dyn} due to the species and the testing machines was examined by conducting an analysis of variance (ANOVA type III) on a General Linear Model (3). The relationship varied significantly by species (p <0.01) and with the test machines (p <0.05). A linear model for the full population of specimens between MoE_{dyn} and MoE_G including species and laboratories as well as their interaction with MoE_{dyn} gave a coefficient of determination $R^2 = 0.87$ (RSE = 0.87), barely improving the prediction power of MOE_{dyn} on its own ($R^2 = 0.86$, RSE = 0.90).

The effect of the test machines changed by species. Table 3 shows (with a 90% confidence interval) that the slopes of the regression lines between MoE_G and MoE_{dyn} change between machines, particularly in Douglas fir and Sitka spruce tested in NUIG. The small dataset of larch tested in NUIG influenced the interval of the slope.

Table 3: *Regression coefficients for 5%-95% confidence interval calculated by bootstrapping for each dataset.*

Study	Intercept	Slope	R^2
PSMN-ENU (n=188)	1.13	0.67	0.83
	1.85	0.74	0.90
PSMN-NUIG (n=384)	-0.45	0.80	0.82
	0.54	0.87	0.88
WLAD-ENU (n=418)	1.25	0.64	0.78
	1.91	0.71	0.87
WLAD-NUIG (n=60)	0.71	0.55	0.55
	3.31	0.74	0.78
WPCS-ENU (n=503)	0.60	0.68	0.70
	1.31	0.76	0.84
WPCS-NUIG (n=472)	-0.19	0.72	0.60
	0.98	0.87	0.69
Equation	MoE_G=Intercept + Slope × MoE_{dyn}		

The changes in the slopes for the given datasets can be seen in Figure 5.

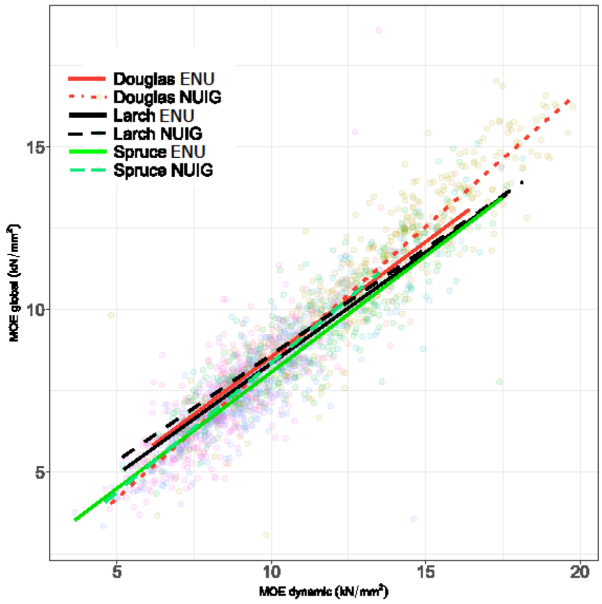

Figure 5. *Relationship MoE_{dyn} – MoE_G by species and machine.*

Following, the relationship between MoE_G and MoE_L was investigated. In the first place, a paired *t*-test showed that the means of MoE_G and MoE_L for both datasets of Douglas fir are not significantly different. However, for Sitka spruce (p<0.05 in ENU and p<0.001 in NUIG) and larch (p<0.001 in ENU and p<0.1 in NUIG) the differences were significant.

The analysis of variance (ANOVA type III) on a General Linear Model between MoE_G and MoE_L determined that both the intercept and slope of the relationship varied with species and machines (p <0.001). Nevertheless, a linear regression between MoE_G and MoE_L including species and test machine as an additional explanatory variable had a negligible effect on the overall fit of the regression (R^2 = 0.86, RSE = 1.06 vs R^2 = 0.84, RSE = 1.14).

Ignoring the influence of species, Figure 6 shows the overall fit of the regression for each test machine. The rate of change between MoE_G and MoE_L changed with the test machine, that is, the test machine influenced the slope of the relationship (p < 0.001) and the intercept (p < 0.001).

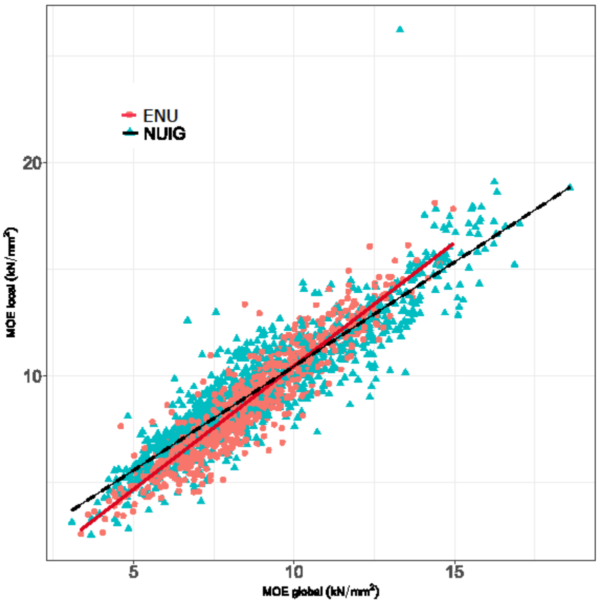

Figure 6. *Linear relationship MoE_G – MoE_L by dataset.*

Table 4 shows a higher intercept using the NUIG test machine (around 2.0 kN/mm²) and the opposite occurs for the rate of change.

Table 4: *Regression coefficients for 5%-95% confidence interval calculated by bootstrapping for each dataset ignoring the difference due to species.*

Laboratory	Intercept	Slope	R^2
NUIG (n=916)	0.49	0.95	0.80
	0.91	1.00	0.86
ENU (n=1109)	-1.46	1.15	0.83
	-1.07	1.19	0.87
Equation	MoE_L = Intercept + Slope × MoE_G		

The regression lines intersect at MoE_G = 10.1 kN/mm², MoE_L = 10.6 kN/mm². More than 80% of the total pieces, and 95% of Sitka spruce, the main species in Ireland and the UK, fall below this point. Thus, it is expected that timber tested in NUIG will provide higher values of local MoE than that tested in ENU, at least for the majority of pieces. How this can impact the timber grading is studied next by species due to the observed influence of those in the relationship between MoE_G and MoE_L.

3.2 INFLUENCE OF TEST MACHINES ON GRADING

Following the model in the European standard EN384, the MoE_G was adjusted to an equivalent "shear free" stiffness (MoE_0) using the linear relationship of Equation (1). The relationship between MoE_0 and MoE_{dyn}, and how the machine used for testing influenced the grading is illustrated by species in Figure 7. In this approach the boards are ranked from the lowest to the highest MoE_{dyn}, and for every board the mean MoE_0 is calculated for all boards with equal or higher MoE_{dyn}. Thus, in this simplified simulation of grading, the first pair of values corresponds with the means of MoE_{dyn} and MoE_0 for the full population, and the last pair of values is the board with the highest MoE_{dyn} and its associated MoE_0 value. As a result of the ranked MoE_{dyn} the mean MoE_{dyn} values increase. Due to the strong relationship between the MoE_{dyn} and the MoE_0 of each board (R^2 = 0.86, RSE = 1.17 kN/mm²) the mean of the latter will also typically increase. Fluctuations can be observed when the number of pieces involved is small because the correlation is not perfect. Figure 7 shows that overall, a population tested with the NUIG machine gave higher mean values of MoE_0 than the ENU machine for the same MoE_{dyn} threshold. For Douglas fir, within the range of mean MoE_{dyn} shared by both machines, there is a systematic difference in the mean values of MoE_0 around 500 N/mm² in favour of the NUIG machine. This must not be understood as the NUIG machine overestimating the measurements, but as not penalising those as much as ENU machine. Differences in larch are initially around 200 N/mm² and they get smaller as the means increase. Sitka spruce was the least stiff species. The means of MoE_0 describes an initial difference of 300 N/mm² that increases considerably at the upper range of values as the number of pieces decreases.

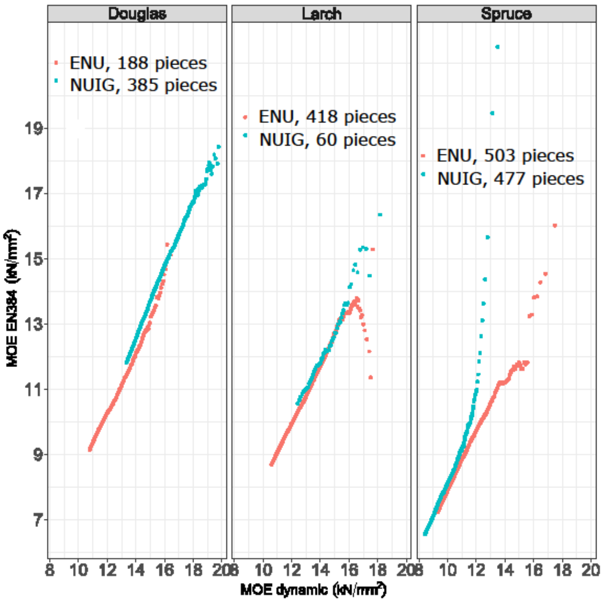

Figure 7. *Comparison of mean MoE_{dyn} vs mean MoE_0.*

For a C16 strength class, a mean MoE_0 of 7.6 kN/mm² is required. For the successive strength classes C18, C20, C22, C24 and C27 the required values are 8,55, 9.025, 9,5, 10.45 and 10.93 kN/mm^2, respectively. For the Sitka spruce tested in NUIG the mean MoE_0 is 6.56 kN/mm^2. Derivation of an empirical equation using the relationship between MoE_G and MoE_L measured for Sitka spruce using the NUIG test machine (Equation (4), $R^2 = 0.82$) gave a mean of 8.05 kN/mm^2. Therefore, the MoE requirement for C16 strength class would not be achieved when using Equation (1), but it would be reached with an empirical equation derived locally. An alternative empirical equation derived using the relationship between MoE_G and MoE_L measured for Sitka spruce using the ENU test machine (Equation (5), $R^2 = 0.80$) and applied to the MoE_G measured at NUIG gives a mean of 6.91 kN/mm^2, still below the C16 requirement. As the requirements increase, for C20 strength class only 16% of the pieces achieve enough MoE_0, 19% using the Equation (5), and 61% using the Equation (4) derived locally.

$$MoE_{0,NUIG,SS} = -0.904 + 1.259 * MoE_G \text{ (kN/mm}^2\text{)} \quad (4)$$

$$MoE_{0,ENU,SS} = -1.533 + 1.186 * MoE_G \text{ (kN/mm}^2\text{)} \quad (5)$$

Figure 8 shows the effect of MoE_0 compared to that from the equations ((4) and (5)) derived locally in this study for Sitka spruce. For the Sitka spruce tested in ENU, the mean MoE_0 is 7.24 kN/mm^2. Applying the locally derived Equation (5), the mean was 7.52 kN/mm^2, enough to grade timber as C16. If Equation (4) was applied the mean was 8.71 kN/mm^2. This overestimation would be a serious concern and rules the equation out to be applied on datasets other than that from which it was derived, which, as it has been shown, safely represents the overall performance of the population.

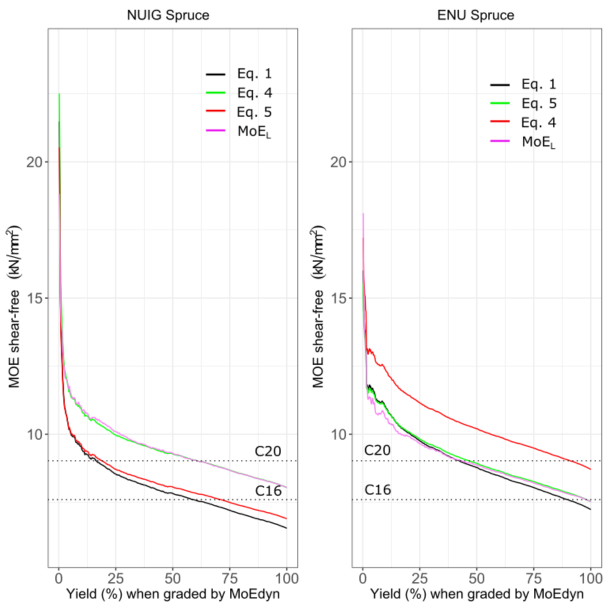

Figure 8. *Comparison of the grading yields of stiffness using MoE_0 and equations derived in this study for Sitka spruce.*

The effect of applying the MoE_0 or the empirical equations obtained here for grading stiffness is summarised in Table 5.

Table 5: *Mean values of MoE (kN/mm^2) for each dataset, applying the empirical equations obtained in the study.*

	NUIG	ENU
WPCS (Spruce)		
$MoE_{0,EN384}$	6.56	7.24
MoE_L	8.05	7.52
$MoE_{0,NUIG,SS}$	8.05	8.71
$MoE_{0,ENU,SS}$	6.98	7.52
PSMN (Douglas fir)		
$MoE_{0, EN384}$	11.8	9.13
MoE_L	11.1	9.16
$MoE_{0,NUIG,DF}$	11.1	8.81
$MoE_{0,ENU,DF}$	11.6	9.16

Similarly, Figure 9 shows the influence on the grading yields of MoE of Douglas fir using different test machines and equations (Equation (6), $R^2 = 0.83$; Equation (7), $R^2 = 0.91$). The datasets tested in NUIG and ENU achieved means of MoE_0 of 11.8 kN/mm^2 (C30 strength class) and 9.13 kN/mm^2 (C20), respectively. For this species the differences between the datasets are larger. It is also observed that for the lower quality of ENU dataset using MoE_0 or the locally derived Equation (7) does not cause important differences on the grading, although those become more apparent as the quality increases. For the higher quality of the NUIG dataset, the mean MoE_0 is 0.7 kN/mm^2 higher than using Equation (6), and the differences increased with the quality. The larch dataset was not examined due to the relatively small population tested in NUIG.

$$MoE_{0,NUIG,DF} = -1.455 + 1.128 * MoE_G \text{ (kN/mm}^2\text{)} \quad (6)$$

$$MoE_{0,ENU,DF} = -1.496 + 1.172 * MoE_G \text{ (kN/mm}^2\text{)} \quad (7)$$

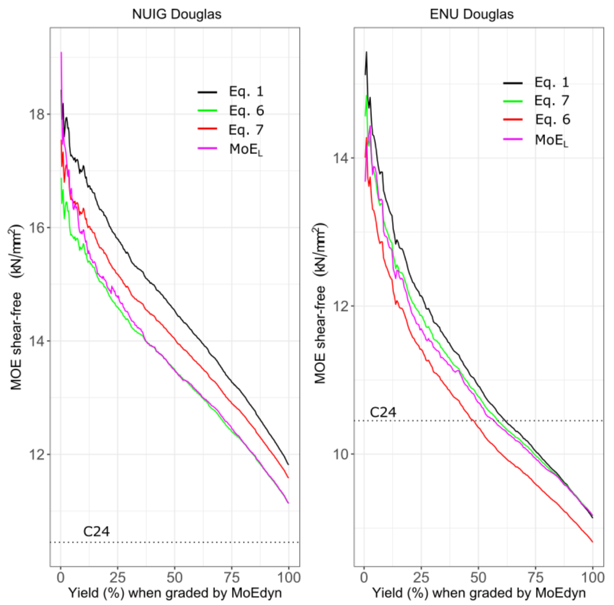

Figure 9. *Comparison of the grading yields of stiffness using MoE_0 and equations derived in this study for Douglas fir. Different scale of y-axis.*

The machine effect in the MoE grading is independent of the equation used to calculate MoE in pure bending from

MoE_G. The adjustment given in EN384 (Equation (1)) gave the highest yields for the MoE grading of Douglas fir, the stiffest species in the study. On the contrary, on Sitka spruce produced the lowest yields for lower quality requirements. For both species, the use of MoE_L or an own derived empirical conversion show very similar results. However, the effect of using equations non-locally derived may vary depending on the quality of the datasets.
In our study, stiffer populations benefit of the conversion given in EN384, which raises questions on the suitability of the equation for very stiff timber. On Sitka spruce, extrapolating equations to the least stiff dataset tested in NUIG penalised the grading. On the contrary, applying the equation derived in NUIG to the ENU dataset largely overestimated the yields. In this regard it is worth remembering that Table 2 showed that the mean MoE_G and MOE_{dyn} of Sitka spruce in NUIG is lower than in ENU, and the opposite occurred for MoE_L. This could be due to the different setup used in NUIG for Sitka spruce compared to the other more comparable setups.
Thus, in the absence of a specifically derived empirical conversion, it is on the safe side to use the equation given in EN384 for grading low stiffness populations of timber, even though it may not fit the dataset well and may underestimate the MoE performance. On the contrary, for high stiffness timber like C30 strength class, the use of MoE_0 as per the standard EN384 could be an advantage for processors.

4 CONCLUSIONS

There exists a machine effect in the MoE measurement that it is transferred to the grading. The effect varies with the quality of the populations and impacts at both board level and population level when grading. At a species level, the effect changed depending on the timber quality, with larger differences for stiffer timber. At a population level, the MoE_G values measured by a more rigid test machine translate into higher mean values, larger as the wood stiffness increases. The differences may not be important for grading to C16 strength class, but they could be critical to improve the yields of high stiffness demand like C24 and above. For populations of strength classes in the range of C14 to C18 where grading is limited by stiffness, the derivation of an specific empirical conversion is strongly recommended based on timber of similar characteristics tested under setups as similar as possible. Extrapolation of models derived from other sources should be avoided as that may affect design safety or reduce the yields. These conclusions are particularly relevant for sawmills grading using output control system, as well as for laboratories assessing timber quality.

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