Investigating the Potential of Strength Grading Green *Eucalyptus grandis* Lumber using Multi-Sensor Technology

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The exploitation of *Eucalyptus grandis* lumber as structural material may take advantage of the finger-jointing and edge-gluing of the boards while they are still wet, so as to reduce the natural susceptibility of the species to warp and split during drying. But the strength grading needed for structural uses, usually performed on dried lumber, should be done before any gluing process, then already in wet condition. Thus, detection and assessment of selected properties of the wet lumber were evaluated. *Eucalyptus grandis* boards were measured by a multi-sensor machine soon after sawing, then dried and measured again. Destructive bending tests were then performed to determine the mechanical properties of the lumber and several predictive models were compared. The determination of non-destructive parameters by the machine was as effective on fresh as on dry lumber. The dynamic modulus of elasticity was the best single predictor of mechanical properties. In contrast, the knot parameter did not show a correlation between strength and stiffness robust enough to justify the efforts to measure it. Wet grading proved to be as effective as dry grading. Therefore, the study suggests that measuring only dynamic modulus of elasticity on fresh lumber is the best approach for the mechanical grading of *Eucalyptus grandis*.

Keywords: Non-destructive measurement; Machine grading; Hardwood; Wet processing

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INTRODUCTION

In South Africa, a small percentage (1%) of the total land area used for commercial forestry is composed of *Pinus* and *Eucalyptus* species (DAFF 2012, 2015). *Pinus* is mainly used for saw logs and *Eucalyptus* for the production of pulp and paper products, wood chips for foreign markets (Chamberlain *et al*. 2005), and a small amount for furniture. Because the demand for saw logs is steadily growing but afforestation is stagnating, a shortage of softwood saw log timber is expected within the next two decades (Crickmay *et al*. 2005). Moreover, the quality of the lumber typically used as structural material is deteriorating due to shorter growth times. The increasing saw log demand has led to an increase in the growth rate by means of breeding programs and silvicultural practices, which has caused an increase in the proportion of juvenile wood entering the processing industry (Wessels *et al*. 2014).

A possible solution to meet the rising need for sawn lumber could be the utilization of rapid-growing plantation hardwoods, *i.e.*, *Eucalyptus* species. Previous research has found that *Eucalyptus grandis* used for sawn lumber provides good mechanical properties (Crafford and Wessels 2016), and other studies have investigated the possibility of producing engineered structural products from *Eucalyptus* (Hague 2013; Franke and Marto 2014). The primary limitation of this resource is its susceptibility to warp and split during drying due to high internal stresses and excessive shrinkage (Yang and Waugh 2001; Malan 2003; Yang 2005; Mugabi *et al*. 2010 and 2011), which can reduce yields.

In recent years, research efforts have been made to address and reduce this problem during processing. Crafford and Wessels (2016) showed the potential of this species for green finger-jointed structural lumber used in roof structures. Green finger-jointing inhibits the boards from end-splitting to a degree. The potential for edge-gluing green boards (un-dried lumber with a high moisture content above the fiber saturation point) to panels before kiln drying was also investigated as an inhibiting factor for warping and splitting behaviors (Pröller *et al*. 2015, 2017; Pröller 2017; Nocetti *et al.* 2017). As the development of certain defects can be minimized or suppressed while the boards are bonded together in panel form, green edge bonding is considered promising for the manufacture of structural products such as laminated products and particularly cross-laminated timber (CLT).

The first step in using lumber for structural products is to perform a mechanical characterization to analyze its performance and provide reliable and proven information on its mechanical properties. It is therefore important to be able to predict the strength and stiffness (modulus of elasticity) properties of dry *Eucalyptus* boards before kiln drying to determine their strength grade, select, and process the green material accordingly. Because the real strength of lumber can only be determined by destructive tests, accurate predictions based on non-destructive parameters, such as density, knots, and dynamic modulus of elasticity, are crucial. In this study, a mechanical characterization of the wood was conducted, followed by an assessment of various parameters regarding their ability to estimate the mechanical properties of the sawn boards, which were combined with predictive models to create a balance between accuracy and simplicity.

There has been a rapid development of multi-sensor devices to improve the mechanical grading of lumber. X-ray technology, 3D laser scanning, optical sensors, laser scattering, acoustic sensors, and optical laser interferometry are some technologies used in the latest mechanical structural grading devices. Mechanical strength grading is a common practice for softwood lumber, but it is not as widely established for hardwood. Some attempts have been made using oak (Riesco Muñoz and Remacha Gete 2012), chestnut (Vega *et al*. 2012), and *Eucalyptus* (Piter *et al*. 2004a). The last study was, however, only based on laboratory measurements. One attempt of machine grading on wet hardwood lumber was performed on chestnut (Nocetti *et al*. 2016), and no research has been published on the relationship between the different wood and mechanical properties of both green and dry *Eucalyptus grandis* lumber grown in South Africa.

The aims of this study were to determine the mechanical properties of kiln-dried sawn *Eucalyptus grandis* lumber and its relationship with non-destructively measured parameters of the board before drying and to evaluate the feasibility of strength grading *Eucalyptus* lumber prior to kiln drying.

EXPERIMENTAL

Material

Over 130 green *Eucalyptus grandis* boards with dimensions of either 2400 mm or 3000 mm x 115 mm x 38 mm were provided by the Merensky Timber sawmill near Tzaneen in Limpopo, South Africa. The material was obtained from the core sections of plantation trees between 20 and 25 years of age. The area where the trees were grown has a sub-tropical climate with an average temperature of 15 °C in the winter and 28 °C during the summer. Rainfall is predominant in mid-summer, between November and March, with an average rainfall of approximately 1230 mm per year. The altitude of the plantations ranges from 900 m to 2000 m above sea level.

Data Collection

Data collection for the green lumber was carried out at the Merensky optimizing dry-mill in Johannesburg (Gauteng, South Africa) by means of several Microtec devices, namely a Goldeneye 506 (multi-sensor board quality scanner capable of determining dimension, density, knot size, and position via 3D laser and X-ray technology) and a ViSCAN (optical laser interferometer) (Bacher 2008).

The Goldeneye 506 determines the exact dimensions and density of the boards as well as the size and position of knots inside the cross sections by means of X-ray sensors (Giudiceandrea 2005). The knot parameter (KN) was calculated by applying an algorithm which combines the position and relative dimension of the knots inside the board.

The ViSCAN device is used to determine the dynamic modulus of elasticity (E_{dyn}) by measuring the natural frequency of vibration along the longitudinal direction of the green boards. The excitation necessary to make the boards vibrate is provided by a steel ball mounted on a spring-retracted piston rod and the frequency is measured by a non-contact laser interferometer. The dynamic modulus of elasticity is calculated according to Eq. 1,

$$E_{dyn} = (4f^2L^2\rho)/10^{12} \tag{1}$$

where f is the natural frequency of vibration in Hz, L is the board length in mm, and ρ the board density as determined by the X-Ray scanning of the Goldeneye 506 in kg/m^3.

The weights and dimensions of the boards were measured manually to calculate moisture content *via* the procedure detailed below and to compare the density to that obtained by the Goldeneye 506.

After completing the data collection for the green boards, the material was sent back to the Merensky sawmill in Tzaneen (Limpopo, South Africa) for kiln drying. Drying was carried out by six-zone progressive kilns manufactured by TF Design (Stellenbosch, South Africa). A medium-temperature drying schedule was followed that allowed the wet lumber to dry to below 12% moisture content over a period of 24 days.

The same mechanical grading procedure used before was repeated with the dried boards, which at the time of testing had dimensions of roughly 2400 mm or 3000 mm x 110 mm x 35 mm.

Once all necessary data were collected, the material was transported to the Department of Forest and Wood Science at Stellenbosch University (Western Cape, South Africa), where the boards were destructively tested to determine their strength and stiffness properties by means of a four-point bending test according to SANS 6122 (2008) using an Instron testing machine (Norwood, MA, USA). The boards were externally supported in two points and loaded in two internal loading, so to divide the span in three equal parts. The specimens were centrally positioned over the test span (random placement of defects), and the load was applied on the center third at a continuous rate of 25 mm/min. The deflection of the boards was measured *via* cross-head movement at the center third of the test span. The static modulus of elasticity was calculated as follows (Eq. 2),

$$E_{stat} = \frac{FL^3}{5.4\,bh^3D} \tag{2}$$

where F is the load increment in N, L is the test span in mm, b is the board thickness in mm, h is the board width in mm, and D is the deflection increment in mm under the increment in load F.

The bending strength was calculated as follows (Eq. 3),

$$f_b = \frac{F_{max}L}{bh^2} \tag{3}$$

where *Fmax* is the maximum load at board failure in N, L is the test span in mm, b is the board thickness, and h is the board width in mm.

Immediately after destructive testing, 50 mm wide samples, free from knots and other wood defects, were prepared to determine their moisture content by gravimetric method according to SANS 1783-1 (2009), and their density by dividing the weight by the volume of the samples. The obtained values are considered representative for the whole boards.

Moisture content at the time of machine grading in wet and dry conditions was calculated from data on the mass of the boards at the time of measurement and mass at a known moisture content in the laboratory.

For the dynamic modulus of elasticity, the dry determinations were adjusted to 12% moisture content, considering a 1% change for every percentage point difference in moisture content; the wet measurements were not adjusted, since the dynamic modulus determined by the natural frequency method remains practically constant above the fiber saturation point (Unterwieser and Schickhofer 2011; Nocetti *et al*. 2015). No adjustments with respect to moisture content were done on laboratory measurements since the standard (SANS 1783-1 2009) recommends to adjust the values of the modulus of elasticity only for specimens with a MC below 10% or above 14%, and the whole sample was in that interval.

Data Analysis

The relationships among the variables and between the measurements in dry and wet conditions of the same property were examined by Pearson correlation coefficients.

Using data from non-destructive testing, multiple linear regressions were used to establish predictive models for the static modulus of elasticity and bending strength. For both models, the main outputs of the machine determinations were included as explanatory variables, namely dynamic modulus of elasticity, density, and knot parameter. To determine which variables were robust enough to include in the final prediction models, the simplest model, including only the dynamic modulus of elasticity, was kept as a reference and the improvement in the explanation of the total variance when including additional variables in the model was verified. The same procedure was repeated to predict stiffness and strength based on non-destructive test data from both dry and wet boards.

Finally, machine strength grading was simulated: the predicted values by the several models were used by a hypothetical machine to assign every single piece of timber to a strength class or reject it, based on thresholds set to the aim. The prediction of the models was compared in terms of the yields (percentage of no-rejected boards) and the characteristic values of the selected boards. The characteristic values were the fifth percentile for bending strength and density and the mean value for modulus of elasticity

RESULTS AND DISCUSSION

Mechanical and Physical Properties of *Eucalyptus grandis*

Table 1 shows the descriptive statistics of the mechanical properties determined in the laboratory and the dynamic modulus of elasticity measured by the grading machine. The moisture content of the boards at the three steps of evaluation (wet and dry for machine measurements and laboratory tests) were also reported. Considering transportation damage and measurement error by the machine or laboratory bending test, only complete data (a total of 122 specimens) were used for the computation of summary statistics and for the following analysis.

Characteristic values are used in the timber industry to assign sawn boards to certain grades and are expressed as statistical properties (*i.e.*, the mean value for stiffness and the 5th percentile for strength); therefore, they can only be determined for a population of specimens. In this study, all tested samples are considered as one population. Names and characteristics values for the structural classes used in South Africa as provided by the national standardization (SANS 10163-1 2003) are reported in Table 2.

The variations in the stiffness and density results were similar to one another and lower than that of the bending strength results, ranging from 13.7% to 16.3%, respectively. In the wet condition, the moisture content of the boards ranged widely from 51% to 150%.

Table 1. Summary Statistics for the Bending Strength, Bending Modulus of Elasticity, and Density Determined in the Laboratory; Moisture Content and Dynamic Modulus of Elasticity Measured in Wet and Dry States

	Bending Strength (MPa)	Static MOE* (MPa)	Density (kg/m^3)	Wet Dynamic MOE* (MPa)	Dry Dynamic MOE* (MPa)	Moisture Content (%)		
						WET*	DRY*	LAB*
Symbol	f_b	E_{stat}	ρ	$E_{dyn,WET}$	$E_{dyn,DRY}$	MC_{wet}	MC_{dry}	MC_{lab}
Mean	42.4	11400	508	11300	13300	83.1	9.9	10.9
SD*	15.4	1900	75	1500	1900	20.5	2.8	1.1
CV* (%)	36.3	16.3	14.7	13.7	14.6	24.7	28.3	10.1
5th perc*	19.3	8100	414	8700	10100	-	-	-

* SD = standard deviation, CV = coefficient of variation, 5th perc = 5th percentile, MOE = modulus of elasticity, WET = wet condition measurements, DRY = dry condition measurements, LAB = measured in the laboratory

In comparing the results of the destructive tests with previous experiments on *Eucalyptus grandis* from South Africa (Crafford and Wessels 2016) and Argentina (Pieter *et al*. 2004b), similar findings were observed, although the latter work had slightly higher density. Overall, the mechanical properties of *Eucalyptus* were more robust compared to the characteristics of South African pine usually used as structural material such as young *Pinus elliottii* × *Pinus caribaea* (Wessels *et al*. 2011) and *Pinus patula* (Dowse and

Wessels 2013; Wessels *et al*. 2014). Specifically, the stiffness values were higher than that observed for pine, which demonstrated a good bending strength, but a too-low modulus of elasticity as required by the grades reported by South African National Standards (SANS 10163-1 2003; Dowse and Wessels 2013; Wessels *et al*. 2014).

Table 2. Strength Classes for Sawn Structural Lumber Using the Characteristic Stresses for Bending Strength, Modulus of Elasticity, and Density Requirements

Grade	Bending strength (MPa)	Modulus of elasticity (MPa)	Modulus of elasticity (MPa)	Density** (kg/m^3)
		Mean	5th percentile*	
S5	11.5	7800	4630	360
S7	15.8	9600	5700	425
S10	23.3	12000	7130	475
* Value from draft version of SANS 10163-1 (2003); ** Value from SANS 1783-2 (2012)				

Relationship Between Properties in Wet and Dry States

The correlation coefficients between the properties measured in the laboratory and the non-destructive measurements conducted by the multi-sensor machine are presented in Table 3. The property that best correlated with bending strength was the static modulus of elasticity. Even if such a correlation was lower than that usually observed for softwood like spruce (Dowse and Wessels 2013) and *Eucalyptus* of Argentinean origin (Piter *et al*. 2004a), it was similar to values observed for other hardwoods like chestnut (Nocetti *et al*. 2016) and South African *Pinus patula* (Dowse and Wessels 2013).

In this study, density correlated moderately with the mechanical properties of *Eucalyptus,* which was similar to that observed by Piter *et al*. (2004a) for the same species. For the non-destructive measurements, the machine was effective in evaluating the density of the lumber. The correlation between the laboratory and machine measurements was very high (r = 0.97). The dynamic modulus of elasticity measured both in dry and wet conditions correlated very well with static modulus (with the highest correlation coefficient) as well as strength and density. The relationship was better than that previously reported for other hardwoods like oak (Kretschmann and Green 1999) and chestnut (Nocetti *et al*. 2016).

In contrast, the knot parameter (KN) was negatively and weakly correlated with bending and stiffness (Table 3).

Table 3. Pearson's Correlation Coefficients between Mechanical and Physical Properties and the Knot Parameter Measured for Green Boards (KN_{WET}) and Dry Boards (KN_{DRY})

	f_b	E_{stat}	ρ (lab)	ρ_{DRY} (scan)	$E_{dyn,WET}$	$E_{dyn,DRY}$	KN_{WET}
E_{stat}	0.66 ***						
ρ (lab)	0.51 ***	0.59 ***					
ρ_{DRY} (scan)	0.53 ***	0.61 ***	0.97 ***				
$E_{dyn,WET}$	0.61 ***	0.89 ***	0.65 ***	0.67 ***			
$E_{dyn,DRY}$	0.60 ***	0.89 ***	0.71 ***	0.72 ***	0.98 ***		
KN_{WET}	-0.34 ***	-0.16 ns	-0.29 **	-0.23 *	-0.12 ns	-0.15 ns	
KN_{DRY}	-0.24 **	-0.21 *	0.06 Ns	0.01 ns	0.11 ns	-0.11 ns	0.82 ***
ns not significant; *significant at 5 % level; **significant at 1 % level; ***significant at 0.1 % level							

The presence and dimension of knots is a fundamental characteristic to take into account in the prediction of the mechanical performance of softwood lumber, but the same is not true for hardwoods: low correlations between several parameters describing knots and bending strength have been reported for *Eucalyptus* (Piter *et al*. 2004a, b), oak (Riesco Muñoz and Remacha Gete 2012), and chestnut (Nocetti *et al*. 2010; Vega *et al*. 2012).

To verify the ability of the machine to quantify the non-destructive parameters on both dry and wet boards, the correlations between the repeated measurements were calculated (Table 3 and Fig. 1).

The dynamic modulus of elasticity measured firstly on wet boards correlated extremely well with the second measurement performed after the drying process. This was partially due to the good repeatability of the machine measurement, but also because the dynamic modulus of elasticity, when determined by the natural frequency of vibration of wood, is independent of the moisture content of the lumber if it is above the fibre saturation point (Unterwieser and Schickhofer 2011; Nocetti *et al*. 2015). Therefore, even if no adjustments are applied, the high variation in moisture content of the wet boards will not affect the determination of the dynamic modulus of elasticity.

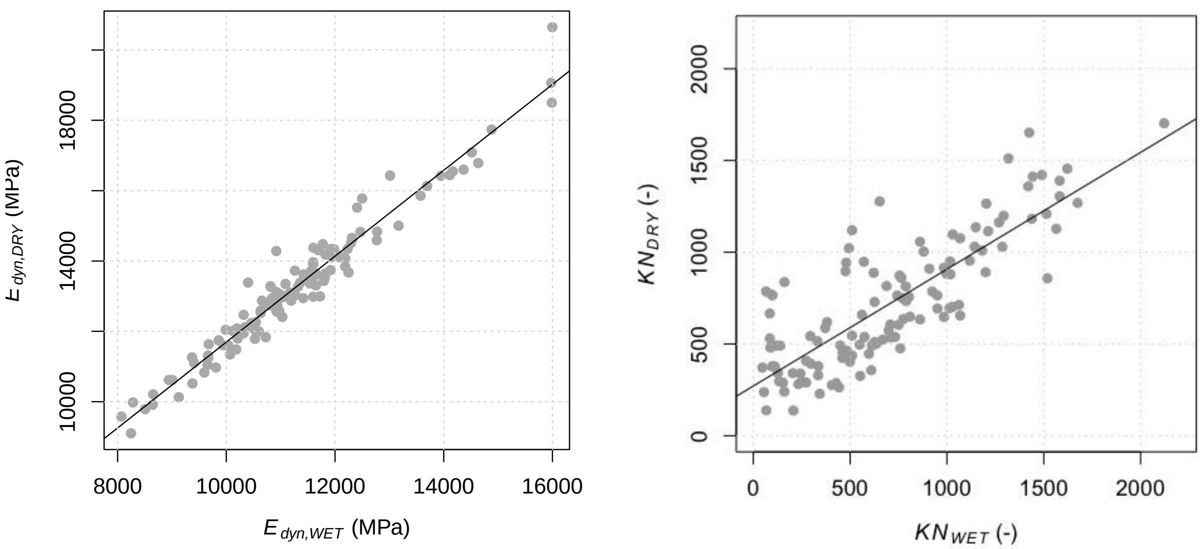

Fig. 1. Correlation plot between dry and wet measurements for dynamic modulus of elasticity (left, $R^2 = 0.96$) and the knot parameter (right, $R^2 = 0.67$) as determined by the machine

The detection of the knots along the boards has shown to be effective both for the measurements on fresh and dry lumber (Fig. 2). The calculation of the knot parameter (see the profile along the length of the piece in the bottom of Fig. 2) was similar for both measurements for most of the specimens (Fig. 1, right).

Some differences between the two evaluations were noticed for wet lumber with a very high moisture content (>120%), for which the differences in density between clear wood and the knot decreased and, even if the detection of the knot position and dimension was still effective, the algorithm returned a smaller value for the knot parameter. Obviously, the algorithm could be adapted to grade very wet lumber, but in this study no changes were made.

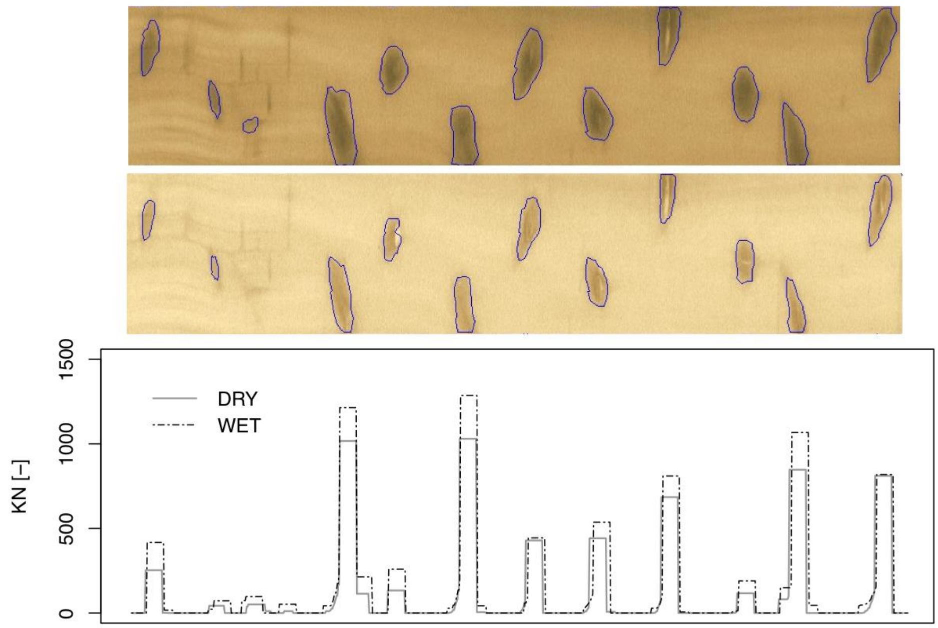

Fig. 2. Knot parameter (KN) as determined by the machine: detection of knots in the wet (top picture, MC = 70.0%) and dry (center picture, MC = 9.3%) board, and profile of the knot parameter (KN) along the board length (bottom)

Prediction of Mechanical Properties by Non-Destructive Evaluation in the Wet and Dry States

Using the non-destructive measurements as independent variables, several models were calculated and compared, aimed at predicting the bending strength and stiffness of the *Eucalyptus* boards.

The best prediction of the static modulus of elasticity was the simple model including the dynamic modulus of elasticity as the explanatory variable (Fig. 3).

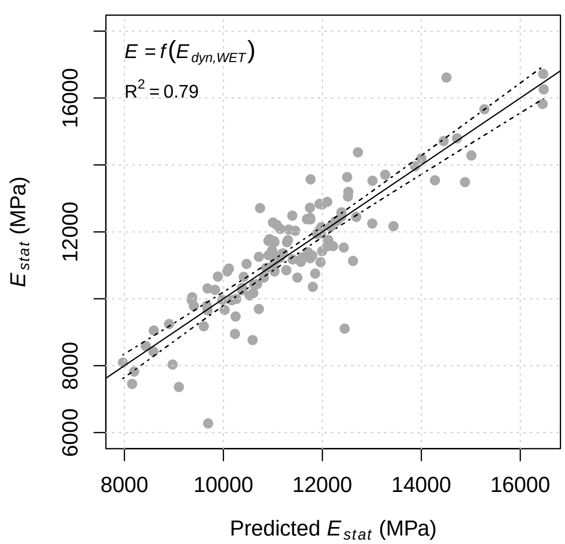

Fig. 3. Static modulus of elasticity *vs.* predicted values from the model including only the dynamic modulus of elasticity measured on wet boards, including the coefficient of determination and the 95% confidence interval

The coefficient of determination was $R^2 = 0.80$ if the dry dynamic modulus was used and $R^2 = 0.79$ if the wet measure was the predictor. Adding other variables such as density and knot parameters did not improve the prediction.

In Table 4, the various models used to predict the bending strength are compared in terms of coefficient of determination and standard error; the significance of the improvement of the prediction by adding an additional variable to the model was also verified. Models 1 and 2, which use the laboratory data as explanatory variables, were compared with the prediction by the machine evaluation.

The modulus of elasticity (both static and dynamic) was clearly the main parameter for predicting strength, with determination coefficients of 0.36 and 0.38 for dry and wet testing, respectively. Density contributed very little to this prediction in the dry evaluation (5% increase in the coefficient of determination), while the inclusion of both density and knot parameters improved the correlation with strength by approximately 14% (Table 4 and Fig. 4).

For the wet evaluation, the inclusion of density as an explanatory variable significantly improved the prediction of bending strength and a further significant improvement was obtained when both density and the knot parameter were included, with a total increase of 11% of the variance explained in respect to the model including simple the dynamic modulus of elasticity (Table 4).

Table 4. Coefficient of Determination (R^2) Values for the Regression Models Estimating the Bending Strength by Laboratory (LAB) and Machine Measurements in Dry and Wet State

Model $f_b = f(x)$					
		x	R^2	SEC (MPa)	Sig.
LAB	[1]	E_{stat}	0.44	11.6	(ref)
	[2]	$E_{stat} + \rho$ (lab)	0.46	11.3	*
DRY	[3]	E_{dyn}	0.36	12.3	(ref)
	[4]	$E_{dyn} + \rho$ (scan)	0.38	12.1	ns
	[5]	E_{dyn} + KN	0.39[1]	12.0	*
	[6]	$E_{dyn} + \rho$ (scan) + KN	0.41	11.8	**
WET	[7]	E_{dyn}	0.38	12.2	(ref)
	[8]	$E_{dyn} + \rho$ (scan)	0.48	11.1	***
	[9]	E_{dyn} + KN	0.46[1]	11.3	***
	[10]	$E_{dyn} + \rho$ (scan) + KN	0.49[2]	11.0	***

[1] Not significantly different from the model $E_{dyn} + \rho$
[2] significantly different at 5% level from the model $E_{dyn} + \rho$
ns not significant; *significant at 5 % level; **significant at 1 % level; ***significant at 0.1 % level
SEC = standard error of calibration; Sig = significance of the difference in respect to the estimation with only the modulus of elasticity (ref); other symbols explained in Table 1

In both evaluations, the addition of two or more independent variables generally resulted in better correlations with strength than when considering them individually, but the improvement in the prediction was not such to justify the construction of a more complex predictive model than the simple use of E_{dyn}. Similar results were concluded in previous studies on hardwoods such as *Eucalyptus* from Argentina, where Piter *et al*. (2004a) found that the highest coefficient of determination for the prediction of strength was obtained with only modulus of elasticity and a slight improvement with the inclusion of knots, and chestnut and oak, where both Vega *et al*. (2012) and Riesco Muñoz and

Remacha Gete (2012), respectively, considered the use of knot parameters not justifiable for predicting strength, but developed a model based only on modulus of elasticity as the predictor variable.

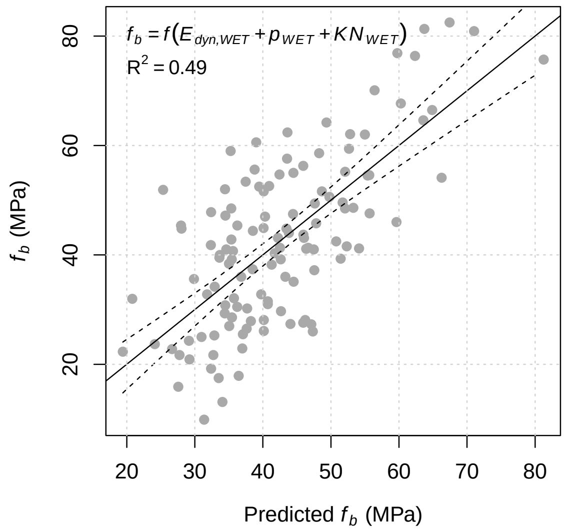

Fig. 4. Bending strength *vs.* predicted values from model 10, including the coefficient of determination and the 95% confidence interval

Wet and Dry Machine Grading

A very simple simulation of machine grading was done assuming possible thresholds of a grading parameter to be used by the machine to sort the lumber. The 5th percentile of bending strength and the mean value of modulus of elasticity were used as required properties for the assignment of the strength class.

The simulations were performed using the simplest grading parameter, *i.e.* only dynamic modulus of elasticity, and the best models to predict the bending strength for both dry and wet evaluations, *i.e.* model n. 6 and model n. 10 of Table 3, respectively. The number of samples tested was not enough to grade more than one class at a time.

First, a simulation was performed to grade the boards in the stress grade S10 according to SANS 10163-1 (2003) (Table 2); the results are reported in Table 5. The S10 class was selected because, as already stated, all ungraded boards fulfilled the requirements for class S7. On the contrary, the S10 class did not seem very efficient for *Eucalyptus* lumber, since the requirements of the class were fulfilled regarding the bending strength (*Eucalyptus* had a bending strength far higher than the requirement) and the modulus of elasticity, which was the limiting factor for grading; while the 5th percentile of density achieved was far lower than that required by the class.

Crafford and Wessels (2016) previously suggested creating a different table of characteristics values and grades more suitable for this species. Therefore, another attempt was made with a more suitable stress grade with the following characteristics: a bending strength (5th percentile) greater than or equal to 20 MPa, a mean modulus of elasticity of 11000 MPa, and a 5th percentile of density greater than or equal to 400 kg/m^3. The results of this second simulation are reported in Table 6.

Comparing the two simulations, it is evident that only dynamic modulus of elasticity used as the grading parameter was as effective as more complex models, especially when grading the S10 class, for which the stiffness was the limiting factor. When the strength was the limiting factor (Table 6), the predictive models for strength reached slightly higher yields compared to only using E_{dyn}.

Again, evaluating the results of the grading simulation in terms of characteristic values and yields reached, it could be observed that both wet and dry grading led to similar results, proving the feasibility and the efficacy of mechanically grading fresh *Eucalyptus grandis* lumber.

Table 5. Thresholds of Grading Parameters, Characteristics Values for Bending Strength (F_b), Static Modulus of Elasticity (E_{stat}), and Density (ρ), and Yields for the Structural Class S10[1], Sorted Using a Single Variable (E_{dyn}) or Predictive Models[2]

Grading Parameter (GP)	Threshold	Characteristic Value			Yield
	(MPa)	f_b (MPa)	E_{stat} (MPa)	ρ (kg/m³)	(%)
DRY E_{dyn}	11800	24.7	12000	426	79.5
WET E_{dyn}	10200	25.4	12000	426	78.7
Model [6], DRY E_{dyn} + ρ (scan) + *KN*	34.7	24.7	12000	425	77.9
Model [10], WET E_{dyn} + ρ (scan) + *KN*	34.1	26.1	12000	419	79.5

[1] according to SANS 10163-1 (2003)

[2] according to Table 4

Table 6. Thresholds of Grading Parameters, Characteristics Values for Bending Strength (f_m), Static Modulus of Elasticity (E_{stat}), and Density (ρ), and Yields for a Hypothetical Structural Class with 20 MPa of Characteristic Strength and 11000 MPa of Mean Modulus of Elasticity[1]

Grading Parameter (GP)	Threshold	Characteristic Value			Yield
	(MPa)	f_b (MPa)	E_{stat} (MPa)	ρ (kg/m³)	(%)
DRY E_{dyn}	11000	20.0	11700	426	90.2
WET E_{dyn}	9100	20.3	11700	423	93.4
Model [6], DRY E_{dyn} + ρ (scan) + *KN*	26.2	20.6	11600	420	95.9
Model [10], WET E_{dyn} + ρ (scan) + *KN*	27.6	20.5	11600	420	95.1

[1] sorted using a single variable (E_{dyn}) or predictive models according to Table 4

CONCLUSIONS

1. The *Eucalyptus grandis* boards tested in this study had very good mechanical properties, especially when compared to South African pine, currently used as the primary structural material in South Africa.
2. The real chance to use this resource as a structural product is subjected to the prerequisite of being mechanically graded, so that the strength and stiffness characteristics of this lumber can be well defined and guaranteed. Here, the machine grading of *Eucalyptus* lumber has been shown to be not only possible, but also efficient, highlighting, however, the need to define new stress grades more suitable for this lumber than present grades reported in the South African standard. The strength class S10 seemed to be the most suitable to describe this assortment, but the requirement for density was not fulfilled and, at the same time, a lower requirement for stiffness could lead to a better exploitation of the material.

3. The option of stress grading the lumber in wet conditions could lead to new processes aimed to limit warping and splitting during the drying phase, delivering a product with fewer defects and therefore higher yields. Wet grading proved to be as effective as dry grading and the prediction of the mechanical performance of the lumber was comparable between the dry and wet conditions.
4. Among the non-destructive parameters available to grade lumber, this study found that the dynamic modulus of elasticity was the best single predictor of mechanical properties. On the contrary, the knot parameter did not show a correlation with strength and stiffness high enough to justify the efforts of also measuring this parameter during grading.
5. Measuring only the dynamic modulus of elasticity on fresh lumber was the best solution for the mechanical grading of *Eucalyptus*. It was shown to be effective when compared to more complex models and, more importantly, it does not need adjustments for moisture content above the fibre saturation point, information that is hard to acquire practically in practice.
6. Finally, the samples used in the present study were not enough to verify further potential developments of the machine grading of wet *Eucalyptus grandis*; for example, the possibility to grade multiple classes simultaneously. Further analyses are necessary using a more samples to confirm the present outcomes and to expand the possibilities of the technique explored here.

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