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# An innovative method based on grain angle measurement to sort veneer and predict mechanical properties of beech laminated veneer lumber

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## Abstract

This study proposes an innovative model based on local grain angle measurements to predict the modulus of elasticity of LVL made from beech. It includes a veneers sorting method industrially compatible thanks to its low computational time. For this study 41 LVL panels were prepared from 123 beech sheets of veneers. Local grain angle was obtained with a two dimensional scanner and veneer density was measured. Several models based on these measurements have been developed and their ability to predict the modulus of elasticity of LVL panels have been compared. The model based only on local grain angle measurements have been proven more efficient than models taking into account the veneer density. The proposed method can be used to sort veneer during the peeling process and grade the production of LVL panels to optimize their mechanical properties even for low-quality veneer.

*Keywords:* Laminated Veneer Lumber, grain angle, mechanical properties, beech, grading

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<sup>1</sup> **List of main symbols :**

$\rho_{veneer}$	Veneer density
$\theta(x, y)$	Local grain angle
$E_{veneer}(x, y)$	Local modulus of elasticity of veneer
$\bar{E}_{veneer}$	Averaged local modulus of elasticity of veneer
$E_{glob,exp}$	Global modulus of elasticity assessed by static bending
$E_{ply}(x, y)$	Local modulus of elasticity of veneer with variables parameters
$E_{mean}(x)$	Averaged local modulus of elasticity along the width of veneer
$E_{glob,mod}(\rho)$	MOE calc. on basis of the proposed model taking into account only the density
$E_{glob,mod}(GA)$	MOE calc. on basis of the proposed model taking into account only the grain angle
$E_{glob,mod}(\rho + GA)$	MOE calc. on basis of the proposed model taking into account both the density and grain angle
$\rho_{panels}$	Panels density
$\bar{E}_{panel}$	Average of $E_{veneer}(x, y)$ of the three constitutive plies
$\bar{E}_{panel-opti}$	Average of $E_{ply}(x, y)$ of the three constitutive plies with optimal parameters
$\bar{\theta}_{abs,veneer}$	Average value of local grain angle in absolute value

### 3 1. Introduction

4 In recent years, interest in the use of beech as a raw material in engineered  
5 wood products for structural purpose has increased in Europe, particularly  
6 in France and Germany, where these renewable resources are available and  
7 not used to their fullest extent. Laminated veneer lumber (LVL) is made  
8 from rotary peeled veneers that have been dried and then glued together.  
9 The grain direction of the layers is mainly oriented in the same direction and  
10 parallel to its length [1]. This product has exhibited superior mechanical  
11 properties in axial bending tests compared to solid wood even when man-  
12 ufactured from lower-grade logs [2, 3]. In LVL, the defects are randomly  
13 distributed throughout the cross-section, which prevents the concentration  
14 of stresses at specific locations. Moreover, using low-grade veneers in the  
15 inner plies can reduce the processing costs without significant decrease in  
16 mechanical properties. Furthermore, the aesthetic value of the final product  
17 is conserved by using free-defect veneers only for visible sides. This approach  
18 is well known for drawing full benefit from second quality wood.

19 The mechanical properties of LVL can be affected by several factors such  
20 as juvenile wood [4, 5], jointing method [6], lathe checks [7, 8], load direction  
21 [9, 10], veneer thickness [11] or silvicultural practice [12].

22 To predict the mechanical properties of LVL some non-destructive test-  
23 ing (NDT) methods were studied in the literature to evaluate the bending  
24 properties. A study on red maple[13] showed that the flexural properties of  
25 LVL can be predicted using ultrasonic method and suggested that the per-  
26 formance of LVL can potentially be enhanced through ultrasonic rating of  
27 individual veneer sheets. The same conclusions have been made in a study



28 for LVL made of *Schizolobium parahayba* [14]. Another study conducted  
29 on southern pine [15] used ultrasonic method and transverse vibration and  
30 showed that the prediction of the bending stiffness using these methods is  
31 less accurate and reliable for LVL compared to solid wood. Pu and Tang [15]  
32 also found a significant effect of veneer grade on the modulus of elasticity  
33 (MOE) of LVL. The efficiency of ultrasonic methods for two different species  
34 has also been discussed by de Souza *et al.* [16] and it has been shown that  
35 the correlation with the MOE was significant for *Pinus kesiya* and that there  
36 was no correlation for *Pinus oocarpa*.

37 The wood material presents a very high variability arising from several  
38 factors. In particular, many studies have shown the existing correlation be-  
39 tween density and mechanical properties [17, 18, 19] of sawn timber.

40 For clear wood in general, the MOE in fibers direction can be considered  
41 to depend on density and microfibril angle (MFA) [20]. However, beech  
42 wood is a very homogeneous specie regarding the density: its coefficient  
43 of variation (CV) can vary between 4% and 6 % only [21, 22]. Therefore,  
44 the level of determination of MOE variation which have a CV up to 16%  
45 [22], by density is expected to be low. The variation in specific modulus  
46 (MOE divided by the density) due to tree growth (juvility, ring width,  
47 tree slenderness, reaction wood...) is on the contrary similar to other species  
48 and driven by MFA variations.

49 At the timber scale, several other studies [23, 24, 3] report the same  
50 tendencies regarding the variation of density (CV from 5% to 6%). More  
51 than 1800 timber beams of beech were characterized in [23], the coefficient  
52 variation of MOE was found to be up to 20% (mean value equal to 14 100

53 MPa) for a coefficient variation of density equal to 6% (mean value equal to  
54  $670 \text{ kg.m}^{-3}$ ). Another study on compression and tension properties of beech  
55 lamination [24] stated that due to its low variation (CV of 5%), density  
56 could not contribute significantly to the strength and stiffness prediction.  
57 This study also showed the poor correlation existing between density and  
58 modulus of elasticity in both tension and compression tests, with a coefficient  
59 of determination found between the density and the modulus of elasticity  
60 lower than 0.06.

61 For beech LVL, the variation of density according to [3] is also low (CV  
62 lower than 5%). In addition, the authors didn't even tried to grade the  
63 veneers according to density based on previous study [25] stating that there  
64 were no relationship between density and strength properties for beech wood.

65 Moreover, local singularities such as knots and grain angle have a strong  
66 influence on the mechanical properties. Indeed, the authors of [24] finally  
67 concluded that strength and stiffness are mainly determined by the knot  
68 area ratio. Several studies have focused on the measurement of the local grain  
69 angle on timber [26, 27, 28]. The potential of the grain angle measurements  
70 has also been studied for strength grading of timber and it has already proven  
71 to be efficient to predict mechanical properties [29, 30, 31, 32]. Other studies  
72 [33, 34] have also shown the potential of grain angle measurements to predict  
73 mechanical properties of glulam beam made of spruce. To the best knowledge  
74 of the authors there are no investigations carried out on local grain angle  
75 measurement to predict LVL mechanical properties.

76 The main purpose of the present study is to develop a method based on  
77 grain angle measurement to predict the modulus of elasticity of LVL made

78 of beech. The second goal is to assess the efficiency of local grain angle  
79 measurements to grade beech LVL.

## 80 **2. Materials and methods**

### 81 *2.1. Veneers production*

82 Two green logs of beech from two different trees (*Fagus Sylvatica L.*)  
83 were selected from the plantation site of Cluny (Burgundy, France) for their  
84 high knotiness. They were soaked at 60°C for 24 hours and then rotary  
85 peeled using a light packaging scale lathe (SEM S500 - knife length 900 mm)  
86 equipped with an angular pressure bar. The veneer's thickness was set to 2  
87 mm and the compression rate was 5% of veneer thickness (a gap of 1.9 mm  
88 between cutting face and pressure bar nose). Subsequently the veneers were  
89 dried in a vacuum dryer with heating plates to limit waviness and to reach  
90 about 12% moisture content. Afterward, dried veneers were cut to 600 ×  
91 75 mm<sup>2</sup> and conditioned in a climatic chamber for 72 h at a temperature  
92 of 20 °C and 65% of relative humidity. After conditioning, each veneer was  
93 weighed to obtain their average specific density  $\rho_{veneer}$ . In total, 123 veneers  
94 were prepared for this study.

### 95 *2.2. Grain angle measurement*

96 Each veneer sheet was characterized with an optical scanner designed  
97 to measure the local grain angle (BobiScan, LaBoMaP). The grain angle is  
98 measured by projecting a line of laser spots on the surface of the veneer.  
99 As a result of wood anisotropic light diffusion properties, an elliptic pattern  
100 oriented parallel to the projection of the fibers axis can be observed on veneer

101 surface. The grain angle can be obtained with Principal Component Analysis  
 102 applied on each ellipse binarized image. The grain angle evolution over the  
 103 whole veneer surface is obtained by illuminating the surface with several  
 104 laser spots along a line (Figure 1 a). The grain angle measurement has been  
 105 conducted only on one face of each veneer (it has been considered that the  
 106 grain angle is the same through the section since the thickness is only 2  
 107 mm). An example of the grain angle measurement is shown in Figure 1 (b)  
 108 where the resolution is 1 mm in x direction and 5 mm in y direction. As  
 109 a final step, a linear interpolation of the raw data was conducted to obtain  
 110 a regular grid (Figure 1 (c)). This accurate technique allows to observe the  
 111 strong deviations of the fibre direction around knots.

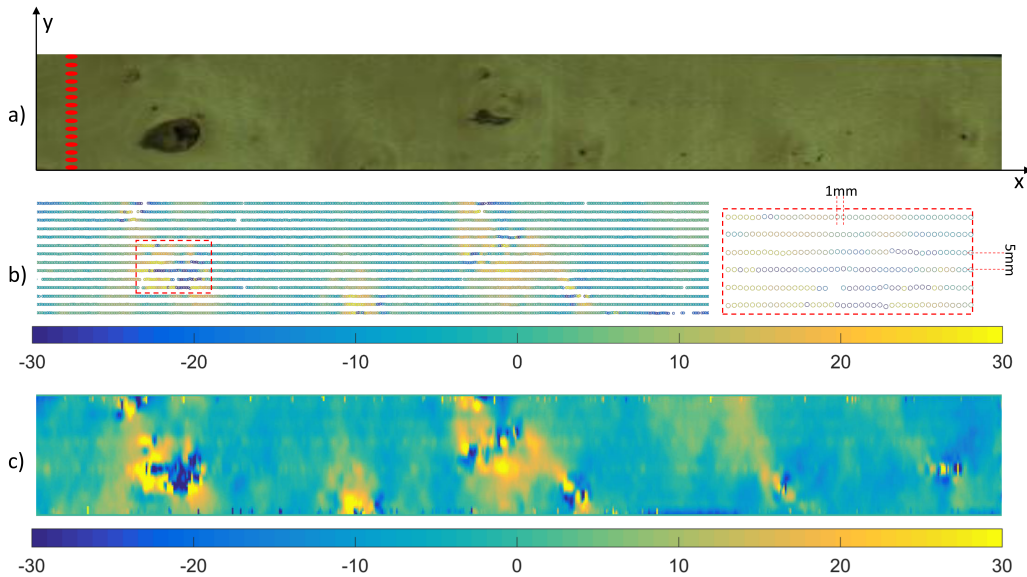


Figure 1: Local grain angle measurement: a) photography, b) raw data c) interpolated data  $\theta(x, y)$  (Angles are represented in  $^{\circ}$ )

112 *2.3. LVL panel manufacturing*

113 The 41 three plies LVL panels were prepared with dimensions  $6 \times 75 \times$   
 114  $600 \text{ mm}^3$  out of 123 veneer sheets. A commercial Polyvinyl acetate (PVAc)  
 115 formulation (0892 100, Wurth) with a spread rate of approximately  $150 \text{ g/m}^2$   
 116 was used. The panels were pressed in a hydraulic press at 3 bars. To max-  
 117 imize the panels mechanical properties variability, the veneers were sorted  
 118 according to the grain angle measurement  $\theta(x, y)$  ( $^\circ$ ) and their density  $\rho_{veneer}$   
 119 ( $\text{kg/m}^3$ ); this variability maximization is described below.

120 For each veneer, a local modulus of elasticity  $E_{veneer}(x, y)$  (MPa) was  
 121 calculated using Equation 1.

$$E_{veneer}(x, y) = (E_0 \left(\frac{\rho_{veneer}}{1000}\right)^{n_\rho}) \frac{k}{\sin^n(\theta(x, y)) + k \cos^n(\theta(x, y))} \quad (1)$$

122 This equation is based on the relationships exhibited in [35] for the mod-  
 123 ulus regarding the density ( $E_0 = 16\,500 \text{ MPa}$  and  $n_\rho = 0.7$  for hardwood).  
 124 The modulus on a given density is multiplied by the Hankinson formula [35].  
 125 The  $k$  parameter represents the ratio between the modulus of elasticity per-  
 126 pendicular to the grain and the modulus of elasticity parallel to the grain  
 127 and has been taken equal to  $\frac{1}{15}$  according to EN 338 [36] and  $n$  has been  
 128 taken equal to 2.

129 Finally, an average modulus of elasticity ( $\bar{E}_{veneer}$ ) was computed for each  
 130 veneer using Equation 2.

$$\bar{E}_{veneer} = \frac{\sum_{x=1}^{n_x} \sum_{y=1}^{n_y} E_{veneer}(x, y)}{n_x n_y} \quad (2)$$

131 The variables  $n_x$  and  $n_y$  respectively represent the number of pixels in  $x$   
 132 and  $y$  direction. Subsequently, veneers were grouped by 3 in ascending order

133 according to  $\bar{E}_{veneer}$  to form the three-ply panels. This process is presented  
 134 in Figure 2.

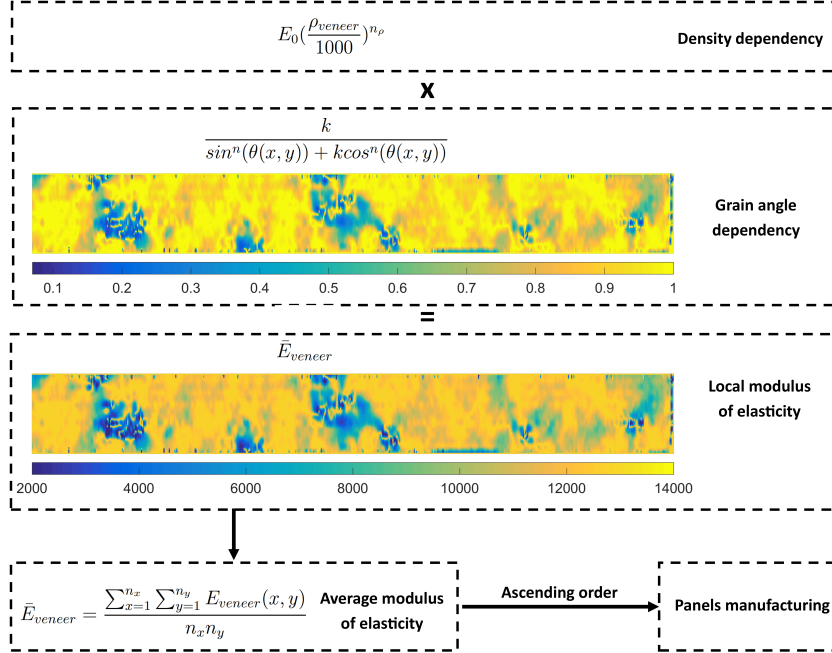


Figure 2: Overview of veneers sorting and panels manufacturing process

#### 135 2.4. Mechanical testing

136 Prior to mechanical testing, all panels were conditioned in a climatic  
 137 chamber for 72 h at a temperature of 20 °C and 65% relative humidity. The  
 138 panels were tested in four-points bending test as shown in Figure 3. The  
 139 global modulus of elasticity was calculated according to Equation 3, where  $h$   
 140 and  $b$  are respectively the beam thickness and depth,  $a$  is equal to 143 mm,  
 141  $l$  is the span,  $F_2 - F_1$  is an increment of load (N) on the linear regression

142 (on the load vs. displacement curve), and  $w_2 - w_1$  is the increment of global  
 143 displacement (mm) corresponding to the load increment  $F_2 - F_1$ .

$$E_{glob,exp} = \frac{3al^2 - 4a^3}{4bh^3 \frac{w_2 - w_1}{F_2 - F_1}} \quad (3)$$

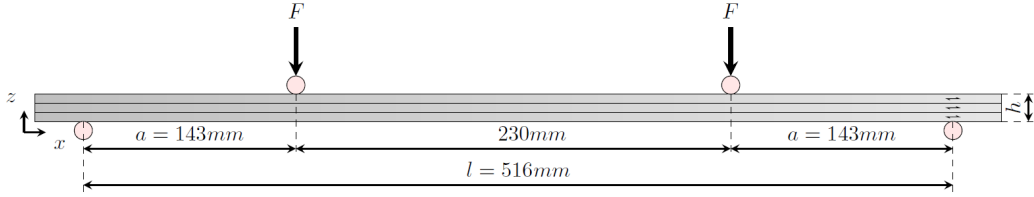


Figure 3: LVL mechanical test setup in 4 points-bending

144 *2.5. Analytical models: prediction of the LVL mechanical properties*

145 In this section, three models based on veneer density, local grain angle  
 146 measurements or a combination of both are presented and their ability to  
 147 predict the modulus of elasticity of LVL panels are compared.

148 *2.5.1. Estimation of the global modulus of elasticity*

149 The first step is to assign a modulus of elasticity  $E_{ply}(x, y)$  to each veneer  
 150 constituting a ply of the LVL panel. The difference between the three models  
 151 rely on the calculation of  $E_{ply}(x, y)$ . For the model based only on the veneer  
 152 density,  $E_{ply}(x, y)$  is calculated using Equation 4. Equation 5 and 6 are used  
 153 for the models using only local grain measurements and a combination of  
 154 both density and grain angle respectively.

$$E_{ply}(x, y) = E_0 \times \left( \frac{\rho_{veneer}}{1000} \right)^{n_\rho} : Density \quad (4)$$

$$E_{ply}(x, y) = E_0 \times \frac{k}{\sin^n(\theta(x, y)) + k \times \cos^n(\theta(x, y))} : \text{Grain angle} \quad (5)$$

$$E_{ply}(x, y) = (E_0 \times (\frac{\rho_{veneer}}{1000})^{n_\rho}) \times \frac{k}{\sin^n(\theta(x, y)) + k \times \cos^n(\theta(x, y))} : \text{Grain angle \& Density} \quad (6)$$

155 The parameter  $E_0$  is a constant representing the modulus of elasticity  
 156 parallel to the grain,  $n_\rho$  a constant,  $k$  the ratio between  $E_0$  and  $E_{90}$  and  $n$  a  
 157 constant. The parameters in these equation are the same as in Equation 1,  
 158 but in this part their values are changing (see Table 1).

159 In the second step  $E_{ply}(x, y)$  was averaged along the y-direction to obtain  
 160 a profile  $E_{mean}(x)$  of the modulus of elasticity along the x-direction for each  
 161 LVL ply. Using these profiles, an effective bending stiffness  $(EI)_{eff}$  was  
 162 calculated for each section along the x-direction of the LVL panels, according  
 163 to the Equation 7.

$$(EI)_{eff}(x) = \sum_{ply=1}^{n_{ply}=3} (E_{mean,ply}(x)I_{ply} + E_{mean,ply}(x)A_{ply}d_{ply}(x)^2) \quad (7)$$

164 Where  $A_{ply}$ ,  $I_{ply}$  and  $d_{ply}(x)$  are respectively: the area, the second mo-  
 165 ment of area, and the distance from the neutral fibre of each element at a  
 166 given x position.  $n_{ply}$  is the total number of plies in z direction.

167 In this section, the deflection at mid-span in the case of a four point  
 168 bending test ( $v(\frac{l}{2})$ ) of the modeled panels is calculated to obtain  $E_{glob,mod}$   
 169 which can be assimilated to an equivalent of  $E_{glob,exp}$ . The deflection at



170 mid-span ( $v(\frac{l}{2})$ ) of the modeled panels can be calculated using the Müller-  
 171 Breslau's principle (see Equation 8).

$$v(\frac{l}{2}) = \sum_{i=1}^{n_x} \frac{M_{f,i} M_{v,i}}{(EI)_{eff,i}} \Delta x \quad (8)$$

172  $M_f$  is the bending moment during a 4-points bending test,  $M_v$  is the  
 173 bending moment induced by an unitary load at midspan,  $(EI)_{eff}$  is the  
 174 effective bending stiffness calculated previously which is dependent of the  
 175 local modulus of elasticity,  $n_x$  is the number of elements along x direction,  
 176 and  $\Delta x=1$  mm corresponds to the resolution of the images along x direction.

177 The modulus of elasticity was calculated according to the beam theory  
 178 in 4 point bending using Equation 9.

$$E_{glob,mod} = \frac{3al^2 - 4a^3}{4bh^3 \frac{v(\frac{l}{2})}{F}} \quad (9)$$

179  $F$  is the load which induced the previous bending momentum  $M_f$ ,  $l$  is  
 180 the span, and the mid-span deflection term  $v(\frac{l}{2})$  is the one calculated by  
 181 Equation 8.  $a$ ,  $b$  and  $h$  are the same than in Equation 3. The different steps  
 182 described above, where only the grain angle is considered, are resumed in  
 183 Figure 4.

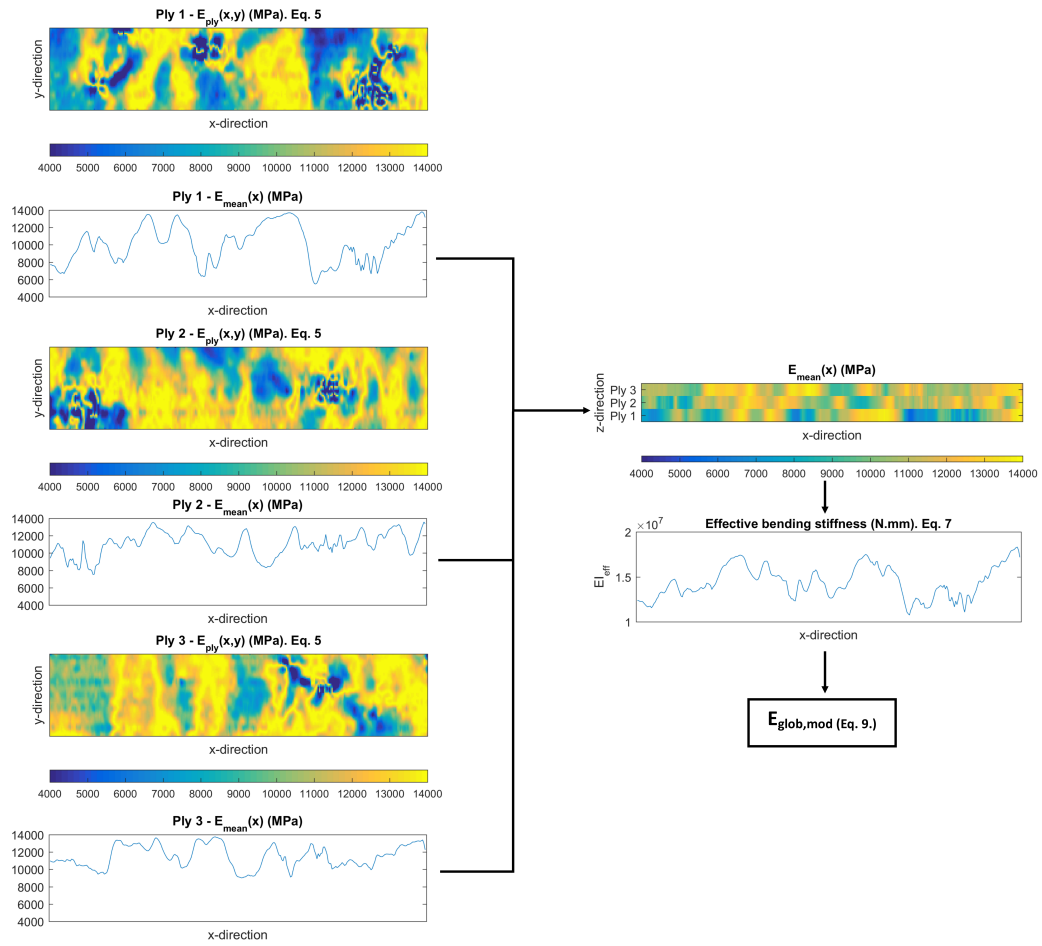


Figure 4: Principle of the analytical modeling in the case Equation 5 is used for  $E_{ply}(x, y)$  calculation

184 *2.5.2. Analytical models parameters optimization*

185 The final predicted global modulus of elasticity depends on different pa-  
 186 rameters:  $E_0$ ,  $n_\rho$ ,  $k$  and  $n$ . Different values for these parameters can be  
 187 found in the literature. In this study the relevant parameters were computed  
 188 by minimizing the root mean square error (RMSE) between  $E_{glob,mod}$  and  
 189  $E_{glob,exp}$ . Each possible  $E_{glob,mod}$  has been calculated using every possible set  
 190 of parameters described in Table 1.  $E_{glob,mod}(\rho)$  is calculated using Equation  
 191 4,  $E_{glob,mod}(GA)$  using Equation 5 and  $E_{glob,mod}(\rho + GA)$  with Equation 6.

Parameters	$E_{glob,mod}(\rho)$				$E_{glob,mod}(GA)$				$E_{glob,mod}(\rho + GA)$			
	Min	Step	Max	N	Min	Step	Max	N	Min	Step	Max	N
$E_0$	8 000	500	22 000	29	8 000	500	22 000	29	8 000	500	22 000	29
$n_\rho$	0.1	0.1	2	20	-	-	-	-	0.1	0.1	2	20
$k$	-	-	-	-	0.01	0.005	0.07	13	0.01	0.005	0.07	13
$n$	-	-	-	-	1.5	0.05	2.5	21	1.5	0.05	2.5	21
	Total scenarios			580	Total scenarios			7 917	Total scenarios			158 340

Table 1: Bounds, step size and number of scenario tested for each parameter of each model

192 **3. Results and discussions**

193 *3.1. Veneers physical properties*

194 Descriptive statistics of measured and calculated properties of the differ-  
 195 ent veneers are presented in Table 2. The coefficient of variation of the veneer  
 196 density  $\rho_{veneer}$  is equal to 5.3% which is really close to what can be found in  
 197 the literature. The average local modulus of elasticity  $\bar{E}_{veneer}$  (calculated us-  
 198 ing Equation 2 i.e with parameters from the literature) seems to have a very  
 199 low coefficient of variation (7.6%) in comparison with what could be expected

200 from the literature. This could be explained by the fact that the parameters  
 201 used in the calculation of  $\bar{E}_{veneer}$  have been computed for hardwood and not  
 202 in particular for beech or simply by the fact that this parameter is a simple  
 203 average and do not represent a modulus of elasticity. The mean absolute value  
 204 of the local grain angle  $\bar{\theta}_{abs,veneer}$  have been computed, its range goes from  
 205 1.9 ° to 11.9 °. In addition, the coefficient of correlation R between  $\bar{\theta}_{abs,veneer}$   
 206 and  $\bar{E}_{veneer}$  is equal to -0.88 showing the negative influence of the grain angle  
 207 on  $\bar{E}_{veneer}$ . Finally, the thickness  $h$  of individual veneer is also described,  
 208 the mean is really close to the target and the coefficient of variation is very  
 209 low (CV = 3.3%).

	Min	Mean	Max	StD	CV(%)	R <sup>2</sup> ( <i>p-value</i> )	$\bar{E}_{veneer}$	$\bar{\theta}_{abs,veneer}$
$\rho_{veneer}$	588.9	670.9	761.5	35.6	5.3	$\rho_{veneer}$	0.08 (1.6E-3)	0.04 (2.1E-2)
$\bar{E}_{veneer}$	7958.8	10657.5	12467.6	813.3	7.6	$\bar{E}_{veneer}$	-	0.77 (5.5E-40)
$\bar{\theta}_{abs,veneer}$	1.9	6.0	11.9	-	-			
$h$	1.85	2.02	2.30	0.07	3.34			

Table 2: Minimum, mean, maximum, standard deviations (StD), coefficient of variation (CV), and coefficient of determination for different measured veneer properties

### 210 3.2. Panels physical properties

211 The measured and calculated properties of the different panels, i.e density,  
 212  $\bar{E}_{panel}$  (which is the average between the three  $\bar{E}_{veneer}$  constitutive of each  
 213 panels) and  $E_{glob,exp}$  are presented in Table 3. The mean modulus of elasticity  
 214  $E_{glob,exp}$  appears quite low (9 350 MPa) for LVL made of beech; indeed in  
 215 the literature [3], this value reach approximately 16 000 MPa. This might  
 216 be due to two reasons, the first one is that only very low quality veneers  
 217 have been used and the second one is that the panels are only composed of

218 three veneers which reduce the potential for a good homogenization of the  
 219 mechanical properties. The coefficient of variation of  $E_{glob,exp}$  is higher than  
 220 in the literature [3] due to the process we used to produce the panels by  
 221 maximizing the variability. The average density  $\rho_{panels}$  (which is the average  
 222 between the three  $\rho_{veneer}$  constitutive of each panels) is on the contrary close  
 223 to what can be found in the literature. The coefficient of determination  
 224 between  $\rho_{panels}$  and  $E_{glob,exp}$  is only equal to 0.12 and this correlation is not  
 225 significant at the 0.01 level ( $p\text{-value} = 0.026$ ). Furthermore, the coefficient of  
 226 variation of  $\rho_{panels}$  is only 3.9% maybe due to the fact that only two logs have  
 227 been used and probably leads to a density explaining only 12% of  $E_{glob,exp}$   
 228 variance. A relatively good correlation exists between  $\bar{E}_{panel}$  and  $E_{glob,exp}$   
 229 ( $R^2 = 0.69$ ,  $p\text{-value} = 9.4\text{E-}12$ ) which corroborate the efficiency of the grain  
 230 angle measurement to predict mechanical properties of LVL made of beech.  
 231 Nevertheless, the range and the coefficient of variation of  $\bar{E}_{panel}$  is much  
 232 lower than the ones for  $E_{glob,exp}$ . This result highlights the fact that a true  
 233 computation of a modeled modulus is needed instead of a simple average and  
 234 also that some optimization is needed on the parameters involved in  $\bar{E}_{panel}$   
 235 calculation.

	Min	Mean	Max	StD	CV(%)	$R^2$ ( $p\text{-value}$ )	$\rho_{panels}$	$\bar{E}_{panel}$
$E_{glob,exp}$	5504.1	9348.8	14442.6	1985.9	21.2	$E_{glob,exp}$	0.12 (0.026)	0.69 (9.4E-12)
$\rho_{panels}$	624.3	670.9	748.9	26.6	3.9	$\rho_{panels}$	-	0.29 (2.5E-4)
$\bar{E}_{panel}$	8541.6	10657.5	12256.1	800.8	7.5			

Table 3: Minimum, mean, maximum, standard deviations (StD), coefficient of variation (CV), and coefficient of determination for different measured panel properties

236 Furthermore, one can notice that the coefficient of variation of  $\bar{E}_{panel}$  and

237  $\bar{E}_{veneer}$  are really close to each other (7.5% and 7.6% respectively). This  
 238 result could be surprising since one of the advantage of producing LVL is  
 239 to homogenize the mechanical properties. However, it was expected in this  
 240 study because of the process used to select the constitutive veneer of each  
 241 panels in ascending order of  $\bar{E}_{veneer}$  to maximize their variability. The average  
 242 coefficient of variation of  $\bar{E}_{panel}$  that could have been observed if the veneers  
 243 had been selected at random is approximately 4.4%. This value have been  
 244 calculated thanks to randoms permutation of  $\bar{E}_{veneer}$  to constitute LVL panels  
 245 and is the average coefficient of variation observed for 1000 repetitions.

### 246 3.3. Prediction of the LVL properties by analytic modeling

#### 247 3.3.1. Model based only on density $E_{glob,mod}(\rho)$

248 The results of the model using only the density as input data are presented  
 249 in Figure 5. The left part of the Figure 5 shows the sensibility analysis of  
 250 the two parameters involved in this model ( $n_\rho$  and  $E_0$ ). The z-axis and  
 251 the colors represents the RMSE between  $E_{glob,mod}(\rho)$  and  $E_{glob,exp}$ . It can  
 252 be seen that a significant amount of parameters can give nearly the same  
 253 results (i.e a RMSE value close to 2 000 MPa) revealing the poor correlation  
 254 between density and modulus of elasticity. The optimal parameters are 1.9  
 255 and 20 000 respectively for  $n_\rho$  and  $E_0$ . The corresponding RMSE for this  
 256 scenario is equal to 1841.3 MPa, the coefficient of determination is equal  
 257 to 0.12 and has nearly the same level of significance than the one between  
 258  $\rho_{panels}$  and  $E_{glob,exp}$  ( $p\text{-value} = 0.027$ ). Those results show that taking into  
 259 account the position of the different plies and the bending solicitation does  
 260 not improve the prediction of the final modulus of elasticity if only the density  
 261 is considered as an input data.

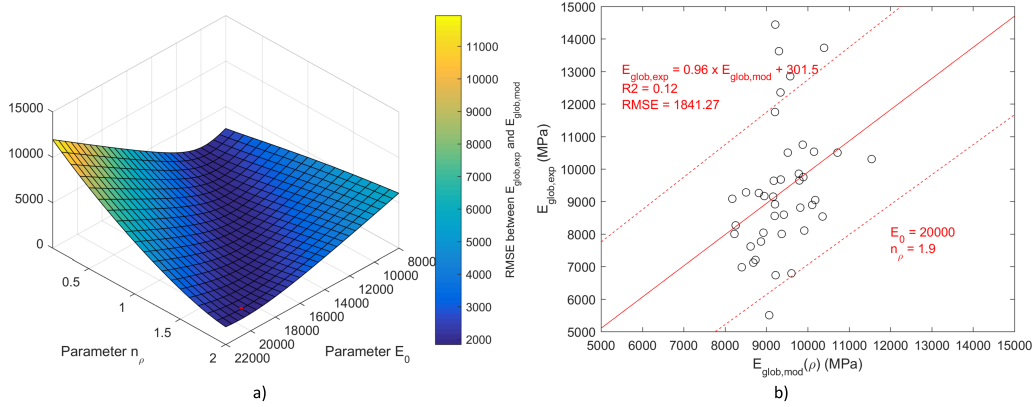


Figure 5: a) Sensibility analysis of the different parameters and b) prediction results for  $E_{glob,mod}(\rho)$

### 262 3.3.2. Model based only on grain angle $E_{glob,mod}(GA)$

263 The results of the different simulations for the model taking into account  
 264 only the grain angle measurement are presented in Figure 6. The Figure 6  
 265 (a) represents the RMSE between  $E_{glob,exp}$  and  $E_{glob,mod}(GA)$  on the basis  
 266 of  $E_0$  parameter. Each vertical set of points (at a given  $E_0$ ) represents the  
 267 total amount of simulation in which the  $k$  and  $n$  parameters vary. The  
 268 smallest RMSE is found for  $E_0 = 16\ 000$  MPa and the variation between  
 269  $E_0 = 14\ 000$  and  $E_0 = 18\ 000$  MPa is quite low. The largest part of the  
 270 variation of the RMSE is due to the variation of the two other parameters  
 271 ( $k$  and  $n$ ). The sensibility analysis of those parameters for the optimal  $E_0$   
 272 is presented in Figure 6 (b). The minimum of the RMSE is reached for  $k$   
 273  $= 0.02$  and  $n = 1.75$ , it can be noted than other sets of these parameters  
 274 give similar results. The Figure 6 (c) shows the comparison in terms of MOE  
 275 variation according to grain angle for the optimal parameters compared to

276 parameters declared by two commercial LVL producers (beech LVL from  
277 Pollmeier and Kerto-S tested in flatwise from Mets Wood). The ratio  $k$  is  
278 equal to  $\frac{470}{16800} = 0.028$  for beech LVL and  $\frac{130}{1380} = 0.009$  for Kerto-S. The  $n$   
279 parameter is taken equal to 2 in accordance with EN 1995. The influence  
280 of the grain angle seems to be much larger according to this comparison at  
281 least in the case of beech LVL produced by Pollmeier. This could be due  
282 to the fact that the grain angle deviation in the present study is mainly  
283 caused by the presence of knots. Thereby, in the vicinity of knots, diving  
284 angle is probably also present which induce an even higher reduction of the  
285 mechanical properties. Also, the contribution of the shear modulus is not  
286 taken into account in this formula and could lead to a virtual decrease of  
287 the  $n$  parameter. Those facts could explain why an higher influence of the  
288 grain angle is found by the optimization process. The optimal parameters are  
289 anyways consistent within the comparison given in Figure 6 (c). Finally, the  
290 quality of the prediction using optimal parameters is presented in Figure 6  
291 (d). The coefficient of determination is equal to 0.73, and the RMSE is equal  
292 to 1028.82 MPa which indicates the efficiency of grain angle measurements  
293 in order to predict mechanical properties of LVL.



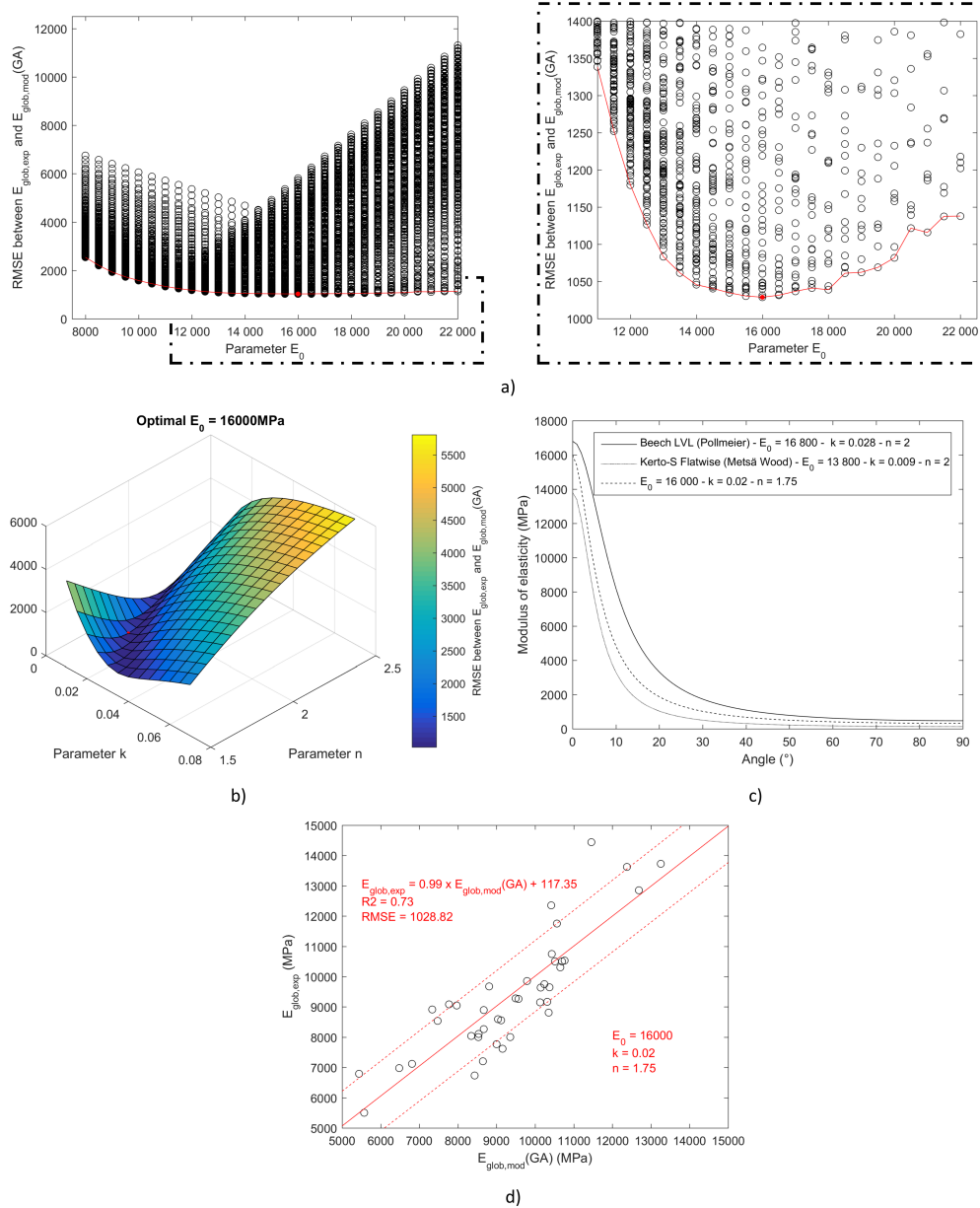


Figure 6: a) Sensibility analysis for  $E_0$  parameter, b) sensibility analysis for  $k$  and  $n$  parameters, c) relevance of the different parameters and d) prediction results for  $E_{glob,mod}(GA)$

294 *3.3.3. Model based on density and grain angle  $E_{glob,mod}(\rho + GA)$*

295 The results of the developed model taking into account both the density  
 296 and the grain angle is given in Figure 7. The coefficient of determination  
 297 between  $E_{glob,exp}$  and  $E_{glob,mod}(\rho + GA)$  is equal to 0.72 and the RMSE to  
 298 1148 MPa. Those results are actually lower than in the case of  $E_{glob,mod}(GA)$ .  
 299 Since the result depends on four parameters it is difficult to plot the influence  
 300 of the different parameters. The optimization sets the  $n_\rho$  parameter close to  
 301 0 when the grain angle is part of the input data, which indicates the low  
 302 influence of the density. The part of the equation modeling this dependency  
 303 only represents a variation of less than 300 MPa for the studied batch of  
 304 panels when  $n_\rho = 0.1$ .

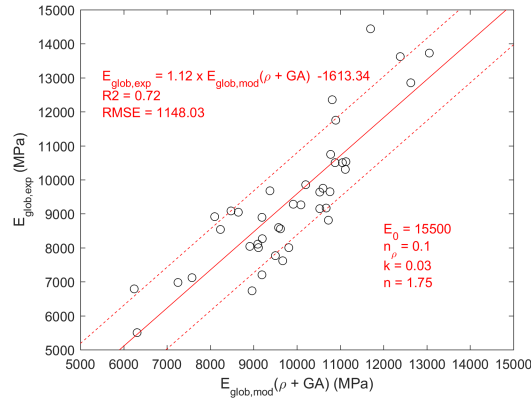


Figure 7: Prediction results for  $E_{glob,mod}(\rho + GA)$

305 *3.3.4. Potential of different methods to predict the modulus of elasticity*

306 A summary of the correlation obtained between different measured or  
 307 calculated estimates and  $E_{glob,exp}$  is presented in Table 4. The analysis of  
 308 results reveals that the density is not a suitable predictor of the modulus of

309 elasticity of LVL made of beech. Indeed, the coefficients of determination  
310 between  $E_{glob,exp}$  and respectively  $\rho_{panels}$  and  $E_{glob,mod}(\rho)$  are both equal to  
311 0.12. Even after taking into account the density differences in each ply and  
312 modeling a 4-points bending test, the correlation is still rather low with a low  
313 significance level. On the contrary, the coefficient of determination between  
314  $E_{glob,mod}(GA)$  and  $E_{glob,exp}$  is equal to 0.73, which is even better than the  
315 coefficient of determination between  $E_{glob,mod}(\rho + GA)$  and  $E_{glob,exp}$ . Taking  
316 both the density and the grain angle into account has not been proven to  
317 be useful due to the low correlation existing between density and the global  
318 modulus of elasticity.

319 The coefficient of determination between  $\bar{E}_{panel}$  and  $\bar{E}_{panel-opti}$  (which is  
320 calculated in the same way as  $\bar{E}_{panel}$  but with the optimal parameters found  
321 for  $E_{glob,mod}(GA)$ ) and  $E_{glob,exp}$  are respectively equal to 0.69 and 0.71. This is  
322 slightly lower than the one between  $E_{glob,mod}(GA)$  and  $E_{glob,exp}$  but this rather  
323 high correlation is an encouraging result to sort veneers in order to produce  
324 LVL made of beech. Indeed, these properties do not take into account the  
325 layup or the type of loading and could easily be used in a production line  
326 to grade and sort veneers. However, these results are based on 3-ply panels,  
327 and the difference between the mechanical models and the simple averaging  
328 might be higher in the case of LVL panels with a higher number of plies.  
329 Indeed, in this case the plies in the outer part have a much higher influence  
330 that the ones in the inner part, which can only be taken into account with a  
331 model such as the one described here.

332 The range of the obtained values and their coefficient of variation are  
333 also described in Table 4. The closest range compared to  $E_{glob,exp}$  is found

334 for  $E_{glob,mod}(GA)$ . The difference of optimizing the different parameters on  
335 the coefficient of variation can also be seen : the coefficient of variation goes  
336 from 7.5% to 12.6% for  $\bar{E}_{panel}$  and  $\bar{E}_{panel-opti}$  respectively. An improvement  
337 in terms of coefficient of variation thanks to the modeling is also observable  
338 : the coefficient of variation goes from 12.6% for  $\bar{E}_{panel-opti}$  to 18.3% for  
339  $E_{glob,mod}(GA)$ . This coefficient of variation is really close to the one observed  
340 for  $E_{glob,exp}$  (21.2%).

	Statistics					Correlation		Parameters			
	Min	Mean	Max	Std	CV (%)	R2	<i>p-value</i>	$E_0$	$n_\rho$	$k$	$n$
$\rho_{panels}$	624.3	670.9	748.9	26.6	3.9	0.12	0.026	-	-	-	-
$\bar{E}_{panel}$	8541.6	10657.5	12256.1	800.8	7.5	0.69	9.4E-12	16 500	0.7	0.07	2
$E_{glob,mod}(\rho)$	8171.1	9381.3	11545.3	711.3	7.6	0.12	0.027	20 000	1.9	-	-
$E_{glob,mod}(GA)$	5441.6	9350.6	13252.8	1712.8	18.3	0.73	1.7E-12	<b>16 000</b>	-	<b>0.02</b>	<b>1.75</b>
$E_{glob,mod}(\rho + GA)$	6245.8	9818.1	13057.9	1511.9	15.4	0.72	2E-12	15 500	0.1	0.03	1.75
$\bar{E}_{panel-opti}$	7488.9	11128.1	13841.6	1398.4	12.6	0.71	5E-12	<b>16 000</b>	-	<b>0.02</b>	<b>1.75</b>
$E_{glob,exp}$	5504.1	9348.8	14442.6	1985.9	21.2	-	-	-	-	-	-

Table 4: Summary of the relationship between measured or calculated properties and  $E_{glob,exp}$

### 341 3.4. Grading LVL panels according to grain angle

342 In order to evaluate the potential of this method to grade LVL panels,  
343 a grading method inspired by the method used to perform strength grading  
344 of solid timber [36] is presented in Figure 8. Unlike in the case of solid  
345 timber where the characteristic bending strength and density need to fulfill  
346 requirements, in this case, only the average modulus of elasticity is considered  
347 as a required parameter to reach a grade.

348 The proposed method to grade LVL is based on finding threshold values  
 349 on predictive properties ( $\bar{E}_{panel-opti}$  in this case); such that panels have an  
 350 average modulus of elasticity higher than a given value (10 500 MPa in this  
 351 case). To assess the efficiency of the grading, it is necessary to perform  
 352 an optimal grading made on the basis of the modulus of elasticity obtained  
 353 during the mechanical tests. In this case, the grading is done by sorting the  
 354 values of modulus of elasticity in ascending order and removing the lowest  
 355 values until the average modulus of elasticity of the remaining panels is higher  
 356 than 10 500 MPa. In this particular application grade 1 represents the higher  
 357 grade and grade 2 the lower grade.

358 Knowing the optimal grading and the grading obtained by this method,  
 359 it is therefore possible to assess the performance of this method. The results  
 360 show remarkable accuracy of the method; the yield obtained by the method  
 361 reach 51% compared to 58% obtained by the optimal grading for grade 1.

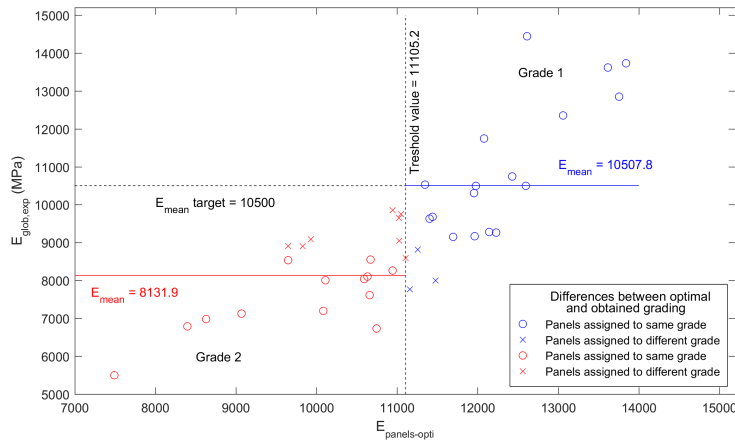


Figure 8: Method to sort panels into two grades

## 362 **4. Conclusions**

363 This study shows that it is possible to predict the modulus of elasticity of  
364 LVL made of beech using local grain angle measurements. In addition, this  
365 study demonstrates that the average density is not a good predictor of the  
366 modulus of elasticity. Encouraging outcomes have been highlighted consid-  
367 ering the sorting based on local grain angle measurements. This method can  
368 be used to efficiently define different grades of LVL panels and to lower the  
369 variability of the final product even for low grade LVL made of low quality  
370 veneer. The results presented in this study are only based on three layer  
371 panels subjected to flatwise bending. These results need to be extended to  
372 LVL composed of much more layers solicited in both loading directions. In  
373 particular, in edgewise bending the results need to be investigated. Indeed,  
374 sorting the veneer could still lead to lower the variability within grades even  
375 in edgewise but the prediction results could be less convincing. The results  
376 should also be extended with more logs. For such an extent and to improve  
377 the quality of the prediction, measuring the ultrasonic speed to take into  
378 account MFA variation which is mostly a tree effect and a property inherent  
379 to clear wood could be insightful.

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