Analysis of Relations between the Moduli of Elasticity in Compression, Tension, and Static Bending of Hardwoods

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Accurate estimation of average modulus of elasticity in compression parallel to the grain (E_{c0}) is of paramount importance for rational sizing of timber structures, given the use of this property in the estimation of stability of compressed parts (ultimate limit state, ULS) and in calculation of excessive strains (serviceability limit state, SLS). In Brazil, if values cannot be experimentally determined, ABNT NBR 7190 (1997) allows for estimation of E_{c0} through relations to average modulus of elasticity both in tension parallel to the grain (E_{t0}) ($E_{c0} = E_{t0}$) and in bending (E_M) ($E_{c0} = E_M/0.90$). This research aimed to access the efficiency of these relations by testing 30 tropical wood species. The analysis of variance results showed that E_{c0} and E_{t0} were statistically equal. However, E_{c0} and $E_M/0.90$ were not statistically equal, and the method of least squares resulted in a coefficient of 0.98, which was 8.89% higher than the one suggested by ABNT NBR 7190 (1997) and close to 1, thus, validating the results of ANOVA, which pointed on the equivalence between E_{c0} and E_M ($E_{c0} = E_M$). As an alternative to simplified equations of the standard, two-parameter regression models were used. The geometric model with $R^2 = 91.67\%$ proved to be the model of best fit, which demonstrated that E_{c0} could be calculated as a function of E_M.

Keywords: Hardwood; Regression model; Mechanical properties; Timber structure

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INTRODUCTION

Considered the material of the future (Kuzman and Sandberg 2017; Żmijewki and Wojtowicz-Jankowska 2017), timber is becoming increasingly popular and widely applied in civil construction (Wieruszewski and Mazela 2017). This is not only because wood is a natural, biodegradable, renewable, recyclable and, hence, environmentally friendly raw material (Wang *et al*. 2014; Araujo *et al*. 2016; Lima, Jr. *et al*. 2018; Souza *et al*. 2018), but also due to characteristics that make it an efficient building material compared to traditionally used steel and concrete (Ramage *et al*. 2017).

One such characteristic of wood is its excellent mechanical strength-to-density ratio (Pries and Mai 2013; Ramage *et al*. 2017; Huber *et al*. 2018; Lima, Jr. *et al*. 2018) that favors the use of wood in construction applications where weight of the structure itself presents a considerable load (*e.g.*, roofs, bridges, and tall buildings) as well as in buildings subjected to seismic loading, given that heavier structures are subjected to higher seismic load (Ramage *et al*. 2017).

Given the effectiveness of wood as a structural element, timber constructions have become the most common, practical, and economical housing solution for most countries in the northern hemisphere (Araujo *et al*. 2016), leading to widespread use of timber in countries such as Austria, Japan, Scotland, and New Zealand, where 40%, 45%, 83%, and 85% of houses are made of wood, respectively (Mahapatra *et al*. 2012; Hurmekoski *et al*. 2015; Araujo *et al*. 2018).

Nevertheless, in Brazil, despite having the largest biodiversity of species on the planet (Beech *et al*. 2017), with evident reforestation potential, and a growing demand for housing, the use of timber for dwelling construction is still low (Araujo *et al*. 2018). This motivates the development of research that disseminates, mainly to the consumer market, information regarding benefits of timber constructions and physical-mechanical properties of wood that are necessary for rational elaboration of structural design.

Among these properties, average value of modulus of elasticity in compression parallel to the grain (E_{c0}) is of paramount importance, given its use in checks of stability of compressed parts (buckling) in the ultimate limit state (ULS) and in calculation of excessive strains in compliance with the serviceability limit state (SLS).

In Brazil, Annex B of ABNT NBR 7190 (1997) "Design of wooden structures" provides experimental methods for the determination of physical-mechanical properties of wood. Given that there are 17 physical-mechanical properties that need to be estimated, a complete characterization of species requires an extensive number of tests. The execution of these tests is time-consuming, expensive, and implies expenditure with materials and labor.

Given the many catalogued tree species in the Amazonian region as a whole, and in the Brazilian Amazon specifically (12000 and 7696, respectively, according to Steege *et al*. (2016)), any procedure aimed at reducing the number of tests is greatly desirable.

To simplify the assessment of E_{c0}, ABNT NBR 7190 (1997) allows estimation of the E_{c0} value through relation with the average value of modulus of elasticity in tension parallel to the grain (E_{t0}) and static three-point bending (E_M), as shown in Eqs. 1 and 2, respectively:

$$E_{c0} = E_{t0} \tag{1}$$

$$E_{c0} = E_M / 0.90 \tag{2}$$

Several previous works have sought to determine correlations between wood properties, particularly, with bulk density (ρ_{ap} - an easily determinable physical property), which proves the academic interest in simplifying the characterization of wood.

Igartúa *et al*. (2015) studied the Argentinian species *Acacia melanoxyon* and found a strong correlation (with coefficient of determination (R^2) above 70%) between ρ_{ap} and parallel and normal to the grain compressive strength, as well as between ρ_{ap} and modulus of elasticity and conventional bending strength.

Silva *et al*. (2018) used regression models to study whether physical-mechanical properties of *Goupia glabra* Aubl. (popularly called Cupiúba in Brazil) can be estimated as a function of ρ_{ap}. They obtained regression models with good precision ($R^2 \approx 70\%$) for 15 studied relations. The most significant relation ($R^2 = 87.96\%$) was between ρ_{ap} and hardness parallel to the grain.

Almeida *et al.* (2017) and Dias *et al.* (2019) studied wood shrinkage estimation as a function of ρ_{ap} with regression models based on experimental results from 15 and 43 tropical wood species, respectively. In both works, analysis of variance (ANOVA) results demonstrated weak correlation between investigated parameters, showing that ρ_{ap} is not a reliable estimator for dimensional stability of wood.

In recent years, research has assessed the accuracy of estimated properties obtained through relationships provided by ABNT NBR 7190 (1997) and determined coefficients that best fit the proposed relationships. Matos and Molina (2016) studied correlations between characteristic shear strength ($f_{v0,k}$) and compressive strength parallel to the grain ($f_{c0,k}$) of conifer ($f_{v0,k} = 0.15 \cdot f_{c0,k}$) and dicot ($f_{v0,k} = 0.12 \cdot f_{c0,k}$) woods. The authors evaluated *Pinus elliotti* and *Eucalyptus saligna* species and for conifer woods obtained a relation approximately 95% higher compared to that from ABNT NBR 7190 (1997).

Based on three- and four-point static bending tests, Lahr *et al.* (2017) determined a relation between longitudinal (E) and tangential (G) modulus of elasticity. From the results obtained of five different tropical wood species tested, the authors determined the relation $E = 35 \cdot G$, with the coefficient being 75% higher than the one given by ABNT NBR 7190 (1997) ($E = 20 \cdot G$).

Recently, Christoforo *et al.* (2019) studied relations between characteristic compression strength ($f_{c0,k}$), characteristic tensile strength parallel to the grain ($f_{t0,k}$), and characteristic shear strength ($f_{v0,k}$). The coefficients (α) they obtained after testing five tropical wood species were 0.96 and 0.23 for relations $f_{c0,k} = \alpha \cdot f_{t0,k}$ and $f_{v0,k} = \alpha \cdot f_{c0,k}$, respectively, which were 25% and 92% higher than the coefficients specified by ABNT NBR 7190 (1997).

These studies demonstrate that some relations between properties of wood prescribed by ABNT NBR 7190 (1997) need to be revised to obtain reliable estimates for structural design. Thus, the aim of this work was to investigate statistical equivalence between modulus of elasticity obtained in bending, compression, and tension parallel to the grain (Eq. 1 and Eq. 2) and, in case equivalence is not confirmed, to define correlations between these properties that would give more accurate E_{c0} estimates.

EXPERIMENTAL

Materials

Thirty different wood species were used in this study (Table 1), and these were obtained, from local companies, in the same manner as timber used in Brazilian civil construction, in the form of boards sized approximately 6 cm × 11 cm × 200 cm. Therefore, it was not possible to identify origin and age for the trees.

The wood was properly stocked and tested in three different research labs in the country: the Laboratory of Wood and Timber Structure (LaMEM) of the University of São Paulo (USP); the laboratories of Federal University of Minas Gerais (UFMG), campus Belo Horizonte (State of Minas Gerais); and at the laboratories of São Paulo State University (UNESP), campus Itapeva (State of São Paulo).

Methods

To determine E_{c0}, E_{t0}, and E_M, the static three-point bending test (Fig. 1a), compression (Fig. 1b), and tensile test (Fig. 1c) parallel to the grain were performed, respectively.

Table 1. Brazilian Tropical Wood Species Used in the Study

ID	Brazilian Popular Name	Scientific Name *	ID	Brazilian Popular Name	Scientific Name *
1	Angelim amargoso	*Vatairea fusca* (Ducke) Ducke	16	Copaíba	*Copaifera multijuga* Hayne
2	Angelim araroba	*Vataireopsis araroba* (Aguiar) Ducke	17	Cutiúba	*Goupia paraensis* Huber
3	Angelim ferro	*Hymenolobium* cf. *heterocarpum* Ducke	18	Goiabão	*Planchonella pachycarpa* Pires
4	Angelim pedra	*Hymenolobium petraeum* Ducke	19	Guaiçara	*Luetzelburgia* cf. *guaissara* Toledo
5	Angelim vermelho	*Dinizia excelsa* Ducke	20	Guajará	*Micropholis venulosa* (Mart. & Eichler) Pierre
6	Angico preto	*Anadenanthera colubrina* var. *cebil* (Griseb.) Altschul	21	Guarucaia	*Peltophorum dubium* (Spreng.) Taub.
7	Branquilho	*Sebastiania commersoniana* (Baill.) L. B. Sm. & Downs	22	Itaúba	*Mezilaurus itauba* (Meisn.) Taub. ex Mez
8	Cafearana	*Andira anthelmia* (Vell.) Benth	23	Jatobá	*Hymenaea courbaril* L.
9	Canafístula	*Cassia ferruginea* (Schrad.) Schrad. ex DC.	24	Louro preto	*Ocotea neesiana* (Mig.) Kosterm.
10	Casca grossa	*Pouteria* cf. *pachyphylla* T. D. Penn.	25	Louro verde	*Sextonia* cf. *rubra* (Mez) van der Werff
11	Castanheira	*Bertholletia excelsa* Bonpl.	26	Maçaranduba	*Manilkara* cf. *inundata* (Ducke) Ducke
12	Cedro amargo	*Cedrela odotara* L.	27	Parinari	*Parinari excelsa* Sabine
13	Cedro doce	*Cedrela* cf. *fissilis* Vell.	28	Piolho	*Tapirira* sp. Aubl.
14	Cedroarana	*Cedrelinga cataniformis* (Ducke) Ducke	29	Sucupira	*Diplotropis* sp. Benth.
15	Champanhe	*Dypterix odotora* (Aubl.) Willd.	30	Tachi	*Tachigali glauca* Tul.

* According to Rio de Janeiro Botanical Garden (Jardim Botânico do Rio de Janeiro 2019)

For each species and mechanical property, 12 specimens were produced and tested, which gave a total of 1080 experimental results. All the tests were conducted on the universal testing machine AMSLER (250 kN loading capacity) (Shimadzu Corporation, Kyoto, Japan) following the procedure described in Annex B (Determination of wood properties for structural design) of ABNT NBR 7190 (1997).

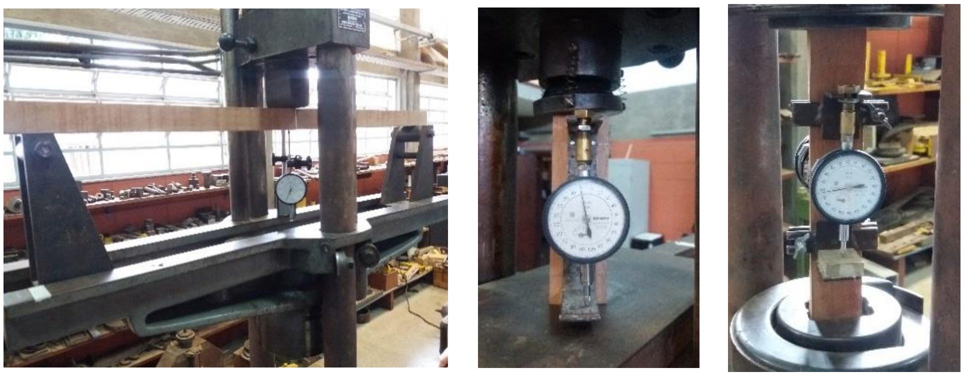

Fig. 1. Static bending test (a), compression test parallel to the grain (b), and tensile test parallel to the grain (c)

The wooden boards were ambient-dried. After drying, the boards presented moisture level around 12%. According to the ABNT NBR 7190 (1997), 12% is a reference moisture level for presentation of the experimental results. Values of stiffness properties (E_{c0}, E_{t0}, and E_M) obtained with moisture levels (U%) different from 12% were adjusted for 12% moisture level using Eq. 3, as prescribed by the ABNT NBR 7190 (1997), where $E_{12\%}$ and $E_{U\%}$ are values corresponding to moisture levels of 12% and U%, respectively.

$$E_{12\%} = E_{U\%} \cdot \left[1 + \frac{2 \cdot (U\% - 12)}{100}\right] \tag{3}$$

The accuracy of relations proposed by ABNT NBR 7190 (1997) (Eqs. 1 and 2) was evaluated using ANOVA at the 5% significance level through BioEstat5.3® software (Mamirauá Institute, Belém, PA, Brazil). A null hypothesis (H_0) was that the average of the groups (E_{c0} and E_{t0}, E_{c0}, and $0.90/E_M$) was equal, and the alternative hypothesis (H_1) was non-equivalence. Hence, a p-value higher or equal than the selected significance level (p-value ≥ 0.05) implied accepting H_0 (tested relation was accurate). Otherwise (p-value < 0.05), H_1 should be accepted.

Upon discovering non-equivalence (p-value < 0.05), two-parameter (a e b) regression models (Eq. 4 to Eq. 7) were used to estimate E_{c0} (dependent variable – y) as a function of E_{t0} and E_M (independent variables – x):

$$y = a + b \cdot x \quad \text{(Linear)} \tag{4}$$

$$y = a \cdot e^{b \cdot x} \quad \text{(Exponential)} \tag{5}$$

$$y = a + b \cdot ln(x) \quad \text{(Logarithmic)} \tag{6}$$

$$y = a \cdot x^{b} \quad \text{(Geometric)} \tag{7}$$

Regression models based on ANOVA at a 5% significance level were used in considering the grouping of species and respective average values of properties. For ANOVA of regression models, a null hypothesis (H_0: $\beta = 0$) was that the tested models were not representative and an alternative hypothesis (H_1: $\beta \neq 0$) was that they were representative.

P-values higher than the selected significance level (p-value > 0.05) implied accepting H_0 (tested regression model was not representative - variations of x did not explain variations of y). In the opposite case, this hypothesis would be rejected (p-value $\leq$ 0.05 - regression model was representative).

In addition to ANOVA, values of coefficient of determination (R^2) were obtained, which allowed for evaluation of the quality of estimated fit and determination of the most accurate representative model (p-value $\leq$ 0.05), that is, the model that best described variations of dependent variable y as a function of independent variable x.

Along with regression models, the least squares method (Eq. 8 and Eq. 9 - used in studies by Christoforo *et al.* (2012), Icimoto *et al.* (2015), Ferro *et al.* (2015), Lahr *et al.* (2017), Almeida *et al.* (2018), and Christoforo *et al.* (2019)) using Newton's method with quadratic approximation was applied for determination of the optimal coefficient (λ) for relations $E_{c0} = \lambda \cdot E_{t0}$ and $E_{c0} = E_M/\lambda$:

$$f(\lambda) = \frac{1}{2} \cdot \sum_{i=1}^{n} (E_{c0_i} - \lambda \cdot E_{t0_i})^2 \tag{8}$$

$$f(\lambda) = \frac{1}{2} \cdot \sum_{i=1}^{n} (E_{M_i} - \lambda \cdot E_{c0_i})^2 \tag{9}$$

RESULTS AND DISCUSSION

Table 2 shows the experimentally obtained average values (X_m) and coefficients of variation (C_v) of stiffness properties (E_{c0}, E_{t0}, and E_M) for each tested species.

Table 2. Stiffness Properties of 30 Studied Wood Species

ID	E_{c0}		E_{t0}		E_M		ID	E_{c0}		E_{t0}		E_M	
	X_m (MPa)	C_v (%)	X_m (MPa)	C_v (%)	X_m (MPa)	C_v (%)		X_m (MPa)	C_v (%)	X_m (MPa)	C_v (%)	X_m (MPa)	C_v (%)
1	15242	16	16393	16	15562	13	16	12400	17	13604	13	11947	6
2	11467	12	11085	12	11132	20	17	18317	14	15093	14	16851	19
3	17054	13	18318	20	17196	9	18	19003	16	18345	22	19213	20
4	10529	8	10407	18	9793	17	19	15168	12	17016	12	14811	12
5	16744	11	17271	13	15314	10	20	20754	13	21885	17	20292	14
6	14731	23	16854	19	16625	11	21	17273	13	14507	15	16105	26
7	13706	15	14654	17	16573	22	22	17038	11	17691	9	16902	14
8	13766	28	12491	21	13673	16	23	22543	12	21350	3	21842	11
9	15149	18	14798	10	16026	13	24	15731	8	14232	13	15873	31
10	17564	9	18995	10	16993	9	25	15395	14	13619	14	16872	12
11	15441	14	13021	10	14044	14	26	22699	11	22078	6	20191	15
12	10094	6	9472	13	9136	6	27	21843	9	18781	6	18391	8
13	8499	17	9896	25	8814	16	28	13683	28	12889	19	12431	17
14	9828	11	9822	14	9527	9	29	20754	13	21885	17	20292	14
15	22732	11	21165	9	24653	10	30	19025	15	18746	27	20294	16

Both coefficients of variation and average stiffness values were consistent with experimental results from Gonçalez and Gonçalves (2001), Grobério and Lahr (2002), Dias and Lahr (2004), Araújo (2007), Faria *et al.* (2012), Ferro *et al.* (2015), Jesus *et al.* (2015), Moreira *et al.* (2017), Lahr *et al.* (2017), Aquino *et al.* (2018), and Almeida *et al.* (2018) that determined some of the stiffness properties of the species studied here.

The values of E_{c0} determined in this study and found in the literature were in agreement with values presented in Appendix E (Common average strength and stiffness values of some native and afforestation woods) of ABNT NBR 7190 (1997), which includes among its 50 hardwood species 18 wood species tested in this work (*Vataireopsis araroba* (Aguiar) Ducke, *Hymenolobium* cf. *heterocarpum* Ducke, *Hymenolobium petraeum* Ducke, *Dinizia excelsa* Ducke, *Sebastiania commersoniana* (Baill.) L.B. Sm. & Downs, *Andira anthelmia* (Vell.) Benth, *Cassia ferruginea* (Schrad.) Schrad. ex DC., *Pouteria* cf. *pachyphylla* T.D.Penn., *Cedrela odotara* L., *Cedrela* cf. *fissilis* Vell., *Dypterix odotora* (Aubl.) Willd., *Goupia paraensis* Huber, *Luetzelburgia* cf. *guaissara* Toledo, *Peltophorum dubium* (Spreng.) Taub., *Hymenaea courbaril* L., *Ocotea neesiana* (Mig.) Kosterm., and *Manilkara* cf. *inundata* (Ducke) Ducke). These comparisons supported the results shown in Table 2.

The ANOVA showed that group means of E_{c0} and E_{t0} were statistically equal because the p-value was higher than the significance level (p-value ≥ 0.05). Hence, the relation $E_{c0} = E_{t0}$ was accurate and gave a good estimate of E_{c0}. For the relation between E_{c0} and E_M, the p-value was less than the significance level (p-value < 0.05), which indicated that group means of E_{c0} and $E_M/0.90$ were not statistically equivalent. Hence, the equation $E_{c0} = E_M/0.90$ did not estimate E_{c0} value accurately.

The regression models (Eq. 4 to Eq. 7) and least squares method (Eq. 9) were used as an alternative to the equation $E_{c0} = E_M/0.90$, for formulation of equations that could accurately estimate E_{c0} values as a function of E_M. All models (linear, exponential, logarithmic, and geometric) were significant (p-value < 0.05), and the geometric model described by Eq. 10 showed the best fit ($R^2 = 91.67\%$):

$$E_{c0} = 1.82 \cdot \left(E_M\right)^{0.94} \tag{10}$$

The least squares method gave the optimal coefficient for the relation $E_{c0} = E_M/\lambda$ for the entire group of species equal to 0.98 (Eq. 11) that was 8.89% higher than the coefficient (0.90) provided by ABNT NBR 7190 (1997):

$$E_{c0} = E_M / 0.98 \tag{11}$$

It should be mentioned that $E_{c0} = E_M/0.90$ ratio was established by the Brazilian standard ABNT NBR 7190 (1997) without an adequate statistical analysis that would prove the reliability in the comparison of the groups of values (E_{c0} and E_M). In the present work, ANOVA was applied in order to investigate the relationship between E_{c0} and E_M ($E_{c0} = E_M$), which showed equivalence between the two groups. This result shows that the $E_{c0} = E_M$ ratio is more precise than the $E_{c0} = E_M/0.90$ equation, proposed by the Brazilian standard. This highlighting the need for revision of this item in future versions.

CONCLUSIONS

1. The ANOVA at 5% significance level demonstrated an equivalence between group means of E_{c0} and E_{t0}, which indicated the accuracy of E_{c0} estimation for hardwood species through the equation $E_{c0} = E_{t0}$ proposed by ABNT NBR 7190 (1997).

2. The ANOVA at 5% significance level demonstrated that group means of E_{c0} and $E_M/0.90$ were not equal, which indicated that the coefficient of 0.90 did not give an accurate estimation of E_{c0} through the equation $E_{c0} = E_M/0.90$.
3. All regression models used for estimation of E_{c0} as a function of E_M were significant and with a good fit. The best fit was achieved by the geometric model, which showed that E_{c0} could be estimated by Eq. 10.
4. The optimal coefficient obtained by the least squares method (Eq. 11) for the relation between E_{c0} and E_M was higher than the one established by ABNT NBR 7190 (1997). The value of this coefficient was around 1, thus, validating the results of ANOVA that indicated equivalence between E_{c0} and E_M ($E_{c0} = E_M$).
5. Given the significant number of species tested in this study, $E_{c0} = E_M$ ratio appeared to be widely applicable model for estimation of E_{c0}.

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REFERENCES CITED

ABNT NBR 7190 (1997). "Projeto de estruturas de madeira [Design of wooden structures]," Brazilian Association of Technical Standards, Rio de Janeiro, Brazil.

Almeida, A. S., Lanini, T. L. S., Caetano, J. A., Christoforo, A. L., and Lahr, F. A. R. (2018). "Evaluation of stiffness in compression perpendicular to grain of Brazilian tropical wood species," *Curr. J. Appl. Sci. Technol.* 28(5), 1-7. DOI: 10.9734/CJAST/2018/42945

Almeida, T. H., Almeida, D. H., Araujo, V. A, Silva, S. A. M., Christoforo, A. L., and Lahr, F. A. R. (2017). "Density as estimator of dimensional stability quantities of Brazilian tropical woods," *BioResources* 12(3), 6579-6590. DOI: 10.15376/biores.12.3.6579-6590

Aquino, V. B. M., Almeida, J. P. B., Almeida, D. H., Almeida, T. H., Panzera, T. H., Christoforo, A. L., and Lahr, F. A. R. (2018). "Physical and mechanical characterization of *Copaifera* sp. wood species," *Int. J. Mater. Eng.* 8(3), 55-58. DOI: 10.5923/j.ijme.20180803.03

Araújo, H. J. B. (2007). "Relações funcionais entre propriedades físicas e mecânicas de madeiras tropicais brasileiras [Functional relations between physical and mechanical properties of Brazilian tropical woods]," *Floresta* 37(3), 399-416. DOI: 10.5380/rf.v37i3.9937

Araujo, V. A., Cortez-Barbosa, J., Gava, M., Garcia, J. N., Souza, A. J. D., Savi, A. F., Morales, E. A. M., Molina, J. C., Vasconcelos, J. S., Christoforo, A. L., *et al.* (2016).

"Classification of wooden housing building systems," *BioResources* 11(3), 7889-7901. DOI: 10.15376/biores.11.3.DeAraujo

Araujo, V. A., Vasconcelos, J. S., Morales, E. A. M., Savi, A. F., Hindman, D. P., O'Brien, M. J., Negrão, J. H. J. O., Christoforo, A. L., Lahr, F. A. R., Cortez-Barbosa, J., *et al.* (2018). "Difficulties of wooden housing production sector in Brazil," *Wood Mater. Sci. Eng.* 11(3), 1-10. DOI: 10.1080/17480272.2018.1484513

Beech, E., Rivers, M., Oldfield, S., and Smith, P. P. (2017). "GlobalTreeSearch: The first complete global database of tree species and country distributions," *J. Sustain. For.* 36(5), 454-489. DOI: 10.1080/10549811.2017.1310049

Christoforo, A. L., Almeida, A. S., Lanini, T. L. S., Nogueira, R. S., and Lahr, F. A. R. (2019). "Estimation of the characteristic value of wood strength," *J. Braz. Assoc. Agric. Eng.* 39(1), 127-132. DOI: 10.1590/1809-4430-Eng.Agric.v39n1p127-132/2019

Christoforo, A. L., Lahr, F. A. R., Morales, E. A. M., Panzera, T. H., and Borges, P. H. R. (2012). "Numerical evaluation of longitudinal modulus of elasticity of *Eucalyptus grandis* timber beams," *Int. J. Agric. For.* 2(4), 166-170. DOI: 10.5923/j.ijaf.20120204.06

Dias, F. M., Almeida, T. H., Araújo, V. A., Panzera, T. H., Christoforo, A. L., and Lahr, F. A. R. (2019). "Influence of the apparent density on the shrinkage of 43 tropical wood species," *Acta Sci. Technol.* 41(1), 2-7. DOI: 10.4025/actascitechnol.v41i2.30947

Dias, F. M., and Lahr, F. A. R. (2004). "Estimativa de propriedades de resistência e rigidez da madeira através da densidade aparente [Strength and stiffness properties of wood esteemed through the specific gravity]," *Sci. For.* 65, 102-113.

Faria, O. B., Silva, D. A. L., Lahr, F. A. R., Chahud, E., and Varanda, L. D. (2012). "Influence of wood moisture content on modulus of elasticity on tension parallel to the grain of Brazilian species," *Eur. Int. J. Sci. Technol.* 1(2), 11-22.

Ferro, F. S., Icimoto, F. H., Almeida, D. H., Christoforo, A. L., and Lahr, F. A. R. (2015). "Influência da posição dos instrumentos de medida na determinação do módulo de elasticidade da madeira na compressão paralela às fibras (E_{c0}) [Influence of the position of the measuring instruments in the determination of the elasticity modulus of wood in compression parallel to grain (E_{c0})]," *Rev. Árvore* 39(4), 743-749. DOI: 10.1590/0100-67622015000400017

Gonçalez, J. C., and Gonçalves, D. M. (2001). "Valorização de duas espécies de madeira *Cedrelinga catenaeformis* e *Enterolobium shomburgkii* para a indústria madeireira [Valorization of two Brazilian timbers *Cedrelinga catenaeformis* and *Enterolobium shomburgkii*]," *Bras. Florestal* 71, 69-74.

Grobério, M. P., and Lahr, F. A. R. (2002). "Indicações para o emprego da madeira de espécies tropicais do Brasil [Indications for the use of wood tropical species from Brazil]," *Revista Madeira: Arquitetura e Engenharia* 3(8).

Huber, J. A. J., Ekevad, M., Girhammar, U. A., and Berg, S. (2018). "Structural robustness and timber buildings – A review," *Wood Mater. Sci. Eng.* 14(2), 107-128. DOI: 10.1080/17480272.2018.1446052

Hurmekoski, E., Jonsson, R., and Nord, T. (2015). "Context, drivers, and future potential for wood-frame multi-story construction in Europe," *Technol. Forecast. Soc. Change* 99, 181-196. DOI: 10.1016/j.techfore.2015.07.002

Icimoto, F. H., Ferro, F. S., Almeida, D. H., Christoforo, A. L., and Lahr, F. A. R. (2015). "Influence of specimen orientation on determination of elasticity in static bending," *Maderas- Cienc. Tecnol.* 17(2), 229-238. DOI: 10.4067/S0718-221X2015005000022

Igartúa, D. V., Moreno, K., Piter, J. C., and Monteoliva, S. (2015). "Density and mechanical properties of Argentinean *Acacia melanoxylon*," *Maderas- Cienc. Tecnol.* 17(4), 809-820. DOI: 10.4067/S0718-221X2015005000070

Jardim Botânico do Rio de Janeiro (2019). "Brazilian Flora 2020 under construction," (http://floradobrasil.jbrj.gov.br/), Accessed 23 Nov 2019.

Jesus, J. M. H., Logsdon, N. B., and Finger, Z. (2015). "Classes de resistência de algumas madeiras de Mato Grosso [Strength classes of resistance of some timbers from Mato Grosso]," *Eng. Sci.* 1(3), 35-42.

Kuzman, M. K., and Sandberg, D. (2017). "Comparison of timber-house technologies and initiatives supporting use timber in Slovenia and in Sweden – The state of the art," *iForest – Biogeosci. For.* 10(6), 930-938. DOI: 10.3832/ifor2397-010

Lahr, F. A. R., Christoforo, A. L., Varanda, L. D., Chahud, E., Araujo, V. A., and Branco, L. A. M. N. (2017). "Shear and longitudinal modulus of elasticity in wood: Relations based on static bending tests," *Acta Sci. Technol.* 39(4), 433-437. DOI: 10.4025/actascitechnol.v39i4.30512

Lima, Jr., M. P., Biazzon, J. C., Araujo, V. A., Munis, R. A., Martins, J. C., Cortez-Barbosa, J., Gava, M., Valarelli, I. D., and Morales, E. A. M. (2018). "Mechanical properties evaluation of *Eucalyptus grandis* wood at three different heights by impulse excitation technique (IET)," *BioResources* 13(2), 3377-3385. DOI: 10.15376/biores.13.2.3377-3385

Mahapatra, K., Gustavsson, L., and Hemström, K. (2012). "Multi-storey wood-frame buildings in Germany, Sweden and the UK," *Constr. Innovation* 12(1), 62-85. DOI: 10.1108/14714171211197508

Matos, G., and Molina, J. C. (2016). "Resistência da madeira ao cisalhamento paralelo às fibras segundo as normas ABNT NBR 7190:1997 e ISO 13910:2005 [Shear strength of wood in direction parallel to the grain according to the standards ABNT NBR 7190:1997 and ISO 13910:2005]," *Revista Matéria* 21(4), 1069-1079. DOI: 10.1590/S1517-707620160004.0098

Moreira, A. P., Silveira, E., Almeida, D. H., Almeida, T. H., Panzera, T. H., Christoforo, A. L., and Rocco, F. A. (2017). "Toughness and impact strength in dynamic bending of wood as a function of the modulus of elasticity and the strength in compression to the grain," *Int. J. Mater. Eng.* 7(4), 61-67. DOI: 10.5923/j.ijme.20170704.01

Pries, M., and Mai, C. (2013). "Fire resistance of wood treated with a cationic silica sol," *Eur. J. Wood Wood Prod.* 71(2), 237-244. DOI: 10.1007/s00107-013-0674-7

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., *et al.* (2017). "The wood from the tress: The use of timber in construction," *Renew. Sust. Energy Rev.* 68, 333-359. DOI: 10.1016/j.rser.2016.09.107

Silva, C. E. G., Almeida, D. H., Almeida, T. H., Chahud, E., Branco, L. A. M. N., Campos, C. I., Lahr, F. A. R., and Christoforo, A. L. (2018). "Influence of the procurement site on physical and mechanical properties of Cupiúba wood species," *BioResources* 13(2), 4118-4131. DOI: 10.15376/biores.13.2.4118-4131

Souza, A. M., Nascimento, M. F., Almeida, D. H., Lopes Silva, D. A., Almeida, T. H., Christoforo, A. L., and Lahr, F. A. R. (2018). "Wood-based composite made of wood waste and epoxy based ink-waste as adhesive: A cleaner production alternative," *J. Clean. Prod.* 193, 549-562. DOI: 10.1016/j.jclepro.2018.05.087

Steege, H., Vaessen, R. W, Cárdenas-López, D., Sabatier, D., Antonelli, A., Oliveira, S. M., Pitman, N. C. A., Jørgensen, P. M., and Salomão, R. P. (2016). "The discovery of the Amazonian tree flora with an updated checklist of all known tree taxa," *Sci. Rep.* 6(29549), 1-15. DOI: 10.1038/srep29549

Wang, L., Toppinen, A., and Juslin, H. (2014). "Use of wood in green building: A study of expert perspectives from the UK," *J. Clean. Prod.* 65, 350-361. DOI: 10.1016/j.jclepro.2013.08.023

Wieruszewski, M., and Mazela, B. (2017). "Cross laminated timber (CLT) as an alternative form of construction wood," *Drvna Ind.* 68(4), 359-367. DOI: 10.5552/drind.2017.1728

Żmijewki, T., and Wojtowicz-Jankowska, D. (2017). "Timber – Material of the future – Examples of small wooden architectural structures," *IOP Conf. Ser.: Mater. Sci. Eng.* 245, 1-9. DOI: 10.1088/1757-899X/245/8/082019

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