Neutrosophic Sets and Systems, Vol. 101, 2026
University of New Mexico

Neutrosophic Multi-Criteria Assessment of the Structural Performance of Finger-Jointed Glued Laminated Timber from Five Tropical Wood Species

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Abstract: Previous studies on finger-jointed glued laminated timber typically compare mechanical properties in isolation through classical statistical tests, which limits the ability to answer a question of greater relevance for structural design: which species most consistently retains its mechanical performance under experimental uncertainty and contradictory behavior across indicators. This study comparatively assessed the structural performance of finger-jointed glued laminated timber from five tropical forest species (cedro, tornillo, almendro, moena itauba and huayruro) by integrating physical-mechanical indicators, inferential statistics and a neutrosophic CRITIC-TOPSIS multi-criteria model that quantifies the uncertainty associated with the retention of mechanical properties after lamination. Basic density, proportional limit stress (PLS), modulus of rupture (MOR), modulus of elasticity (MOE) and compression parallel to the grain were determined for solid and laminated wood (5 cm x 5 cm x 76 cm, 10 specimens per species and condition), using a glue weight of 200 g/cm2 and a pressure of 1200 kg, following standards NTP 251.016 and NTP 251.012. Beyond the independent-samples t-test, a single-valued neutrosophic number (T, I, F) was built for each species and property from the mechanical retention ratio and the statistical significance level; criteria were weighted through neutrosophic CRITIC and species were ranked through neutrosophic TOPSIS, complemented by two original indices, the Neutrosophic Mechanical Performance Retention Index (N-MPRI) and the Neutrosophic Degradation Index (NDI). Moena itauba showed the highest density (0.68 g/cm3). MOR and MOE decreased significantly in cedro and huayruro, compression decreased significantly in all species, and MOE improved significantly in tornillo. The CRITIC-TOPSIS model ranked moena itauba (CC = 0.677) and tornillo (CC = 0.585) with the highest structural aptitude under uncertainty, followed by huayruro (CC = 0.412) and almendro (CC = 0.409), while cedro obtained the lowest aptitude

(CC = 0.303); these results were consistent with the N-MPRI and the NDI, and were confirmed as reasonably robust by a sensitivity analysis using five weighting schemes and four indeterminacy levels.

Keywords: neutrosophy; CRITIC-TOPSIS; glued laminated timber; finger joints; mechanical retention; structural uncertainty

1. INTRODUCTION

Finger-jointed glued laminated timber is a well-established alternative for structural use from short commercial-dimension wood. Meyer et al. [9] found that glued laminated poplar wood can reach a compressive strength above 40 N/mm2 and an average modulus of elasticity of 12 N/mm2, while Ndong Bidzo et al. [12] reported that the mechanical performance of tropical laminated beams depends largely on the position of the lamina and the finger joint within the section, factors that condition the loss of bending strength without necessarily affecting stiffness. Ngadianto et al. [13] and Mohamad et al. [10] showed that lamina configuration, whether in single or mixed tropical fast-growing species, modifies the modulus of rupture and the modulus of elasticity of the laminated product in a non-uniform way, and Vafadar et al. [16], using digital image correlation, demonstrated that the local stiffness of a finger joint inside a laminated beam can differ substantially from that measured in individual specimens. Bourscheid and Figueiredo [3] indicated that reinforcing finger-joint zones with fibers improves the performance of laminated Eucalyptus spp., and Cañola et al. [4] showed that toothed metal plates increase the homogeneity and load-bearing capacity of Glulam beams. These studies agree on one point: the effect of lamination and finger jointing on mechanical properties is not uniform, but depends on the species, the mechanical property evaluated and the quality of the gluing process.

This lack of uniformity raises a methodological problem that classical statistical tests, applied property by property, do not fully resolve. Comparing density, PLS, MOR, MOE and compression in isolation shows whether significant differences exist between solid and laminated wood, but cannot answer a question of greater interest for structural design: when mechanical indicators behave contradictorily (for instance, a species that gains stiffness but loses compressive strength, or whose difference is significant in one test but not in another), which species retains the best overall structural aptitude after moving from solid to laminated wood? Answering this requires a framework able to represent favorable evidence, unfavorable evidence and statistical indeterminacy simultaneously, and to combine them into a single decision criterion.

Neutrosophic set theory, proposed by Smarandache [15] and formalized as single-valued neutrosophic sets (SVNS) by Wang et al. [17], provides such a framework: each alternative is represented by a triplet (T, I, F) that expresses, independently, the degree of truth or favorable evidence (T), the degree of indeterminacy (I) and the degree of falsity or unfavorable evidence (F). Unlike classical fuzzy logic, neutrosophy does not require T and I+F to be complementary, which makes it suitable for modeling experimental data in which statistical significance, and not only the magnitude of change, is part of the evidence. Combined with multi-criteria decision-making (MCDM) methods, neutrosophy has been applied to objective criteria weighting through CRITIC [5] and to alternative ranking through TOPSIS [7], producing hybrid neutrosophic CRITIC-TOPSIS schemes recently used in material selection and in engineering problems with incomplete or contradictory information [8]. To the best of the authors' knowledge, this integration has not yet been applied to the comparative evaluation of forest species for structural laminated timber, which is the methodological opportunity addressed by this study.

Given that the city of Pucallpa is an industrial hub dedicated to the mechanical transformation of forest wood, there is a need to make productive use of the short commercial wood of cedro, huayruro, almendro, moena itauba and tornillo, species for which no consolidated structural reuse alternative currently exists. This raises the questions of whether short commercial wood, transformed into finger-jointed laminated timber, can constitute a viable structural alternative, how to evaluate the structural aptitude of these species when mechanical indicators show contradictory behavior and different levels of uncertainty, and which species offers the best combination of strength, stiffness and retention of mechanical properties when moving from solid to laminated wood. The general objective of this study was therefore to comparatively assess the structural performance of finger-jointed glued laminated timber from five forest species by integrating physical-mechanical indicators, statistical analysis and a neutrosophic multi-criteria model able to quantify uncertainty, determine the retention of mechanical properties and establish the relative structural aptitude of each species.

2. MATERIALS AND METHODS

This applied, technological, experimental-level study was carried out in the carpentry workshop and the wood technology laboratory of Universidad Nacional de Ucayali. Five tropical forest species were used to manufacture finger-jointed glued laminated timber: cedro (Cedrela odorata L.), tornillo (Cedrelinga cateniformis (Ducke) Ducke), almendro (Caryocar glabrum (Aubl.) Pers.), moena itauba (Aniba perutilis Hemsl.) and huayruro (Ormosia coccinea (Aubl.) Jacks.). The population consisted of 250 board feet of short commercial wood obtained from first-transformation industries in the district of Manantay, province of Coronel Portillo, Ucayali region, air-dried for approximately 45 days to a moisture content of 19%. The sample comprised 10 solid-wood specimens and 10 laminated-wood specimens per species (100 specimens in total), each measuring 5 cm x 5 cm x 76 cm.

Wood blocks were sawn into laminae 1.5 cm thick and 5 cm wide. Finger joints, vertically oriented, were produced at the Inforhuay SAC facility: the ends of the laminae were first joined into a continuous finger-jointed piece under 1200 kg of horizontal pressure and a glue weight of 200 g/cm2, after which the laminae were pressed together at 1200 kg to form a four-lamina block with a final 5 cm x 5 cm cross-section. Mechanical tests were performed on a Tinius Olsen universal testing machine (30-ton capacity) following standards NTP 251.016 (compression test) and NTP 251.012 (static bending), determining basic density, proportional limit stress (PLS), modulus of rupture (MOR), modulus of elasticity (MOE) and compression parallel to the grain in both solid and laminated wood. Solid and laminated wood of each species were compared using the independent-samples t-test, with significance levels of 0.05 (significant) and 0.01 (highly significant); this classical analysis provided the empirical basis on which the neutrosophic representation described below was built.

2.1 Neutrosophic CRITIC-TOPSIS model for structural aptitude under uncertainty

To overcome the limitation of evaluating each mechanical property in isolation, a five-stage procedure was designed to transform the experimental results into a single criterion of structural aptitude under uncertainty: (1) calculation of the mechanical retention ratio, (2) neutrosophic representation of each species-criterion pair, (3) neutrosophic CRITIC weighting, (4) neutrosophic TOPSIS ranking and (5) sensitivity analysis. The model was applied to the three criteria for which an inferential significance test was available between solid and laminated wood: MOR, MOE and compression parallel to the grain. Basic density was kept as a descriptive reference indicator, and PLS was analyzed through its PLS/MOR ratio, since neither had an inferential test from which a statistical indeterminacy component could be built.

a) Mechanical retention ratio (RR). For each species i and criterion j, the ratio between the mean value in laminated wood and the mean value in solid wood was calculated: $RR_{ij} = X_{laminated,ij} / X_{solid,ij}$. A value of RR greater than or equal to 1 indicates that the property was maintained or improved by lamination; a value below 1 indicates a loss of performance.

b) Neutrosophic representation (T, I, F). For each species i and criterion j, a single-valued neutrosophic number was built from RR_{ij} and the p-value of the corresponding independent-samples t-test (p_{ij}), according to the following expressions:

$$\mathbf{T_{ij} = \min(RR_{ij} / RR_{max,j} \,;\, 1)}$$

$$\mathbf{F_{ij} = \max(0 \,;\, 1 - \min(RR_{ij} \,;\, 1)) \times (1 - p_{ij})}$$

$$\mathbf{I_{ij} = p_{ij}}$$

where $RR_{max,j}$ is the highest retention ratio observed for criterion j among the five species. The T component expresses the favorable evidence of retention, normalized against the species with the best relative performance for that criterion; the F component expresses the magnitude of the performance loss (1 - RR) weighted by the statistical confidence that the loss is real (1 - p); and the I component expresses the indeterminacy of the comparison, given directly by the p-value of the t-test: the higher the probability that the observed difference is due to chance, the higher the indeterminacy. When RR_{ij} is greater than or equal to 1 (full retention or improvement), F is set to 0, since there is no loss to attribute to statistical uncertainty.

c) Neutrosophic scoring function. For the weighting and ranking stages, the score $S_{ij} = (2 + T_{ij} - I_{ij} - F_{ij}) / 3$ was used, a function commonly applied in the single-valued neutrosophic set literature, which converts each (T, I, F) triplet into a comparable value in the interval [0, 1] while preserving the meaning of the three components.

d) Neutrosophic CRITIC weighting. Objective weights for the three criteria were obtained by applying the CRITIC method [5] to the score matrix S. The matrix was normalized by the max-min method, the standard deviation of each criterion (contrast) and the Pearson correlation matrix between criteria (conflict) were calculated, and the amount of information $C_j = \sigma_j \times \sum_k (1 - r_{jk})$ was obtained, from which the weight $w_j = C_j / \sum(C_j)$ was derived. Criteria that discriminate better between species and provide less redundant information thus receive a higher weight, without subjective intervention from the researcher.

e) Neutrosophic TOPSIS ranking. On the score matrix S, vector-normalized and weighted with the CRITIC weights, the TOPSIS method [7] was applied: the positive ideal solution (maximum of each criterion) and the negative ideal solution (minimum of each criterion) were determined, the Euclidean distances of each species to both solutions (D^+ and D^-) were calculated, and the relative closeness coefficient $CC_i = D_i^- / (D_i^+ + D_i^-)$ was obtained. Species were ranked from highest to lowest CC, the highest value indicating the greatest relative structural aptitude.

f) Original indices N-MPRI and NDI. As an additional methodological contribution, two synthetic indices were defined per species. The Neutrosophic Mechanical Performance Retention Index (N-MPRI) was calculated as the CRITIC-weighted average of the neutrosophic scores, $\text{N-MPRI}_i = \sum_j w_j S_{ij}$, and expresses the proportion of the combined mechanical performance that each species retains when moving from solid to laminated wood. The Neutrosophic Degradation Index (NDI) was calculated as $NDI_i = \sum_j w_j (F_{ij} + 0.5 I_{ij})$, and quantifies each species' combined exposure to statistically confirmed performance loss and unresolved uncertainty, i.e., how sensitive each species is to the lamination and finger-joint process.

g) Sensitivity analysis. To verify that the species ranking did not depend exclusively on the CRITIC weighting, the neutrosophic TOPSIS was recalculated under four alternative weighting schemes (equal weights and three schemes emphasizing MOR, MOE and compression, respectively) and, independently, the stability of the ranking was evaluated by uniformly scaling the indeterminacy component I with a factor lambda (0, 0.5, 1.0 and 1.5), recalculating the CRITIC weights and the TOPSIS ranking in each case.

3. RESULTS

3.1 Basic density

Table 1. Basic density of the five forest species

Property	Cedro	Tornillo	Almendro	Moena itauba	Huayruro
Basic density (g/cm3)	0.42	0.45	0.65	0.68	0.61

Table 1 shows the basic density of the five species studied. Moena itauba presented the highest basic density (0.68 g/cm3), followed by almendro (0.65 g/cm3), huayruro (0.61 g/cm3) and tornillo (0.45 g/cm3), while cedro presented the lowest basic density (0.42 g/cm3).

3.2 Proportional limit stress and modulus of rupture (PLS/MOR ratio)

Table 2. Proportional limit stress and modulus of rupture of solid and laminated wood of five forest species (kg/cm2)

Species	Condition	PLS	MOR	PLS/MOR
Cedro	Solid	338.87	475.50	0.71
Cedro	Laminated	143.97	340.76	0.42
Tornillo	Solid	145.33	156.73	0.93
Tornillo	Laminated	173.90	197.50	0.88
Almendro	Solid	166.34	192.10	0.87
Almendro	Laminated	139.36	146.35	0.95
Moena itauba	Solid	168.94	209.30	0.81
Moena itauba	Laminated	171.25	217.70	0.79
Huayruro	Solid	333.98	548.01	0.61
Huayruro	Laminated	149.12	156.20	0.95

The PLS/MOR ratio indicates the proportion between the point where the stress-strain relationship stops being linear and the maximum load-bearing capacity of the piece. Solid cedro shows little difference between the elastic zone and maximum strength, while laminated cedro shows a larger difference. Solid tornillo behaves almost linearly to failure, whereas laminated tornillo shows a deformation margin of 12% before rupture. Solid almendro has a small non-linear zone (13%), while laminated almendro fails almost immediately after PLS (5%). Solid moena itauba works elastically up to 81% of its maximum capacity, and laminated moena itauba up to 79%. Solid huayruro shows a margin of 39% between the end of linear behavior and rupture, while laminated huayruro reaches only 5%, indicating that finger jointing markedly reduces the available plastic deformation margin before failure in this species.

3.3 Mechanical properties: independent-samples t-test (MOR, MOE and compression)

Table 3. Independent-samples t-test for the modulus of rupture, modulus of elasticity and compression parallel to the grain of solid and laminated wood of five forest species (kg/cm2)

Species	Property	Solid wood	Laminated wood	t	df	p-value
Cedro	MOR	475.50	340.76	3.829	18	0.001**
Tornillo	MOR	156.73	197.50	-1.422	19	0.171 NS
Almendro	MOR	192.10	146.35	1.560	18	0.136 NS
Moena itauba	MOR	209.30	217.70	-0.377	18	0.711 NS
Huayruro	MOR	548.01	156.20	7.673	18	0.000**
Cedro	MOE	53451.50	10856.30	25.670	18	0.000**
Tornillo	MOE	52927.27	66720.00	-4.031	18	0.001**
Almendro	MOE	66010.00	51780.00	4.251	18	0.000**
Moena itauba	MOE	61950.00	68390.00	-0.970	18	0.350 NS
Huayruro	MOE	96450.00	54673.00	3.943	18	0.001**
Cedro	Compression	198.57	89.36	51.146	18	0.000**
Tornillo	Compression	126.68	60.81	17.346	18	0.000**
Almendro	Compression	281.51	126.68	18.556	18	0.000**
Moena itauba	Compression	378.39	324.21	5.648	18	0.000**
Huayruro	Compression	413.77	310.32	18.237	18	0.000**

*Note: ** highly significant; NS = not significant.*

MOR differed highly significantly between solid and laminated wood in cedro and huayruro, both with a reduction of the mean value, while tornillo, almendro and moena itauba showed no significant differences. MOE decreased highly significantly in cedro, almendro and huayruro, increased significantly in tornillo, and did not differ significantly in moena itauba. Compression parallel to the grain decreased highly significantly in all five species, with a considerable reduction in load-bearing capacity across the board.

3.4 Mechanical retention ratio (RR)

Table 4. Mechanical retention ratio (laminated wood / solid wood) by species and property

Species	RR PLS	RR MOR	RR MOE	RR Compression
Cedro	0.42	0.72	0.20	0.45
Tornillo	1.20	1.26	1.26	0.48
Almendro	0.84	0.76	0.78	0.45
Moena itauba	1.01	1.04	1.10	0.86
Huayruro	0.45	0.28	0.57	0.75

Table 4 summarizes, for each species, the proportion of the solid-wood value that is retained in laminated wood. A value close to or above 1 indicates full retention or improvement of performance; a low value indicates a marked loss. Cedro showed the lowest retention in three of the four properties (PLS, MOE and compression), while tornillo and moena itauba were the only species with RR above 1 in PLS, MOR and MOE. Compression parallel to the grain was, for all five species, the property with the lowest relative retention, confirming that finger-jointed lamination affects compressive capacity more broadly than bending strength or stiffness.

3.5 Neutrosophic CRITIC-TOPSIS model, N-MPRI and NDI

Table 5. Neutrosophic decision matrix (T, I, F), relative closeness coefficient (TOPSIS), N-MPRI and NDI by species

Species	MOR (T,I,F)	MOE (T,I,F)	Compression (T,I,F)	CC (TOPSIS)	Rank	N-MPRI	NDI
Moena itauba	0.83/0.71/0.00	0.88/0.35/0.00	1.00/0.00/0.14	0.677	1	0.852	0.216
Tornillo	1.00/0.17/0.00	1.00/0.00/0.00	0.56/0.00/0.52	0.585	2	0.830	0.274
Huayruro	0.23/0.00/0.72	0.45/0.00/0.43	0.88/0.00/0.25	0.412	3	0.717	0.433
Almendro	0.61/0.14/0.21	0.62/0.00/0.22	0.53/0.00/0.55	0.409	4	0.719	0.393
Cedro	0.57/0.00/0.28	0.16/0.00/0.80	0.53/0.00/0.55	0.303	5	0.647	0.520

Note: CRITIC weights, MOR = 0.310, MOE = 0.214, compression = 0.477.

The highest indeterminacy values corresponded to moena itauba in MOR (I = 0.71) and MOE (I = 0.35), matching the cases in which the t-test detected no significant difference between solid and laminated wood; in these cases the loss component (F) drops to zero, not because there is no variation in the means, but because there is insufficient statistical certainty to attribute that variation to lamination. In contrast, huayruro showed the highest falsity component in MOR (F = 0.72) and cedro the highest in MOE (F = 0.80), representing the performance loss confirmed with the greatest statistical confidence in the study. Compression received the highest CRITIC weight (0.477), since it showed the greatest dispersion among species and the lowest, even negative, correlation with MOR, contributing the least redundant information to the model.

Moena itauba and tornillo obtained the highest relative closeness coefficients (CC = 0.677 and 0.585, respectively, Figure 1), positioning them as the species with the highest relative structural aptitude among the five evaluated; huayruro and almendro occupied a close intermediate position (CC = 0.412 and 0.409), and cedro obtained the lowest value (CC = 0.303). The N-MPRI reproduced the same overall ranking, with moena itauba (0.852) and tornillo (0.830) showing the highest combined mechanical retention and cedro (0.647) the lowest, while the NDI confirmed cedro as the species most sensitive to lamination and finger jointing (NDI = 0.520), followed by huayruro (0.433) and almendro (0.393), with moena itauba as the least affected (NDI = 0.216). The consistency among the three indicators, obtained through different mathematical procedures (geometric distance to ideal solutions for TOPSIS, weighted averages for N-MPRI and NDI), supports the robustness of the ranking obtained.

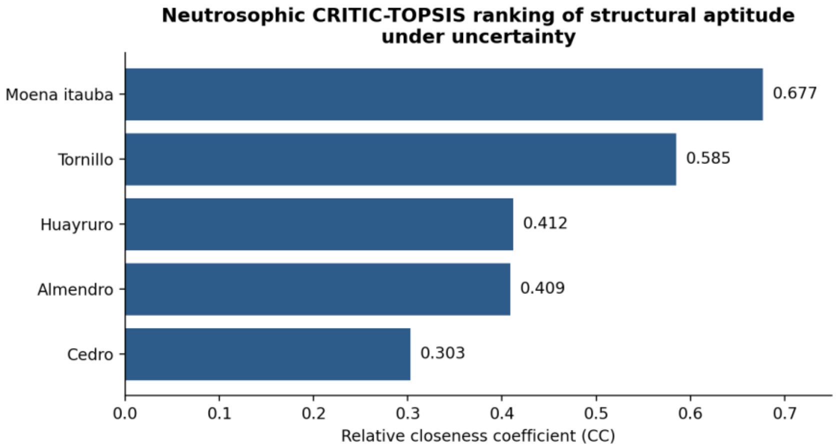

Figure 1. Neutrosophic CRITIC-TOPSIS ranking of structural aptitude under uncertainty

3.6 Sensitivity analysis

Table 6. Neutrosophic TOPSIS ranking under different weighting schemes and indeterminacy levels

Scenario	Weights (MOR, MOE, Compression)	Ranking (highest to lowest aptitude)
CRITIC (base)	0.31 / 0.21 / 0.48	Moena itauba > Tornillo > Huayruro > Almendro > Cedro

Scenario	Weights (MOR, MOE, Compression)	Ranking (highest to lowest aptitude)
Equal weights	0.33 / 0.33 / 0.33	Tornillo > Moena itauba > Almendro > Huayruro > Cedro
Emphasis on MOR	0.60 / 0.20 / 0.20	Tornillo > Almendro > Moena itauba > Cedro > Huayruro
Emphasis on MOE	0.20 / 0.60 / 0.20	Tornillo > Moena itauba > Almendro > Huayruro > Cedro
Emphasis on Compression	0.20 / 0.20 / 0.60	Moena itauba > Huayruro > Tornillo > Almendro > Cedro
Indeterminacy lambda = 0	-	Moena itauba > Tornillo > Almendro > Huayruro > Cedro
Indeterminacy lambda = 1.5	-	Tornillo > Moena itauba > Almendro > Huayruro > Cedro

The sensitivity analysis shows that the model is reasonably robust to changes in criteria weighting: in all five weighting schemes evaluated, including the CRITIC scheme, cedro remained in the last position, and moena itauba and tornillo ranked as the two best-performing species in four of the five scenarios, alternating first and second place depending on which criterion received the greatest weight. The relative order of huayruro and almendro was more sensitive to weighting, indicating that the difference between them is small and depends on the relative importance given to compression versus bending. Scaling the indeterminacy level (lambda) left the ranking stable for lambda <= 1 and altered it only at lambda = 1.5, a scenario that artificially amplifies the weight of moena itauba's uncertainty in MOR and MOE in favor of tornillo; this confirms that moena itauba and tornillo as the two species of highest aptitude, and cedro as the species of lowest aptitude, do not depend on a single model assumption.

4. DISCUSSION

Based on basic density alone, moena itauba would be expected to show the best mechanical properties, followed by almendro and huayruro. However, the neutrosophic CRITIC-TOPSIS model shows that density alone does not predict structural aptitude under lamination: huayruro, despite a relatively high density (0.61 g/cm3), ranks in an intermediate-low position (CC = 0.412), while tornillo, with the second-lowest density (0.45 g/cm3), ranks second (CC = 0.585). This agrees with Parra [14], who reports that density strongly influences gluability, since denser wood absorbs more adhesive and tends to form lower-quality joints unless the gluing pressure is adjusted, so that a high density does not by itself guarantee better retention of mechanical performance after lamination.

The PLS/MOR ratio revealed species-specific failure behavior that is directly reflected in the indeterminacy (I) component of the neutrosophic model. Laminated almendro and huayruro show PLS/MOR ratios close to 1, indicating failure almost immediately after the elastic limit, whereas cedro shows the largest margin between PLS and MOR, that is, a greater deformation capacity before failure. Together with the statistical significance level, these differences in failure type, brittle versus more ductile, are the basis on which the T, I and F components of the model were constructed: a species with consistent behavior and clearly significant differences, such as huayruro in MOR (F = 0.72), contributes loss evidence with high confidence, while a species with non-significant results, such as moena itauba in MOR (I = 0.71), contributes mainly indeterminacy rather than evidence of improvement or loss.

The reduction in MOR observed in cedro and huayruro can be explained by finger-joint quality: a deficient joint yields low bending stresses, and reinforcement with clamps or additional elements has been suggested to address this [6]. Tooth geometry, glue weight per tooth, slope, pitch, length and thickness are determining factors of joint strength [1], and digital image correlation studies show that the local stiffness of a finger joint inside a laminated beam can differ from that measured in isolated joint specimens [16], suggesting that part of the MOR loss observed in cedro and huayruro may relate not only to gluing quality but also to the interaction between the finger joint and the geometry of the laminated section. The gluing process itself depends on surface condition, adhesive mobility and applied pressure [2], factors that, being uneven across species of different density and anatomical structure, help explain why the falsity component (F) of the neutrosophic model is higher in some species than in others. In MOE, the considerable stiffness reduction in cedro, almendro and huayruro is likewise associated with surface quality and wood chemical composition, which can hinder adhesive adherence [14], as well as with inadequate adhesive preparation, pressing time and gluing temperature [2]. In contrast, the significant MOE improvement observed in tornillo is consistent with reports for tropical fast-growing species [13, 10], in which lamina configuration can compensate for the internal variability of lower-density solid pieces, producing a more homogeneous, and in some cases stiffer, laminated product; this is precisely the behavior captured by the T component as favorable retention evidence (T = 1.00 in MOR and MOE for tornillo), explaining why this species is consistently among the two best-performing alternatives in nearly all sensitivity scenarios.

Compression parallel to the grain was the property most affected by lamination in all five species, a result recognized by the CRITIC model through the highest objective weight (0.477): being the criterion with the greatest dispersion among species and the lowest redundancy with MOR, it concentrates much of the model's discriminating power. This generalized reduction points to the need for more efficient gluing and jointing techniques, or metal reinforcement elements that increase the homogeneity and load-bearing capacity of laminated timber [4], since tooth geometry and joint orientation also influence this loss [1], and the finger-jointed zone is known to concentrate stresses that weaken the piece [11], particularly where the number of joints per unit length is proportionally higher, as in compression. Finally, the agreement between the TOPSIS ranking, the N-MPRI and the NDI, three indicators obtained through different mathematical procedures from the same neutrosophic matrix, supports the interpretation that moena itauba and tornillo are the species with the greatest relative aptitude for finger-jointed laminated timber, while cedro is the most sensitive to the lamination process, followed by huayruro and almendro in intermediate positions. This integrated reading, not attainable through property-by-property t-tests alone, shifts the discussion from a descriptive comparison of statistical differences toward a comparative, decision-oriented discussion of which species best retains, overall, the structural aptitude needed to justify its use as laminated timber.

5. CONCLUSIONS

Basic density was highest in moena itauba, followed by almendro and huayruro, while cedro and tornillo showed the lowest values. However, basic density alone did not explain the structural aptitude under lamination obtained by the multi-criteria model.

The proportional limit stress (PLS) of cedro, almendro and huayruro was higher in solid wood and lower in laminated wood; in tornillo and moena itauba, PLS was higher in laminated wood than in solid wood.

The modulus of rupture (MOR) of cedro and huayruro decreased significantly from solid to laminated wood; no significant differences were observed in tornillo, almendro and moena itauba.

The modulus of elasticity (MOE) of cedro, almendro and huayruro decreased significantly from solid to laminated wood; MOE improved significantly in tornillo, and no significant difference was found in moena itauba.

Compression parallel to the grain decreased significantly from solid to laminated wood in all five species, making it the property with the lowest relative retention and the highest objective weight in the CRITIC model.

The neutrosophic CRITIC-TOPSIS model, built from the mechanical retention ratio and the statistical significance level of each comparison, integrated these five results into a single criterion of structural aptitude under uncertainty. Moena itauba (CC = 0.677) and tornillo (CC = 0.585) showed the highest relative structural aptitude, huayruro (0.412) and almendro (0.409) an intermediate aptitude, and cedro (0.303) the lowest among the five species evaluated.

The N-MPRI confirmed this ranking, with moena itauba (0.852) and tornillo (0.830) as the species with the highest combined mechanical retention, and the NDI identified cedro (0.520) as the species most sensitive to lamination and finger jointing, followed by huayruro (0.433) and almendro (0.393), with moena itauba (0.216) as the least affected.

The sensitivity analysis, applied to both criteria weighting and the indeterminacy level, showed that the ranking obtained is reasonably robust: cedro remained in the last position in every scenario evaluated, and moena itauba and tornillo remained the best-performing alternatives in most scenarios, supporting their preferential recommendation for the structural use of finger-jointed glued laminated timber from short commercial wood in the Ucayali region.

Funding: This research received no external funding from any funding agency.

Conflicts of Interest: The authors declare no conflict of interest.

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