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Original article

Mechanical behavior of five non-traditional species for furniture production from shaped parts: Relationship with gluing parameters (viscosity and consumption)

Comportamiento mecánico de cinco especies no tradicionales para producción de muebles a partir de piezas conformadas: Relación con parámetros de encolado (viscosidad y consumo)

Comportamento mecânico de cinco espécies não tradicionais para produção de móveis a partir de peças moldadas: Relação com parâmetros de colagem (viscosidade e consumo)

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ABSTRACT

The industry of the Furniture faces the need to replace traditional, overexploited wood species with others with elderly availability. This study aims to identify the kind of better behavior mechanic for the furniture manufacturing using shaped pieces of wood veneer, starting from the Technical evaluation of 5 species from the EAF Macurijes in Pinar del Río and EAF Costa Sur In Artemisa, a classification method was created to identify the most influential factors in the formation process, highlighting glue consumption, glue viscosity, and species. Ten specimens of each species were analyzed using standardized (GOST) compression, static bending, and splitting tests, processed in laboratories at MICONS and the University of *Pinar* Río, and compared using the nonparametric Kruskal-Wallis test. *citriodora* (Hook.) KDHill & LASJohnson stood out with the highest compressive strength ($71{,}79 \pm 1{,}92\ MPa$) and flexural strength (101.92 ± 3.2 MPa), significantly outperforming other species. Using response surface models (RSM) and the L-BFGS-B algorithm, gluing parameters were optimized, identifying optimal ranges of 140-150 s/BZ4 for viscosity and 170-180 g/m ^{2} for glue consumption. These values maximize mechanical strength and reduce spillage during shaping. The results validate *C. citriodora* as an optimal material for high-performance furniture, offering a sustainable alternative to at-risk species.

Keywords: glue consumption, *Corymbia citriodora,* mechanical resistance, optimization, viscosity.

RESUMEN

La industria del mueble enfrenta la necesidad de sustituir especies maderables tradicionales, sobreexplotadas, por otras con mayor disponibilidad. Este estudio tiene como objetivo identificar la especie de mejor comportamiento mecánico para la fabricación de muebles mediante piezas conformadas de chapas de madera, partiendo de la evaluación técnica de 5 especies provenientes de la EAF Macurijes en Pinar del Río y EAF Costa Sur en Artemisa. Se creó un método clasificatorio para identificar los factores más influyentes en el proceso de conformación, destacando el consumo de cola, la viscosidad de la cola y la especie. Se analizaron 10 probetas por cada especie mediante ensayos normalizados (GOST) de compresión, flexión estática e hienda, procesadas en laboratorios del MICONS y la Universidad de Pinar Río, las cuales se compararon mediante la prueba no paramétrica Kruskal-Wallis. *Corymbia citriodora* (Hook.) K.D.Hill & L.A.S.Johnson se destacó con la mayor resistencia a compresión ($71{,}79 \pm 1{,}92\ MPa$) y flexión (101,92 ± 3,2 MPa), superando significativamente a las demás especies. Mediante modelos de superficie de respuesta (RSM) y el algoritmo L-BFGS-B, se optimizaron los parámetros de encolado, identificando como rangos óptimos 140-150 s/BZ4 para la viscosidad y 170-180 g/m² para el consumo de cola. Estos valores maximizan la resistencia mecánica y reducen derrames durante la conformación. Los resultados validan a *C. citriodora* como material óptimo para mobiliario de alto rendimiento, ofreciendo una alternativa sostenible a especies en riesgo.

Palabras clave: consumo de cola, *Corymbia citriodora*, resistencia mecánica, optimización, viscosidad.

RESUMO

A indústria moveleira enfrenta a necessidade de substituir espécies de madeira tradicionais e superexploradas por outras mais amplamente disponíveis. Este estudo tem como objetivo identificar as espécies com melhor desempenho mecânico para a fabricação de móveis utilizando peças de folheado moldadas. Este estudo baseia-se na avaliação técnica de cinco espécies provenientes do FEA Macurijes em Pinar del Río e do FEA Costa Sur em Artemisa. Um método de classificação foi desenvolvido para identificar os fatores mais influentes no processo de conformação, destacando o consumo de cola, a viscosidade da cola e a espécie. Dez corpos de prova de cada espécie foram analisados por meio de ensaios padronizados (GOST) de compressão, flexão estática e fendilhamento. Esses ensaios foram processados nos laboratórios do MICONS e da Universidade de Pinar Río. Esses ensaios foram comparados por meio do teste não paramétrico de Kruskal-Wallis. Corymbia citriodora (Hook.) K.D.Hill & L.A.S.Johnson destacou-se com as maiores resistências à compressão (71,79 ± 1,92 MPa) e à flexão (101,92 ± 3,2 MPa), superando significativamente as demais espécies. Utilizando a modelagem de superfície de resposta (RSM) e o algoritmo L-BFGS-B, os parâmetros de colagem foram otimizados, identificando faixas ótimas de 140-150 s/BZ4 para viscosidade e 170-180 g/m2 para consumo de cola. Esses valores maximizam a resistência mecânica e reduzem o derramamento durante a conformação. Os resultados validam C. citriodora como um material ideal para móveis de alto desempenho, oferecendo uma alternativa sustentável para espécies em risco.

Palavras-chave: consumo de cola, Corymbia citriodora, resistência mecânica, otimização, viscosidade.

INTRODUCTION

The furniture industry in Cuba faces a dual challenge: meeting the demand for materials with robust mechanical properties and, at the same time, mitigating the overexploitation of traditional wood species such as *Swietenia mahagoni* (L.) Jacq and *Cedrela odorata* L., whose populations are declining drastically (Valdés *et al.* 2022; 2014) . This problem has prompted the search for sustainable alternatives, among which fast-growing species such as *Eucalyptus stand out. sp* . and *Pinus caribaea* Morelet var. *caribaea* Barret & Golfari, widely available in regions such as Pinar del Río and Artemisa (Valdés *et al.* 2022) . However, its industrial adoption requires technical validation of its suitability for advanced processes, such as the formation of glued curved pieces using wood veneers, a technology that combines design versatility with production efficiency (Panić, Nezirević and Hodžić 2016; Ramos 2014)

Previous studies (Cordero, Álvarez, and Estévez 2022) have evaluated the basic properties of these species; however, they have not characterized their performance by varying specific technological parameters, such as viscosity and glue consumption, factors that, according to Pizzi and Mittal (2003), determine the structural integrity of the parts. This omission limits the ability to predict the actual behavior of materials in complex industrial processes, where the interaction between technical variables can significantly affect final quality.

Currently, there is a need to develop studies that address these limitations through a multidisciplinary approach that integrates standardized tests (GOST standards), numerical and statistical methods, response surface models, and nonlinear optimization methods, as well as the design of innovative classification methods to prioritize key variables. These tools will allow not only the systematic evaluation of critical parameters and the establishment of quantitative relationships between technological variables and mechanical properties, but also the integration of qualitative criteria derived from the experience of specialists, by transforming them into classifiable hierarchical indices, for informed decision-making.

To address this problem, this research aims to identify the non-traditional species of better behavior mechanic for the furniture manufacturing using shaped pieces of wood veneer, starting from the Technical evaluation of 5 species from the Macurijes Agroforestry Company (EAF) in Pinar del Río and EAF Costa Sur in Artemis.

This study will contribute significantly to the furniture sector in our country, since it will allow us to select non- traditional species with optimal performance mechanic for the manufacturing of shaped parts, reducing the dependence on increasingly scarce species. In addition, technical gluing parameters must be established to work with these species in a way that maximizes their mechanical strength and the productive efficiency of the process.

MATERIALS AND METHODS

Geographic location of the study area

The Macurije Agroforestry Company is located in the westernmost region of Pinar del Río province, encompassing parts of the municipalities of Guane and Mantua. It borders the coastline to the north, from Baja Inlet to Garnacha Inlet; to the east, the municipality of San Juan y Martínez, which belongs to the Pinar del Río Agroforestry Company; to the south, the municipality of Sandino, which belongs to the Guanacahabibes Agroforestry Company (EAF); and to the southeast, the Gulf of Mexico coast (Martínez *et al.* 2022) .

The Costa Sur Agroforestry Company is located in the west of Artemisa province and has forest assets in all 11 municipalities. It borders the Atlantic Ocean to the north, the Caribbean Sea to the south, Havana province to the east, and Pinar del Río province to the west (Valdés, Álvarez, and Fernández 2021) (Figure 1).

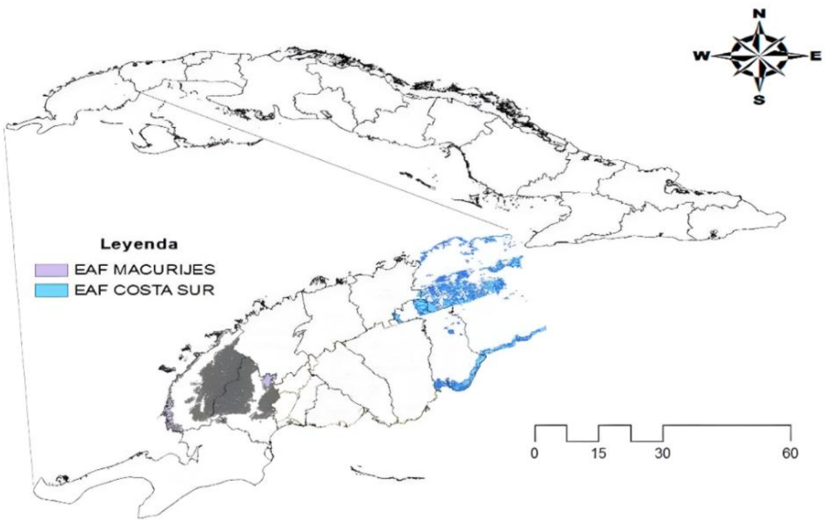

Fig. 1*Geographic location of the study area*

Prior preparation

To make the wood veneers, 10 logs were taken from *Pinus caribaea* Morelet var. *caribaea* Barret & Golfari, *Eucalyptus saligna* Sm., *Corymbia citriodora* (Hook.) KDHill & LASJohnson from the Macurije Agroforestry Company *and* 10 *of Bursera simaruba* (L.) Sarg. and *Cedrela odorata* L. from the Costa Sur Agroforestry Company; these were subjected to prior hydrothermal preparation to achieve optimal wood plasticity, thus facilitating the debarking and unwinding processes.

This hydrothermal treatment consisted of spraying the logs with water at room temperature, using sprinklers that moistened them periodically for 15 days. The logs were processed at the Camilo Cienfuegos Central, located in the municipality of Quivican, province of Mayabeque.

Determination of the main factors influencing the manufacturing process of glued curved parts

To identify the factors influencing the veneer forming process, a survey was conducted among wood technology specialists and forestry researchers.

Participants were presented with a list of factors (Table 1) potentially relevant to the strength of formed parts and were asked to assign each factor a value ranging from 1 to 12, which characterizes its role in the process; 1 being the most important and 12 the least.

Table 1- *Factors influencing the veneer forming process*

Notation	Factors
x_1	Species
x_2	Surface roughness
x_3	Cola consumption
x_4	Glue viscosity
x_5	Specific forming pressure
x_6	Mold surface heating temperature
x_7	Humidity of wood veneers
x_8	Gluing exposure time
x_9	Ambient temperature
x_{10}	Tail type
x_{11}	Sheet thickness
x_{12}	Gluing method

To analyze the survey results, it was assumed that each factor $x_i(i \in \mathbb{N}, 1 \leq i \leq 12)$ is associated with a continuous function $f_i(e)$, which assigns to each specialist $e = 1,2,3,\cdots,12$the value given by him to the factor x_i. To quantify the cumulative importance of each factor, these functions were numerically integrated using the trapezoid method (Sauer 2012) , taking advantage of the equidistance between the points $(h = 1)$: Equation 1)

$$\int_1^{12} f_i(e)\, de \approx h\left(\frac{1}{2} f_i(e_1) + f_i(e_2) + \cdots + f_i(e_{11}) + \frac{1}{2} f_i(e_{12})\right) \quad (1)$$

thresholding function was designed (Equation 2 and 3):

$$d(m) = \begin{cases} 0, & m = 0 \\ 20 \sum_{i=1}^{m} (3 - i + 1), & m \neq 0 \end{cases}, \quad m = 0,1,2,3 \quad (2)$$

where:

- m: *cluster number* ($m = 0$*is a reference empty cluster),*
- $d(m)$:*maximum value allowed for cluster elements* m.

Then, a factor $x_i$is assigned to the cluster m, if it satisfies:

$$d(m-1) \leq \int_1^{12} f_i(e)\, de < d(m) (3)$$

The analysis of these groups of factors allowed us to develop the strategy for subsequent experiments.

Determination of the mechanical resistance of the parts

Rectangular prism-shaped specimens were used according to GOST 9623-87, GOST 9624-2009, GOST 9625-2013 standards. For each species, 5 glued curved blocks were made, of which 10 specimens per block were processed for a total of 50 specimens per mechanical test, following the methodology of Álvarez (1991), cited by Cordero, Álvarez and Estévez (2022) . The dimensions of the specimens in the tests carried out were as follows:

1) Compressive strength:10 $mm \times 20\ mm \times 100\ mm$
2) Static flexural strength:10 $mm \times 20\ mm \times 150\ mm$
3) Resistance to cleft:15 $mm \times 30\ mm \times 150\ mm$

During the experiments, carried out in the laboratories of MICONS and the University of Pinar del Río, the action time of the force directed and applied to the test piece was 60 seconds and the following experimental factors were kept constant:

- Humidity of the sheets:6 %
- Forming temperature:90 ℃
- Forming time: 1 min/mmpackage thickness
- Glue type: urea formaldehyde
- Resin viscosity:140 $s/BZ4$
- Cola consumption:160 g/m^2
- Catalyst: NH4Cl2 at 1 %concentration
- Glue hardening speed at 90 °C:75 seg

Dunn-Bonferroni correction was used, because some of the data did not meet the assumption of normality.

For the species that exhibited the greatest mechanical resistance (C. *citriodora)* in the previous tests, a complete factorial design with 3 levels per factor ($3^2 = 9$) was implemented, evaluating:

- Glue viscosity:$60, 120, 180$ s/BZ4
- Cola consumption:$100, 180, 260$ g/m^2

Second-order response surface models (RSMs) were generated for each resistance, normalizing the variables using standard scaling (Myers, Montgomery, and Anderson-Cook 2009; Montgomery 2013) . The significance of the terms was validated with p-values ($< 0,05$) and goodness of fit was measured with $R^2$and $R^2_{ajustado}$.

To maximize each resistance, the nonlinear optimization algorithm L-BFGS-B was implemented with multiple initial points to avoid convergence to local optima. The search ranges were set according to experimental limits.

Finally, the individual models were integrated into a weighted multi-objective function, assigning weights according to the technical relevance of each resistance, defining an optimal operating zone where the combined performance exceeds the 95 %theoretical maximum.

Computational tools

Data analysis was implemented in Python 3.9.6, using the following libraries:

- SciPy: For numerical optimization (L-BFGS-B method) and non-parametric Kruskal-Wallis statistical testing.
- scikit-learn: Building response surface models (RSM) with polynomial regression.
- scikit-posthocs: Applying non-parametric post-hoc tests (Dunn-Bonferroni) after significant results in Kruskal-Wallis.
- statsmodels: Validation of statistical significance using p-values and calculation of R^2y $R^2_{ajustado}$adjusted for the models.

- Matplotlib: Generation of 3D response surface plots and contour maps.

RESULTS AND DISCUSSION

Analysis of the main factors influencing the manufacturing process of glued curved parts

The analysis of the survey results from Equation (1) , the function defined in (2) and the relationship (3) , allowed the factors to be classified into three clusters according to their relative impact on mechanical resistance, with cluster I being the most influential, and cluster III the least influential.

I. $x_7, x_3, x_4, x_{10}, x_1, x_5$

II. x_8, x_6, x_{12}

III. x_2, x_{11}, x_9

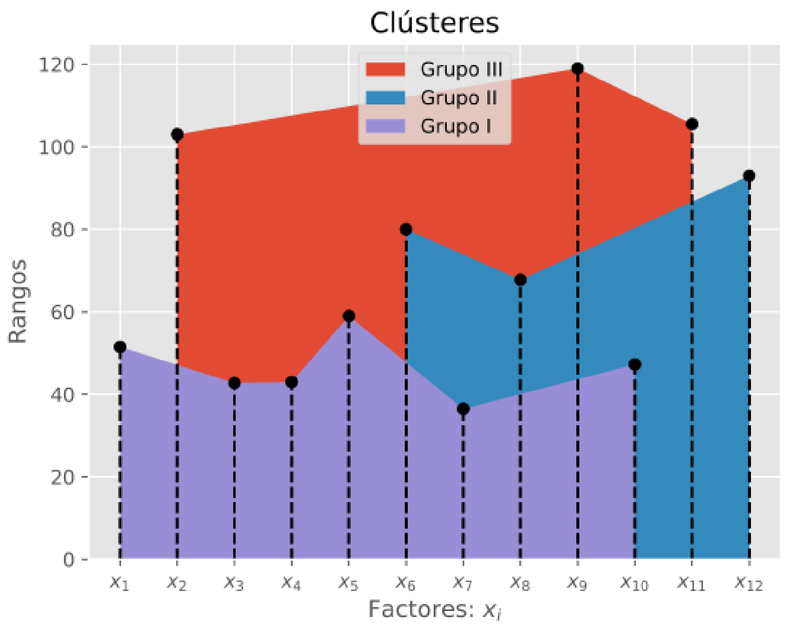

Fig. 2- *Representation of the clusters obtained for the factors* $\boldsymbol{x_i}$

Taking into account the factors that make up cluster I, it was decided to carry out the analysis of the mechanical resistance of the pieces of various species to determine which of them is the best option, so that in the general experiment only that species will be taken (x_1).

With the species established, the experiment focused on optimizing the technological parameters glue consumption (x_3) and glue viscosity (x_4), given their correlation and their role in gluing strength. The factors (x_5, x_7) were kept constant at standard levels, and urea formaldehyde glue) was used (x_{10}as it is one of the most widely used).

Analysis of the mechanical resistance of the parts

The results obtained (Table 2) indicate that the species analyzed meet the international mechanical requirements for glued bentwood veneer technology applied to the furniture industry. The species of the genus *Eucalyptus Corymbia* stood out significantly *citriodora* recorded the highest compressive strength (71.78 ± 1.92 MPa), followed by *Eucalyptus saligna* (70.62 ± 1.28 MPa), significantly exceeding the other species studied ($p < 0{,}0000$), coinciding with Cordero *et al.* (2022) .

Table 2- *Comparison of the average values of the mechanical resistance of the wood sheets*

Species	Mean ± Standard Deviation		
	Compression (MPa)	**Static bending (MPa)**	**Cleavage (MPa)**
Pinus caribaea	62.83 ± 3.36 ^{ab}	71.41 ± 2.96 ^{c}	0.34 ± 0.05 ^{bc}
Eucalyptus saligna	70.62 ± 1.28 ^{a}	99.30 ± 1.50 ^{ab}	0.38 ± 0.04 ^{ab}
Corymbia citriodora	71.78 ± 1.92 ^{a}	101.92 ± 3.20 ^{a}	0.39 ± 0.03 ^{a}
Bursera simaruba	34.51 ± 1.06 ^{b}	67.22 ± 1.70 ^{c}	0.33 ± 0.02 ^{c}
Cedrela odorata	37.39 ± 1.70 ^{b}	98.30 ± 3.34 ^{bc}	0.38 ± 0.03 ^{ab}

Note: Different letters indicate significant differences ($p < 0.05$).

The combination of high static flexural strength in *Corymbia citriodora* (101.92 ± 3.20 MPa) and *Eucalyptus saligna* (99.30 ± 1.50 MPa), together with their compressive performance, suggests that these species are optimal for structural components. While Pupo *et al.* (2018) warn about growth stresses in *Eucalyptus sp* . which cause deformations during sawing, the use of laminated veneers, as in this study and in Cordero Quintans *et al.*

(2022), mitigates these effects by redistributing stresses, maximizing its intrinsic strength.

Regarding resistance to cleft, the results confirm that *Corymbia citriodora* (0.39 ± 0.03 MPa) and *Cedrela odorata* (0.38 ± 0.03 MPa) They exhibit efficient adhesion, which is critical for the structural integrity of glued pieces. This is consistent with the observation made by Cordero *et al.* (2022) that these species bond well.

Corymbia pieces citriodora depending on consumption and glue viscosity

The normalized RSM models for compressive (Γ_{comp}), flexural (Γ_{flex}) and split (Γ_{hienda}) strengths, described in Equations (4), (5) and (6), showed a statistically robust fit, explaining more than 80% of the data variability. All model terms (linear, quadratic and interaction) were significant ($p < 0{,}05$) evidencing the non-linear influence of viscosity and glue consumption, coinciding with that reported by (Jerásio *et al*. 2021) in their study on adhesives in *Eucalyptus sp.*

$$\Gamma_{comp} = 58,262 + 4{,}745x_3 + 3{,}672x_4 - 4{,}224x_3^2 - 2{,}950x_4^2 - 3{,}715x_3x_4 (4)$$

$$\Gamma_{flex} = 106,672 - 0{,}624x_3 + 13{,}952x_4 - 12{,}895x_3^2 - 2{,}449x_4^2 - 5{,}236x_3x_4 (5)$$

$$\Gamma_{hienda} = 0{,}408 - 0{,}006x_3 + 0{,}005x_4 - 0{,}044x_3^2 + 0{,}015x_4^2 - 0{,}029x_3x_4 (6)$$

Jerásio *et al.* (2017) and Jerásio et *al.* (2021) highlighted that the heterogeneous porosity of *Eucalyptus sp* . demands a balance between adhesive penetration (favored by low-medium viscosity) and cohesive layer formation (requiring medium-high consumption). Our RSM models ($R^2 > 0{,}8$) support this duality: compressive strength was maximized at moderate viscosity ($\sim 135\ s/BZ4$) and high consumption ($\sim 210\ g/m^2$), while bending required higher viscosity ($\sim 180\ s/BZ4$) to compensate for reduced consumption ($\sim 170\ g/m^2$) (see Fig. 3, Table 3). This trade-off reflects the dilemma between penetration and continuous adhesive line formation, also described in studies with phenolic adhesives for porous woods.

Table 3- *Optimum values of viscosity, glue consumption and maximum strength obtained by RSM and L-BFGS-B*

	Goo ($\boldsymbol{s/BZ4}$)	Cola consumption ($\boldsymbol{g/m^2}$)	Maximum resistance ($\boldsymbol{MPa}$)
$\boldsymbol{\Gamma_{comp}}$	135.4	209.5	59.91
$\boldsymbol{\Gamma_{flex}}$	180.0	170.8	116.16
$\boldsymbol{\Gamma_{hienda}}$	123.2	176.4	0.41

According to Table 3, maximum strengths are achieved with viscosity between $120 - 180\ s/BZ4$and glue consumption between $170 - 210\ g/m^2$. However, applying consumptions higher than 180 $g/m^2$is technically impractical due to glue spillage when joining the sheets. Therefore, it is proposed to increase the viscosity and limit the consumption to a maximum of 180 $g/m^2$to optimize the process, coinciding with the observations of Jerásio, *et al.* (2021) and Jerásio *et al.* (2017) in structural adhesives applied to *Eucalyptus grandis* where consumption $> 200\ g/m^2$generated internal stress due to excess polymeric material.

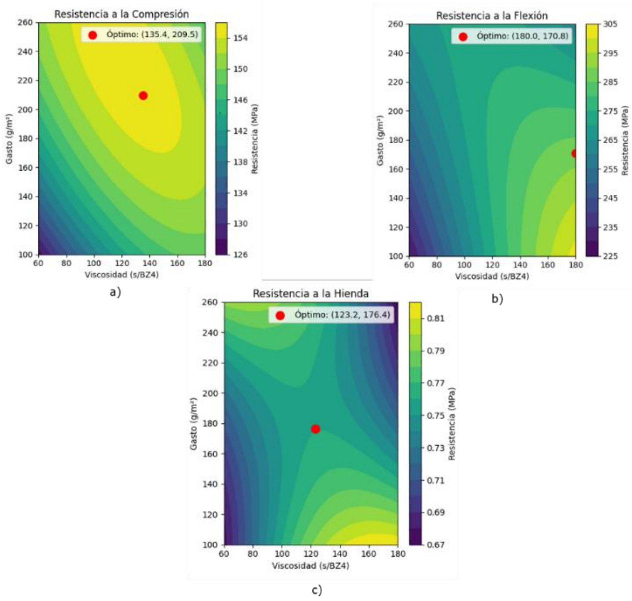

Fig. 3- *Contour lines of the response surfaces for compressive strength a), flexural strength b) and splitting strength c) with indication of the optimal points*

Weighted optimization (20 % compression,40 % flexion,40 % (cleft) identified a break-even point at $x_3 = 180{,}0\ g/m^2$and $x_4 = 147{,}7\ s/BZ4$, reaching the 92 %maximum combined performance (Fig. 4). Therefore, the recommended operating area is the region within the ranges:

- Cola consumption:$170 - 180\ g/m^2$
- Glue viscosity:$140 - 155\ s/BZ4$

This region balances technical efficiency and operational robustness, ensuring greater than the theoretical maximum for compressive strength 85 %, and greater than the 90 %theoretical maximum for flexural and splitting strength.

The discrepancy between the individual optima (Table 3) and the weighted solution (Fig. 4) reveals that parameter selection depends on the final application. For example, in structural elements where bending is critical (40% weight in the optimization), increasing the viscosity compensates for the 180 $s/BZ4$consumption reduction , aligning with the conclusions of Jerásio et *al.* (2021) for joints subjected to dynamic loads.

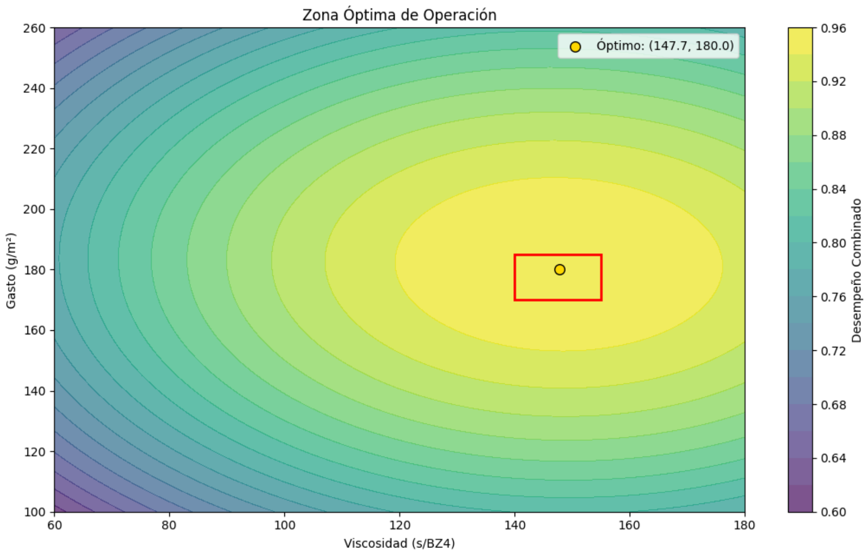

Fig. 4- *Combined performance map and optimal operating zone*

This region not only maximizes compressive, flexural, and splitting strengths, but also mitigates glue spillage during compaction, optimizing costs and operational efficiency.

Operating within these ranges ensures a balance between technical robustness and profitability. Additionally, the use of *Corymbia citriodora,* a fast-growing species, aligns the process with sustainability criteria, promoting the substitution of traditional woods at risk of overexploitation.

CONCLUSIONS

Glue consumption, glue viscosity and species (in that order of influence) determine the final quality of the formed parts.

Corymbia Citriodora is positioned as the preferred option for high-performance furniture, due to its superior mechanical resistance.

Corymbia citriodora veneer shaped parts is achieved for a viscosity of $140 - 155\ s/BZ4$and glue consumption of $170 - 180\ g/m^2$, so it is recommended to operate within these ranges.

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***Conflicts of interest*:**

The authors declare no conflicts of interest.

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The authors have participated in the writing of the work and analysis of the documents.