

MATERIAL-EFFICIENT PRODUCTION OF LIGHTWEIGHT THREE-LAYER PARTICLEBOARDS FROM LOW-GRADE HARDWOOD ASSORTMENTS WITH VARIABLE WOOD SPECIES CONTENT

Evaluation of Mechanical-Technological Properties

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Abstract:

*In two sub-studies, lightweight, three-layer particleboards with a raw density of 650 kgm⁻³ were produced from defined particle mixtures of the wood species *Betula pendula*, *Fagus sylvatica*, *Alnus glutinosa* and *Populus* spp. Particleboards with densities of 600 kgm⁻³ and 550 kgm⁻³ were also produced for selected particleboard mixtures. In addition, three-layer particleboards were produced with surface layer particles from *Picea abies* and core layer particles from not debarked branch wood of *Tilia cordata* with a bulk density of 600 kgm⁻³. Urea-formaldehyde resin was used as the binder in each case. The mechanical-technological properties of the particleboards were evaluated using standardized test methods. The moduli of elasticity, the internal bond strengths and the surface soundness of all the particleboards produced met the requirements of EN 312 for type P2 particleboards. Only the limit value for bending strength was slightly undercut by the particleboards with a bulk density of 550 kgm⁻³. Overall, it was possible to produce standard-compliant, lightweight particleboards from wood species mixtures of low-grade hardwood assortments.*

Key Words: *hardwood utilization; particleboard; raw material substitution; resource utilization.*

INTRODUCTION

The fundamental suitability of hardwood species for producing three-layer particleboards is well-known (Grigoriou 1981, Roffael and Dix 1988, Marutzky and Schwab 2009, Thole 2012) and extensively researched (Kehr and Schilling 1965, Buchholzer 1988). Global demand for wood and wood-based products has been continuously rising for years. A stagnation of this increasing demand is not expected in the coming decades (FAO 2022). On a product level, particleboards are one of the key drivers of this demand increase (FAO 2022). An increase of 72 % by 2050, starting from 2020, is forecasted for the particleboard and fiberboard market, followed by a 30 % increase in sawn timber products and 5 % for pulp products.

This growing demand is met with a declining supply of homogeneous softwood assortments, currently the dominant raw material for these product groups, including particleboard production. The increasing scarcity of softwood resources highlights the medium-term need to reduce wood consumption in particleboard manufacturing (Benthien 2022). In the long term, it will be necessary to identify, evaluate, and develop alternative, sustainable raw material sources for particleboard production. In this context, numerous materials have already been examined for their suitability as raw material sources (Khan et al. 2022, Kibet et al. 2022, Neitzel et al. 2022). These materials include agricultural by-products (Chaydarreh et al. 2021) and wood waste (Iždinský et al. 2020, Şahin 2020, Lee et al. 2022). Among agricultural by-products, recent

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research has focused particularly on pruning waste from orchards (Kowaluk et al. 2020, Peździk et al. 2022) and lignocellulose-containing nutshells (Mirindi et al. 2021, Narciso et al. 2021). In another study, the suitability of hay after pretreatment with sodium hydroxide for particleboard production was evaluated (Pipíška et al. 2022).

The exclusive use of individual hardwood species for particleboard production has also been addressed in a number of recent studies (Alamsyah et al. 2020, Tayo et al. 2020). Another study focused on using low-grade hardwood assortments for particleboard production with various adhesives (Pauli et al. 2022). A possible approach to further these investigations is to focus on low-grade hardwood assortments with varying wood species content as an alternative raw material source. This approach has only been sporadically addressed in research to date (Vital et al. 1974, Maraghi et al. 2018, Sharma et al. 2021).

The reasons for the limited spread of such approaches are manifold. On the one hand, assortments of mixed wood species do not align with the usual supply and demand patterns of the forestry and wood industries in the timber market. Additionally, their use presents challenges in maintaining consistent quality in particleboard production. The quality of particleboards is primarily measured based on their mechanical-technological properties. It is known that these material properties are influenced by the anatomical structure of the wood species used, as well as the chemical properties of both the wood species and adhesives (Sarı et al. 2012, Baharoğlu et al. 2013). Accordingly, for mixtures of different wood species, a significant influence of wood species content on the resulting bending strength of the particleboards has been demonstrated in some cases (Habibi et al. 2011). Overall, previous studies confirm variations in the bending properties of particleboards made from mixed wood species, depending on the wood species combinations used (Iswanto et al. 2017).

While the targeted blending of hardwood species in particleboard production has so far occurred only to a limited extent, commercial particleboards nevertheless contain a wide range of different hardwood particles (Sieburg-Rockel and Koch 2020). Previous studies have also shown that the mechanical properties of particleboards with higher density wood species in the core layer can be specifically improved when combined with face layers made of lower-density wood species (Rofii et al. 2017). To systematically make combinations of hardwood species usable for industrial particleboard production, a deeper understanding of the equivalence of particle mixtures with variable wood species content is required. The actual use of low-value hardwood assortments in the particleboard industry remains stagnant at a low level (Mantau 2023).

Given the increasing scarcity of softwood resources and the intensifying competition for this strategic raw material from competing industries, the need for research into substitution strategies that can be implemented in the short and medium term is evident. It is currently expected that there will be a future increase in low-grade hardwood assortments with variable wood species composition. This creates a research gap to investigate how these assortments can be used for industrial material purposes.

OBJECTIVE

The present study addresses this research need by connecting two fields of investigation: softwood substitution and hardwood utilization. The primary goal of this investigation, conducted through two sub-studies, was to assess to what extent the existing technological requirements for particleboards of type P2, according to EN 312, can be met by lightweight three-layer particleboards made from wood mixtures of low-grade hardwood assortments with variable species content and their combination with spruce particles. The first secondary objective was to test the hypothesis that different wood species content in the particle mixtures does not significantly affect the bending properties of the resulting particleboards. Another secondary objective, building on this, was to derive minimum bulk densities for P2-type particleboards made from wood mixtures with variable hardwood species content.

In the process, conditions corresponding to the current state of industrial particleboard production had to be maintained. The procedure used should, in principle, be transferable to industrial particleboard manufacturing processes. To achieve this, three-layer particleboards were produced from defined wood mixtures with different proportions of various hardwood species using the flat-press process, and the mechanical and technological properties of the particleboards were evaluated based on standardized material testing procedures. The raw materials used were low-value hardwood assortments, which could not be used for sawing or peeling, from species such as birch (*Betula pendula*), beech (*Fagus sylvatica*), alder (*Alnus glutinosa*), poplar (*Populus* spp.), as well as branch wood from small-leaved lime (*Tilia cordata*). Pure spruce particles (*Picea abies*) served as the reference material.

The research findings presented here aim to contribute to increasing the material-efficient production of lightweight, three-layer particleboards from low-value hardwood assortments with variable species content in an industrial context, taking into account shifting resource availability.

METHOD

The presented research was conducted as part of two self-contained sub-studies. Essentially, two combination forms of wood species mixtures for particleboard production can be distinguished: First, the mixture of several wood species in both the surface and core layer particles. This approach was followed in

Sub-study 1 (Cordier 2017). Second, the combination of surface and core layers, each made from different wood species. This approach was followed in Sub-study 2. The process parameters applied in Sub-study 1 were evaluated and optimized based on the results. The optimized process parameters were then applied as the foundation for conducting Sub-study 2.

Raw Material and Particleboard Production

Three-layer particleboards were produced, differing in the mixture ratios of the hardwood species used. After being processed into chips using a drum chipper and a knife ring flaker, and further refined by a hammer mill for oversize particles, the hardwoods were fractionated into surface and core layer particles (Table 1).

Table 1

Particle type	Screen mesh sizes and particle sizes for particle fractionation						
	Protrusion		Core layer fraction		Surface layer fraction		Dust fraction
	Upper limit (mm)	Lower limit (mm)	Upper limit (mm)	Lower limit (mm)	Upper limit (mm)	Lower limit (mm)	Upper limit (mm)
Size	>4	-	1×4	1×3	1×3	0,4×0,4	0,4

In Sub-study 1, spruce chips served as the reference material. In Sub-study 2, industrially produced spruce chips (ekla Holzwerke GmbH, Morbach, Germany) were used. The binding agent applied was the urea-formaldehyde resin Kaurit® R 350 (BASF SE, Ludwigshafen, Germany). The binder content was 10% solid resin on an absolutely dry (atro) basis for the surface layers and 8% solid resin on an atro basis for the core layer. The weight proportions were 40% (2 × 20%) for the surface layers and 60% for the core layer. The pressing temperature was 200°C, with pressing carried out to the target thickness. The pressing factor was 12 sec mm⁻¹ (Table 2).

Table 2

Particleboard production parameters	
Number of layers	3
Mass percentage surface layer (%)	40
Mass percentage core layer (%)	60
Pressing temperatur (°C)	200
Specific pressure (N mm ⁻²)	3,2-5
Press time factor (sek mm ⁻¹)	12

In both sub-studies, three-layer particleboards made from pure spruce particles, produced under identical conditions, served as the reference. For each particleboard variant, three gluing operations were performed, and one board was produced per gluing operation.

Sub-study 1

In Sub-study 1, three-layer particleboards were produced from bark-free wood mixtures with varying proportions of birch, beech, alder, and poplar (Table 3). The target bulk density was 650 kgm⁻³. Some variants were also produced with target bulk densities of 600 kgm⁻³ and 550 kgm⁻³. The target thickness was 20mm. A hydrophobizing agent and a hardener accelerator were added to the glue mixture. HydroWax® 730 (Sasol Germany GmbH, Hamburg, Germany) was added at 1% on an atro basis as a hydrophobizing agent. A 40% ammonium sulfate solution was added as a hardener accelerator at 0.5% on an atro basis in the surface layers and 2% on an atro basis in the core layer. The particleboards were sanded on both sides to a target thickness of 18mm before being cut into test specimens.

Table 3

Particleboard variants from sub-study 1 with the percentage of mixed wood species in the surface layers (SL) and core layers (CL)

Variant	Target density (kg m ⁻³)	Proportion of wood species (%) by core layers (CL) and surface layers (SL)									
		Spruce		Birch		Beech		Alder		Poplar	
		CL	SL	CL	SL	CL	SL	CL	SL	CL	SL
T1_1_550	550			40	40	20	20	20	20	20	20
T1_1_600	600			40	40	20	20	20	20	20	20
T1_1_650	650	-	-	40	40	20	20	20	20	20	20
T1_2	650	-	-	-	-	33,3	33,3	33,3	33,3	33,3	33,3
T1_3	650	-	-	25	25	25	25	25	25	25	25
T1_ref	650	100	100								

Sub-study 2

In Sub-study 2, three-layer particleboards were produced with a reduced target bulk density of 600 kgm⁻³ and a target thickness of 19mm (Table 4). The surface layers were made of spruce particles, and the core layer consisted of branch wood particles from small-leaved lime with bark. No hydrophobizing agents or hardener accelerators were added during production. The particleboards were cut into test specimens at a nominal thickness of 19mm without sanding. Sub-study 2 was conducted in collaboration with the Fraunhofer Institute for Wood Research, Wilhelm-Klauditz-Institut (WKI).

Table 4

Particleboard variants from sub-study 2 with the percentage of mixed wood species in the surface layers (SL) and core layers (CL)

Variant	Target density (kg m ⁻³)	Proportion of wood species (%) by core layers (CL) and surface layers (SL)			
		Spruce		Lime	
		CL	SL	CL	SL
T2_1	600	-	100	100	-
T2_ref	600	100	100	-	-

Bulk Densities

The bulk densities of the particles used in Sub-study 1 were determined based on five individual measurements per wood species, separated into surface and core layer particles. Based on the results, the bulk densities of the particle mixtures were calculated according to the percentage proportions of the wood species in the mixtures.

Evaluation of Mechanical-Technological Properties

To determine the mechanical-technological properties, the particleboards were cut into test specimens according to EN 326-1 and conditioned until mass constancy was achieved at 20°C and 65% relative humidity (EN 326-1 1994). The bulk density of the test specimens was determined according to EN 323 (EN 323 1993). The bending strength f_m (N mm⁻²) and modulus of elasticity E_m (N mm⁻²) were determined according to EN 310 (EN 310 1993). The tensile strength perpendicular to the surface f_t (N mm⁻²), referred to as internal bond strength, was measured according to EN 319 (EN 319 1993). The surface soundness SS (N mm⁻²) was determined in accordance with EN 311 (EN 311 2002). The tests for bending strength, internal bond strength perpendicular to the surface, and surface soundness were performed using a ZwickRoell universal testing machine (ZwickRoell GmbH & Co. KG, Ulm, Germany). Based on the results, the particleboard variants were evaluated in reference to the requirements of EN 312. To meet the normative requirements for the material properties according to EN 312, Type P2, these must be met by the 5% quantile values (EN 312 2010). However, due to the small sample size, the evaluation and comparison of the tested particleboard variants were based on more robust median values rather than the 5% quantile values, which are represented by additional dotted whiskers in the box plots. The bulk density profiles of selected test specimens were determined using a bulk density profile measurement device (Weinig Grecon GmbH & KG, Alfeld, Germany).

Statistical Analysis

The material testing results were statistically analyzed for interpretation. The linear correlation between bulk density and bending strength was determined using Pearson's correlation coefficient. This was performed based on the results for the variants T1_550, T1_600, and T1_650 across the bulk density gradient. The hypothesis that varying proportions of hardwood species in the wood particle mixtures, while maintaining constant board bulk density, would result in equivalent bending strengths in the produced particleboards was tested using Welch's two-sample t-tests. Null hypothesis significance tests (NHST) and equivalence tests using two one-sided tests (TOST) were applied. The significance level was set at $\alpha = 0.05$. Two null hypotheses were tested: Null Hypothesis 1 stated that the true difference in the arithmetic means of the bending strength for two particleboard variants is equal to 0 (NHST). Null Hypothesis 2 stated that the true difference in the arithmetic means of the bending strength for two particleboard variants is greater than 0.5 or less than -0.5. The derivation of the minimum bulk densities to be adhered to was based on the correlation between bulk densities and bending strengths. The statistical analysis and graphical representation of the results were conducted using the R software package (The R Foundation for Statistical Computing, Wien, Austria).

RESULT & DISCUSSION

Bulk Density of the Particle Mixes

The bulk density of the surface layer particles ranged from 108 kgm^{-3} to 119 kgm^{-3} for the particle mixes in Sub-study 1, and was 67 kgm^{-3} for the reference spruce. The bulk density of the core layer particles varied between 108 kgm^{-3} and 114 kgm^{-3} for the mixes, while the reference had a bulk density of 77 kgm^{-3} (Table 5). The results showed no significant difference in bulk density between the surface and core layer particles in the particle mixes. Additionally, the bulk densities of the different mixes only varied slightly. It is known that as bulk density decreases, the compression of the particles increases, leading to a higher compression ratio, which affects the development of the bulk density profile (Friese 2014). In this context, the minimal deviations in bulk densities between the mixes are a positive outcome, as they limit stronger effects on the bulk density profile. This offers advantages, particularly when using lower-grade hardwood assortments with varying proportions of multiple hardwood species. By regulating the proportions of species in the particle mix, bulk density fluctuations can be minimized and controlled to some extent.

Table 5

Bulk density of the particle mixtures used in sub-study 1 for the surface layers (SL) and core layers (CL)

Particle mixture	T1_ref	T1_1	T1_2	T1_3
	(kg m^{-3})			
Surface layer (SL)	67	119	108	115
Core layer (CL)	77	108	114	110

Bending Strength and Modulus of Elasticity

The median values for the bending strengths f_m of the particleboard variants tested ranged from 10.3 Nmm^2 to 17.0 Nmm^2 . The T1_ref variant achieved 26.0 Nmm^2 (Fig. 1).

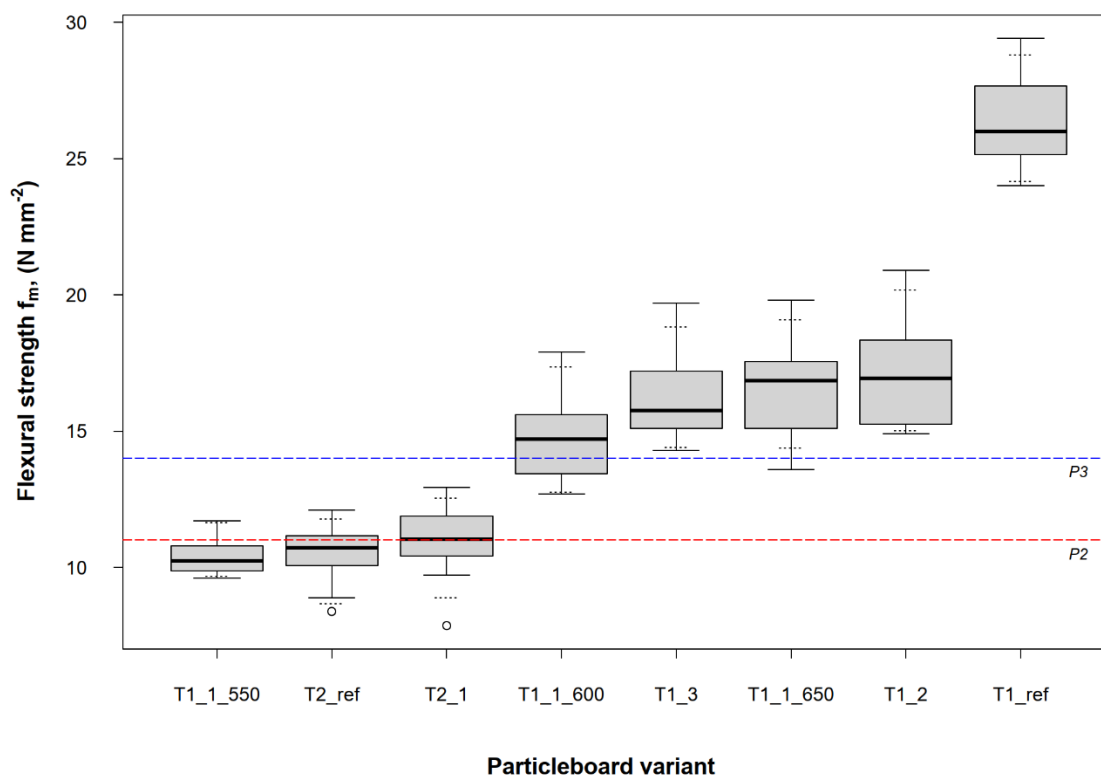


Fig. 1.

Flexural strength f_m (Nmm⁻²) of the three-layer particleboards. The dashed horizontal red line represents the minimum requirement for particleboard with a thickness of 13 to 20mm of type P2 according to EN 312 with 11 Nmm⁻² ($n = 12$, 3 boards \times 4 test specimens).

With the exception of the T1_1_550 and T2_ref variants, all other variants had median values for bending strength that exceeded the normative requirements according to EN 312 for Type P2 particleboards. Several variants also met the requirements for bending strength for Type P3 particleboards based on median values. At the same raw density, variants with different proportions of wood species in the mixes showed only minor deviations in median bending strengths. The results demonstrate that mixes of different hardwood species can be used to produce particleboards conforming to the standards for Type P2. An increase in the 5% quantile, which is relevant for normative classification, appears achievable through optimization of production parameters. A target value of 11 Nmm⁻² for the mixed hardwood variants was met with a raw density of 600 kgm⁻³. Increasing the raw densities beyond 650 kgm⁻³ does not appear necessary based on the results. Lowering the raw density below 600 kgm⁻³ should be avoided to ensure sufficient strength reserves, as confirmed by the correlation between raw density and bending strength (Section Correlation between Raw Density and Bending Strength). A significant effect of bulk density on bending strength was confirmed only in comparison with the spruce reference, due to the more efficient glue utilization. Recent studies have shown that basalt fiber fabrics effectively reinforce three-layer particleboards against bending stresses and have a positive impact on the strength-to-weight ratio of particleboards (Mayer and Mai 2024). Incorporating basalt fiber fabrics offers a potential method for optimizing the weight-to-strength ratio of particleboards made from hardwood mixes compared to spruce-based reference particleboards. The median values for the modulus of elasticity E_m for the variants made from mixes of different wood species ranged from 1962 Nmm² to 3085 Nmm². The median value for the T1_ref variant was 3575 Nmm² (Fig. 2).

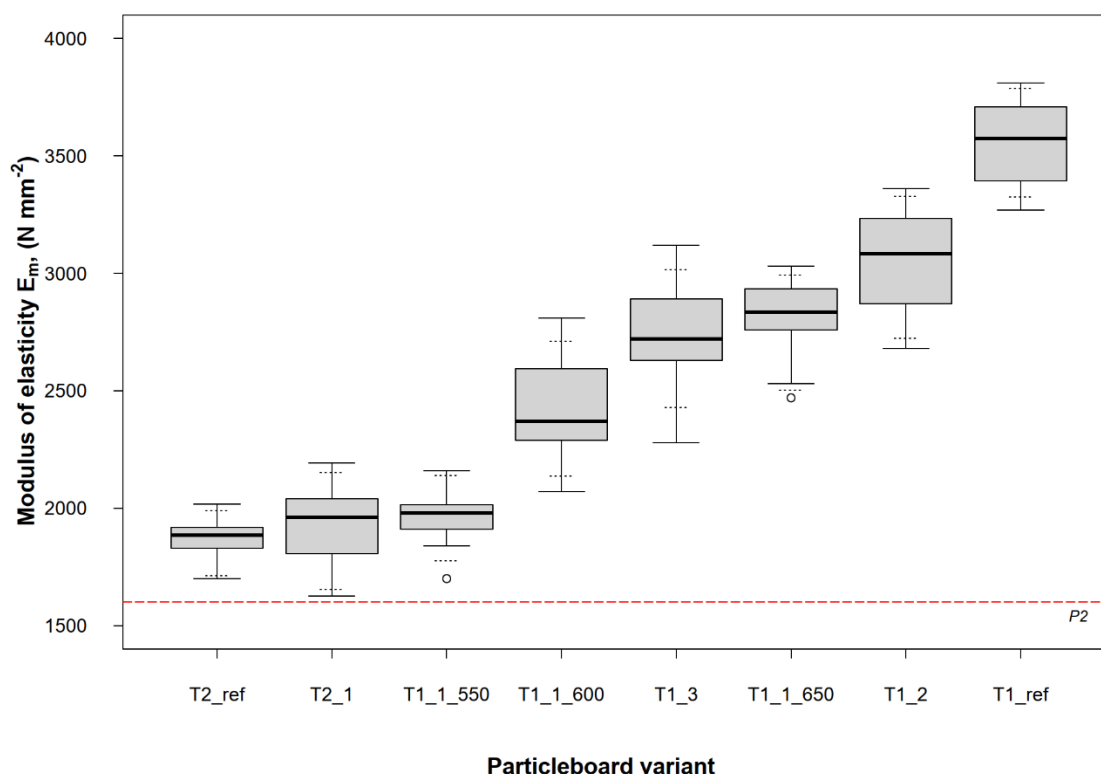


Fig. 2.

Modulus of elasticity E_m (Nmm⁻²) of the three-layer particleboards. The dashed horizontal red line represents the minimum requirement for particleboard with a thickness of 13 to 20mm of type P2 according to EN 312 with 1600 Nmm⁻² ($n = 12$, 3 boards \times 4 test specimens).

The median modulus of elasticity values for all variants exceeded the minimum requirements for Type P2 particleboards according to EN 312. The 5% quantile requirements for Type P2 particleboards were also met by all variants. Comparing the increase in bending strength with the modulus of elasticity shows larger deviations in the modulus of elasticity between the variants than in the bending strength. The median values for the modulus of elasticity are considered sufficient for typical application scenarios for Type P2 particleboards. In the future, incorporating reinforcement materials into the surface layers could increase both bending strength and the modulus of elasticity.

Internal Bond Strength

The median internal bond strength f_t values of the particleboard variants made from different wood species ranged from 0.11 Nmm⁻² to 0.74 Nmm⁻². The T1_ref variant achieved 0.90 Nmm⁻² (Fig. 3).

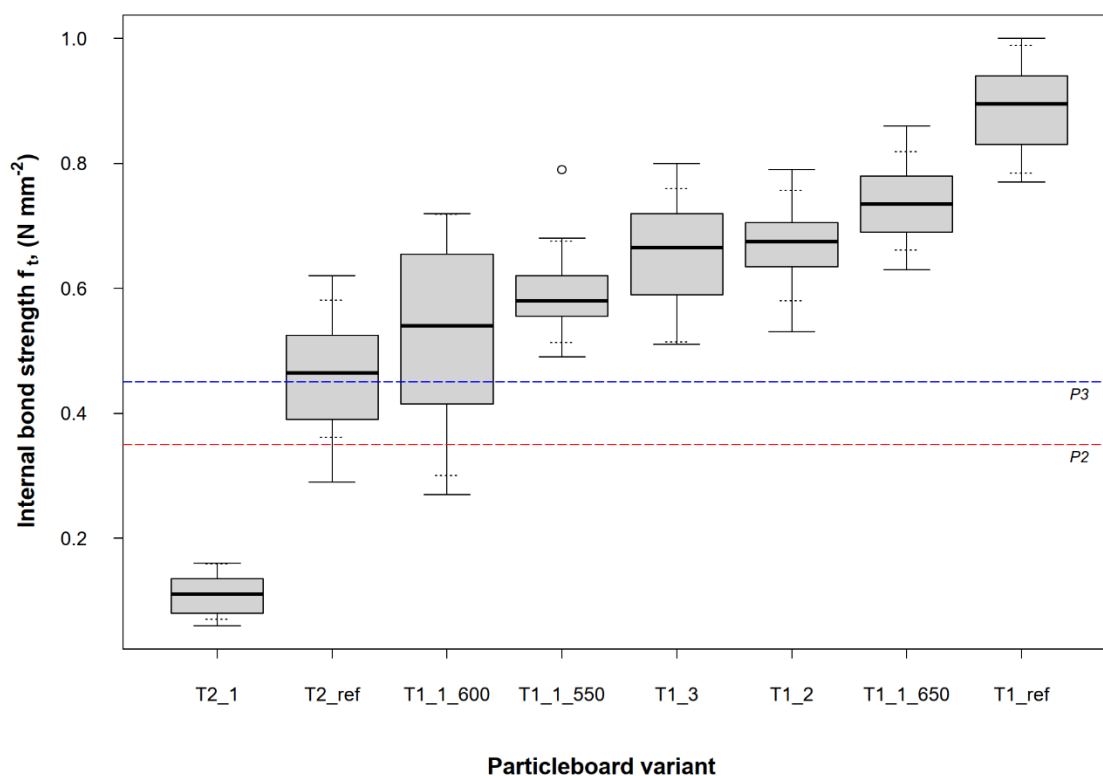


Fig. 3.

Internal bond strengths f_t (Nmm⁻²) of the three-layer particleboards according to EN 319. The dashed horizontal red line represents the minimum requirements for particleboards with a thickness of 13 to 20mm of type P2 according to EN 312 with 0.35 Nmm⁻² ($n = 24$, 3 boards \times 8 test specimens).

With the exception of the T2_1 variant, the median values of all variants exceeded the minimum requirements for Type P2 particleboards according to EN 312. The median values for internal bond strength also met the requirements for Type P3 particleboards. However, the 5 % quantile value for the T1_1_600 variant did not meet the EN 312 requirements. The results suggest that particle mixes made from different wood species, combined with the chosen manufacturing parameters, are generally suitable for producing particleboards compliant with Type P2 standards according to EN 312. This opens up the possibility of utilizing low-grade roundwood assortments with variable species compositions for particleboard production, providing a substitute for softwood assortments and expanding the raw material base for particleboard manufacturing. Internal bond strength is influenced by glue utilization, raw wood density, and particle compression. Previous studies on mixed particleboards made from *Paulownia* spp. and *Fagus sylvatica* indicated that achievable internal bond strength is more dependent on particle compression and subsequent adhesion improvement than on density alone (Nelis and Mai 2019). With varying degrees of compression in particles from different species, the more compressible particles tend to envelop the less compressible ones. The development and optimization of bio-based adhesives are central to the resource-efficient advancement of particleboards and are the subject of numerous research projects (Zuber et al. 2020, Tayo et al. 2022, 2024). Further research aims to adapt these adhesives to the specific challenges of bonding particles from various hardwood species, along with optimizing production parameters.

Surface Soundness

The median surface soundness SS values ranged from 0.83 Nmm⁻² to 1.43 Nmm⁻² for the variants made from different wood species. The median value for the T1_ref variant was 1.51 Nmm⁻² (Fig. 4).

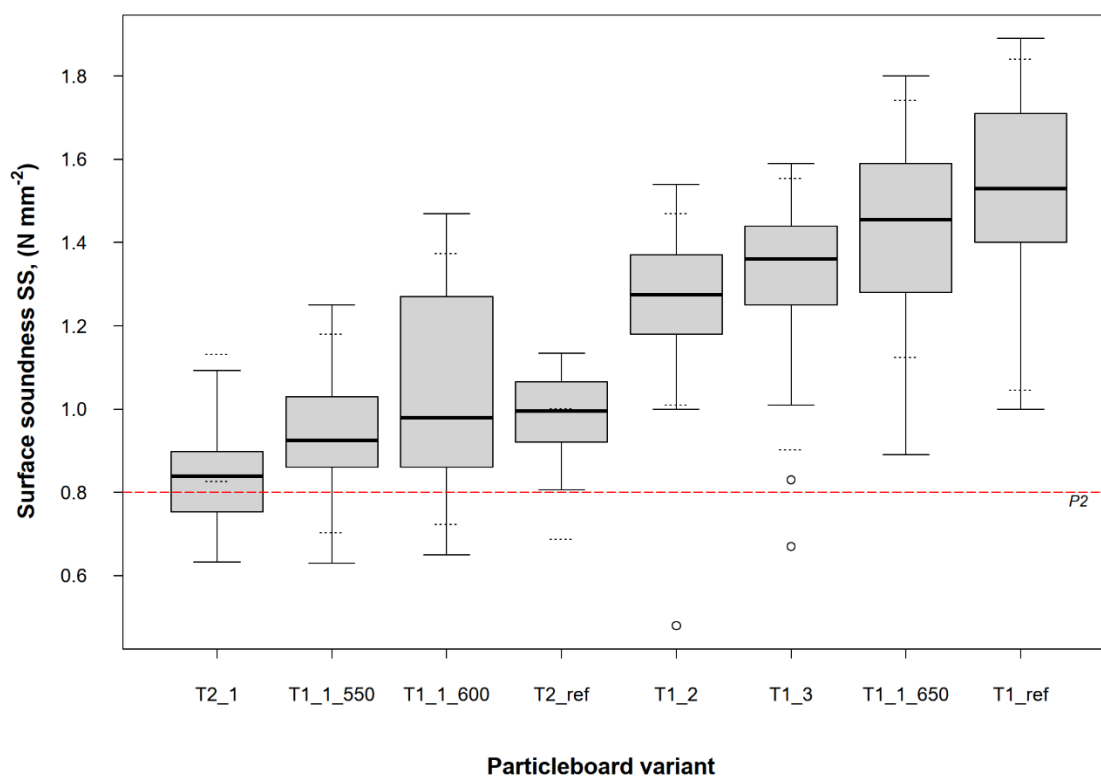


Fig. 4.

Surface soundness SS (Nmm^{-2}) of the three-layer particleboards. The dashed horizontal red line represents the minimum requirement for particleboards with a thickness of 13 to 20mm of type P2 according to EN 312 with $0.8 Nmm^{-2}$ ($n = 30$, 3 boards \times 10 test specimens).

The median values for surface soundness were mostly above the normative threshold of $0.8 N/mm^2$. However, the 5% quantile values only reached the threshold at raw densities above $600 kgm^{-3}$. Comparing surface soundness between the variants shows a continuous increase in surface soundness with increasing raw density at constant wood species proportions (Section Raw Density and Density Profiles). A possible reason for this is the proportionally higher compression of the surface layers in variants with a target raw density of $650 kgm^{-3}$. The raw density profiles of these variants exhibit a more pronounced U-shape than those with target raw densities of $550 kgm^{-3}$ and $600 kgm^{-3}$ (Section Raw Density and Density Profiles). The choice of wood species for the surface layers is known to affect the surface soundness (Grigoriou 1981). Furthermore, previous research demonstrated that effective glue utilization depends on particle density (Nelis and Mai 2021). Depending on particle density, different degrees of compression result from varying levels of glue utilization efficiency. An increase in target raw density shifts the dominant effect from efficient glue utilization through compression to the effect of particle density. The strength of this effect increases with higher particle density (Nelis and Mai 2021). The potential effect of reinforcing materials like basalt fiber fabrics on surface soundness remains largely unexplored. Future research will evaluate these relationships, particularly when combining different wood species in particle mixes and using bio-based adhesive systems.

Raw Density and Density Profiles

All particleboard variants were successfully manufactured with the targeted raw densities without any issues (Table 6). The produced particleboards exhibited typical U-shaped density profiles (Fig. 5).

Table 6

Mean values of the raw densities (kg m^{-3}) of the particleboard variants according to EN 323, determined on the test specimens for the bending test according to EN 310 ($n=12$)

Variant	T1_1_550	T1_1_600	T1_1_650	T1_2	T1_3	T1_ref	T2_1	T2_ref
Target density (kg m^{-3})	550	600	650	650	650	650	600	600
Actual density \bar{x} (kg m^{-3})	564	612	666	646	670	666	595	590

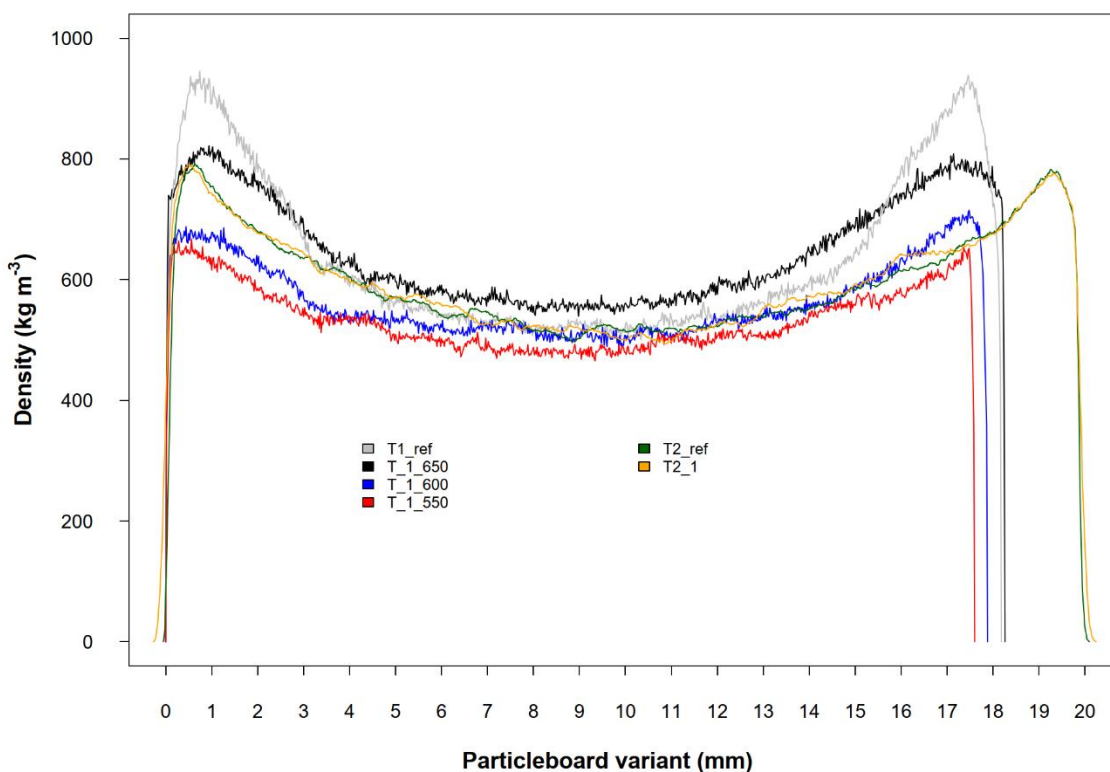


Fig. 5.
Density profiles of selected three-layer particleboard specimens.

The density profiles showed higher compression in the surface layers and lower compression in the core layers (“double T-beam effect”). With respect to load-bearing capacity during bending, the reduction in raw density towards the neutral axis in the board's core aligns with the intended goal. The effect of reducing raw density on the density profile line was noticeable when wood species proportions in the mix remained constant, leading to a steady bulk density. A more pronounced U-profile was achieved only at target raw densities above 600 kg m^{-3} , with significantly more compressed surface layers compared to the core. The correlation between bending strength and raw density supports these observations. When transferring the results to other mix proportions and species combinations, other influencing factors such as bulk density, particle geometry, and fraction composition must be considered (Niemz 1993, Benthien and Ohlmeyer 2016).

Equivalence Test on the Relationship Between Species Mix Proportions and Bending Strength

For the compared variants, both the equivalence tests and the null hypothesis significance tests were not significant, as both *p*-values were greater than the alpha level of 0.05 (Table 7).

Table 7

Results of the equivalence tests from the pairwise comparisons of the particleboard variants for the influence of the wood species composition of the particleboard material on the bending strength

Comparison of variants	Equivalence tests		Effect size					
	TOST	NHST	Mean value difference			Hedges's g (av)		
	p	p	SE	LL	UL	SE	LL	UL
T1_2 – T1_3	0,687	0,248	0,858	-0,387	2,103	0,466	-0,209	1,217
T1_2 – T1_1-650	0,508	0,499	0,516	-0,776	1,810	0,270	-0,413	0,996
T1_3 – T1_1_650	0,115	0,622	-0,341	-1,517	0,5	-0,196	-0,915	0,491
T2_ref – T2_1	0,027	0,327	-0,489	-1,330	0,350	-0,394	-1,137	0,284

SE Standard error of difference
LL Lower limit
UL Upper limit

Since neither test was significant and the mean differences spanned positive and negative values, the results were inconclusive. Consequently, neither null hypothesis could be rejected. Therefore, no clear statistical conclusion can be drawn on whether the different hardwood particle mix proportions at constant board raw density result in equivalent bending strengths. However, the results show a sufficient tendency for practical use, indicating that the compared species mixes can be used without major process adjustments to produce particleboards with comparable bending strength (Fig. 6).

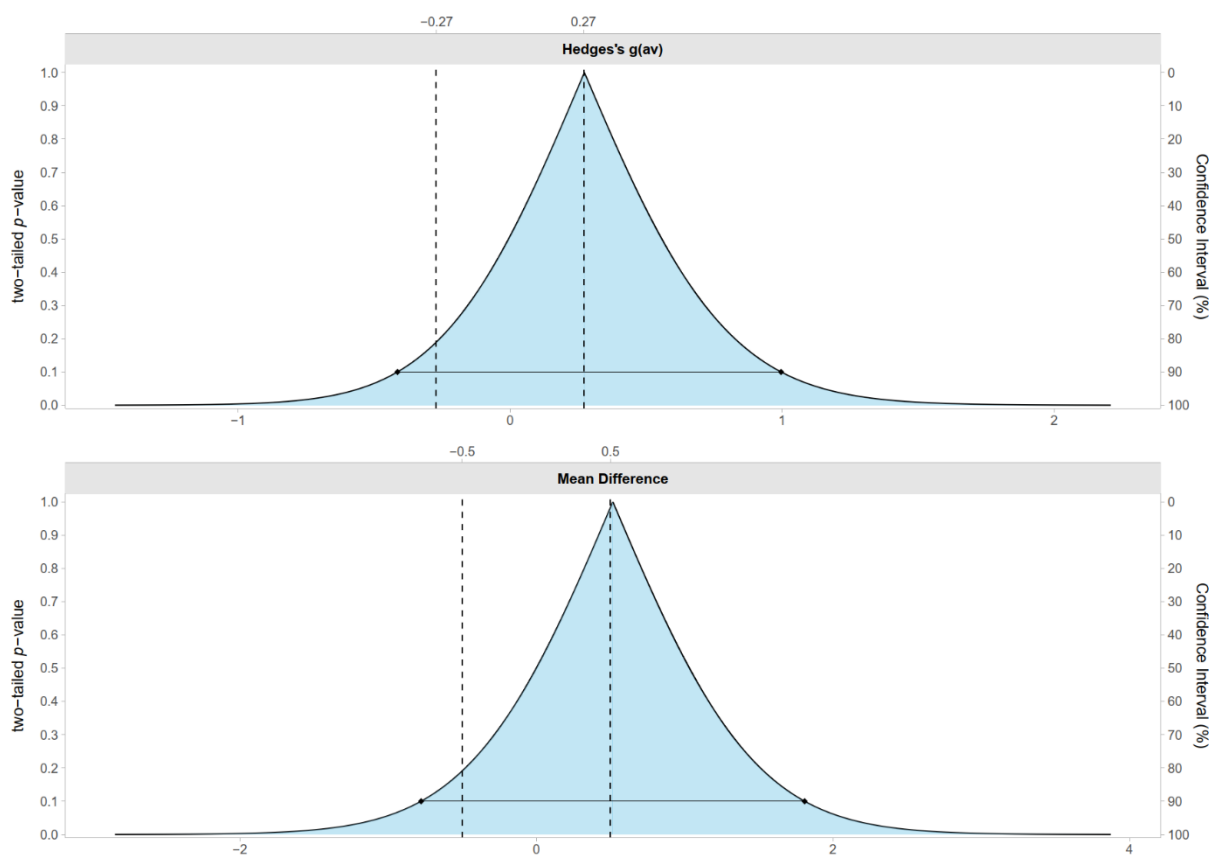


Fig. 6.

Exemplary graphical representation of the results of an equivalence test ($H_0 = T1_2 \equiv T1_1_650$).

Even pure species particles require ongoing monitoring and control of the production process due to natural variations in wood properties. Hence, the threshold values for bending strength derived from the correlation between raw density and bending strength for raw densities of 550 kgm^{-3} , 600 kgm^{-3} , and 650 kgm^{-3} in the T1_1 variant can be applied as reference values to the particleboard variants from mixed species that were tested in the equivalence study. The minimal deviations in bulk density between the particle mixes support this relationship. The results show a different trend compared to an earlier study, which demonstrated a significant difference in the bending strengths of particleboards made from different wood species mixtures (Habibi et al. 2011). However, that study examined much greater fluctuations in wood species composition, with mixing ratios of just two species ranging from 0% to 100% and 66.5% to 33.5%, compared to the present study. Additionally, the aforementioned study focused on *Eucalyptus* spp. and *Populus* spp., which tend to have a higher difference in average raw density than the species investigated in this study. Furthermore, the different statistical methods of the approaches must be considered. For wood species proportions in mixed assortments that are subject to greater fluctuations, the approach presented here - comparing averages with a defined significance level - offers a way to define tolerable fluctuation ranges for mixing ratios and better assess the equivalence of particle mixtures. By applying this approach to other material properties, such as internal bond strength, the tolerable composition of processable particle mixes from low-grade hardwood assortments with variable species compositions can be more precisely defined.

Correlation between Raw Density and Bending Strength

The Pearson correlation confirmed a significantly high positive relationship between the raw density and bending strength of the evaluated particleboard variants T1_1_550, T1_1_600, and T1_1_650, with $r = 0.84$, $p < 0.001$, and $n = 36$ (Fig. 7).

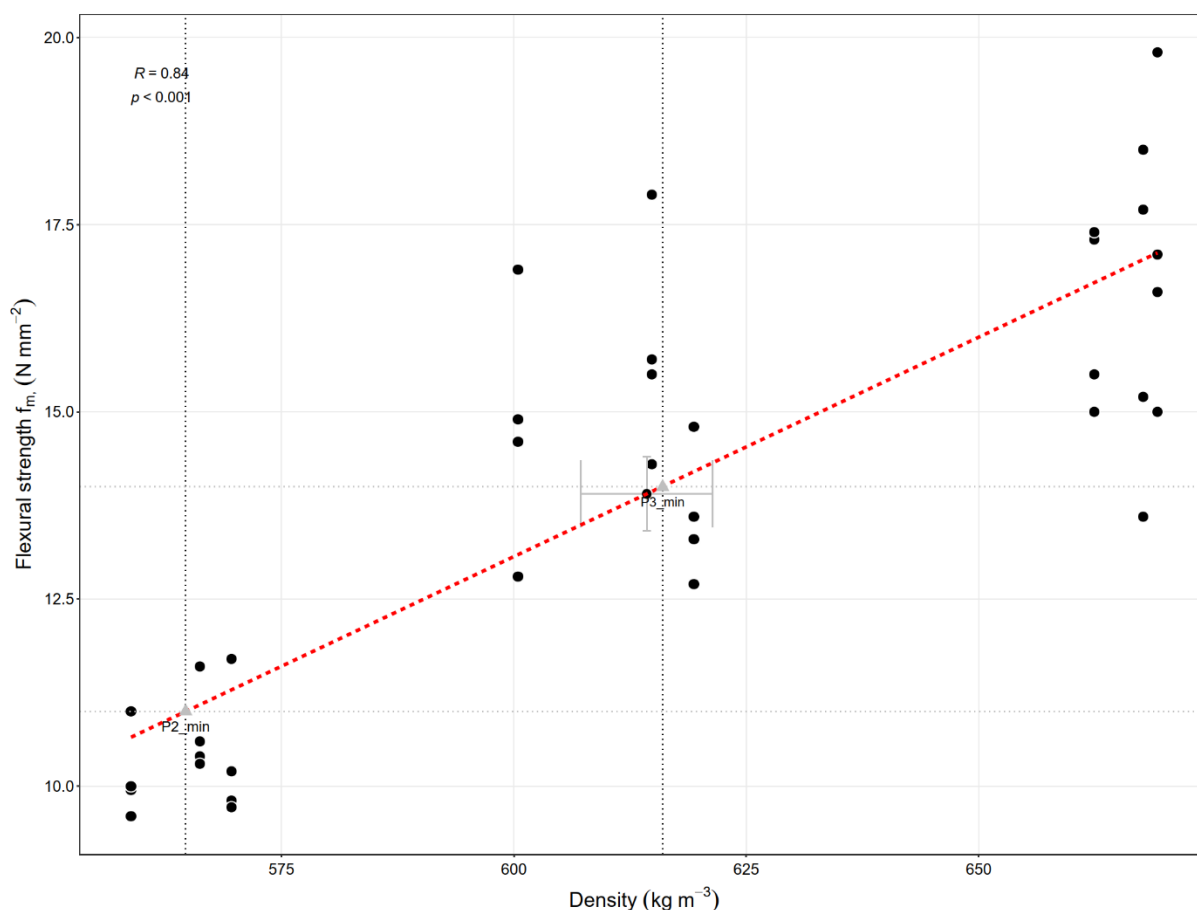


Fig. 7.

Correlation between raw density and flexural strength according to Pearson ($n = 36$, 3 variants \times 3 panels \times 4 test specimens) and derivation of the minimum bulk densities to be complied with for particleboard in accordance with the flexural strength requirements of EN 312.

From the intersection points of the linear function with the lines of the minimum bending strength requirements according to EN 312, minimum values for the raw density were derived. These amounted to

565 kgm⁻³ for P2 particleboards and 616 kgm⁻³ for P3 particleboards. The results follow the generally recognized positive relationship between raw density and bending strength for particleboards (Dunky and Niemz 2002). Regarding the resulting bending strengths, they offer the possibility of optimizing the raw density of P2 and P3 particleboards made from hardwood mixtures. By including coefficients in the calculation of tolerance ranges, the target raw densities for a defined bending strength can be adjusted. The results of the equivalence tests on the relationship between wood species mixing ratios and bending strength suggest that the determined minimum values for raw density can also be applied as guidelines, even with fluctuating proportions of individual hardwood species in the particle material, considering the demonstrated adjustments in bulk density. It should be noted that as the variations in mixing ratios increase, the precision may decrease due to shifts in the effects between effective adhesive utilization and particle material density (Nelis and Mai 2021).

CONCLUSIONS

The results show that the resource-efficient production of lightweight three-layer particleboards from low-grade hardwood assortments with variable wood species proportions is possible. The slight deviations in particleboard properties caused by different proportions of wood species mixtures are tolerable within the limits of the standard deviations of the relevant process parameters. The evaluation of the mechanical and technological properties suggests that, starting from raw densities of 600 kgm⁻³, the material properties for P2 type particleboards can be reliably achieved in an optimized manufacturing process. It was demonstrated that the wood species proportions in the particle mixtures have only a minor and therefore tolerable influence on the material properties of the particleboards. By adjusting the bulk densities in the particle mixtures, the effects of shifts between effective glue utilization and compaction level can be reduced. This facilitates the combined use of various hardwood species for particleboard production.

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