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Greitta Kusuma Dewi*[1], Ragil Widyorini[1], Erlina Nurul Aini[2], Yunida Syafriani Lubis[3]

Water Resistance Ability and Mechanical Strength of Eco-Friendly Particleboard Made from Bamboo Waste and Maltodextrin-Based Adhesive

Vodootpornost i mehanička čvrstoća ekološki prihvatljive iverice izrađene od bambusova otpada i ljepila na bazi maltodekstrina

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ABSTRACT • *Bamboo waste from the handicraft and furniture industry is an excellent source of lignocellulose with significant potential for use as raw material in particleboard production. The bamboo particleboard, when paired with a natural adhesive such as maltodextrin-based adhesive, potentially provides an eco-friendly waste management solution, aligning with Sustainable Development Goals (SDGs) 12 and 13. The optimal manufacturing conditions for maltodextrin/ammonium dihydrogen phosphate (M/ADP)-based particleboard are still under investigation. In this study, our aim was to assess the quality of bamboo-M/ADP particleboard, focusing on its water resistance and mechanical properties, the crucial factors in determining particleboard quality. Various M/ADP ratios were used, namely 100/0, 90/10, and 80/20 wt%. The pressing conditions used a temperature of 200 °C at 3 MPa, with pressing times of 1, 3, 5, 7.5, and 10 minutes. The results showed that particleboard with a M/ADP ratio of 90/10 and 80/20 wt% demonstrated satisfactory water resistance, as supported by the results of thickness swelling and aging evaluations. Overall, the M/ADP 80/20 wt% at 10 minutes of pressing time exhibited optimal particleboard properties, i.e., thickness swelling 5.08 %, thickness change after aging treatment 5.29 %, water absorption 38.47 %, surface roughness 8.92 µm, internal bonding strength 0.21 N/mm², modulus of rupture 4.8 MPa, modulus of elasticity 1.72 GPa, and brittleness 41.7 %.*

KEYWORDS: *maltodextrin; ammonium dihydrogen phosphate; bamboo waste; particleboard*

SAŽETAK • *Bambusov otpad iz radionica rukotvorina i industrije namještaja odličan je izvor lignoceluloze s velikim potencijalom za iskorištenje u proizvodnji ploča iverica. Bambusova iverica, u kombinaciji s prirodnim ljepilom kao što je ljepilo na bazi maltodekstrina, potencijalno je ekološki prihvatljivo rješenje za gospodarenje otpadom u skladu s ciljevima održivog razvoja (SDGs) 12 i 13. Optimalni uvjeti proizvodnje iverice na bazi malto-*

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dekstrin/amonijeva dihidrogen fosfata (M/ADP) još su u fazi istraživanja. Cilj ovog istraživanja bio je procijeniti kvalitetu bambus-M/ADP iverice, s fokusom na njezinoj otpornosti prema vodi i na mehaničkim svojstvima, što su najvažniji pokazatelji kvalitete iverice. Primijenjeni su različiti M/ADP omjeri: 100/0, 90/10 i 80/20 težinskih postotaka. Za prešanje je odabrana temperatura od 200 °C pri 3 MPa, a vremenima prešanja iznosila su 1, 3, 5, 7,5 i 10 minuta. Rezultati su pokazali da je iverica s M/ADP omjerom od 90/10 i 80/20 težinskih postotaka pokazala zadovoljavajuću otpornost na vodu, što je potkrijepljeno rezultatima ocjene debljinskog bubrenja i promjene debljine nakon tretmana ubrzanog starenja iverice. Zaključno, optimalna svojstva iverice dobivena su s M/ADP 80/20 težinskih postotaka, pri prešanju od 10 minuta, i iznosila su: debljinsko bubrenje 5,08 %, promjena debljine nakon tretmana ubrzanim starenjem 5,29 %, upijanje vode 38,47 %, hrapavost površine 8,92 µm, unutarnja čvrstoća na raslojavanje 0,21 N/mm², modul loma 4,8 MPa, modul elastičnosti 1,72 GPa i krtost 41,7 %.

KLJUČNE RIJEČI: *maltodekstrin; amonijev dihidrogen fosfat; otpad od bambusa; iverica*

1 INTRODUCTION
1. UVOD

Solid waste from the forestry sector and industry has many potential uses due to its lignocellulosic substance and other chemical substances. These solid wastes generally consisted of wood bark, wood chips, and other wooden materials chips, e.g., bamboo waste (Millati *et al*., 2019). Bamboo waste was predicted to increase in linearity with the increased use of bamboo worldwide, especially in construction and interior design, handicrafts, and furniture industries (Dlamini *et al*., 2022). About 30-50 % of bamboo chip waste was usually generated in handicrafts and furniture; meanwhile, 14.6-33.5 % was generated in building/construction components of the total production (Wiwoho *et al*., 2017; Fadillah *et al*., 2022). Furthermore, in Indonesia, which has the third-largest bamboo plantation area after China and India, the volume production of bamboo surprisingly increased five times from 2020 to 2021 (Statistics Indonesia, 2020, 2021; Park *et al*., 2021). The total business unit recorded in the handicraft industry in Bali, Indonesia, was 3655 units. In Anji, China, the total bamboo waste was around 0.16 million tons/year in 2015 (Tong *et al*., 2021), uncountable yet for other areas. The waste was huge and might pollute the environment if not handled or processed for reuse. Furthermore, the processing and utilization of bamboo/wooden waste into some products support the sustainable development goals (SDGs) 12 and 13, which is consistent with responsible consumption and production as well as with the requirements for controlling climate change (Pinho and Calmon, 2023).

The bamboo chip waste has been studied as a versatile material for bioenergy (biopellet, bioethanol, charcoal briquette), pulp and paper, advanced material (cellulose nanofiber, green adhesive, activated carbon), biocomposite, etc (Zaia *et al*., 2015; Kaur *et al*., 2022). This is due to the similar chemical composition between the bamboo waste and the raw bamboo, namely the holocellulose (69-82 %) and lignin (21-30 %) (Maulana *et al.,* 2020). For biocomposite application, bamboo chip waste was proven as a good reinforced/raw material with many adhesives/matrices, such as urea formaldehyde, polystyrene, polyurethane, etc. (Biswas *et al.,* 2011; Zaia *et al.,* 2015; Abdulkareem and Adeniyi, 2017). Nowadays, due to increasing sustainability awareness and demand for eco-friendly products, this waste was studied as the raw material of binderless particleboard and the particleboard with some natural adhesives such as tannin, citric acid, citric acid/starch, sucrose/ammonium dihydrogen phosphate (ADP), etc (Aini *et al*., 2020; Widyorini *et al*., 2020; Guan *et al*., 2022; Santoso *et al*., 2022). The particle board had excellent properties, and some properties were similar to some synthetic adhesives. Furthermore, the exploration of natural adhesives for particleboard production focused on substituting the formaldehyde-based adhesives that constituted more than 90 % of particleboard adhesives globally with a potentially harmful emission and the issue of non-renewability (Flores *et al.,* 2011).

Recently, our studies found that maltodextrin/ADP could be a promising natural adhesive for salacca frond particleboard with excellent dimensional stability (Dewi *et al.,* 2022). Maltodextrin is a hydrolysis product of starch that is abundant, widely available globally, and one of the major agricultural commodities (Whistler *et al.,* 1984). Meanwhile, ADP could catalyze the dehydration of sugar (sucrose) into 5-hydroxymethyl furfural (5-HMF), which is responsible for increasing the physical and mechanical properties of particleboards (Umemura *et al.,* 2017; Zhao *et al.,* 2018). The composition of maltodextrin/ADP was known to affect the physical and mechanical properties of particleboard, identically with sucrose/ADP (Zhao *et al.,* 2018; Dewi *et al.,* 2022). Due to the catalysis effect of ADP, the optimal pressing time of the particleboard might be affected. Lehmann *et al.* (1973) stated that the addition of a catalyst into urea-formaldehyde adhesive could reduce up to a certain level the pressing time.

This research aimed to investigate the effect of maltodextrin/ADP ratio and pressing time on the properties of particleboard made from bamboo waste. Some physical and mechanical properties of the particleboard were evaluated, along with the chemical fingerprint (Fourier transform infrared analysis) of the particleboard and thermal properties of the sprayed particles to clarify the possible scenario during particleboard production.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Petung bamboo particle waste was obtained from bamboo crafts central in Cebongan, Yogyakarta, Indonesia. The characteristics of bamboo particles after being ground in a knife ring flaker are presented in Table 1. Maltodextrin (DE 10-15 %, powder, food grade) was purchased from Zhucheng Dongxiao Biotechnology Co. Ltd. (Zhucheng, China), meanwhile ammonium dihydrogen phosphate (ADP) (powder, pro-analysis grade) was obtained from Merck, Darmstadt, Germany. The solvent used was distilled water (pH 7).

2.1 Adhesive solution preparation
2.1. Priprema ljepila

The maltodextrin-based adhesive solution was prepared at 50 wt% concentration, as reported by Dewi *et al.* (2022). The maltodextrin was dissolved in the distilled water at 80°C. Three maltodextrin/ADP ratios were used, namely 100/0, 90/10, and 80/20 wt%. The adhesive content was 20 wt% based on the air-dried particle's weight. The adhesive solution was cooled and used at ±43 °C in order to maintain the easiness of glue spreading.

2.2 Analysis of sprayed particles and particleboard manufacturing
2.2. Analiza iverja i proizvodnja iverice

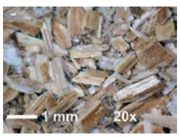
The warm adhesive solution was spread into the particles evenly, and then oven-dried at ±2.5 cm bulk height at 80 °C for 4 h. The intended moisture content of the sprayed particles was ±6 %. One gram of each sprayed particle was analyzed for its thermal properties using thermogravimetry analysis. Prior to the test, it was ground, screened into a 100-mesh screen, then oven-dried at 60 °C for 12 h. The analysis was performed using TGA801 (Leco, Michigan, USA). It was subjected to heat subsequently at 27-400 °C at a rate of 10 °C/min under a 35 mL/min nitrogen purging. For the comparison, the thermal analysis of the bamboo raw material and maltodextrin was also conducted.

The remaining sprayed particles were hand-formed into a mat with a 25 cm × 25 cm size. The mat was hot-pressed at 200 °C at 3 MPa specific pressure into 1 cm thickness. The targeted density of the particleboard was 0.7 g/cm³. The pressing time and the pressing method are presented in Table 2, and the board was manufactured in triplicate. Particleboard with 1 min pressing time at 100/0 M/ADP ratio failed to be manufactured. The particleboards were then conditioned at room condition (±27 °C, 77 % relative humidity) for 7 days prior to the board properties test.

2.3 Evaluation of particleboard properties
2.3. Ocjena svojstava iverice

The properties of bamboo particleboard were tested according to the modified Japanese Industrial Standard (JIS) A 5908 (2015). The thickness swelling and water absorption (TSWA) tests were conducted simultaneously by immersing the 5 cm × 5 cm sample horizontally for 24 hours at room temperature. The percentage of thickness and the weight changes based on the initial thickness and weight were TSWA values. A

Table 1 Characteristics of bamboo particle waste
Tablica 1. Svojstva iverja od bambusova otpada

	Particle distribution, % *Distribucija iverja, %*	**Particle appearance** *Izgled iverja*	***MC**, %**	**Bulk density, g/cm³** *Nasipna gustoća, g/cm³*	**CWAH*, mm**
-10+40 mesh (0.42 – 2 mm)	77.1		12	0.136±0.003	1040.4±22.0
-40+60 mesh (0.25 – 0.42 mm)	8.4				
-60+100 mesh (0.15 – 0.25 mm)	7.8				
-100 mesh (max 0.15 mm)	6.7				

**MC* – moisture content, CWAH – corrected water absorption weight by Bodig (1962)
**MC – sadržaj vode, CWAH – korigirana težina upijene vode prema Bodigu (1962.)*

Table 2 Preparation of bamboo particleboards
Tablica 2. Priprema bambusove iverice

	Pressing time / *Vrijeme prešanja*				
	1 min	3 min	5 min	7.5 min	10 min
MADP/mixture ratios, wt% *MADP/omjeri miješanja,* težinski postoci	-	100/0	100/0	100/0	100/0
	90/10	90/10	90/10	90/10	90/10
	80/20	80/20	80/20	80/20	80/20
Pressing methods *Metoda prešanja*	Single step	Single step	Three-step (2.5 min – 1 min – 2.5 min)	Three-step (3.75 min – 1 min – 3.75 min)	Three-step (5 min – 1 min – 5 min)

cyclic accelerated aging treatment was also conducted subsequently after TSWA test to investigate the dimensional stability of the bamboo particleboard bonded with maltodextrin/ADP adhesive. The test was carried out according to Kusumah *et al.* (2017). Following the 24 h-water immersion at room temperature, the samples were oven-dried at 105 °C for 10 h, immersed in warm water (70±2) °C for 24 h, oven-dried at 105 °C for 10 h, immersed in boiling water for 4 h, and oven-dried at 105 °C for 10 h, respectively. The thickness change was measured after each of those treatments compared to the initial thickness. The moisture content (*MC*) was measured in a 5 cm × 5 cm sample. The surface roughness (*SR*) was measured using SRG4000 (Bosworth Instrument, Ohio, USA) at 6 random points in each 20 cm × 5 cm sample. Furthermore, the color testing of particleboard was carried out using a Color Reader CR-10 (Konica Minolta Sensing Inc., Japan) after SR test.

Internal bonding (*IB*) was tested by applying a tension load vertically to the board surface at 2 mm/min speed using UTM3369 (Instron, Massachusetts, USA) until the bonding failed. Three-point bonding strength (BS) test was carried out by applying a load with 10 mm/min speed perpendicular to the board surface of a 20 cm × 5 cm sample in a 15 cm span until cracking. Based on the load-deflection curve of the bending test, the brittleness was calculated by dividing the elastic area to the total area of the curve. The elastic area and the total area up to the maximum load were measured with the ImageJ software.

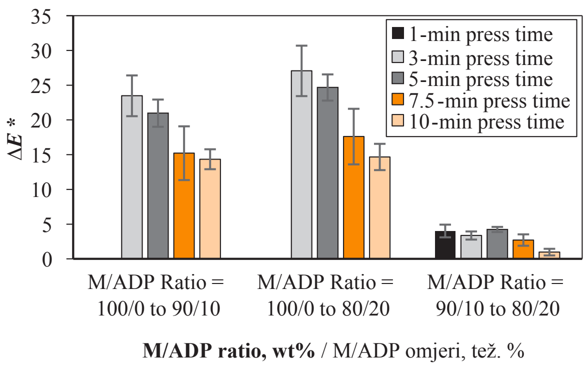
2.4 Fourier Transform Infrared (FTIR)
2.4. Fourierova infracrvena spektroskopija (FTIR)

The samples chosen for FTIR analysis were particleboards with a press time of 10 minutes at all compositions (100/0, 90/10, and 80/20 wt%) and particleboards with a M/ADP composition of 80/20 wt% at all press times (1 min, 3 min, 5 min, 7.5 min, and 10 min). The particleboard sample was boiled for 2 h, followed by water immersion at 27 °C for 1 h, then ground into a powder size (less than 100 mesh) and oven-dried at 60 °C for 15 h prior to the test. The boiling and the immersion were conducted to eliminate the unreacted adhesive. The analysis used KBr disk methods and was recorded at a 10 scan with a 16 cm^{-1} resolution in FTIR spectrometer IR-Prestige 21 (Shimadzu, Kyoto, Japan).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

All the bamboo particleboards were successfully manufactured without any defects. The surface color of the particleboards was darkened visually from light brown to dark brown in accordance with the higher ADP ratio and longer pressing time. The same result has been observed in binderless particleboards made from the inner part of oil palm trees with an additional ratio of ADP (Komariah *et al.,* 2019). The brightness (L^*) level measurement also proves the phenomenon. The L^* value of the board with 100/0 M/ADP ratio at 3 to 10 minutes press time was 33 – 45.54, while in 90/10 and 80/20 boards, the L^* values were 25.03 – 28.93 and 25.50 – 27.23, respectively. The decreased trend of the L^* value of particleboards with the increase in ADP content and press time showed that the boards color became dark.

In addition to brightness measurement, Figure 1 shows the color change (ΔE^*) in the particleboard as the effect of addition of ADP and press time variation. The ΔE^* values of the particleboard due to the addition of ADP and variation of press time ranged from 1.11 to 27.39 and 0.77 to 16.45. Based on ΔE values, the effect of ADP addition on the particleboard color was more notable than the effect of press time. Similar to the wood heating treatment, the darkening of the surface color of the particleboard was allegedly expected due to the increased chromophores formed by oxidation and dehydration of lignin or carbohydrates (Srinivas and Pandey, 2012) and also by the increased dehydration and caramelization of maltodextrin at high temperature for a time duration. The ADP existence is also



Colour Change/ ΔE	M/ADP ratio (wt%)		
	100/0	90/10	80/20
ΔE from 1-min to 3-min press time	-	0.90±0.72	0.77±0.34
ΔE from 1-min to 5-min press time	-	1.62±0.58	1.09±0.75
ΔE from 1-min to 7.5-min press time	-	3.30±1.06	1.86±0.78
ΔE from 1-min to 10-min press time	-	6.33±1.26	2.88±0.62
ΔE from 3-min to 5-min press time	4.06±1.52	1.45±0.06	1.58±0.77
ΔE from 3-min to 7.5-min press time	12.59±5.40	3.48±0.18	2.23±0.69
ΔE from 3-min to 10-min press time	16.45±2.42	6.52±0.35	3.29±0.80
ΔE from 5-min to 7.5-min press time	8.74±5.03	2.72±0.62	1.05±0.22
ΔE from 5-min to 10-min press time	12.69±1.96	5.60±0.39	2.01±0.12
ΔE from 7-min to 10-min press time	8.93±1.24	3.25±0.34	1.14±0.25

Figure 1 Effect of (a) ADP addition and (b) pressing time on color change (ΔE^*) level of bamboo particleboards
Slika 1. Utjecaj (a) dodavanja ADP-a i (b) vremena prešanja na razinu promjene boje (ΔE^*) bambusove iverice

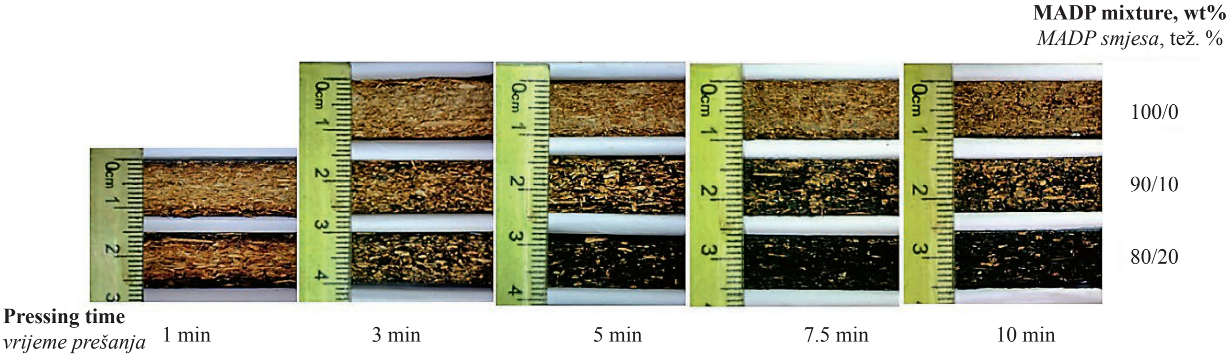


Figure 2 Thickness of bamboo particleboards
Slika 2. Debljine bambusovih iverica

Table 3 Physical properties and surface roughness of bamboo particleboards
Tablica 3. Fizička svojstva i hrapavost površine bambusove iverice

M/ADP mixture ratios, wt% *M/ADP omjeri miješanja,* tež. %	**Pressing time, min** *Vrijeme prešanja,* min	**Physical properties and surface roughness** *Fizička svojstva i hrapavost površine*		
		***TS±SD*, %**	***WA±SD*, %**	***Ra±SD*, µm**
90/10	1	Uncountable values (board destroyed)		13.41 ± 2.81
80/20				13.36 ± 3.50
100/0	3	104.57 ± 26.86	240.54 ± 7.29	14.63 ± 1.73
90/10		81.49 ± 7.10	189.22 ± 1.17	12.24 ± 2.00
80/20		48.48 ± 7.33	131.69 ± 11.15	10.96 ± 1.42
100/0	5	53.34 ± 7.85*	197.03 ± 11.83*	14.97 ± 1.86*
90/10		20.13 ± 0.66*	110.57 ± 11.30*	11.98 ± 1.97*
80/20		8.58 ± 2.23*	69.26 ± 12.42*	10.10 ± 1.74*
100/0	7.5	52.91 ± 10.72	160.92 ± 30.73	14.02 ± 1.41
90/10		7.44 ± 0.99	62.44 ± 14.92	10.70 ± 1.72
80/20		7.02 ± 1.27	50.40 ± 4.04	10.20 ± 1.85
100/0	10	38.96 ± 5.65	103.78 ± 2.19	11.52 ± 1.42
90/10		6.65 ± 1.24	64.33 ± 11.04	9.60 ± 1.80
80/20		5.08 ± 0.92	38.47 ± 1.15	8.92 ± 1.38

TS – thickness swelling, *SD* – standard deviation, *WA* – water absorption, *Ra* – arithmetic average of absolute values of roughness profile ordinates, *Dewi *et al*. (2023)
*TS – debljinsko bubrenje, SD – standardna devijacija, WA – upijanje vode, Ra – aritmetička sredina apsolutnih vrijednosti ordinata profila hrapavosti, *Dewi et al. (2023.)*

likely to act as a catalyst for the dehydration and caramelization of maltodextrin. Ammonium phosphate effectively catalyzes the sugar and starch transformation/caramelization into furan compounds and generates a dark color (Stofko, 1980; Liu *et al.,* 2013).

The effect of pressing time and ADP ratio on the particleboard was clearly shown with respect to thickness (Figure 2). A shorter duration of hot-pressing time turned out to merely harden/cure the adhesive on the surface; meanwhile, the core is still not cured due to low heat transfer on the core part. It was particularly obvious in 1 minute pressing time. Heat transfer during hot pressing was easily seen by a color change of maltodextrin caramelization and lignocellulose dehydration in the presence of ADP. A longer hot-pressing time was anticipated to improve heat transfer to the core. In the shorter hot-pressing time, the addition of ADP was expected to enhance the caramelization and the hardened reaction of maltodextrin in all areas of the board. It was apparently seen that a dark particleboard color could be obtained by the 5-minute pressing time with 20 % ADP. Meanwhile, a darker particleboard color with 100 % maltodextrin would be obtained by the 10-minute pressing time or more.

Table 3 shows the physical properties and surface roughness (*SR*) of bamboo particleboard with various M/ADP mixtures and pressing times. The *TS* and *WA* values of particleboards ranged from 5.08 % to 104.57 % and 38.47 % to 240.54 %, respectively. After the addition of ADP, the thickness swelling decreased notably by 22-87 %, while the water absorption decreased by 21-69 %. This decrease tended to get bigger with the longer pressing time. Good dimensional stability and water resistance of particleboards were achieved with longer pressing time and in the presence of ADP. Particleboards with M/ADP 90/10 and 80/20 at pressing times of 7.5 and 10 minutes met the TS standard of JIS A 5908 (2003) that required a maximum *TS* of 12 %. Interestingly, the 5-minute pressing time could also meet the standard only with 20 % ADP. Dewi *et al.*

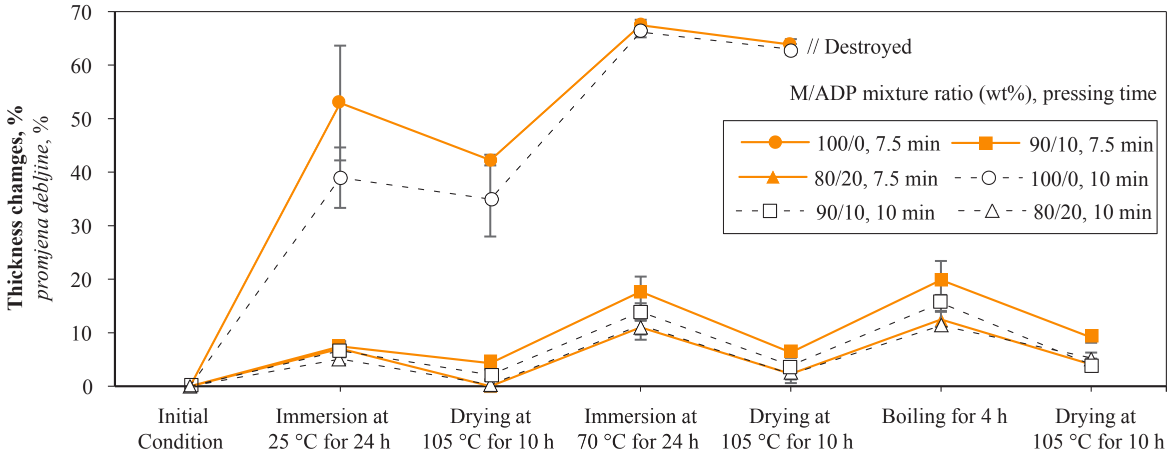


Figure 3 Thickness change of bamboo particleboard after accelerated cyclic aging treatment at pressing time of 7.5 and 10 minutes
Slika 3. Promjena debljine bambusove iverice nakon tretmana ubrzanim cikličnim starenjem pri vremenu prešanja od 7,5 i 10 minuta

(2022) mentioned that the addition of ADP promoted maltodextrin into highly water-resistant substances involving furan that might be generated by caramelization and dehydration.

Particleboards produced by a higher ADP ratio and longer pressing time exhibited lower surface roughness (Table 3). Tabarsa *et al.* (2011) also found that the particleboard surface was smoother with a longer pressing time, from 6 to 8 minutes. The improvement of the surface smoothness related to pressing time and the addition of ADP may be due to the fact that both parameters facilitated the good curing process of the adhesive and compression of the board. The surface roughness (*SR*) of this bamboo particleboard was close to the *SR* of the sanded and unsanded commercial Indonesian particleboard made from rubberwood (6.13-14.20 µm) (Hiziroglu *et al.,* 2008).

Figure 3 shows the thickness change of bamboo particleboard in the 7.5 minutes and 10 minutes pressing time after accelerated cyclic aging treatment. The most notable thickness change in the first immersion (25 °C for 24 h) was earned in the 100/0 M/ADP in both pressing times. The thickness change increased with further severe aging treatment, and it was damaged after the boiling treatment for 4 hours. It showed that the bonding of maltodextrin was susceptible to water. The thickness change was decreased with the addition of ADP and pressing time. Even the thickness change of the particleboard bonded with maltodextrin/ADP 80/20 at both pressing times is still in the range of 12.5-13.4 % after all of the cycles till the boiling step. At the same manufacturing condition (pressing temperature, pressing time, and adhesive content), our particleboard quality was better than some particleboards bonded with citric acid/sucrose 100/0-15/85 (Kusumah *et al.,* 2017) and tannin/sucrose 25/75 (Zhao and Umemura, 2014). It demonstrated that ADP addition into maltodextrin accompanied by heat (temperature and duration) enhances the dimensional stability of the particleboards against water. Dewi *et al.* (2021) showed that the insoluble matter rate of maltodextrin apparently increased with the increase of ADP addition accompanied by higher heating temperature and longer heating time, causing a change in maltodextrin and making it a high-water resistance substance.

The mechanical properties were also in line with the physical properties that showed an improvement in increasing the ADP ratio and pressing time. IB, MOR, MOE and brittleness increased with the increasing ADP ratio and pressing time (Figure 4-5). Increasing the ADP ratio could increase the mechanical properties of both the sucrose and maltodextrin-based particleboard (Dewi *et al.,* 2022; Komariah *et al.,* 2022). Meanwhile, increasing the pressing time was known to increase the mechanical properties of particleboard (Nemli *et al.,* 2007). In 1-minute pressing time, ADP ratio seemed to not affect the IB, but affected the IB at 3-10– minute pressing time, especially between with and without ADP. ADP would perform its catalyzing effect on sugar-based components deformation into furan-type components in the presence of heat (Umemura *et al.,* 2017), and 1-minute pressing time might be a relatively short time to provide heat for the entire section of the board. The board with a 5-minute pressing time and 20 % ADP had an IB value that almost met the JIS standard. Furthermore, the IB value of the board with 10 and 20 % ADP at 7.5– and 10-minutes pressing time met the JIS type 8 (0.15 N/mm^2). The IB value of the board with 20 % ADP and 10-minute pressing time even met the JIS type 13 (0.2 N/mm^2).

None of the *MOR* and *MOE* values met the JIS requirement. Some improvements had to be made in order to increase the *MOR* and *MOE* values, e.g., the use of particles with high slenderness/aspect ratio, as

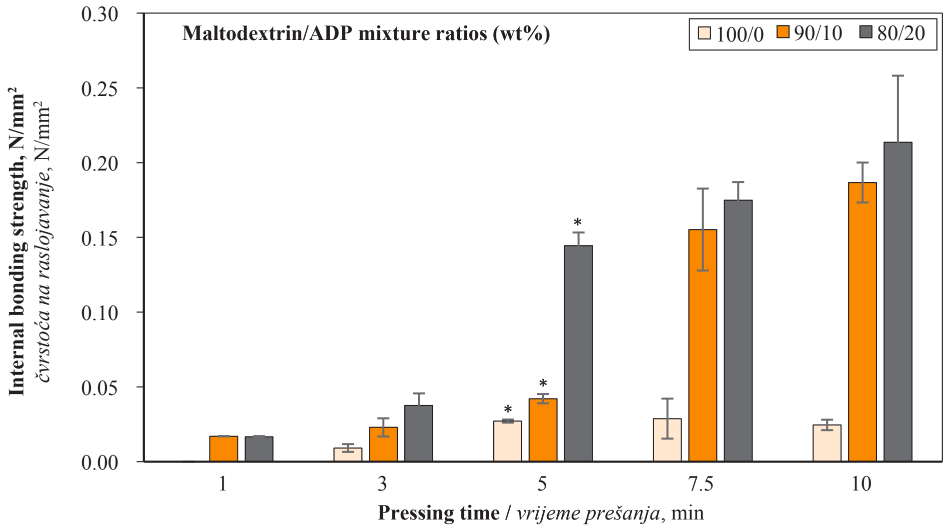
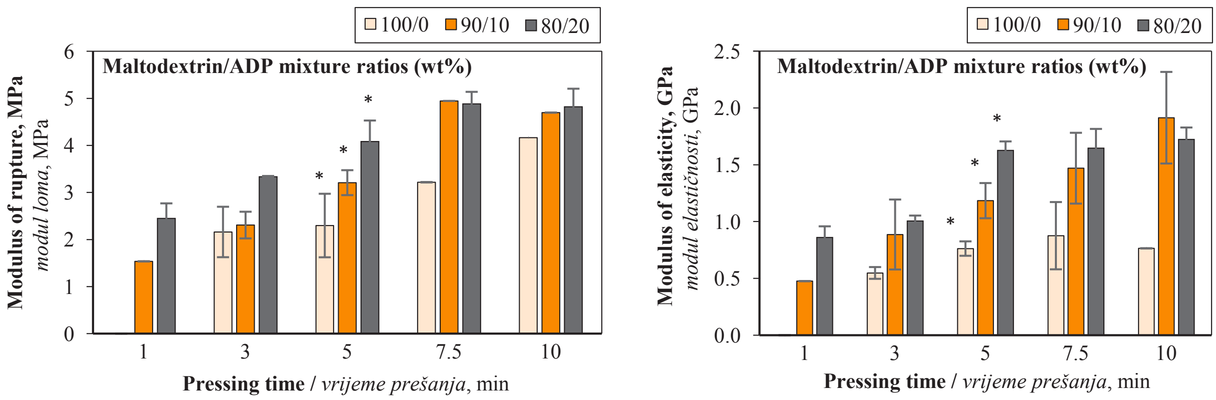


Figure 4 Internal bonding strength of bamboo particleboards, *Dewi *et al*. (2023)
Slika 4. Čvrstoća bambusove iverice na raslojavanje, * Dewi *et al*. (2023.)



a) b)

Figure 5 a) *MOR*, b) *MOE* of particleboard, *Dewi *et al*. (2023)
Slika 5. a) *MOR*, b) *MOE* iverice, * Dewi *et al*. (2023.)

well as increasing the board density and resin content. Jin-shu *et al.* (2006) summarised that the density was a significant factor that affected the *MOR*, *MOE*, and IB. But, Arabi *et al.* (2011) showed that the use of particles with a high slenderness ratio could compensate for the reduction of density and resin content in intending to increase the MOR and *MOE* while significantly saving the production cost. Due to low *MOR* and *MOE* value, the brittleness was also low (namely 4.6-41.7 %) compared to sorghum bagasse particleoard bonded with citric acid (namely 90 %) by Kusumah *et al*. (2017). Similar to *MOE*, the brittleness was increased on the increasing of ADP ratio and pressing time.

The effect of M/ADP ratios and pressing time on the chemical properties of the bamboo particleboard is shown in Figure 6. The higher ADP ratios on the maltodextrin adhesive and the higher pressing time, the more clearly visible the absorbance of 1705 cm^{-1} (carbonyl of ketone) and 1620 cm^{-1} (carbonyl of the aromatic ring) (Umemura *et al.,* 2017). However, the absorbance of the carbohydrate fingerprint (1458-833 cm^{-1}) (Sritham and Gunasekaran, 2017) was more invisible. This showed that increasing the ADP ratio and increasing the pressing time was expected to assist the carbohydrate dehydration/hydrolysis (either from the maltodextrin or the hemicellulose of the raw material) into other substances, i.e. 5-hydroxymethyl 2-furfural (5-HMF). Tomasik *et al.* (1989) and Chheda *et al.* (2007) stated that carbohydrates were hydrolyzed into 5-HMF at high temperatures. The 1705 cm^{-1} peak was expected from carbonyl (C=O groups) of 5-HMF.

The thermogravimetry analysis of the maltodextrin, petung bamboo, and dried mixtures at M/ADP 100/0 wt% and 80/20 wt% could be shown in Figure 7. The onset temperature of weight loss was rather different in each component and showed a different reactivity toward the heat treatment. The maltodextrin has the highest onset temperature of weight loss (266 °C). The preliminary weight loss temperatures were around 240 °C when the maltodextrin 100/0 wt% was mixed with bamboo. Dewi *et al.* (2022) also found that when ADP was added to maltodextrin and mixture with Salacca

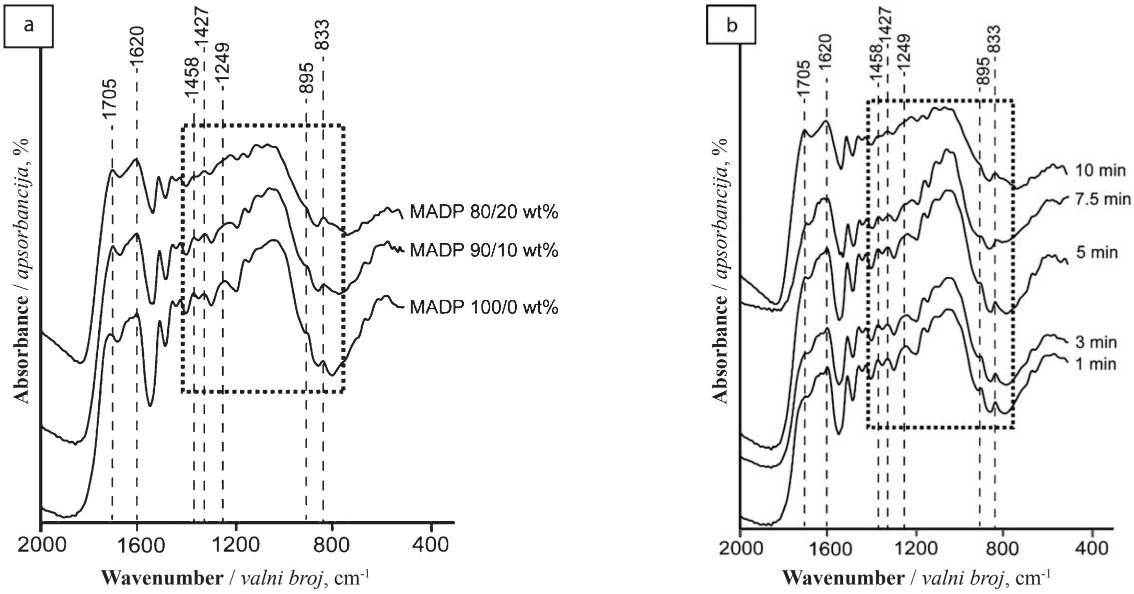


Figure 6 The infrared spectrum of the bamboo particleboards on various a) M/ADP mixture ratios at 10 minutes pressing time, b) pressing temperatures at M/ADP 80/20 wt%
Slika 6. Infracrveni spektri bambusove iverice s obzirom na (a) M/ADP omjere pri vremenu prešanja od 10 minuta i (b) na temperature prešanja pri M/ADP omjeru 80/20 tež. %

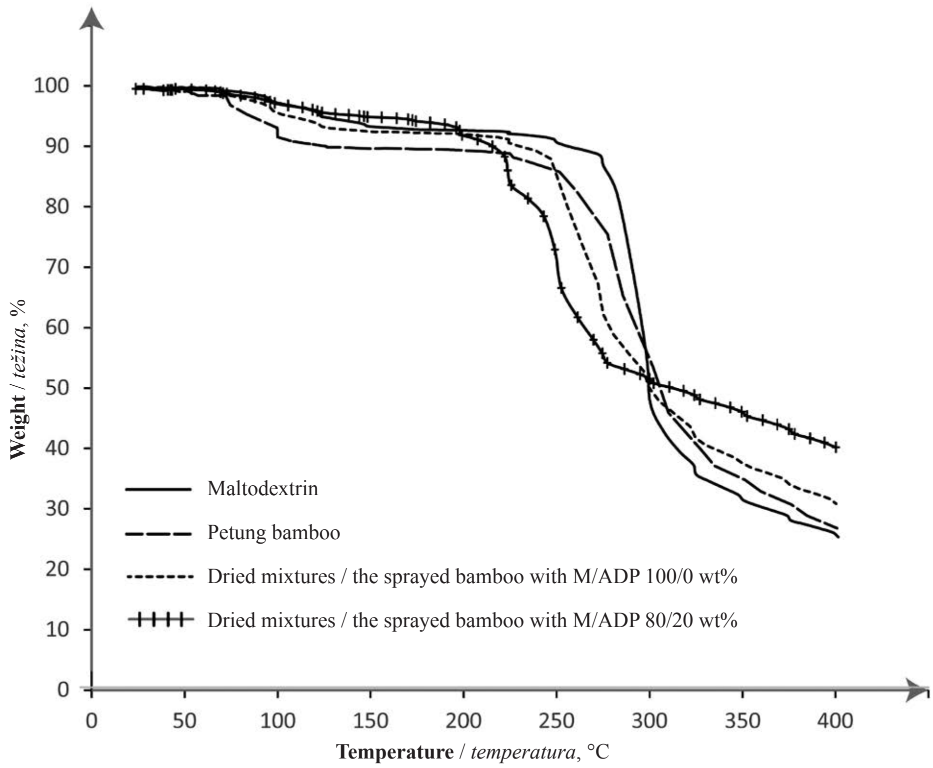


Figure 7 Thermogravimetry of the maltodextrin adhesives, the bamboo raw material, and the adhesive-sprayed bamboo particle
Slika 7. Termogravimetrija maltodekstrinskih ljepila, sirovine od bambusa i oblijepljenog iverja bambusa

frond particle, the weight loss temperature was around 156 °C. These findings demonstrated that the addition of ADP resulted in a drop in the weight-reduction onset temperature. The onset temperature of weight reduction shifted to 200 °C for the dried mixture of bamboo with M/ADP 80/20 wt%, and then the bamboo raw material tended to be stable on heating at room temperature to 230 °C with 10 % weight reduction at 80 °C. Ardhyananta *et al.* (2019) also stated that the onset weight loss of Petung bamboo at 267 °C.

4 CONCLUSIONS
4. ZAKLJUČAK

This research aimed to utilize bamboo particle waste, combined with a maltodextrin/ADP natural adhesive, to produce an environmentally friendly particleboard. Based on the research results, increasing the M/ADP ratio and pressing time improved the physical and mechanical properties of the bamboo particleboard. However, the modulus of rupture and modulus of elasticity still required enhancement. A M/ADP ratio of 90/10 and 80/20 wt% with a pressing time of 7.5 and 10 minutes achieved satisfactory water resistance, as indicated by thickness swelling and aging evaluations. The best particleboard properties were obtained with a M/ADP ratio of 80/20 wt% at a pressing time of 10 minutes, making it suitable for water-related applications. FTIR spectra revealed the presence of a furan-type component in the treatment, which may contribute to the improved properties. This method of particleboard production could serve as an alternative for managing bamboo waste effectively.

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Anatomical, Physical and Mechanical Properties of Lesser-Known Wood Species of Simpur (*Dillenia serrata*) from Indonesia and Its Potential Uses

Anatomska, fizikalna i mehanička svojstva manje poznate vrste drva simpura (*Dillenia serrata*) iz Indonezije i njegova potencijalna uporaba

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ABSTRACT • *Simpur (Dillenia serrata Baehni) is a lesser-known wood species extracted from the natural tropical forest in East Luwu District, South Sulawesi Province of Indonesia. This research examined its basic properties and determined its potential use by considering those properties. The wood properties examined were anatomical, physical, and mechanical. General characteristics were observed using whole wood or plank-shaped samples that had been placed on the surface; incision preparations were made following the Sass procedure; anatomical characteristics were observed according to the IAWA list of microscopic features for hardwood identification and fibers dimensions using maceration. The method for testing the physical and mechanical properties follow the Japanese Industrial Standard (JIS). The results showed that simpur is reddish brown and its heartwood and sapwood are distinguishable. The wood has a plain style figure, straight grain or occasionally slightly interlocked, slightly coarse and even texture, somewhat dull gloss, and a slightly rough touch impression. The growth rings are vague, diffuse, vessels with large radii, very long fibers, a very wide fiber diameter, and thin to thick cell wall thickness. The wood is classified as medium specific gravity, very high shrinkage, and second-class strength. The wood can be potentially used for medium-to-weight construction structural materials, veneer and plywood, particle board, pulp, and paper.*

KEYWORDS: *lesser-known wood species; Dillenia serrata; wood properties; potential use*

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SAŽETAK • *Simpur (Dillenia serrata Baehni) manje je poznata vrsta drva iz prirodne tropske šume u okrugu East Luwu, pokrajina Južni Sulawesi u Indoneziji. Ispitana su anatomska, fizička i mehanička svojstva drva kako bi se odredile mogućnosti njegove potencijalne uporabe. Opća su svojstva drva određena promatranjem trupca ili piljenica. Napravljene su pripreme za rez prema Sass postupku, anatomska obilježja promatrana su prema IAWA popisu mikroskopskih značajki za identifikaciju tvrdog drva, a dimenzije vlakana analizirane su uz pomoć maceracije. Fizička i mehanička svojstava ispitana su prema japanskom standardu (JIS-u). Rezultati su pokazali da je drvo simpura crvenkastosmeđe boje, s uočljivom razlikom drva srži i bjeljike. Drvo je neutralnog izgleda, ima ravnu do blago uvijenu žicu, pomalo grubu i ujednačenu teksturu, zagasit sjaj i blago hrapavu površinu. Pripada difuzno poroznim vrstama drva sa slabo vidljivim godovima, trahejama velikog promjera, vrlo dugačkim i širokim vlaknima, a debljina stanične stijenke drva simpura varira od tanke do debele. Klasificirano je kao drvo srednje gustoće, izrazitog utezanja i čvrstoće druge klase. Drvo se potencijalno može upotrebljavati za izradu srednjih do teških građevnih konstrukcijskih materijala, furnira i furnirskih ploča, iverica, celuloze i papira.*

KLJUČNE RIJEČI: *manje poznate vrste drva; Dillenia serrata; svojstva drva; potencijalna uporaba*

1 INTRODUCTION
1. UVOD

The Plant Resources of South East Asia categorized wood species in Southeast Asia based on their trades: least-known, lesser-known, minor, and major wood species. Due to intensive exploitation, major and minor wood species (commercial wood) are becoming scarcer, affecting their supply, which continuously declines (Lemmens *et al.*, 1995). On the other hand, commercial wood demand for building and industrial materials tends to increase. The severely reduced availability of commercial woods can be replaced by lesser-known and underutilized woods found in various regions. Unfortunately, the properties of most wood species are not known enough to promote their use (Marbun *et al*., 2023), so the wood-based industry is not fully ready to use all wood species. According to Lempang (2014), wood of lesser-known species can be used and act as a substitute for commercial wood; it is necessary to identify the properties of the wood and evaluate its potential use. Until now, many studies have examined lesser-known wood species from Southeast Asia and other countries to find a substitute for commercial wood. Some of them are *Artocarpus altilis* wood from Nigeria (Areo, 2021), *Schima wallichii, Duabanga grandiflora, Callicarpa arborea, Castanopsis tribuloides, Anogeissus acuminata* wood from India (Hedge, 2019), such as *Myristica linifolia, Pterospermum acerifolium* and *Trewia nudiflora* wood from Bangladesh (Chowdhury *et al*., 2017), Malaysia (Hamdan *et al*., 2020), and *Artocarpus odoratissimus*, *Duabanga moluccana*, *Horsfieldia hellwigii*, *Octomeles sumatrana* wood from Indonesia (Marbun *et al*., 2019). The use of wood is generally based on its basic properties. These properties can be used to predict the proper processing and utilization of wood (Hidayat *et al*., 2017; Purusatama *et al*., 2018), and they can also influence its commercial value (Riki *et al*., 2019).

Dillenia is a genus of about 100 species of flowering plants in subtropical and tropical trees of Southern Asia, the Indian Ocean Islands, and Australasia (Yazan and Armania, 2014). Some species of *Dillenia* grow naturally in the evergreen and moist forests of the Philippines, West Malaysia, Brunei Darussalam, and Indonesia (Yazan and Armania, 2014). *D. serrata* Thunb. is an endemic species of Indonesia (Marbun *et al.,* 2019), widely found and distributed in the islands of Sulawesi, Sumatera, Jawa, and Kalimantan (Marbun *et al.,* 2023), and commonly known as Simpur (Indonesia) and Simpor or Simpoh (Malaysia) (Yazan and Armania, 2014). Simpur is one of the lesser-known species, fast-growing (Adi *et al*., 2015), species with a tree habitus, medium size, and evergreen, up to 30 m tall with free-branching stems up to 16 m and up to 70 cm in diameter (Pitopang, 2008). Accurate information about the properties of a wood species is essential, especially when selecting raw materials, to produce a high-quality product. The aim of this research is to examine the wood properties (anatomical, physical, and mechanical) and predict its potential use.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Material
2.1. Materijal

The wood material for this study was obtained from two trees of simpur (*D. serrata*) with a trunk diameter of 40.2 and 43.0 cm. Three samples were taken from each tree, from the bottom, medium and top part. The wood originates from natural tropical forests in the South Sulawesi Province of Indonesia with GPS location: latitude 2°38’50.82” N and longitude 121°5’47.53.71 E. The test sample trees had an average (bottom and top part) trunk diameter of 42.6 cm, a clear bole (branch-free stem) length of 4.8 m, a sapwood thickness of 2.5 cm, a bark thickness of 2.0 cm, reddish-colored bark, scaly bark, and flaky bark scales. The schematic of the sample preparation is shown in Figure 1. Three discs with a thickness of 5.0 cm and three logs with a length of 100.0 cm were taken from each position (bottom, middle, and top) part of the tree trunk. The discs were used to make

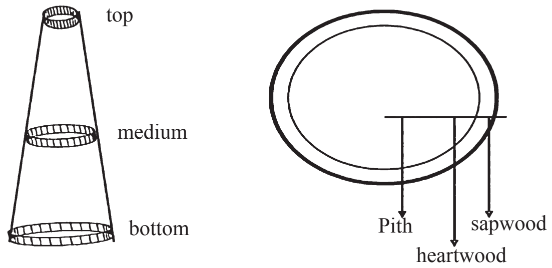


Figure 1 Schematic of sample preparation
Slika 1. Shema pripreme uzorka

samples for anatomical observation and chemical analysis, while the logs were used to make samples for testing of physical and mechanical properties.

2.2 Methods
2.2. Metode

2.2.1 Anatomical observation
2.2.1. Analiza anatomskih svojstava

Anatomical characterization of wood includes general properties, structure and fiber dimensions. General properties were observed using solid wood and samples in the form of planks that had been planned for the surface, including color, figure, grain direction, texture, gloss, and touch. The wood structures (bottom, medium and top part) were observed using incision preparations made following the Sass procedure (Rulliyati, 2014). The observations of wood cell type, including vessels, rays, parenchyma, fibers, and others, were carried out accordingly by the IAWA Hardwood List of the International Association of Wood Anatomists Committee (Wheeler *et al.,* 2008). Fiber dimensions were measured through maceration preparations made based on a modification of Franklin's method (Rulliyati, 2014). The quality class of wood fiber could be determined by derived values of fiber dimensions, namely Muhlsteph ratio (MR), Runkel ratio (RR), flexibility ratio (FR), coefficient of rigidity (CR), and felting power (FP) (Marbun *et al*., 2023). The fiber quality of simpur was assessed based on wood fiber quality criteria for pulp and paper (Marbun *et al.,* 2023).

2.2.2 Physical and Mechanical Testing
2.2.2. Ispitivanje fizičkih i mehaničkih svojstava

Logs taken from the base, middle, and ends of the simpur stems were sawn into blocks with a size of 6 cm × 6 cm × 120 cm for physical and mechanical test samples. The size of the test samples and the method for testing the physical and mechanical properties followed the Japanese Industrial Standard (JIS, 2003). The determination of the simpur strength class followed the wood strength classification used in Indonesia, which is based on wood specific gravity, bending strength at failure (*MOR*), and compressive strength parallel to grain (Oey, 1990).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

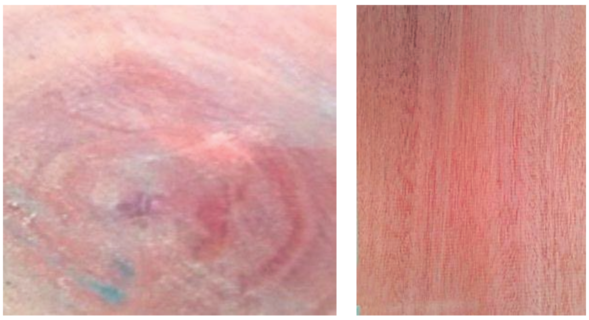
3.1 Wood anatomical characteristics
3.1. Anatomska svojstva drva

3.1.1 General characteristics
3.1.1. Opća svojstva drva

There was no clear distinction between the heartwood and sapwood. The color of both the heartwood and sapwood was brown and reddish brown. The growth rings were vague. The figure was in plain style. The grain directions were straight and somewhat interlocked. The texture was rather coarse and even. The gloss of the wood surface was rather dull. The texture of the wood surface was rather rough. The impression of touch or roughness on the surface of the wood was not only caused by the tools used to work the wood; it was also caused by the internal structure of the wood, which has cavities in the form of pores and cell lumens (Csanady and Magoss, 2013).

3.1.2 Wood structure
3.1.2. Struktura drva

The wood was diffuse and the distribution of vessels on cross section was almost entirely solitary. The vessel length was 526.61 μm, with the diameter of 170.01 μm and frequency of 5 mm^{-2}. The perforation plate was scalariform; inter-vessel pits were alternate with medium size (>7-10 μm); vessel-ray pits with narrow to simple pages; pits were horizontal or vertical. The apotracheal axial parenchyma was scattered and scattered in clusters, with strand lengths of 8 (5 – 8) cells per strand. The rays were large, generally 4 – 10 series, with a ray cell composition of more than 4 upright cell rows and/or square marginal cells and a ray height >1 mm. The fiber elementary tissue was with well-defined page pits. There were graffiti crystals included in ray cells. The existence of crystals may be important for mechanical support in certain cells (Cipta *et al*., 2022). Wood macro– and microstructures of simpur are shown in Figures 2 and 3.



a) b)

Figure 2 Wood macrostructure of simpur (*D. serrata*): (a) cross section / transversal surface; (b) tangential surface
Slika 2. Makrostruktura drva simpura (*D. serrata*): a) poprečni presjek; b) tangentni presjek

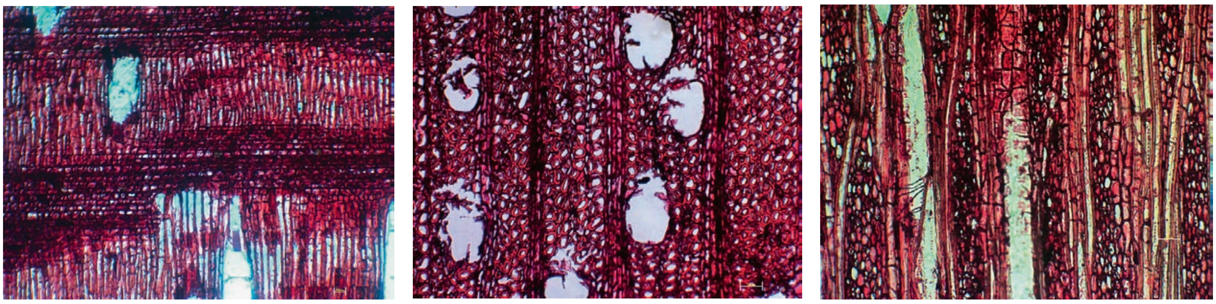


Figure 3 Wood microstructure of simpur (*D. serrata*): a) radial surface, b) tangential surface, c) transversal surface
Slika 3. Mikrostruktura drva simpura (*D. serrata)*: a) radijalni presjek; b) tangentni presjek, c) poprečni presjek

3.1.3 Fiber dimensions and quality
3.1.3. Dimenzije i kvaliteta vlakana

Simpur is classified as a hardwood species (broadleaf). Hardwood generally has short fibers (200 – 1.200 µm in length) and is slender (about 20 µm in diameter) (Shmulky and Jones, 2019). Wood fiber dimensions of simpur are presented in Table 1.

Wood fibers of simpur were classified into very long, very wide diameter, very wide lumen diameter, and thin to thick wall thickness. Although simpur fiber has a wall thickness of 10.61 µm (very thick), the fiber wall of this wood is classified as thin to thick, because it has a lumen diameter (40.05 µm) less than three times the thickness of its two fiber walls and still looks open (Wheeler *et al*., 2008).

Anatomical properties, particularly the fiber dimensions, can predict the quality of wood for pulping purposes. The fiber quality between species of wood varies greatly. The role of fiber dimensions such as fiber length, fiber diameter, and wall thickness has complex relationships with each other and fundamentally influences the physical properties of pulp, and paper, and other wood products (Lempang, 2016). The dimension of fiber and its derivatives is one of the important properties of wood, which can be used to predict the properties of the pulp produced (Syafii and Siregar, 2006). The wood fiber quality of simpur as a raw material for paper pulp is presented in Table 2.

Fiber length has a significant relationship with paper strength, especially in the tear index, tensile index, and folding index (Rizqiani *et al.*, 2019). Fiber length affects the tensile strength and slightly affects the crease resistance of the paper (Rizqiani *et al.,* 2019); the longer the fiber, the greater the tear resistance of the paper; thin to thick fiber walls will flatten easily when milled, and very long fibers produce strong weaving power. The fiber wall of simpur is classified as thin to thick, but the lumen diameter is wide enough so that the

Table 1 Wood fiber dimension of simpur (*D. serrata*)
Tablica 1. Dimenzije vlakana drva simpura (*D. serrata*)

Fiber dimensions *Dimenzije vlakana*	**Average, µm** *Srednja vrijednost,* µm	**Standard deviation** *Standardna devijacija*	**Classification*** *Klasifikacija vlakana**
Length / *duljina*	3,234.78	± 360.43	Very long / *vrlo dugačka*
Diameter / *promjer*	61.26	± 11.16	Very wide / *vrlo širok*
Lumen diameter / *promjer lumena*	40.05	± 9.26	Very wide / *vrlo širok*
Wall thickness / *debljina stijenke*	10.61	± 1.90	Thin to thick / *tanka do debela*

*IAWA classification of fiber dimension of hardwood / *IAWA klasifikacija dimenzija listača*

Table 2 Wood fiber quality of simpur (*D. serrata*) as raw material for pulp and paper
Tablica 2. Kvaliteta vlakana drva simpura (*D. serrata*) kao sirovine za proizvodnju celuloze i papira

Fiber dimension and fiber dimension-derived values *Dimenzija vlakana i vrijednosti izvedene iz tih dimenzija*	**Average** *Srednja vrijednost*	**Standard deviation** *Standardna devijacija*	**Score*** *Rezultat**
Fiber length, µm / *duljina vlakana,* µm	3,234.78	± 360.00	100
Runkle ratio / *Runkelov omjer*	0.55	± 0.12	50
Felting power / *brzina filcanja*	55.23	± 0.05	50
Flexibility ratio / *omjer fleksibilnosti*	0.65	± 0.05	75
Muhlsteph ratio, % / *Muhlstephov omjer*, %	57.61	± 5.57	75
Coefficient of rigidity / *koeficijent krutosti*	0.18	± 0.03	50
Total / *ukupno*			400
Class of fiber quality / *klasa kvalitete vlakana*			II

*Oey, 1996

Runkel ratio obtained is relatively low. The lower the Runkel ratio (≤1), the better the quality of the pulp produced because the fibers will be easily flattened in the manufacture of pulp sheets (Rulliyati, 2014).

In general, the data in Table 2 shows that the simpur fiber studied has a total score of fiber length and fiber derivative dimension of 400. This indicates that simpur fiber is classified as good quality (quality class II) as a raw material for making paper pulp. Wood in this category has short to long fibers, thin to thick fiber walls, and narrow to wide lumen diameters, so that the fibers will flatten quite easily when milled and the fiber bonds are quite good. This type of fiber is thought to be able to produce sheets with relatively high tear, crack, and tensile strength.

3.2 Physical properties
3.2. Fizička svojstva drva

The important physical properties of wood are moisture content, specific gravity, and shrinkage. The physical properties of simpur wood are presented in Table 3.

The moisture content of wood in living trees varies from 25 % to 250 % or more (Djarwanto *et al*., 2017). Variations in freshwater content in each wood species depend on the location where it was grown, age, season when harvested, and tree size (Shmulky and Jones, 2019). Indonesian National Standards (SNI 7973-2013) require a maximum moisture content of 19 % for wood used for dry conditions in closed structures (Badan Standardisasi Nasional, 2013). In practice, wood is generally used at a moisture content of 6.2-13.1 (Djarwanto *et al*., 2017).

Simpur has a specific gravity of 0.69 and 0.64 g/cm^3 density. Most of the physical and mechanical properties of wood are closely related and can be predicted by the specific gravity of the wood (Machado *et al*., 2014). The research results on mangium (*Acacia mangium* Wild.) showed that the specific gravity of wood had a significantly positive correlation with radial and tangential shrinkage and compressive strength parallel and perpendicular to the grain (Hidayat *et al*., 2016). Therefore, the specific gravity of wood is a good indicator for predicting other physical and mechanical properties of wood. The strength and toughness of wood increase with increasing specific gravity. Likewise with the machining properties of wood, the higher the specific gravity of wood, the better the machining properties (Rianawati *et al.,* 2015). The yield of paper pulp per unit volume of raw material is directly related to the specific gravity. Based on IAWA criteria (Wheeler *et al.,* 2008), the specific gravity of wood was divided into three groups, namely low (< 0.40), medium (0.40 – 0.75) and high (> 0.75). Wood, often used as raw material for paper pulp, is a wood species with a medium-specific gravity. A hardwood species widely used as raw material for paper pulp is mangium, with a specific gravity of 0.60 (Arsad, 2012). The specific gravity of simpur (0.69) is higher than that of mangium, but both mangium and simpur are classified as wood species with a medium specific gravity (0.40 – 0.75).

Dimensional stability is one of the properties of wood that must be considered in determining its use (Basri and Saefudin, 2021). This is related to temperature and humidity fluctuations where the wood will be installed or placed (Schonfelder *et al*., 2018). The shrinkage of simpur from wet to oven-dry in the radial axes (R) is 3.37 %, and the tangential axes (T) are 10.30 %. Since the T shrinkage from the wet to oven-dry state is higher than 3.5 %, simpur is classified as a wood with very high shrinkage. T shrinkage of the wood is generally greater (1.5 – 3.0 times) than R shrinkage, partly due to the presence of ray cells, and the frequency of pitch on the cell walls in R is higher than in T (Shmulky and Jones, 2019). The shrinkage

Table 3 Wood physical properties of simpur (*D. serrata*)
Tablica 3. Fizička svojstva drva simpura (*D. serrata*)

Physical properties *Fizička svojstva*	**Average** *Srednja vrijednost*	**Standard deviation** *Standardna devijacija*
Green moisture content, % / *sadržaj vode u sirovom drvu,* %	37.73	± 3.32
Air dry moisture content, % / *sadržaj vode u drvu sušenom na zraku*, %	11.23	± 0.20
Nominal green specific gravity / *specifična gustoća sirovog drva*	0.55	± 0.01
Air dry specific gravity / *specifična gustoća drva sušenog na zraku*	0.69	± 0.02
Density, g/cm^3 / *gustoća,* g/cm^3	0.64	± 0.02
Shrinkage from green to air dry: *Utezanje od sirovog do zrakosuhog stanja*		
-Radial, % / *radijalno,* %	2.25	± 0.42
-Tangential, % / *tangentno,* %	6.87	± 0.58
Shrinkage from green to oven dry: *utezanje od sirovog do apsolutno suhog stanja*		
-Radial, % / *radijalno,* %	3.37	± 0.55
-Tangential, % / *tangentno,* %	10.3	± 0.75

Table 4 Wood mechanical properties of simpur (*D. serrata*)
Tablica 4. Mehanička svojstva drva simpura (*D. serrata*)

Mechanical properties *Mehanička svojstva*	**Average** *Srednja vrijednost*	**Standard deviation** *Standardna devijacija*
Air dry specific gravity / *specifična gustoća drva sušenog na zraku*	0.69	_
Strength class / *klasa čvrstoće*	II	_
Bending stress at proportional limit, kPa *čvrstoća na savijanje u linearnom području,* kPa	61,412.18	± 10736
Bending stress at failure (*MOR*)*, kPa / *modul loma,* kPa	94,127.17	± 9958
Modulus of elasticity, MPa / *modul elastičnosti,* MPa	10,467.33	± 1538
Compression parallel to grain, kPa / *čvrstoća na tlak u smjeru vlakanaca,* kPa	7,710.97	± 4785
Compression perpendicular to grain, kPa *čvrstoća na tlak okomito na vlakanca,* kPa	16,737.99	± 1805
Shear parallel to grain, kPa / *smična čvrstoća u smjeru vlakanaca,* kPa	11,726.79	± 1736

**MOR* – Modulus of rupture / *MOR – modul loma*

ratio of T to R (T/R ratio) of simpur is 3.06. Wood with a T/R ratio of more than 2 has relatively low dimensional stability compared to wood with a balanced T/R ratio of less than 2 (Basri *et al*., 2012). Ideally, the T/R ratio of wood is 1, where the T shrinkage equals the R shrinkage (Anish *et al*., 2015). However, the results of a study of 87 Indonesian wood species revealed that only ares (*Gmelina moluccana* Backer ex K. Heyne) showed a T/R ratio equal to 1 (Basri *et al*., 2020). The shape of a wood piece can be distorted by the combined effect of shrinkage in the radial and tangential axes. Wood with low dimensional stability (T/R ratio > 2) tends to undergo deformations such as cupping, bowing and twisting when dried (Basri and Wahyudi, 2013). Simpur has a very high shrinkage, a very high T/R ratio, and very unstable dimensions. It is suspected that besides being difficult to glue, it is also difficult to dry because it will be deformed when dry. The dimensional stability of wood is related to fluctuations in temperature and humidity where the wood will be installed or placed (Schonfelder *et al*., 2018). Therefore, dimensional stability is one of the properties of wood that must be considered in determining its use.

3.3 Mechanical properties
3.3. Mehanička svojstva drva

The mechanical properties of wood are the wood's ability to withstand a load. Important mechanical properties are known for the use of wood in civil construction (Nascimento *et al*., 2017). Several factors affect the mechanical properties of wood, including specific gravity, moisture content, anatomical structure of wood, temperature, duration of loading, and repetition of loading. Wood mechanical properties of simpur are presented in Table 4.

Table 4 shows that the bending stress at failure/ *MOR* is 94,127.17 kPa, and the compression parallel to grain is 7,710.97 kPa. The mechanical properties of simpur wood are relatively the same compared to conventional teakwood aged 14 years, with *MOR* of 92,280 kPa and compression parallel to grain is 7,910 kPa (Hidayat *et al*., 2017). Wood strength classification is determined using the relationship between air-dry specific gravity, bending stress at failure (*MOR*) and compression parallel to grain (Oey, 1990). The strength of wood is classified into five classes, from very strong (strength class I) to very weak (strength class V) (Oey, 1990). The wood strength class of simpur is II.

4 CONCLUSIONS
4. ZAKLJUČAK

Heartwood and sapwood of simpur (*D. serrata)* can be distinguishable. The heartwood color is reddish brown and has the same color as the sapwood: plain-style figure, straight grain or occasionally slightly interlocked, slightly coarse and even texture, somewhat dull gloss, and a slightly rough touch impression. The growth rings are vague, diffuse vessels with large radii, very long fibers, a very wide fiber diameter, and a thin to thick cell wall thickness. The wood is classified as medium specific gravity, very high shrinkage, and strength class II. Potential uses for medium to heavy construction structural materials include low-cost furniture, veneer and plywood, particleboard, pulp, and paper.

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Auxeticity and Wood

Auksetičnost i drvo

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ABSTRACT • *Poisson's ratio, one of the elastic constants, describes the ratio of lateral strain to axial strain when a material is subjected to stress. The range of Poisson's ratios greatly varies in terms of material types and their structures. Furthermore, some materials present negative Poisson's ratios which are attributed to auxeticity. Wood material has six Poisson's ratios corresponding to the neighboring planes of the essential axes of Longitudinal, Radial, and Tangential. Due to the polar orthotropic nature of wood, six of them are different, and generally reported Poisson's ratios are positive. Limited studies focused on the auxetic behavior of wood. This study was focused on the auxeticity evaluation of poplar wood by ultrasonic testing over annual ring inclinations (30°, 45°, and 60°). The elasticity (E_L, E_R, and E_T), and shear (G_{LR}, G_{LT}, and G_{RT}) moduli and Poisson's ratios (μ_{LR}, μ_{LT}, μ_{RL}, μ_{RT}, μ_{TL}, and μ_{TR}) were calculated. According to the results, auxetic behavior was not observed for 30° samples. Furthermore, negative Poisson's ratios were not seen in μ_{TR} and μ_{RT} in all inclinations. However, μ_{LT} and μ_{TL} in 45° and μ_{LR} and μ_{RL} in 60° presented auxetic behavior. Furthermore, higher than 1 Poisson's ratio values were also observed, which is not common for wood material. Also, moduli were determined using a simple formula and stiffness tensor. Considerable differences were observed in elasticity moduli (up to -70 % for E_T), while shear moduli were almost the same. By the increase in inclination, ultrasonic wave velocities were differently affected in terms of increases, decreases, and oscillations. However, the impact of inclination on velocities, and all elastic constants were statistically significant. The coefficients of determination between density and Poisson's ratios were close to zero.*

KEYWORDS: *negative Poisson's ratio; Populus canadensis; ultrasonic; auxeticity*

SAŽETAK • *Poissonov omjer, jedna od konstanti elastičnosti, opisuje omjer bočne i aksijalne deformacije kada je materijal izložen naprezanju. Raspon Poissonovih omjera uvelike varira ovisno o vrsti materijala i njegovoj strukturi. Nadalje, neki materijali pokazuju negativne Poissonove omjere, koji se pripisuju auksetičnosti. Drvni materijal ima šest Poissonovih omjera koji odgovaraju susjednim ravninama glavnih osi – uzdužne, radijalne i tangencijalne. Zbog polarne ortotropne prirode drva, šest Poissonovih omjera ima različite vrijednosti i uglavnom se navodi da su one pozitivne. Ograničen broj istraživanja usmjeren je na auksetično ponašanje drva. Ovo je istraživanje bilo usmjereno na procjenu auksetičnosti drva topole ultrazvučnim ispitivanjem pri kutu otklona godova od 30°, 45° i 60°. Izračunani su moduli elastičnosti (E_L, E_R i E_T), moduli smicanja (G_{LR}, G_{LT} i G_{RT}) i Poissonovi omjeri (μ_{LR}, μ_{LT}, μ_{RL}, μ_{RT}, μ_{TL} i μ_{TR}). Prema rezultatima, auksetično ponašanje nije primijećeno na uzorcima s kutom otklona godova od 30°. Nadalje, negativni Poissonovi omjeri nisu zabilježeni za Poissonove omjere μ_{TR} i μ_{RT} pri svim kutovima otklona godova. Međutim, Poissonovi omjeri μ_{LT} i μ_{TL} pri 45° te Poissonovi omjeri μ_{LR} i μ_{RL} pri 60° pokazali su auksetično ponašanje. Nadalje, primijećene su i vrijednosti Poissonova omjera veće od 1, što nije uobičajeno za drvni materijal. Moduli su određeni uz pomoć jednostavne formule i tenzora krutosti. Uočene su*

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značajne razlike u modulima elastičnosti (do -70 % za E_T), dok su moduli smicanja bili gotovo jednaki. Povećanje kuta otklona godova različito je utjecalo na brzine ultrazvučnih valova u obliku povećanja, smanjenja i oscilacija. Utjecaj kuta otklona godova na brzine i sve elastične konstante bio je statistički značajan. Koeficijenti determinacije između gustoće i Poissonovih omjera bili su blizu nule.

KLJUČNE RIJEČI: *negativan Poissonov omjer; Populus canadensis; ultrazvučni; auksetičnost*

1 INTRODUCTION
1. UVOD

The auxeticity refers to the property of certain materials to exhibit a negative Poisson's ratio, meaning they expand in transverse directions when stretched. In other words, instead of contracting in the transverse direction as typical materials do, auxetic materials widen or increase in thickness. This unique behavior is a result of the internal structure or arrangement of the constituent elements in the material. Auxetic materials often have a specific geometric or structural pattern that allows them to exhibit this counterintuitive property. This can include structures such as specialized cellular, chiral, origami-inspired, and engineered structures, re-entrant honeycombs (HC), certain woven or knitted fabrics, certain foams, and crystals.

The auxetic property of materials has attracted interest in various fields, including engineering, materials science, textiles, and biomedical applications. It offers potential advantages such as enhanced impact resistance, improved energy absorption, and increased flexibility in certain applications. However, it is important to note that not all materials possess auxeticity, and the property is specific to certain structures or compositions.

The formation of auxetic materials or structures involves creating a geometric or structural arrangement that exhibits a negative Poisson's ratio, allowing for expansion in transverse directions when subjected to stretching or deformation. The following are a few common approaches to auxetic formation: geometric reconfiguration, material manipulation, origami and kirigami techniques, and additive manufacturing (AM) or 3D printing. The formation of auxetic materials often requires careful design, analysis, and fabrication techniques to achieve the desired properties. By leveraging the unique properties of auxetic structures, innovative designs, and materials can be developed for diverse purposes. Researchers and engineers continue to explore novel methods and materials to create auxetic structures with enhanced functionalities for various applications. For example, composite seat with auxetic springs (Smardzewski, 2013a; Smardzewski *et al*., 2014), auxetic dowels for furniture joints *(Kasal et al*., 2020; Kuşkun *et al.,* 2023, 2021), elastic properties of auxetic cells (Wojnowska *et al.,* 2017), AM of auxetic lattice truss cores (Smardzewski *et al.,* 2018), sandwich panels (SP) with auxetic lattice truss cores (Smardzewski *et al.,* 2021), seat of auxetic spring skeleton (Janus-Michalska *et al.,* 2013), auxetic structure of seat skeleton (Jasińska *et al.,* 2012) elastic features of wood boards with auxetic cores (Smardzewski, 2013b), two dimensional (2D) numerical simulation of auxetic foams (Pozniak *et al.,* 2013), synclastic SP with auxetic wood-based HC cores (Peliński and Smardzewski, 2022), auxetic spring elements for elastically supporting a sitting or lying (Smardzewski and Majewski, 2011), synclastic wood-based auxetic SP' stiffness (Peliński *et al.,* 2020), bending performance of auxetic cellular cored lightweight wood-based sandwich beams (Peliński and Smardzewski, 2020), the preparation of auxetic foams by three dimensional (3D) printing and their features (Critchley *et al.,* 2013), determining the rigidity, strength and energy absorbing capacity in novel SP with HC core produced using wood which has oval cells in the auxetic core (Smardzewski, 2019).

Apart from the abovementioned studies, the auxetic behavior of wood material was evaluated by limited studies for limited species. Marmier *et al.* (2018) evaluated the auxetic behavior of *Pinus strobus* by off-axis compression test and comparison with the finite element analysis. The authors reported -0.02 and -0.74 negative Poisson's ratios (NPR) in H (R 45°) direction but the proof for the auxeticity in wood was weak and scattered. Marmier *et al*. (2023) evaluated the NPR of *Picea* spp, *Pinus densiflora*, *Pseudotsuga menziesii*, *Taxus baccata*, *Ochroma pyramidale*, *Betula platyphylla*, *Fraxinus excelsior*, *Fagus* sp., *Quercus gilva*, and *Goupia glabra*. The authors noticed that NPR, ranging from -2.98 (*Picea Jezoensis* in RTL direction) to 0.07 (*Goupia glabra* +T direction)), were observed in off-axis directions, and that almost all woods with the density lower than 800 kg/m³ were auxetic. In the literature, the NPR was generally related to off-axis characteristics of wood. For example, Yamani (1957) found -0.42 NPR for *Cryptomeria Japonica* at 30° off the L axis. For the same inclination, Kawahara (Kawahara *et al*., 2015) reported -0.22 NPR for *Japanese cypress* and -0.05 NPR for Kalopanax. Sliker and Yu (1993) reported -0.37 NPR for Basswood in the 20° off-axis. Bucur and Najafi (2003) found higher (-0.95) NPR for Douglas fir determined by ultrasonic measurements. However, the authors did not mention the propagation angle or inclination with the essential axes. Therefore, auxetic behavior can be observed in both softwood and hardwood species.

When subjected to tensile stress, wood contracts in the transverse direction and elongates in the axial direction, following the conventional behavior of most materials. Since a few NPR have been reported for limited species, the auxetic behavior of wood needs to be further evaluated. Therefore, figuring out the possible auxetic behavior of wood related to its grain angle was the main motivation of this study particularly using the poplar species. The influence of ring angle on elastic constants of poplar, which has not been reported before, was also determined.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Populus x canadensis Moench wood was used. As can be seen in Figure 1, rings with 30°, 45°, and 60° were marked and samples were cut. Flawless samples (20 for each group) were conditioned at (20 ± 1) °C and 65 % relative humidity till their weight became constant. Following the equilibration, the density of the samples was calculated according to TS ISO 13061-2 (2021).

The elasticity (E_L, E_R, and E_T) and shear (G_{LR}, G_{LT}, and G_{RT}) moduli, and Poisson's ratios (µLR, µLT, µRT, µRL, µTL, and µTR) were dynamically determined by ultrasonic wave propagation. EPOCH 650 (Olympus, USA) ultrasonic flaw detector was used for propagation time measurements. Two types of waves, shear and longitudinal, were transmitted using V153-RM (1 MHz) and A133S-RM (2.25 MHz) contact-type transducers (Panametrics NDT, USA) in through transmission mode. Obtained times in µs were used to calculate axis and off-axis ultrasonic wave velocities (UWV) presented in Table 1. Stiffness matrix' terms (Eq. 1) were calculated and inversed to determine the compliance matrix (Eq. 2) that estimates the elastic constants.

$$[C] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (1)$$

Where: C_{ii} are diagonal and C_{ij} and C_{ji} are off-diagonal terms.

$$[S] = \begin{bmatrix} \frac{1}{E_L} & -\frac{\upsilon_{21}}{E_R} & -\frac{\upsilon_{31}}{E_T} & 0 & 0 & 0 \\ -\frac{\upsilon_{12}}{E_L} & \frac{1}{E_R} & -\frac{\upsilon_{32}}{E_T} & 0 & 0 & 0 \\ -\frac{\upsilon_{13}}{E_L} & -\frac{\upsilon_{23}}{E_R} & \frac{1}{E_T} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} \end{bmatrix} \quad (2)$$

Where: E_i is Young's modulus, G_{ij} is shear modulus, and v_{ij} and v_{ji} are Poisson's ratios.

To figure out the influence of the calculation method, elasticity, and shear moduli were also determined using the following formulas and compared to matrix results.

Table 1 Equations for determining matrix elements (Gonçalves *et al*., 2014; Ozyhar *et al*., 2013)
Tablica 1. Jednadžbe za određivanje elemenata matrice (Gonçalves *et al*., 2014.; Ozyhar *et al*., 2013.)

Propagation-Polarization *Propagacija – polarizacija*	**Type of wave** *Vrsta vala*		**Equation for diagonal and off-diagonal terms** *Jednadžba za dijagonalne i nedijagonalne članove*
Axis (L, R and T)	V_{LL}	Longitudinal *uzdužni*	$C_{11} = C_{LL} = \rho V_{LL}^2$
	V_{RR}		$C_{22} = C_{RR} = \rho V_{RR}^2$
	V_{TT}		$C_{33} = C_{TT} = \rho V_{TT}^2$
	$V_{TR/RT}$	Shear (Transverse) *smicanje (poprečno)*	$C_{44} = C_{RT} = (\rho V_{RT}^2 + \rho V_{TR}^2)/2$
	$V_{LT/TL}$		$C_{55} = C_{LT} = (\rho V_{LT}^2 + \rho V_{TL}^2)/2$
	$V_{LR/RL}$		$C_{66} = C_{RL} = (\rho V_{RL}^2 + \rho V_{LR}^2)/2$
Off-axis (RT 45°)	$V_{RT/RT}$	Quasi-shear (Transverse) *kvazismicanje (poprečno)*	$(C_{23} + C_{44})n_2 n_3 = \pm\sqrt{[(C_{22}n_2^2 + C_{44}n_3^2 - \rho V_\alpha^2)(C_{44}n_2^2 + C_{33}n_3^2 - \rho V_\alpha^2)]}$
Off-axis (LT 45°)	$V_{LT/LT}$		$(C_{13} + C_{55})n_1 n_3 = \pm\sqrt{[(C_{11}n_1^2 + C_{55}n_3^2 - \rho V_\alpha^2)(C_{55}n_1^2 + C_{33}n_3^2 - \rho V_\alpha^2)]}$
Off-axis (LR45°)	$V_{LR/LR}$		$(C_{12} + C_{66})n_1 n_2 = \pm\sqrt{[(C_{11}n_1^2 + C_{66}n_2^2 - \rho V_\alpha^2)(C_{66}n_1^2 + C_{22}n_2^2 - \rho V_\alpha^2)]}$

Where: ρ (kg/m) is density, V_{ii} is longitudinal UWV (m/s), V_{IJ} is transverse UWV (m/s), and $V\alpha$ is quasi-transverse UWV (m/s) (Vázquez *et al*., 2015), n_1 = cosα; n_2 = sinα, and n_3 = 0 for C_{23}, n_1 = cosα; n_3 = sinα, and n_2 = 0 for C_{13}, and n^2 = cosα; n_3 = sinα, and n_1 = 0 for C_{12} (Gonçalves *et al.,* 2014).

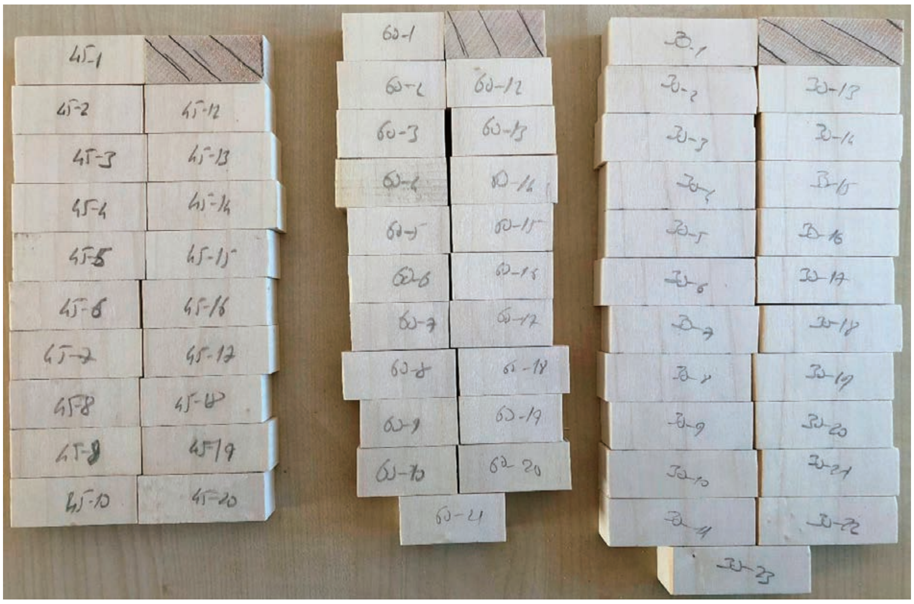

Figure 1 30°, 45°, and 60° samples
Slika 1. Uzorci od 30°, 45° i 60°

$$E_i = \rho\ V_{ii}^2\ 10^{-6} \qquad (3)$$

Where: E_i is elasticity modulus (MPa) in the I direction, ρ is sample density (kg/m³), and V_{II} is longitudinal UWV (m/s).

$$G_{iJ} = \rho\ ((V_{ij} + V_{ji})/2)^2\ 10^{-6} \qquad (4)$$

Where G_{IJ} is shear modulus (MPa) in IJ planes, ρ is sample density (kg/m³), and $V_{IJ} \neq V_{JI}$ is transverse UWV (m/s) in I or J direction with J or I polarization. The means were compared by one-way ANOVA and post hoc multiple comparison (Duncan) was performed.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The density of the samples ranged from 332 to 354 kg/m³. The reported means of *Populus x canadensis* solid wood are 334-374 kg/m³ (Casado *et al.,* 2010), 345-354 kg/m³ (Aydın and Yılmaz Aydın, 2023), 395 kg/m³ (Papandrea *et al.,* 2022), 405.6 kg/m³ (Hodoušek *et al*., 2016), 464 kg/m³ (Villasante *et al.,* 2021), and 372-468 kg/m³ (YingJie *et al.,* 2017). As can be seen in Table 2, the means are in harmony with the reported averages and no statistically significant differences in the means were observed.

The averages and statistics for UWVs are presented in Table 2, and as can be seen, V_{RR}, $V_{LR,}$ and V_{RL} were increased with the increase in ring angle, while others fluctuated. The increase in ring angle did not cause the same influences on the UWVs. Furthermore, the ANOVA results reflected these differentiations as ring inclination caused statistically significant differences ($P < 0.05$) in the means. Increases (V_{RR}, V_{LR}, and V_{RL}), decreases (V_{LL}), and increases and then decreases (V_{TT}, V_{LT}, V_{TL}, V_{TR}, and V_{RT}) were observed when the angle increased from 30° to 45° and 60°. Espinoza *et al*. (2018) reported 1193 to 1745 m/s UWV for yellow poplar and figured out that UWV decreases when the angle increases from 0° (radial direction) to 90° (tangential direction) but the decreasing tendency is higher through 30° to 60°. However, such decreases and then increases as in this study were also reported for some other wood species.

The 1782-1850 m/s (V_{RR}), 1463-1501 m/s (V_{LR}), 1491-1588 m/s (V_{RL}), 532-565 m/s (V_{RT}), and 504-522 m/s (V_{TR}) (Aydın and Yılmaz Aydın, 2023) are the reported UWVs for *Populus canadensis*. The 3360 m/s (V_{LL}), 1850 m/s (V_{RR}), 1380 m/s (V_{TT}), 1370 m/s (V_{LR}), 1250 m/s (V_{RL}), 1140 m/s (V_{LT}), 1350 m/s (V_{TL}), 670 m/s (V_{RT}), 650 m/s (V_{TR}), 1510 m/s ($V_{LR\ 45°}$), 1210 m/s ($V_{LT\ 45°}$), and 740 m/s ($V_{RT\ 45°}$) for *Populus deltoides* (Zahedi *et al.,* 2022), and 5433-5887 m/s (V_{LL}) for *Populus Euroamericana* (Ettelaei *et al.,* 2019) are the reported UWVs for other poplar species. Saadatnia *et al.* (2016) reported L, R, and T direction UWVs of *Populus deltoids* as 2900-4100 m/s (normal wood) and 3400 to 4200 m/s (tension wood), 1500 m/s, and 1000 m/s, respectively. In general, the UWVs of this study are comparable to the reported velocities.

Elasticity and shear moduli averages and statistics are presented in Table 3. The 899-1211 MPa (E_R), 772-876 MPa (G_{LR}), and 93-111 MPa (G_{RT}) values were reported for *Populus x canadensis* (Aydın and Yılmaz Aydın, 2023). As can be seen in Table 3, when the propagation direction inclined from the essential axes, moduli values dramatically differed (-76 % to -22 % for E_R, -33.4 % to 6.5 % for G_{LR}, and 696.8 % to 377.5 % for G_{LT}) in comparison to (Aydın and Yılmaz Aydın, 2023). Based on outstanding differences of $G_{LT,}$ it can be assumed that the propagation properties of a transverse

Table 2 Descriptives and statistics for density and UWVs
Tablica 2. Statistička analiza rezultata za gustoću i brzinu ultrazvučnih valova

Properties *Svojstva*	**Groups** *Skupine*	**Mean** *Srednja vrijednost*	**Std. Dev.** *Standardna devijacija*	**ANOVA**	
				F.	**Sig.**
Density, kg/m³ *gustoća*, kg/m³	30°	340 a*	2.822	2.336	0.106
	45°	342 a (0.6)**	3.572		
	60°	339 a (-0.3)	5.665		
V_{LL}, m/s	30°	4176 a	169.515	20.522	0.000
	45°	4074 b (-2.4)	28.263		
	60°	3960 c (-5.2)	68.162		
V_{RR}, m/s	30°	1204 b	66.907	114.622	0.000
	45°	1227 b (1.9)	65.274		
	60°	1448 a (20.3)	28.595		
V_{TT}, m/s	30°	1329 b	32.601	146.715	0.000
	45°	1428 a (7.4)	39.545		
	60°	1238 c (-6.8)	32.436		
V_{LR}, m/s	30°	1453 c	10.280	40.698	0.000
	45°	1496 b (3.0)	41.383		
	60°	1543 a (6.2)	34.703		
V_{LT}, m/s	30°	1447 b	10.137	498.816	0.000
	45°	1515 a (4.7)	38.993		
	60°	1249 c (-13.7)	25.733		
V_{TL}, m/s	30°	1410 a	25.483	130.959	0.000
	45°	1427 a (1.2)	21.991		
	60°	1268 b (-10.1)	48.752		
V_{TR}, m/s	30°	633 c	11.403	19.220	0.000
	45°	667 a (5.4)	8.097		
	60°	655 b (3.5)	27.425		
V_{RT}, m/s	30°	601 b	16.370	222.621	0.000
	45°	683 a (13.6)	5.202		
	60°	593 b (-1.3)	19.155		
V_{RL}, m/s	30°	1167 c	10.927	5200.206	0.000
	45°	1463 b (25.4)	14.328		
	60°	1592 a (36.4)	14.901		

*Duncan homogeneity groups, ** difference from 30° group (%)
**Duncanove grupe homogenosti, **razlika od skupine 30° (%)*

wave are in tune with radial direction and tangential polarization which provided similar moduli values.

Comparison of all moduli for *Populus canadensis* was not possible due to the lack of reported data. However, 4.52 GPa E_L, 1.37 GPa E_R, 0.74 GPa E_T, 0.69 GPa G_{LR}, 0.62 GPa G_{LT}, and 0.17 GPa G_{RT} (Zahedi *et al.,* 2022) values of *Populus deltoides,* determined by ultrasonic measurements, and 1103 MPa (E_R), 516 MPa (E_T), and 132 MPa (G_{RT}) values for yellow poplar (Espinosa *et al*., 2018) show somewhat similarity with the results of this study except for E_R. Furthermore, the results of this study can be compared to E_L, $G_{LR,}$ and G_{RT} of *Populus* as reported by Roohnia *et al*. (2010).

The calculation methods have considerable numerical differences in the elasticity moduli, while the shear moduli are almost the same as presented in Table 3 and illustrated in Figure 2. However, dramatic differences were observed between the 60° groups, particularly for E_L and E_T. The longitudinal waves do not have polarization and through the L direction of the wood, V_{LL} decreased only 5.2 %, which was not such a dramatic decrease. The simple formula supports such an assumption. Therefore, the interaction of the other UWVs in the complex formulation in the matrixes caused such a diffraction.

According to ANOVA results, inclination has statistically significant influences on the moduli. Furthermore, as illustrated in Figure 2, different tendencies with the increase in angle were observed instead of stable behavior, particularly for elasticity modules. Moreover, Figures 4 and 5 show the relationships between ring angle, UWV, and moduli.

The Poisson's ratio ranges for hardwood are 0.297-0.495 (μ_{LR}), 0.374-0.651 (μ_{LT}), 0.560-0.912 (μ_{RT}), 0.213-0.496 (μ_{TR}), 0.018-0.086 (μ_{RL}), and 0.009-0.051 (μ_{TL}) and there are considerable variations within and between species (Kretschmann, 2010) and higher than one and negative values are not common for wood material. For isotropic 2D and 3D materials in the elasticity theory, Poisson's ratios range from -1 to 1 (Wojciechowski, 2003) and -1 to 0.5 (Mott and Roland, 2013), respectively. However, large positive or negative Poisson's ra-

Table 3 Descriptives and statistics for moduli
Tablica 3. Statistička analiza rezultata za module

Proper-ties *Svojstva*	**Groups** *Skupine*	**By Equations** / *Prema jednadžbama*				**By Matrix** / *Prema matricama*			
		Mean *Srednja vrijednost*	**Std. Dev.** *Standardna devijacija*	**ANOVA**		**Mean** *Srednja vrijednost*	**Std. Dev.** *Standardna devijacija*	**ANOVA**	
				F.	**Sig.**			***F.***	**Sig.**
E_L, MPa	30°	5937 a*	497	26.075	0.000	4226 b [-28.8] ***	549	260.535	0.000
	45°	5676 b (-4.4)**	74			5179 a (22.6) [-8.8]	340		
	60°	5243 c (-11.7)	176			1930 c (-54.3) [-63.2]	475		
E_R, MPa	30°	494 b	54	119.452	0.000	315 b [-36.2]	66	10.159	0.000
	45°	516 b (4.5)	53			375 a (19.0) [-27.3]	48		
	60°	701 a (41.9)	29			291 b (-7.6) [-58.5]	67		
E_T, MPa	30°	600 b	32	186.100	0.000	494 b [-17.7]	29	842.181	0.000
	45°	697 a (16.2)	35			535 a (8.3) [-23.2]	32		
	60°	513 c (-14.5)	22			154 c (-68.8) [-70.0]	35		
G_{LR}, MPa	30°	583 c	8	610.461	0.000	590 c [1.2]	8	575.535	0.000
	45°	749 b (28.5)	26			749 b (26.9) [0.0]	26		
	60°	822 a (41.0)	27			822 a (39.3) [0.0]	27		
G_{LT}, MPa	30°	694 b	17	474.970	0.000	694 b [0.0]	17	476.918	0.000
	45°	740 a (6.6)	22			741 a (6.8) [0.1]	22		
	60°	530 c (-23.6)	28			530 c (-23.6) [0.0]	28		
G_{RT}, MPa	30°	129 b	4	133.815	0.000	130 b [0.8]	4	130.774	0.000
	45°	156 a (20.9)	3			156 a (20.0) [0.0]	3		
	60°	130 b (0.8)	9			131 b (0.8) [0.8]	9		

*Duncan homogeneity groups, **(%) difference from 30° group, and ***(%) difference between the calculation methods (equations and matrix)
**Duncanove grupe homogenosti, **razlika od skupine 30°* (%), ****razlika između metoda proračuna (jednadžbe i matrice)* (%)

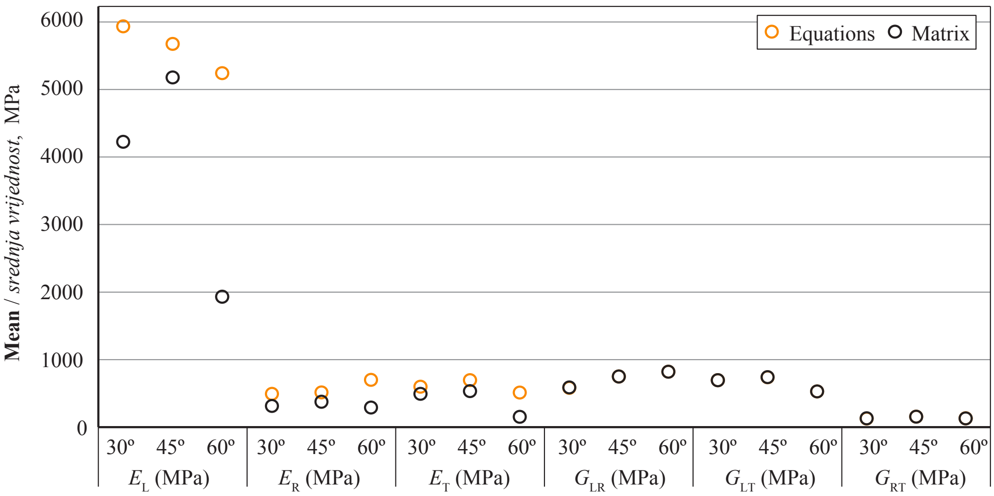

Figure 2 Differences in moduli caused by calculation methods
Slika 2. Razlike u modulima kao rezultat različitih metoda proračuna

tios are the fact for anisotropic elastic materials (Ting and Chen, 2005). Furthermore, for anisotropic or orthotropic 3D structures, Poisson's ratios significantly differ by the directions, and partial auxeticity (presents at least one but not all the directions) is the fact for some materials (Brańka *et al*., 2011, 2012; Carneiro *et al*., 2013; Narojczyk and Wojciechowski, 2010). Even though isotropic materials generally present a positive Poisson's ratio, it was highlighted that negative values can be seen for porous materials (Lakes, 1987). For example, Bucur and Najafi (2003) and Murata and Tanahashi (2010) reported NPRs. As seen in Table 4, partial auxeticity and higher than 1 Poisson's ratios were observed. Furthermore, the influence of ring inclination on all Poisson's ratios is statistically significant.

Poisson's ratio of wood can vary depending on factors such as the specific species, moisture content, and growth conditions. Furthermore, while it is challenging to provide precise values for all wood species, Poisson's ratio can also change with the direction of measurement within the wood sample. Extraordinary Poisson's ratios due to inclination (20° - 45°) were reported (Garab *et al.*, 2010; Liu, 2002; Murata and Tanahashi, 2010; Qing and Mishnaevsky, 2010; Reiterer and

Table 4 Descriptives and statistics for Poisson's ratios calculated by Matrix
Tablica 4. Statistička analiza rezultata za Poissonove omjere izračunane uz pomoć matrice

Properties *Svojstva*	**Groups** *Skupine*	**Mean** *Srednja vrijednost*	**Std. Dev.** *Standardna devijacija*	**ANOVA**	
				***F*.**	**Sig.**
μ_{RL}	30°	0.127 a*	0.0236	914.110	0.000
	45°	0.065 b	0.0321		
	60°	-0.264 c	0.0362		
μ_{TL}	30°	0.013 b	0.0325	376.768	0.000
	45°	-0.032 c	0.0384		
	60°	0.221 a	0.0194		
μ_{LR}	30°	1.773 a	0.5016	355.338	0.000
	45°	0.929 b	0.5073		
	60°	-1.744 c	0.2454		
μ_{TR}	30°	0.436 b	0.0862	20.370	0.000
	45°	0.561 a	0.0537		
	60°	0.548 a	0.0607		
μ_{LT}	30°	0.139 b	0.2476	650.469	0.000
	45°	-0.300 c	0.3849		
	60°	2.749 a	0.2029		
μ_{RT}	30°	0.276 c	0.0681	580.268	0.000
	45°	0.394 b	0.0636		
	60°	1.029 a	0.0908		

*Duncan homogeneity groups / *Duncanove grupe homogenosti*

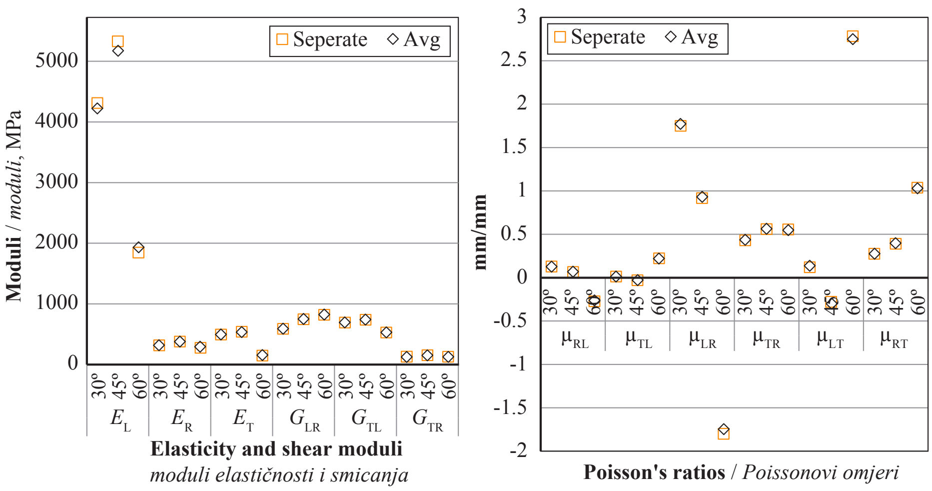

Figure 3 Diffraction illustrations of constants in terms of separate and averaged UWV utilization
Slika 3. Difrakcijske ilustracije konstanti u smislu zasebnoga i prosječnog iskorištenja brzine ultrazvučnih valova

Table 5 Elastic constant means calculated by averaged UWV using Matrix
Tablica 5. Srednje vrijednosti elastične konstante izračunane uz pomoć matrice i primjenom prosječne brzine ultrazvučnih valova

Groups *Skupine*	E_L	E_R	E_T	G_{TR}	G_{TL}	G_{LR}	μ_{RL}	μ_{TL}	μ_{LR}	μ_{TR}	μ_{LT}	μ_{RT}
30°	4313 (2.06)*	316 (0.32)	496 (0.40)	129 (-0.77)	694 (0)	590 (0)	0.128 (0.79)	0.014 (7.69)	1.751 (-1.24)	0.432 (-0.92)	0.122 (-12.23)	0.275 (-0.36)
45°	5331 (2.93)	380 (1.33)	543 (1.50)	156 (0)	740 (-0.13)	748 (-0.13)	0.065 (0)	-0.028 (12.50)	0.918 (-1.18)	0.561 (0)	-0.279 (7.00)	0.392 (-0.51)
60°	1848 (-4.25)	278 (-4.47)	149 (-3.25)	131 (0)	530 (0)	822 (0)	-0.271 (-2.65)	0.224 (1.36)	-1.800 (3.21)	0.556 (1.46)	2.785 (1.31)	1.039 (0.97)

* % difference from constants calculated separately by matrix and then averaged (Table 3)
* *%-tna razlika u odnosu prema konstantama koje su izračunane zasebno prema matrici i zatim uprosječene (tab. 3.)*

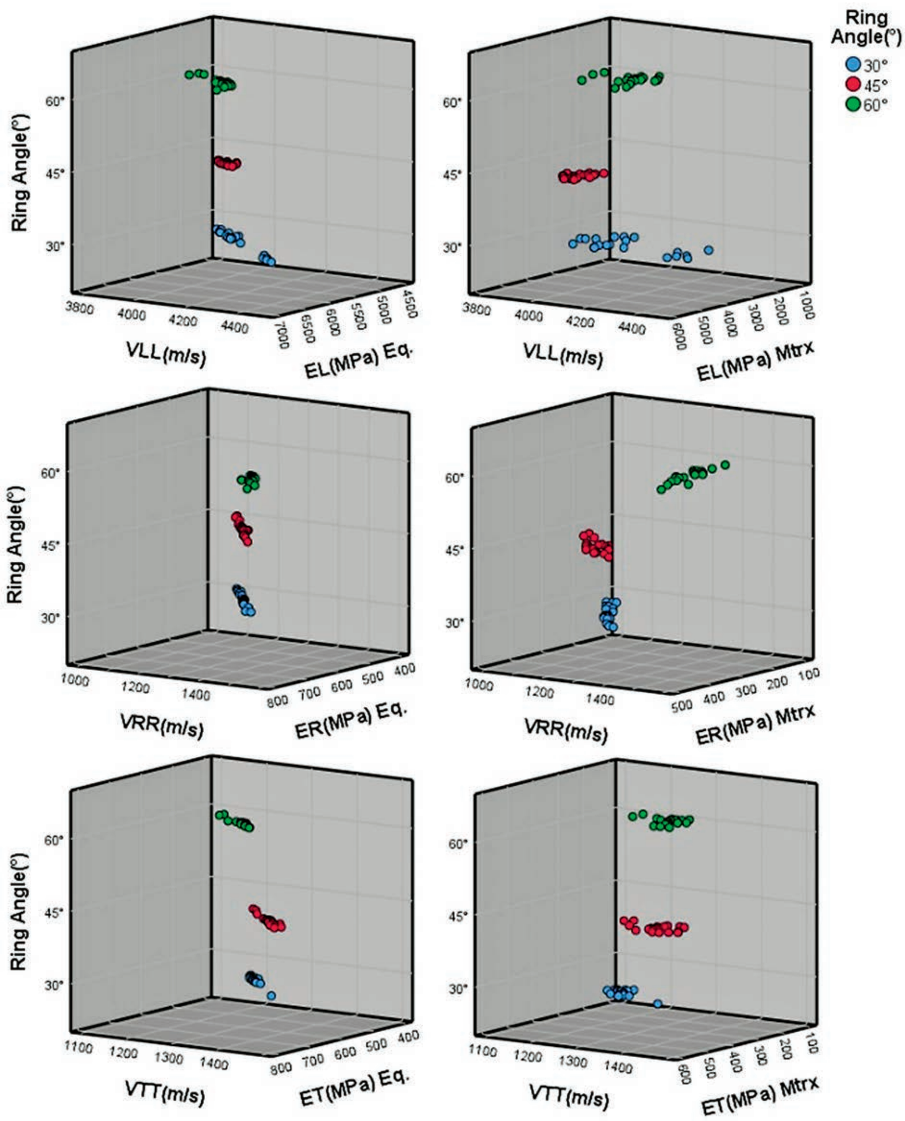

Figure 4 3D scatter of ring angle by longitudinal UWV by elasticity moduli
Slika 4. 3D dijagram raspršenosti kuta otklona goda prema uzdužnoj brzini ultrazvučnih valova i modulu elastičnosti

Stanzl-Tschegg, 2001). Kawahara *et al.* (2015) reported that Poisson's ratios of wood strike their extrema with grain inclination angle of approximately 30°, which was considered to be raised by the effect of shear forces in the L axes of wood. Furthermore, NPRs were observed in the LT plane when the inclination range was 15°-45°. Mascia and Nicolas (2013) determined Poisson's ratios of some Brazilian wood species and figured out the influence of fiber angles (0°, 20°, 45°, 70°, and 90°) on Poisson's ratios of LT, LR, and RT planes. However, no NPR was observed. As seen in Table 4, µLT is negative for 45° but, NPRs were not observed at 30°. Furthermore, LR and RL presented NPR in 60° inclination, and as illustrated in Figure 3, 30° inclination did not provide extrema Poisson's ratios, except for LR.

Numerical differences in the elastic constants due to individual and averaged UWV utilization in the matrix are presented in Table 5 and illustrated in Figure 3, respectively. As can be seen, moduli were slightly changed while diffractions in Poisson's ratios are more notable.

Bodig and Goodman (1973) stated that there is no reported clear interaction between Poisson's ratios and mechanical (moduli or strength) and physical (density) properties. Furthermore, according to Kawahara *et al.* (2015) variation of Poisson's ratios in wood in terms of direction or plane is barely figured out. In this study, the coefficients of determination (R^2) between density and Poisson's ratios are presented in Figure 6. Overall, structural hierarchy (Lakes, 1993), mechanical behavior of wood at the cellular level (Gibson, 2005), microporous structure of wood (Bertoldi *et al.,* 2010), and lots of interacting mechanical processes that occur at the microscopic grade (Ozyhar *et al.,* 2013) are attributed to NPR. Moreover, the anisotropic nature of wood exhibits viscoelastic behavior, and the time-dependent Poisson's impact is known as the viscoelastic Poisson's ratio.

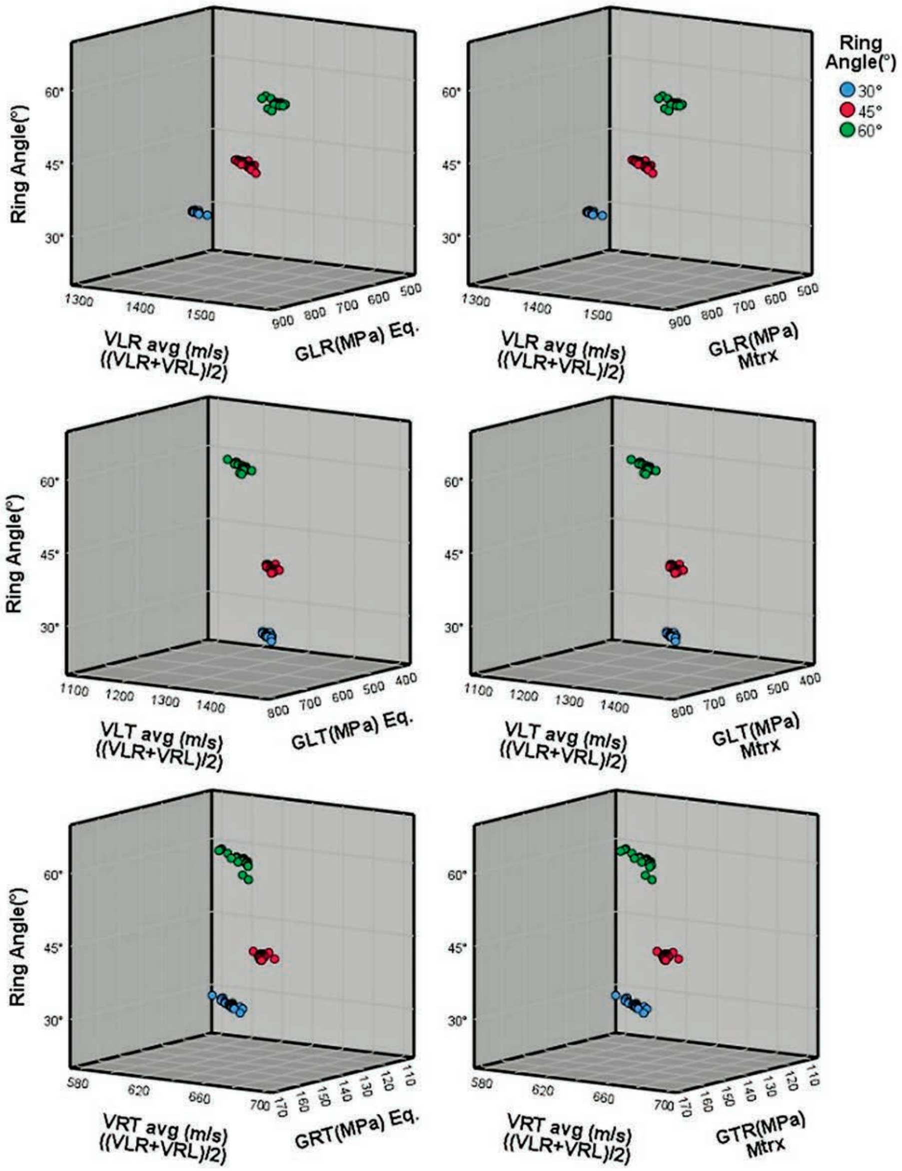

Figure 5 3D scatter of ring angle by averaged shear wave velocity by shear moduli
Slika 5. 3D dijagram raspršenosti kuta otklona goda prema prosječnoj brzini posmičnih valova i modulu smicanja

4 CONCLUSIONS
4. ZAKLJUČAK

Ultrasonic characterization provides valuable information about the structural properties, quality, and potential defects in wood, making it a useful tool for various applications, including wood grading, assessment of wood products, and research on wood properties.

Partial auxeticity was figured out for poplar wood in certain angles. However, a complete auxeticity is not a fact. However, it can be said that wood can be assumed as an auxetic material when the right cutting angles are ensured for obtaining NPRs.

Particularly for elasticity moduli, stiffness tensor provided remarkably lower values against simple formula calculation. Furthermore, the utilization of averaged density and UWV values in the tensor also caused some differences in elasticity and Poisson's ratios.

Almost no numerical differences were found for shear moduli in terms of calculation methods. Therefore, a simple formula can easily be used.

In general, the increase in inclination did not represent the stable behavior of UWV and elastic constants, but the impact is significant.

According to regression models, density was found to be unable to explain the Poisson's ratios.

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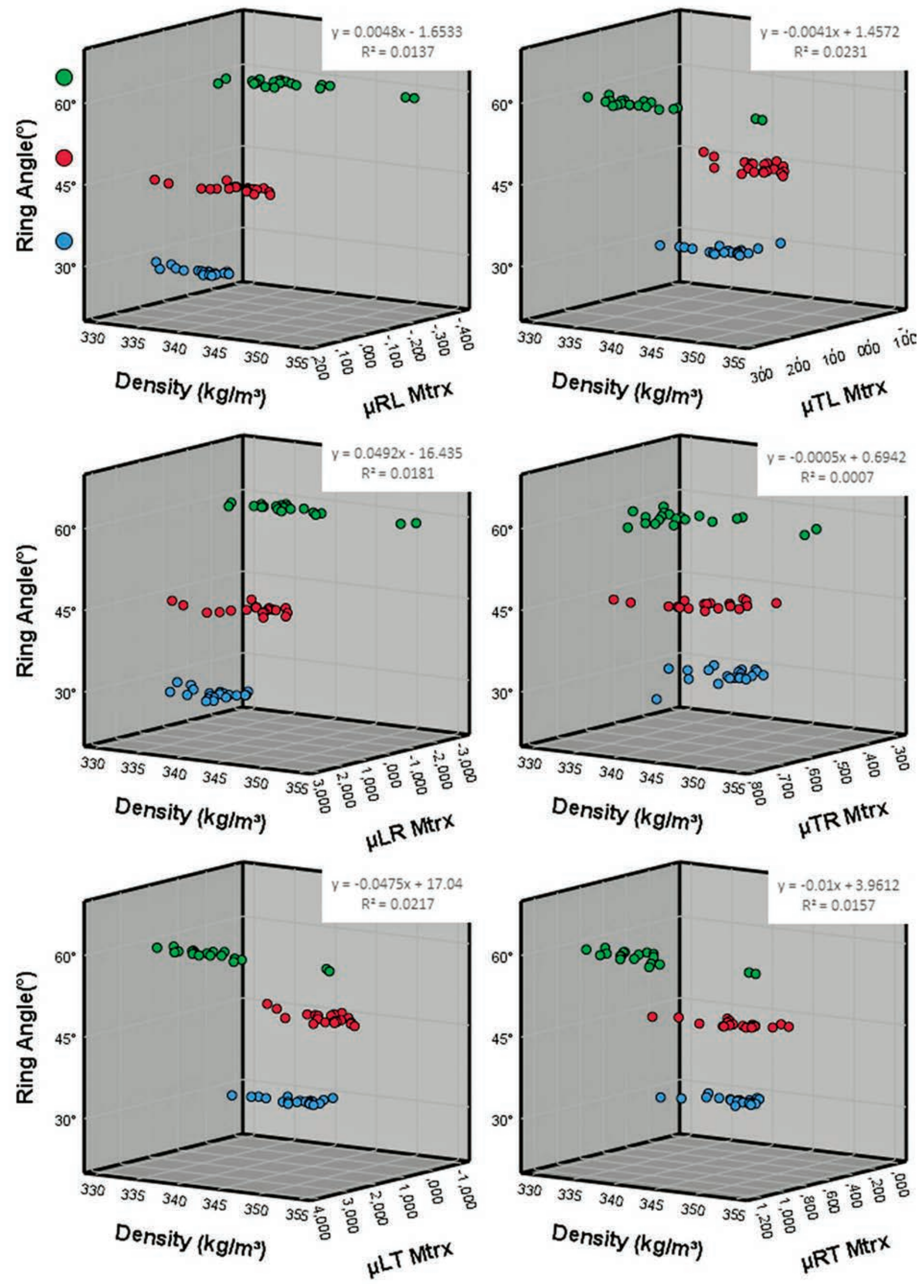

Figure 6 3D scatter of ring angle by density by Poisson's ratios
Slika 6. 3D dijagram raspršenosti kuta otklona goda prema gustoći i Poissonovim omjerima

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A Pythagorean Fuzzy Approach to Identify and Prioritize Factors Affecting Import Decisions in Wood Supply Chain

Pitagorin neizraziti pristup za prepoznavanje i određivanje prioritetnih čimbenika koji utječu na odluke o uvozu u lancu opskrbe drvom

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ABSTRACT • *Wood is a highly sought-after commodity traded internationally to meet the global demand for building materials, furniture, and paper products. The decision-making process for wood imports is intricate and influenced by various factors. Prioritizing these factors helps decision-makers allocate resources, time, and attention efficiently and make well-informed and strategically effective decisions. This study proposes an interval-valued Pythagorean fuzzy analytic hierarchy process (AHP)-based decision-making framework to identify and analyze factors influencing wood import decisions. With the aim in mind, four main factors are determined: "economic factors", "political factors", "material-related factors", and "market factors". Each main factor has four sub-factors. The interval-valued Pythagorean fuzzy AHP method reveals the weight of each factor based on experts' perspectives. According to the results, the most important main factor is "economic factors". The sub-factors with the highest local importance are: "supply chain and logistics management" in the "economic factors" group, "political stability" in the "political factors" group, "wood species" in the "material-related factors" group, and "demand and demand trends" in the "market factors" group. The global weights show that the most important sub-factors are "supply chain and logistics management", "political stability", and "wood species". The model's robustness is assessed through sensitivity, validity, and comparative analyses, and high stability is observed in the ranking of the factors.*

KEYWORDS: *wood import; analytic hierarchy process; Pythagorean fuzzy set; expert perspective; supply chain*

SAŽETAK • *Drvo je vrlo tražena roba kojom se trguje na međunarodnoj razini kako bi se zadovoljila globalna potražnja za građevnim materijalom, namještajem i proizvodima od papira. Proces donošenja odluka o uvozu drva zamršen je i na nj utječu različiti čimbenici. Određivanje prioritetnih činitelja pomaže donositeljima odluka da učinkovito rasporede resurse, vrijeme i pozornost te da donesu dobro utemeljene i strateški učinkovite odluke. Ova je studija prijedlog okvira odlučivanja utemeljenoga na Pitagorinu neizrazitom analitičkom hijerarhijskom procesu (AHP) s intervalnim vrijednostima za prepoznavanje i analizu utjecaja na odluke o uvozu drva. S tim ci-*

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ljem utvrđene su četiri osnovne skupine utjecajnih čimbenika: ekonomski čimbenici, politički čimbenici, čimbenici povezani s materijalom i tržišni čimbenici. Svaka skupina tih čimbenika ima četiri podčimbenika. Pitagorina neizrazita AHP metoda s intervalnim vrijednostima otkriva važnost svakog čimbenika na temelju stajališta stručnjaka. Prema rezultatima istraživanja, najvažniju skupinu glavnih čimbenika čine ekonomski utjecaji. Podčimbenici s najvećom lokalnom važnosti jesu upravljanje opskrbnim lancem i logistikom u skupini ekonomskih čimbenika, politička stabilnost u skupini političkih čimbenika, vrsta drva u skupini čimbenika povezanih s materijalima te potražnja i trendovi potražnje u skupini tržišnih čimbenika. Globalni ponderi pokazuju da su najvažniji podčimbenici upravljanje opskrbnim lancem i logistikom, politička stabilnost i vrsta drva. Robusnost modela procjenjuje se na temelju osjetljivosti, valjanosti i komparativne analize, a visoka stabilnost uočena je u rangiranju čimbenika.

KLJUČNE RIJEČI: *uvoz drva; analitički hijerarhijski proces; Pitagorin neizraziti skup; stručna perspektiva; opskrbni lanac*

1 INTRODUCTION
1. UVOD

Wood is a highly popular natural material utilized extensively across the globe. Its broad spectrum of applications stems from its strength, aesthetic appeal, durability, ease of processing, and lightweight nature. Wood is commonly used in the construction industry for various purposes such as building frames, flooring, roofing, and walls (De Araujo *et al*., 2016). Additionally, it is extensively used in the furniture industry for manufacturing chairs, tables, and cabinets (Geng *et al*., 2019). The paper industry relies heavily on wood pulp for manufacturing paper products. Wood is also used for decorative purposes such as interior design, sculptures, and handicrafts (Park *et al*., 2010). The global demand for wood has been steadily increasing over the years, driven by population growth, urbanization, and economic development. As a result, the international trade of wood and wood products has risen to meet both domestic and foreign demands (Bit and Banerjee, 2014).

Wood import provides access to wood materials that might not be available in a specific region due to several reasons such as unsuitable climate or lack of resources for growing specific species of trees or limited domestic production capacity. Wood import helps to meet the growing demand for wood products, reduces dependency on a single source of wood, mitigates the risks associated with fluctuations in supply and price, and supports various industries such as construction, furniture making, and paper production (Gültekin *et al*., 2009). Importing wood is a complex process that is influenced by various factors such as cost, quality, and availability (Vu *et al*., 2020). Understanding which factors are most important and prioritizing them accordingly helps decision-makers make more informed and effective choices. By weighing up these factors, organizations can optimize their decision-making processes, reduce risks, and make more strategic decisions about their wood sourcing and supply chain management.

The literature contains several studies examining the purchase and sale of wood and wood products. Arabatzis and Klonaris (2009) evaluated the import demand for different categories of wood and wood products in Greece between 1969 and 2001 using a linear approximation of the quadratic AIDS model. Gültekin *et al*. (2009) identified the capacities and amounts of raw materials purchased by the subsectors of the Turkish forest industry and made demand forecasts for future periods. Limaei *et al*. (2011) detected significant relationships between wood imports and population, gross domestic product, and domestic wood production. Kukrety *et al*. (2013) evaluated the current Red Sanders wood trade in southern India using a SWOT-analytic hierarchy process (AHP) framework. Bit and Banerjee (2014) stated that the import of forestry-based products is increasing in terms of volume, value, and unit prices. Buongiorno (2016) conducted a study on gravity models of forest product trade, while Kolo and Tzanova (2017) focused on forecasting German forest product trade using a vector error correction model. Khosravi *et al*. (2018) examined the level of international trade and intra-industry trade as two indices of globalization and incorporated them into the import demand functions of various wood product categories in Iran. Bayram (2020) used the Entropy-TOPSIS methodology to evaluate the economic contribution of forest product trade in Turkey. Vu *et al*. (2020) analyzed the determinants of Vietnam's wood products trade using a gravity model. The researchers found that economic size, distance, and level of openness of the economy were significant determinants. Adhikari *et al*. (2022) utilized time-series modeling to examine the effects of foreign remittances on timber imports.

The literature review highlights the absence of identification and prioritization of factors influencing wood import decisions in the previous studies. It is challenging to determine which factors are more important than others. However, multicriteria decision-making methods can be employed to ascertain the most significant factors. One of the most popular and widely practiced multicriteria decision-making methods is the AHP. The AHP method involves creating a hierarchy of factors, sub-factors, and alternatives and comparing their relative importance through pairwise comparisons. Decision-makers assign weights to each decision element and use them to prioritize different options (Oblak *et al.*, 2017). One of the key benefits of using the AHP is that it allows decision-makers to incorporate their expertise and judgment into the decision-making process. Furthermore, it is flexible and adaptable to different contexts and allows for easy updating of preferences. The AHP method is very useful in situations where decision-making involves multiple factors that are difficult to quantify or compare directly (Bhutta and Huq, 2002; Ishizaka and Labib, 2009).

Decision-making processes are often influenced by uncertainties and inaccurate information sources. To address these issues, the AHP method can be equipped with the fuzzy set theory. The Pythagorean fuzzy set has emerged as a powerful tool for incorporating fuzziness into the AHP. It provides a new way to model uncertain information by incorporating degrees of membership, non-membership, and indeterminacy. This allows decision-makers to express their preferences in a more nuanced way. The interval-valued Pythagorean fuzzy set is a generalization of the Pythagorean fuzzy set. It assigns an interval instead of a precise value to each element. The interval width provides additional information about the level of uncertainty associated with each element (Milošević *et al.*, 2023).

The decision-making process regarding the importation of wood materials requires careful evaluation of multiple factors. There is a lack of research on the most important factors that influence this decision, and fuzzy decision-making methods have not been applied to this topic. To address this gap in the literature, this study uses the interval-valued Pythagorean fuzzy AHP method to identify and analyze factors influencing wood import decisions. This study makes a novel contribution to the field by being the first to prioritize the key factors related to the wood import process. The results of the current study provide a valuable guide to decision-makers to navigate the complexity of wood imports more effectively.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Interval-valued Pythagorean fuzzy set
2.1. Pitagorin neizraziti skup s intervalnim vrijednostima

The fuzzy set theory enables working with imprecise data and making effective decisions, even when exact values are unattainable (Sorkheh *et al.*, 2018). The Pythagorean fuzzy set is a notable fuzzy extension characterized by membership degrees ($\mu_{\tilde{P}}(x)$) and non-membership degrees ($\nu_{\tilde{P}}(x)$). Unlike the ordinary fuzzy set, the Pythagorean fuzzy set allows the sum to exceed one. However, the sum of their squares is at most one (Zhang and Xu, 2014). The interval-valued Pythagorean fuzzy set builds upon the Pythagorean fuzzy set. This fuzzy set uses a pair of intervals to represent membership and non-membership degrees. The interval-valued Pythagorean fuzzy set offers a more powerful approach to modeling imprecise information. This fuzzy set is formally defined as presented in Eq. (1).

$$\tilde{P} = \left\{ \left\langle x, [\mu_{\tilde{P}_L}(x), \mu_{\tilde{P}_U}(x)], [v_{\tilde{P}_L}(x), v_{\tilde{P}_U}(x)] \right\rangle ; x \epsilon X \right\} \quad (1)$$

The values of the parameters are between zero and one. Indeterminacy degrees are computed using Eq. (2) (Wu *et al.*, 2019).

$$\pi_{\tilde{P}}(x) = \left[\sqrt{1 - \left(\mu_{\tilde{P}_U}(x)\right)^2 - \left(v_{\tilde{P}_U}(x)\right)^2}, \sqrt{1 - \left(\mu_{\tilde{P}_L}(x)\right)^2 - \left(v_{\tilde{P}_L}(x)\right)^2} \right] \quad (2)$$

The following equations elucidate the basic algebraic operations applied to two interval-valued Pythagorean fuzzy numbers (Yanmaz *et al.*, 2020).

$$\tilde{A} \oplus \tilde{B} = \left(\left[\sqrt{(\mu_A^L)^2 + (\mu_B^L)^2 - (\mu_A^L)^2 (\mu_B^L)^2}, \sqrt{(\mu_A^U)^2 + (\mu_B^U)^2 - (\mu_A^U)^2 (\mu_B^U)^2} \right], \left[v_A^L v_B^L, v_A^U v_B^U \right] \right) \quad (3)$$

$$\tilde{A} \otimes \tilde{B} = \left(\left[\mu_A^L \mu_B^L, \mu_A^U \mu_B^U \right], \left[\sqrt{(v_A^L)^2 + (v_B^L)^2 - (v_A^L)^2 (v_B^L)^2}, \sqrt{(v_A^U)^2 + (v_B^U)^2 - (v_A^U)^2 (v_B^U)^2} \right] \right) \quad (4)$$

$$\lambda \tilde{A} = ([\sqrt{1-(1-(\mu_A^L)^2)^\lambda}, \sqrt{1-(1-(\mu_A^U)^2)^\lambda}], [(v_A^L)^\lambda, (v_A^U)^\lambda]) \quad (5)$$

$$\tilde{A}^\lambda = ([(\mu_A^L)^\lambda, (\mu_A^U)^\lambda], [\sqrt{1-(1-(v_A^L)^2)^\lambda}, \sqrt{1-(1-(v_A^U)^2)^\lambda}]) \quad (6)$$

2.2 Interval-valued Pythagorean fuzzy analytic hierarchy process
2.2. Pitagorin neizraziti analitički hijerarhijski proces s intervalnim vrijednostima

The AHP is a widely used decision-making tool that helps individuals and organizations solve complex decision problems. This method involves four main steps. Firstly, the decision problem is hierarchically structured. Secondly, pairwise comparisons are made using a nine-point scale to create comparison matrices showing decision-makers' preferences. Thirdly, inconsistencies in comparisons are identified and corrected. Finally, the importance of decision elements is determined by normalizing the matrices and calculating row averages (Özşahin *et al.*, 2019). Making decisions becomes more difficult when decision-makers' preferences are uncertain or subjective. Decision-makers often prefer to use linguistic terms to express their preferences. Hence, various fuzzy logic-based decision-making methods have been developed to handle uncertain judgments. The interval-valued Pythagorean fuzzy AHP method enables decision-makers to make more flexible and nuanced judgments. Some remarkable studies that have utilized the Pythagorean fuzzy AHP can be listed as follows: landfill site selection (Karasan *et al*., 2019), solar panel manufacturer selection (Seker and Kahraman, 2021), spaceport selection (Demiralay *et al*., 2022), pandemic hospital site selection (Boyacı and Şişman, 2022), building smartness assessment (Milošević *et al*., 2023), and assessment of biomass energy barriers (Shahzad *et al*., 2023). The interval-valued Pythagorean fuzzy AHP procedure considered in this study is as follows:

Step 1: Factors are compared with each other using Table 1 to create pairwise comparison matrices.

The evaluation scale helps decision-makers assign importance to factors through pairwise comparisons. This scale has linguistic terms corresponding to numerical values. Decision-makers use these linguistic terms to indicate how much more important factor i is compared to factor j. Once a linguistic term is selected, it is translated into a corresponding interval-valued Pythagorean fuzzy number. These fuzzy numbers represent decision-makers' judgments in a quantitative form, enabling numerical calculations.

Step 2: Each matrix consistency is assessed by applying Eq. (7). Should the CR index surpass 0.10, responders are required to reevaluate their decisions.

$$CR = \frac{\left(\frac{\lambda_{\max} - n}{n-1}\right)}{RC} \tag{7}$$

Here, $\lambda_{\max}$ refers to the maximum eigenvalue. The table of the RC indexes can be seen in Saaty (1980). The consistency of each matrix is evaluated using crisp score indexes. These values are determined by matching the linguistic terms with Saaty's scale (Karasan *et al*., 2019). For example, the linguistic term "absolutely more important" corresponds to a value of 9 according to Saaty's scale. The consistency ratio is determined by adhering to the traditional AHP framework.

Step 3: Difference matrices are derived using Eqs. (8) and (9).

$$d_{\mathrm{ik}_\mathrm{L}} = \mu^2_{\mathrm{ik}_\mathrm{L}} - v^2_{\mathrm{ik}_\mathrm{U}} \tag{8}$$

$$d_{\mathrm{ik}_\mathrm{U}} = \mu^2_{\mathrm{ik}_\mathrm{U}} - v^2_{\mathrm{ik}_\mathrm{L}} \tag{9}$$

Step 4: Interval multiplicative matrices are derived using the following equations:

$$s_{\mathrm{ik}_\mathrm{L}} = \sqrt{1000^{d_{ik_L}}} \tag{10}$$

$$s_{\mathrm{ik}_\mathrm{U}} = \sqrt{1000^{d_{ik_U}}} \tag{11}$$

Step 5: Indeterminacy values are obtained using Eq. (12).

$$\tau_{\mathrm{ik}} = 1 - (\mu^2_{\mathrm{ik}_\mathrm{U}} - \mu^2_{\mathrm{ik}_\mathrm{L}}) - (v^2_{\mathrm{ik}_\mathrm{U}} - v^2_{\mathrm{ik}_\mathrm{L}}) \tag{12}$$

Step 6: Weight matrices are created in accordance with the following equation:

$$t_{\mathrm{ik}} = \left(\frac{s_{\mathrm{ik}_\mathrm{L}} + s_{\mathrm{ik}_\mathrm{U}}}{2}\right)\tau_{\mathrm{ik}} \tag{13}$$

Step 7: Weights are obtained using Eq. (14).

$$w_{\mathrm{i}} = \frac{\sum_{k=1}^{m} t_{\mathrm{ik}}}{\sum_{i=1}^{m}\sum_{k=1}^{m} t_{\mathrm{ik}}} \tag{14}$$

2.3 Decision-making framework
2.3. Okvir za donošenje odluka

The demand for wood and wood products has increased globally in recent years, resulting in a surge in wood imports in many countries. Wood import decisions are influenced by various factors, including price, wood species, and demand trends. Recognizing the significance of these factors and comprehending how they influence the decision-making process are paramount for decision-makers to allocate resources, time, and attention efficiently and to make well-informed and strategically effective decisions. In this study, the key factors affecting wood import decisions are analyzed using the interval-valued Pythagorean fuzzy AHP method. The

Table 1 Evaluation scale (Seker and Kahraman, 2021)
Tablica 1. Skala ocjenjivanja (Seker i Kahraman, 2021.)

Linguistic term *Lingvistički pojam*	**Interval-valued Pythagorean fuzzy number** *Pitagorin neizraziti broj s intervalnom vrijednošću*			
	μ_L	μ_U	v_L	v_U
Absolutely less important / *apsolutno manje važno*	0.03	0.16	0.74	0.87
Much less important / *dosta manje važno*	0.12	0.25	0.65	0.78
Less important / *manje važno*	0.21	0.34	0.56	0.69
Slightly less important / *malo manje važno*	0.30	0.43	0.47	0.60
Equally important / *jednako važno*	0.38	0.51	0.38	0.51
Slightly more important / *malo važnije*	0.47	0.60	0.30	0.43
More important / *više važno*	0.56	0.69	0.21	0.34
Much more important / *dosta važnije*	0.65	0.78	0.12	0.25
Absolutely more important / *apsolutno važnije*	0.74	0.87	0.03	0.16

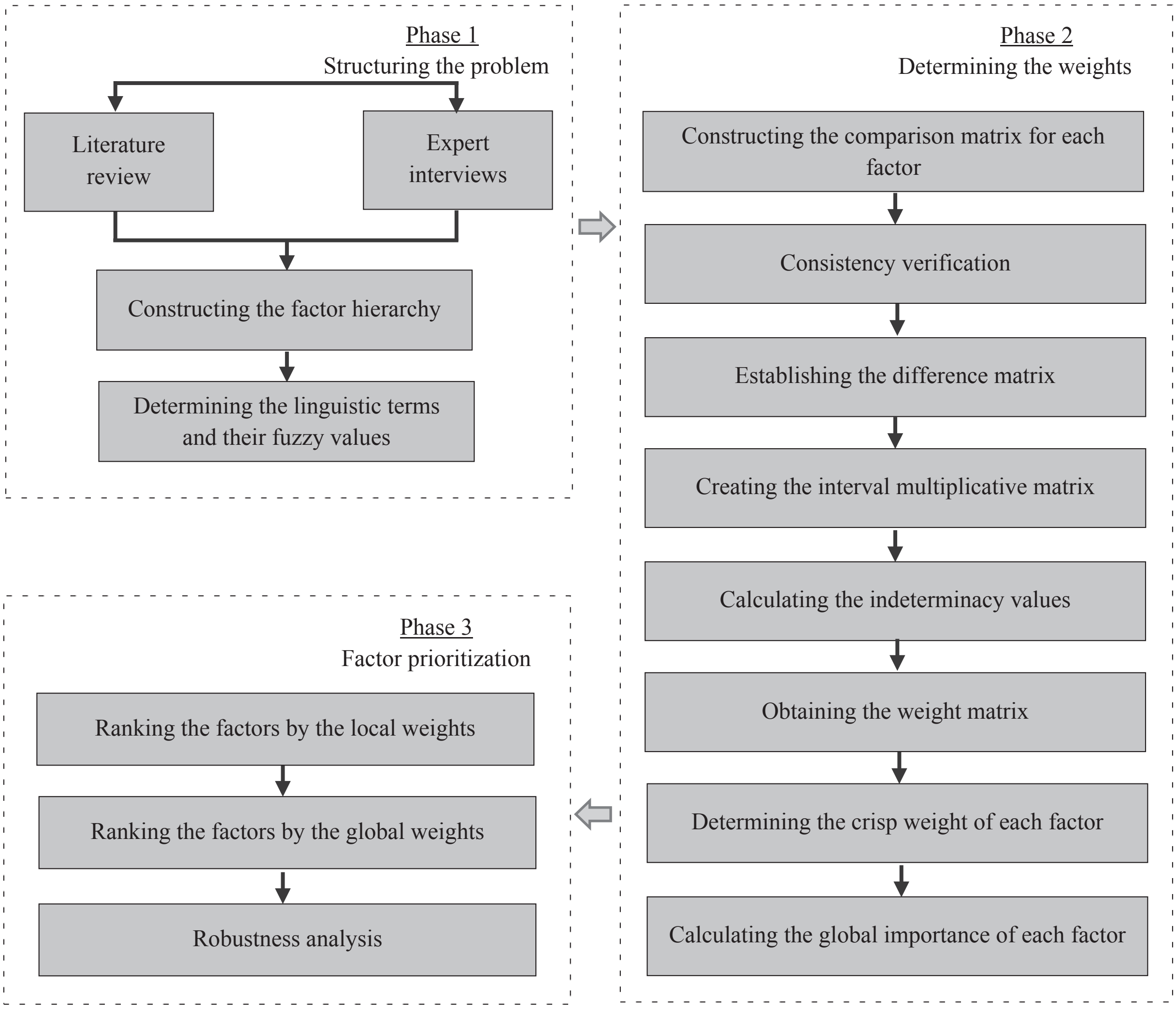

Figure 1 Steps of the present study
Slika 1. Koraci u ovoj studiji

results of the study are supported by a robustness analysis. The steps of this study are shown in Figure 1.

The research was conducted in Turkey. The geographical, economic, and industrial characteristics of the country make it a compelling case for analyzing wood import decisions. Turkey serves as a significant trade hub, linking Europe, Asia, and the Middle East. Its proximity to wood-exporting regions impacts its import patterns and decision-making processes. The construction, furniture, and paper industries in Turkey have experienced substantial growth, leading to a surge in demand for wood. Since domestic forestry production cannot fully meet this demand, imports play a crucial role in maintaining supply chain continuity. The increasing industrial demand makes strategic import decisions essential for meeting the need (Gültekin *et al*., 2009; Bayram, 2020). The insights from this study can guide decision-makers in managing wood imports.

The application of the interval-valued Pythagorean fuzzy AHP method requires input data from decision-makers to rank decision elements. Therefore, an expert team was formed. The selection of team members is based on the following criteria: (i) advanced education (preferably at the postgraduate level), (ii) a minimum of five years of relevant experience, (iii) research publications related to the study topic; and (iv) previous involvement in multicriteria decision-making research. For multicriteria decision-making methods, there are no strict guidelines regarding the number of respondents required. Since the AHP is not a methodology based on statistical principles, it can be effectively applied with a small sample size. The method is technically sound and does not necessitate a large number of participants for its implementation (Ahmadi *et al*., 2015). Hence, ten experts were consulted in the study. The expert panel ensured balanced representation from both academia and industry, comprising specialists in supply chain management, procurement, manufacturing, and trade.

Several factors were discovered from the literature (Gültekin *et al*., 2009; Limaei *et al*., 2011; Kukrety *et al*., 2013; Bit and Banerjee, 2014; Khosravi *et al*., 2018; Bayram, 2020; Vu *et al*., 2020). The list of factors obtained from the literature was refined and ex-

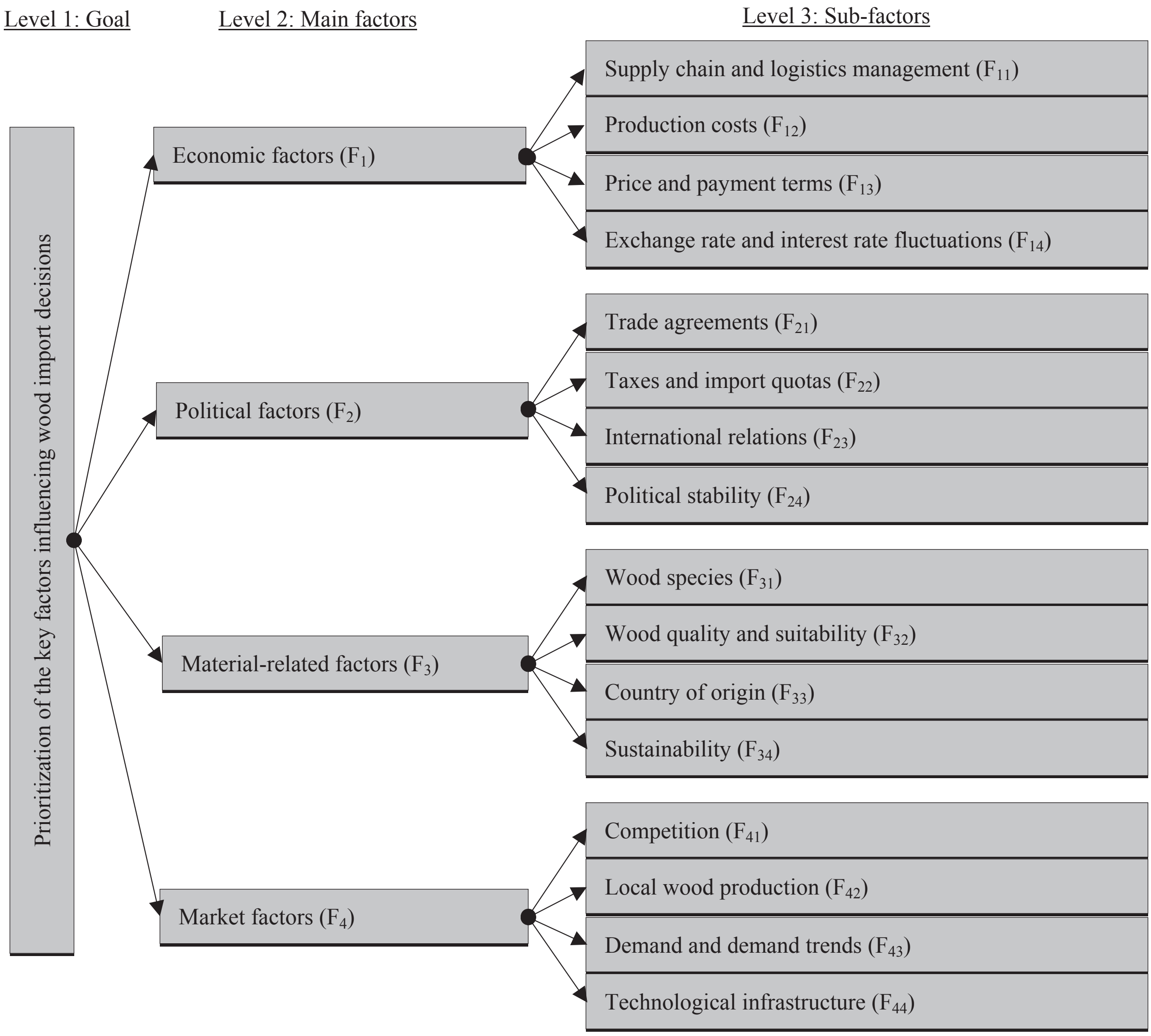

Figure 2 Proposed decision tree
Slika 2. Predloženo stablo odlučivanja

panded by the team. The final hierarchy of factors was predominantly shaped by expert input. The hierarchical structure of the problem was devised with one goal, four main factors, and sixteen sub-factors. Figure 2 illustrates the hierarchical structure devised in the study.

The main factors determined for the problem are "economic factors", "political factors", "material-related factors", and "market factors". The sub-factors of "economic factors" are identified as "supply chain and logistics management", "production costs", "price and payment terms", and "exchange rate and interest rate fluctuations". The sub-factors of "political factors" are defined as "trade agreements", "taxes and import quotas", "international relations", and "political stability". The sub-factors of "material-related factors" are identified as "wood species", "wood quality and suitability", "country of origin", and "sustainability". Lastly, the sub-factors of "market factors" are determined as "competition", "local wood production", "demand and demand trends", and "technological infrastructure".

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The experts in the team were called upon to express their preference between every pair of factors. The research was conducted over a two-month period, from October to November 2023. The completion of the fuzzy AHP questionnaires relies on the utilization of the verbal labels presented in Table 1 (Seker and Kahraman, 2021). The consensus-building process is applied to execute collaborative decision-making. It is carried out over three rounds. The collected responses are analyzed to identify common themes and points of disagreement. In the subsequent round, the experts review the group's feedback and reassess their opinions. The final stage involves reviewing the collected input to confirm the areas of consensus. The linguistic preferences expressed by the experts are converted into the corresponding interval-valued Pythagorean fuzzy numbers. The main factors are assessed in relation to the goal, and the sub-fac-

Table 2 Fuzzy comparison matrix for the main factors
Tablica 2. Neizrazita matrica usporedbe za glavne čimbenike

Factor	F_1	F_2	F_3	F_4
F_1	⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩	⟨[0.56, 0.69], [0.21, 0.34]⟩
F_2		⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩
F_3			⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩
F_4				⟨[0.38, 0.51], [0.38, 0.51]⟩

Table 3 Fuzzy comparison matrix for the "economic factors" group
Tablica 3. Neizrazita matrica usporedbe za skupinu ekonomskih čimbenika

Factor	F_{11}	F_{12}	F_{13}	F_{14}
F_{11}	⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.56, 0.69], [0.21, 0.34]⟩	⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.65, 0.78], [0.12, 0.25]⟩
F_{12}		⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.30, 0.43], [0.47, 0.60]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩
F_{13}			⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.56, 0.69], [0.21, 0.34]⟩
F_{14}				⟨[0.38, 0.51], [0.38, 0.51]⟩

Table 4 Fuzzy comparison matrix for the "political factors" group
Tablica 4. Neizrazita matrica usporedbe za skupinu političkih čimbenika

Factor	F_{21}	F_{22}	F_{23}	F_{24}
F_{21}	⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.30, 0.43], [0.47, 0.60]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩	⟨[0.21, 0.34], [0.56, 0.69]⟩
F_{22}		⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.65, 0.78], [0.12, 0.25]⟩	⟨[0.30, 0.43], [0.47, 0.60]⟩
F_{23}			⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.03, 0.16], [0.74, 0.87]⟩
F_{24}				⟨[0.38, 0.51], [0.38, 0.51]⟩

Table 5 Fuzzy comparison matrix for the "material-related factors" group
Tablica 5. Neizrazita matrica usporedbe za skupinu čimbenika povezanih s materijalom

Factor	F_{31}	F_{32}	F_{33}	F_{34}
F_{31}	⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩	⟨[0.74, 0.87], [0.03, 0.16]⟩	⟨[0.56, 0.69], [0.21, 0.34]⟩
F_{32}		⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.65, 0.78], [0.12, 0.25]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩
F_{33}			⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.38, 0.51], [0.38, 0.51]⟩
F_{34}				⟨[0.38, 0.51], [0.38, 0.51]⟩

Table 6 Fuzzy comparison matrix for the "market factors" group
Tablica 6. Neizrazita matrica usporedbe za skupinu tržišnih čimbenika

Factor	F_{41}	F_{42}	F_{43}	F_{44}
F_{41}	⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.47, 0.60], [0.30, 0.43]⟩	⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.65, 0.78], [0.12, 0.25]⟩
F_{42}		⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.21, 0.34], [0.56, 0.69]⟩	⟨[0.56, 0.69], [0.21, 0.34]⟩
F_{43}			⟨[0.38, 0.51], [0.38, 0.51]⟩	⟨[0.74, 0.87], [0.03, 0.16]⟩
F_{44}				⟨[0.38, 0.51], [0.38, 0.51]⟩

tors are appraised in alignment with their relevant main factor. The matrices constructed for all the factors are presented in Tables 2-6. The consistency ratios calculated for the pairwise comparison matrices are: 0.04 for Table 2, 0.03 for Tables 3 and 4, and 0.05 for Tables 5 and 6. Since the resulting values are below 0.10, the pairwise comparisons are considered acceptable.

The weights of the main factors are determined based on the calculation procedure of the interval-valued Pythagorean fuzzy AHP and are presented in Figure 3. According to the obtained results, "economic factors" (0.361) and "political factors" (0.292) have the most significant impact on wood import decisions.

The weight values obtained for the sub-factors of "economic factors" are presented in Figure 4. The most significant sub-factor is "supply chain and logistics management" (0.450). This sub-factor has the most significant impact on the decision-making process. Supply chain and logistics management involve how efficiently and effectively an organization manages the movement of goods and materials. It can significantly impact a business's ability to meet demand, reduce costs, and maintain product quality. Efficient and reliable management plays a crucial role in ensuring the timely and effective delivery of wood materials. The second most significant sub-factor is "price and payment terms" (0.295). The cost of wood materials and payment terms offered by suppliers influence the decision-making process. Importers should consider criteria such as pricing competitiveness, discounts, credit

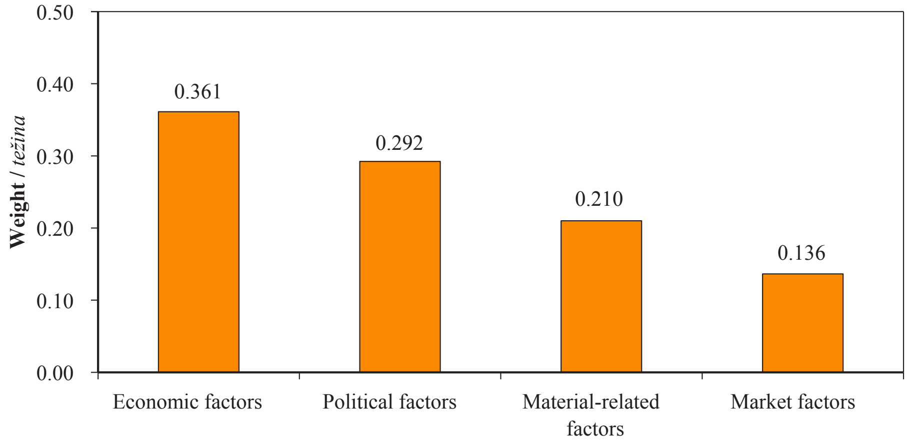

Figure 3 Modeling results for the main factors
Slika 3. Rezultati modeliranja za glavne čimbenike

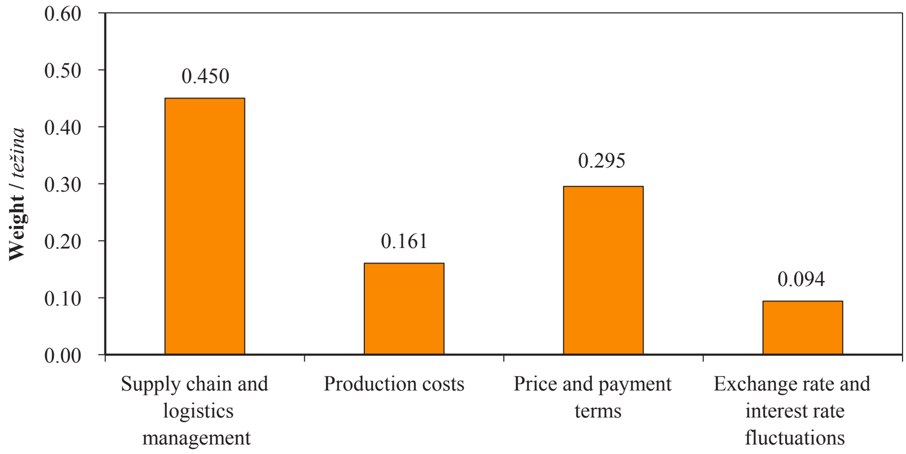

Figure 4 Modeling results for sub-factors of "economic factors"
Slika 4. Rezultati modeliranja za podčimbenike skupine ekonomskih čimbenika

terms, and payment flexibility when importing wood materials. "Production costs" is assigned a weight value of 0.161. "Exchange rate and interest rate fluctuations" has the lowest weight value of 0.094. Importers may monitor these fluctuations to mitigate potential risks but may not consider them as the primary determinants of their import decisions.

Figure 5 illustrates the weights for the "political factors" group. According to the results, the sub-factor with the highest local importance is "political stability" (0.513). The high importance of "political stability" indicates that the experts place significant emphasis on the stability of the political environment in source countries. A stable political environment provides predictability and security, which are essential for the smooth operation of international trade. When a country's political situation is stable, it reduces the risk of disruptions or sudden policy changes that could impact the flow of wood imports. The second most significant sub-factor appears to be "taxes and import quotas" (0.295). Higher taxes and quotas can increase the cost of importing wood, which, in turn, can negatively affect the profitability of businesses. Importers may seek countries or regions with more favorable tax policies and fewer import restrictions to enhance their financial performance. "International relations" (0.066) has the least impact on the decision-making process. While "international relations" has some influence, it is not as critical as the other sub-factors.

When examining the weight values presented in Figure 6, it can be seen that "wood species" (0.518) is the most important sub-factor within the "material-related factors" group. This implies that the type of wood species is a critical factor that affects importers' decision-making process. Different wood species have varying properties such as durability, appearance, and workability. Importers may rank or sort specific wood species to meet the requirements of their customers or applications. The weight value of 0.298 obtained for "wood quality and suitability" indicates that this sub-factor is also a crucial aspect. Importers must ensure that imported wood materials meet specific quality standards and are suitable for their intended applications. This includes some considerations such as moisture content, grain pattern, and defects. "Country of origin" (0.081) is less important than the other sub-factors. Importers may con-

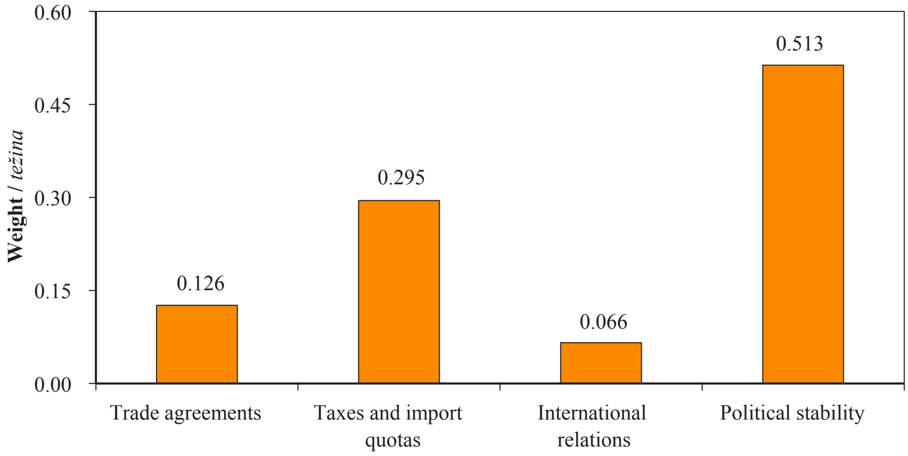

Figure 5 Modeling results for sub-factors of "political factors"
Slika 5. Rezultati modeliranja za podčimbenike skupine političkih čimbenika

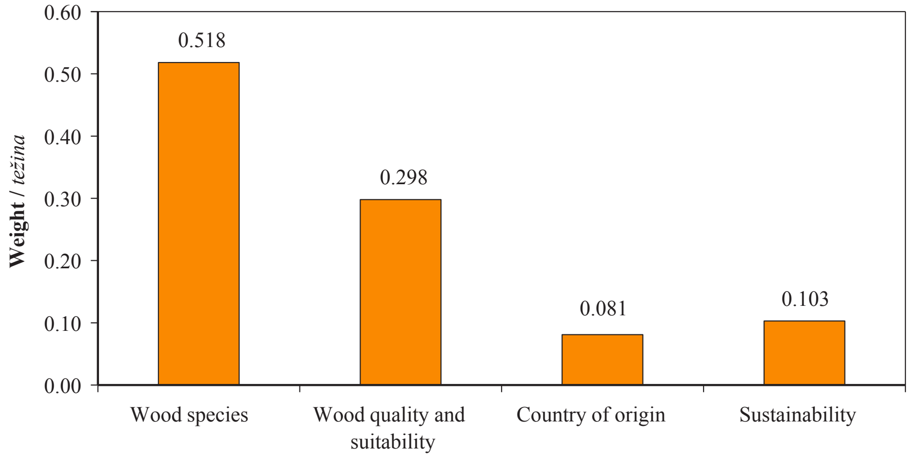

Figure 6 Modeling results for sub-factors of "material-related factors"
Slika 6. Rezultati modeliranja za podčimbenike skupine čimbenika povezanih s materijalom

sider the country of origin for logistical and market perception reasons, but it does not carry as much weight in the decision-making process.

The local importance of the sub-factors of "market factors" can be seen from Figure 7. It is observed that "demand and demand trends" (0.477) is the most significant sub-factor affecting wood import decisions. This indicates that the volume of wood demanded by the market and changes in demand trends are the most important considerations. Factors such as population growth, economic development, and shifts in consumer preferences could all impact the importance of "demand and demand trends". "Competition" (0.302) appears to be a relatively significant sub-factor. Competition in the wood import market can affect prices, availability, and market share. The weight value of 0.056 for "technological infrastructure" indicates that this sub-factor is less important compared to the other sub-factors.

The global weights are determined in order to prioritize the whole sub-factors based on their importance (Figure 8). These weights are obtained by synthesizing the local weights obtained from the pairwise comparisons of the main factors and their sub-factors. "Supply chain and logistics management" emerges as the most important factor, with a weight of 0.163, highlighting the significance of efficient and effective transportation and distribution networks. The ability to track shipments, ensure timely delivery, and manage any potential disruptions is crucial for ensuring a successful import process. "Political stability" is ranked second with a weight of 0.150, emphasizing the importance of a stable political environment in facilitating smooth trade operations. Political instability can lead to uncertain and unpredictable conditions that can negatively impact business operations. A stable political environment can help ensure consistent and reliable trade relationships. "Wood species" and "price and payment terms" are also identified as important factors, with respective weights of 0.109 and 0.107. Different species of wood have different properties such as strength, durability, and aesthetic appeal. Choosing the right species of wood is crucial for ensuring customer satisfaction and the longevity of the final product. On the other hand, the cost of wood can vary widely depending on a range of factors, including the country of origin, wood quality, and availability. It is

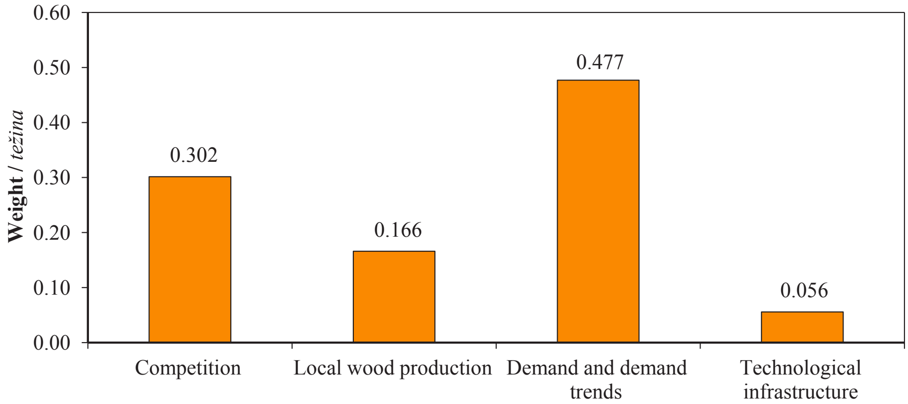

Figure 7 Modeling results for sub-factors of "market factors"
Slika 7. Rezultati modeliranja za podčimbenike skupine tržišnih čimbenika

important to negotiate favorable payment terms such as reasonable pricing and flexible payment options to ensure a profitable and sustainable business. "Taxes and import quotas" is also a significant factor with a weight of 0.086. It can impact the cost and availability of wood materials and can affect the overall profitability of a business. "Demand and demand trends", "wood quality and suitability", and "production costs" are other significant factors.

Sensitivity, validity, and comparative analyses are frequently used to validate model results and assess output changes (Valipour *et al*., 2018; Karasan *et al*., 2019). Hence, a validation analysis is carried out using the ordinary fuzzy and crisp environment with the same method. Subsequently, the BWM (best worst method) and FUCOM (full consistency method) methods are employed to compare the research results. The pairwise comparisons are adapted to align with the specific requirements of these crisp methods. The BWM analysis focuses on comparisons between the best and worst factors with the others, and the FUCOM analysis applies a sequential comparison structure based on the factors. Mathematical details of the BWM and FUCOM methods can be found in Rezaei (2015) and Pamučar *et al*. (2018). Lastly, a sensitivity analysis is conducted by examining four different scenarios. In these scenarios, F1, F2, F3, and F4 represent analyses where the weight of each main factor is individually increased by 25 %. The results obtained are presented in Figure 9.

According to the sensitivity analysis results, "supply chain and logistics management" consistently emerges as the most influential factor across all the scenarios. "Political stability" is another important fac-

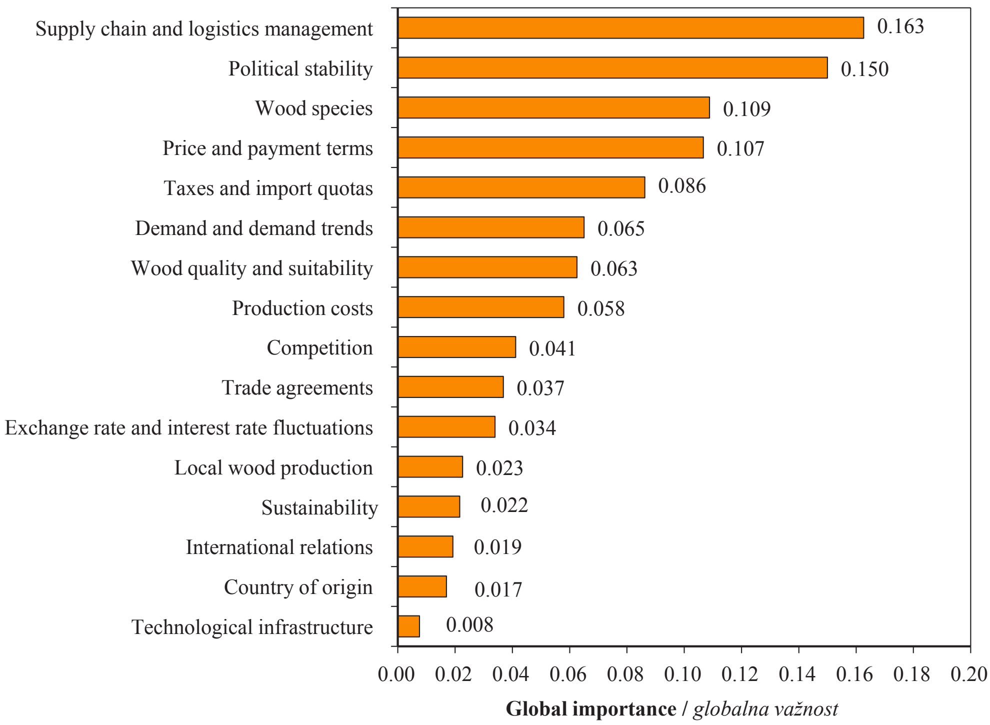

Figure 8 Global weights calculated for sub-factors
Slika 8. Izračunane globalne važnosti podčimbenika

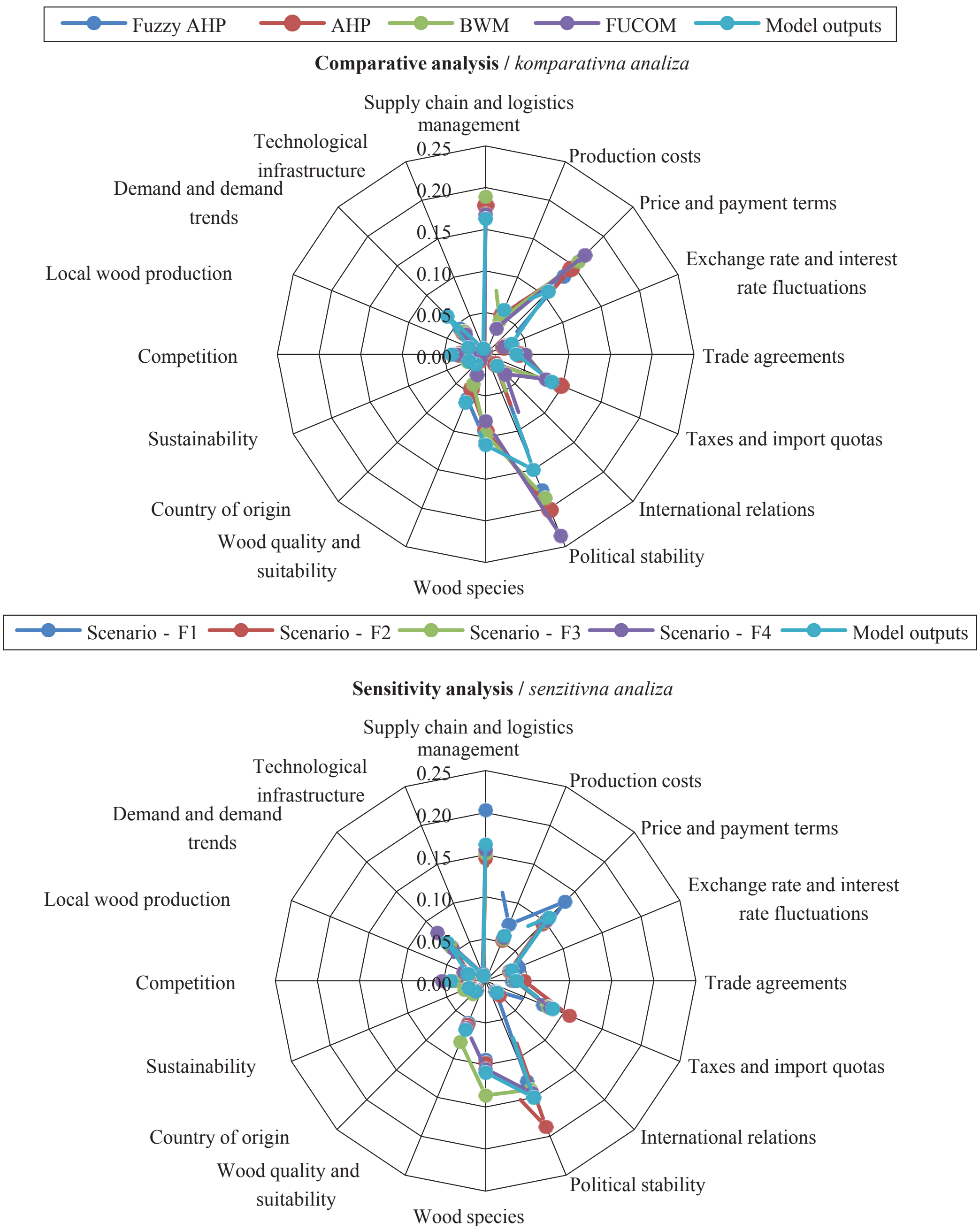

Figure 9 Robustness analysis results
Slika 9. Rezultati robusne analize

tor, holding the top rank in scenario F2 and showing strong stability with a consistent second-place ranking in the scenarios. "Price and payment terms" and "wood species" also prove to be significant, often appearing in the top three or four ranks across the scenarios. Price dynamics and the characteristics of wood particularly influence outcomes in scenarios F1 and F3. The results are highly consistent across the scenarios. Although the weights assigned to the factors by the methods vary, the overall ranking position of the factors tends to remain consistent. The interval-valued Pythagorean fuzzy AHP stands out for its ability to simultaneously consider membership, non-membership, and indeterminacy. It offers a more nuanced perspective compared to the other methods. These advantages make it a valuable tool for decision-making in complex situations. The results of this study can present a roadmap to make informed decisions about wood imports, develop more effective policies, improve supply chain management, and ensure responsible sourcing practices.

4 CONCLUSIONS
4. ZAKLJUČAK

Wood is a highly sought-after commodity traded internationally to meet the global demand for building materials, furniture, and paper products. As the global wood import market continues to expand, importers must make informed import decisions. This study aims to identify and prioritize factors influencing wood import decisions. The study employs a multi-step approach that includes a literature review and expert interviews to identify decision factors. Through this process, sixteen sub-factors are identified and classified into four main factors. The interval-valued Pythagorean fuzzy AHP method is used to assign weights to the factors. According to the results, "economic factors" and "political factors" are the most important main factors. The sub-factors with the highest local importance are: "supply chain and logistics management" in the "economic factors" group, "political stability" in the "political factors" group, "wood species" in the "material-related factors" group, and "demand and demand trends" in the "market factors" group. Furthermore, the global priority of the sub-factors is obtained as follows: "supply chain and logistics management" (16.3 %), "political stability" (15 %), "wood species" (10.9 %), "price and payment terms" (10.7 %), "taxes and import quotas" (8.6 %), "demand and demand trends" (6.5 %), "wood quality and suitability" (6.3 %), "production costs" (5.8 %), "competition" (4.1 %), "trade agreements" (3.7 %), "exchange rate and interest rate fluctuations" (3.4 %), "local wood production" (2.3 %), "sustainability" (2.2 %), "international relations" (1.9 %), "country of origin" (1.7 %), "technological infrastructure" (0.8 %). The model's results allow decision-makers to determine the most important factors in the decision-making process.

The results of the current study have significant implications for businesses and policymakers. With a clear understanding of the key factors, these groups can make more informed choices about sourcing and purchasing wood. For businesses, the study can help identify which factors are most important in the decision-making process. This information can inform business sourcing strategies and supply chain management, ultimately leading to more efficient operations. For policymakers, the study can inform regulations and policies related to the trade, importation, and transportation of wood materials.

The decision model involves gathering expert opinions on the importance of each factor, performing interval-valued Pythagorean fuzzy AHP calculations, determining the importance weights of the factors, and analyzing the ranking results. It can be updated as new information or expert insights become available. The updating process involves incorporating new or revised factors, considering expert opinions, and recalculating the importance weights using the interval-valued Pythagorean fuzzy AHP method. This study provides valuable insights into the wood import process. However, there is a limitation: the challenge of applying the weighted factors to sectors outside the forest industry. The original set of factors and their assigned weights may not fully align with the specific requirements of sectors different from the forest industry. The decision model can be adapted to various contexts beyond the wood supply chain by adjusting the factors.

This research presents a unique and valuable contribution to the field, as it is the first study to rank the most important factors affecting wood import decisions and apply the fuzzy multicriteria decision-making technique to the problem. Specifically, the study stands out in the following ways: (i) identifying, classifying, and prioritizing the most important factors influencing wood import decisions; (ii) conducting a comprehensive analysis of the identified factors; (iii) accounting for uncertainties and indeterminacies in the wood import decision-making process; (iv) incorporating expert perspectives into the problem-solving process; (v) employing the interval-valued Pythagorean fuzzy set to solve the problem; and (vi) providing a valuable guide to decision-makers for making more informed and effective import decisions. In conclusion, this study makes a valuable contribution to the growing literature on import decisions. Further research can explore the interdependency among the identified factors via a fuzzy cognitive map.

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Experimental and Numerical Analysis of Sandwich Panels Made of Different Core Materials with Plywood Facing

Eksperimentalna i numerička analiza sendvič-ploča s jezgrom od različitih materijala obloženih furnirskom pločom

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ABSTRACT • *Sandwich panels composed of different core materials with plywood facings were analyzed using experimental and numerical methods. Particleboard (PB), fiberboard (MDF), and foam materials were used as the core of the sandwich, while beech plywood was laid as the only face material. The layers of the sandwich were adhered with polyurethane adhesive. Elasticities (E) of PB, MDF, and plywood were determined in the laboratory. The E value specified by the manufacturer for the foam was used to determine the flexural behavior of sandwich panels. Results of the study indicated that the type of core material significantly affects the bending behavior of sandwich panels with plywood facings. Sandwich panels with MDF-core were observed to be more resistant in bending compared to PB and foam-core sandwich panels. Core shear failure was the dominant failure type when wood-based materials were used as core material. Buckling or tension in facing was observed when foam was used as core material. The results of the study demonstrate that numerical models can be used to accurately predict the bending behavior of the sandwich panels until failure based on yield stress and tangent modulus of the materials.*

KEYWORDS: *sandwich panels; wood-based panels; finite element analysis; bending*

SAŽETAK • *Eksperimentalnim i numeričkim metodama analizirane su sendvič-ploče s jezgrom od različitih materijala obloženih furnirskom pločom. Kao jezgra sendviča upotrijebljeni su iverica (PB), srednje gusta ploča vlaknatica (MDF) i pjenasti materijali, dok je kao obloga poslužila bukova furnirska ploča. Slojevi sendviča međusobno su zalijepljeni poliuretanskim ljepilom. Elastičnost (E) PB-a, MDF-a i furnirske ploče određena je u laboratoriju. Za određivanje savijanja sendvič-ploča poslužila je elastičnost pjene koju je deklarirao proizvođač. Rezultati istraživanja pokazali su da vrsta materijala jezgre znatno utječe na savijanje sendvič-ploča obloženih furnirskom pločom. Uočeno je da su sendvič-ploče s jezgrom od MDF-a otpornije na savijanje nego ploče s jezgrom od PB-a i pjene. Posmični lom jezgre bio je dominantan tip loma za jezgre na bazi drva. Za sendvič-ploče čija je jezgra bila pjena u oblogama od furnirske ploče uočeno je izvijanje ili vlačno naprezanje. Rezultati studije pokazuju da se, uzimajući u obzir granicu elastičnosti i tangentni modul elastičnosti materijala, numerički modeli mogu primjenjivati za točno predviđanje savijanja sendvič-ploča do loma.*

KLJUČNE RIJEČI: *sendvič-ploče; drvne ploče; analiza konačnih elemenata; savijanje*

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1 INTRODUCTION
1. UVOD

Generally, sandwich panels are structural materials consisting of outer layers with high modulus of elasticity and bending strength, and a low-density middle layer (core) (Birman and Kardomateas, 2018). In wood-based sandwich panels, the outer layers are generally veneer or plywood (PW) made of high-strength wood, and the inner layers can consist of wood-based composites such as particleboard (PB), medium density fiberboard (MDF), oriented strand board (OSB), plastic, foam, paper, or shaped core made of non-wood materials (Klímek *et al.*, 2016). The middle or core layer of sandwich panels is mainly used to transmit the load. Its function is to provide the distance between the two layers and increase the moment of inertia and bending stiffness of the panels (Noor *et al.*, 1996). Due to the low density of the core material, the sandwich panel can greatly reduce its weight under the same bearing capacity (Sandeep and Srinivasa, 2020). Furthermore, the continuous reduction of forest resources, saving materials, and reducing weight have become important in the wood-based industries (Labans and Kalniņs, 2014). Using sandwich panels in wood-based products not only saves resources but also prevents the large deformations that often occur with commercial wood composites.

The use of sandwich structures is increasing day by day. Wood-based sandwich panels are an excellent alternative to similar sandwich panels made of metal or plastics, as they are lighter and have better-bending stiffness compared to their density (Wei *et al.,* 2021). Many wood-based or vegetable materials can be used in the production of these sandwiches (Smardzewski, 2019a). Foam, cork (Kawasaki and Kawai, 2006; Lakreb *et al.*, 2015), and plastics (Kljak and Brezović, 2007) cores are commonly used as core materials in wooden sandwich panels for insulation purposes. It is also possible to manufacture prismatic core sandwich panels using eco-friendly recycled materials (Schneider *et al.,* 2016). Sandwich panels can also be reinforced with carbon fiber nowadays (Susainathan *et al.,* 2018). Besides, it should be noted that sandwich systems include typical wood-based panels covered with laminate or protective and decorative papers (Nemli and Çolakoğlu, 2005). Adhesives such as PVA, polyurethane, and urea-formaldehyde, which are widely used in the woodworking industry, are generally used to bond the layers together. Köhler *et al.* (2022) studied the Loofah sandwich panels and examined fiber-to-adhesive ratios of 1:0.5, 1:0.8, and 1:1.05. An increase in adhesive strength increases material strength and density. Compared with other commercial wood-based panels, wood-based sandwich panels have an advantage in thermal insulation (Wei *et al.,* 2021).

One of the most effective methods of controlling the mechanical properties of panel-type structures is the use of sandwich structures (Gozdecki and Kociszewski, 2021). By varying the material, thickness, and type of core and outer layers, sandwich panels with various properties and performances can be obtained. (Lakreb *et al.*, 2015; Smardzewski, 2019b). The bending properties of sandwich panels largely depend on the configuration of the layers, that is, the stacking order and the layer thickness relative to the midplane. This configuration dependence of flexural properties in sandwich structures can be used in lamination design to optimize the structural properties of sandwiches (Kazemi *et al.,* 2013).

Research in recent years has focused on the development of new sandwich products. However, there was a lack of fundamental research on design theory and modeling of fracture mechanisms. Although there are many types of wood-based sandwich panels, most research has focused on physical and mechanical properties (Kljak and Brezovic, 2007; Güler and Ulay, 2010; Edgars *et al.,* 2017; Gozdecki and Kociszewski, 2021; Köhler *et al.,* 2022). Several studies (Labans and Kalnins, 2014; Schneider *et al.,* 2016; Smardzewski, 2019a) show that the bending stiffness of sandwich panels can be determined by the finite element method. At the same time, bending stiffness could be estimated by ultrasonic method with a different approach (Haseli *et al.,* 2020). The finite element method and non-destructive testing can save a lot of time and economy in estimating the bending stiffness of such materials.

The aim of this study was to investigate the flexural properties of sandwich panels made of PB, MDF, and foam-core and plywood-outer layers. In doing so, (i) a three-point bending test was applied to determine the bending strength of the sandwich panels experimentally, and (ii) the experimental results were compared to numerical results.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Commercial panels were purchased from a local supplier in the dimensions of 210 x 280 cm. PB panels were P2 grade (TS EN 312) with a density of 635 kg/m^3 and thickness of 14 mm, medium-density-fiberboard (MDF) panels were HD grade (TS EN 622-5) with a density of 789 kg/m^3 and 12 mm in thickness, polystyrene (PS) sheets were 10 mm in thickness with a 30 kg/m^3 density. Plywood panels were marine grade (high-moisture resistant) with a thickness of 4 mm and a density of 759 kg/m^3 and consisted of three plies of oriental beech (*Fagus orientalis* L.). All boards were cut into 600 mm × 600 mm dimensions and kept in controlled conditions (temperature 21 °C, relative humidity 65 %). The bending specimens were taken along the length directions of wood-based panels due to fiber direction of faces for PWs and fiber and chips mat directions for MDF and PB. Polyurethane (PUR) glue was used as an adherent between layers. Sandwich panels with outer layers consisting of PW and core layers made of PB, MDF, and PS were prepared using PUR adhesive. The amount of adhesive used for bonding the layers was 200 g/m^2 (Uysal *et al.*, 2022). The produced sandwich panels were kept in cold press under 0.15 - 0.45 MPa pressure for 24 hours at room temperature and left for conditioning. 50 mm-wide bending samples were cut from the produced sandwich panels.

2.2 Methods
2.2. Metode

In the first stage of the study, the bending modulus and bending strength of the materials used in sandwich production were determined. The density and moisture content (MC, %) of the materials were also calculated. The bending strength and modulus of elasticity of MDF, PB, and PW panels were calculated according to TS-EN 310 (1999), the densities of the panels were evaluated according to TS-EN 323 (1999), and their moisture contents were calculated according to TS EN 322 (1999).

In the second part of the study, the bending curves of sandwich panels produced using wood-based composites and PS were obtained. The stiffness curves (*P*/δ) were obtained by subjecting the sandwich panels to the bending test using the SHIMADZU® UTM in the laboratory (Figure 1). Five replications were tested for each sample group. All tests were performed at room temperature of 21 °C and constant relative humidity of 65 %. The span of the bending samples (sandwich) was 20 times the thickness of the samples.

2.3 Numerical analysis of sandwich panels
2.3. Numerička analiza sendvič-ploča

Different modeling techniques are applied to simulate the mechanical behavior of sandwich panels. The

Figure 1 Bending test of sandwich panels constructed in the study
Slika 1. Ispitivanje sendvič-ploča na savijanje

complexity and accuracy of the models depend on what behavior the model was designed to assess. In general, it is advisable to use the simplest possible model to predict the desired phenomena (Di Sciuva *et al.,* 2015). In general, shell elements are used to model face material, while the core is modeled using solid elements.

Numerical calculations were performed using the *ANSYS Mechanical APDL* (Structural, static) *v.2023* (ANSYS, Inc. Canonsburg, Pa, USA). In the numerical models of sandwich panels, all layers of the sandwich are assumed to be isotropic. Material properties presented in Table 1 were used for modeling sandwich panels. The discretization of the numerical model was achieved using *SOLID186* elements with approximately 30,000 elements and 50,000 nodes. *SOLID186* is a high-order 3-dimensional 20-node solid element that exhibits quadratic displacement behavior. It is the most frequently preferred element for modeling structural problems. The element is defined by 20 nodes with three degrees of freedom per node: translations in the nodal *x*, *y*, and z directions. The tetrahedral element option was used. Nodal loads as a force of *P/2* were applied to upper mid-span nodes. Models were simply supported on both ends. A perfect bonding was assumed between the faces and the core at the contact zone so that the glue command available through the

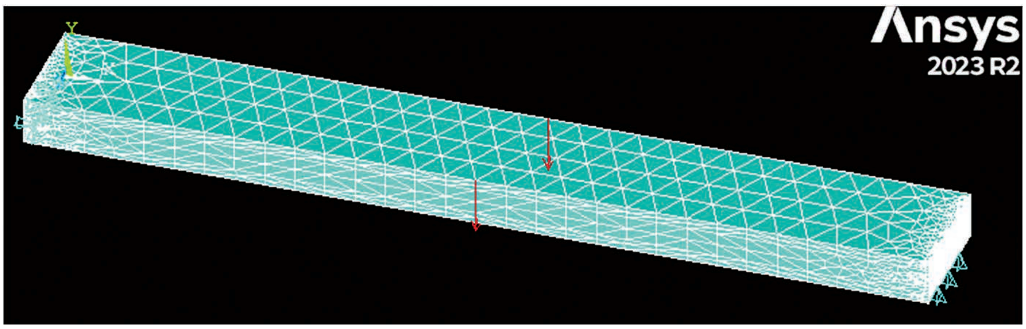


Figure 2 Numerical models created using ANSYS mechanical APDL
Slika 2. Numerički modeli izrađeni uz pomoć ANSYS mehaničkog APDL-a

operate option of the software was applied. The "*Glue Volumes*" module is used in the ANSYS package program to stick the mechanical properties of the model together. The *VGLUE* command (*ANSYS*^{TM}) is used to generate a new volume of the sandwich material by "*gluing*" all three solid parts. This operation is only valid in the case when the interfaces are coplanar. The mid-span panel deflection and maximum stress and strains at various locations on facings were extracted as an output result of numerical analysis. Load/deformation (stiffness) curves were created using the ANSYS and compared with the stiffness curves of real sandwich panels tested in the laboratory. Figure 2 illustrates one of the models created using ANSYS mechanical APDL. Plasticity was introduced using strain hardening (bilinear material) option available through ANSYS, which requires yield and tangent modulus.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The density, *MC* (%), and bending properties of materials tested in the study are presented in Table 1. Average stress-deformation curves representing the materials tested in the laboratory are shown in Figure 3. Although specimens belong to wood-based composite materials, their stress-deformation behavior differs due to their raw materials and manufacturing processes. Bending curves illustrated that plywood had superior bending capacity compared to other wood-based materials. The experimental results of wood-based panels indicated that stress-deformation curves can be considered as bilinear, having linear region, yield, and following plastic region (Figure 2). This information is crucial to construct numerical models by using ANSYS. Tested plywood, MDF, and PB panels seemed to have a yield point of approximately 90, 20, and 7 MPa, respectively. Those of the tangent modulus were calculated as 2000, 1700, and 300 MPa, respectively. The bending properties of sandwich panels tested in this study are similar to those reported by Gozdecki and Kociszewski (2021).

Figures 4-6 show the bending test results and numerical modeling obtained from sandwich composite panels with different core materials. The stress–deflection curves of the sandwich panels presented bilinear curves, which include initial linear elastic region fol-

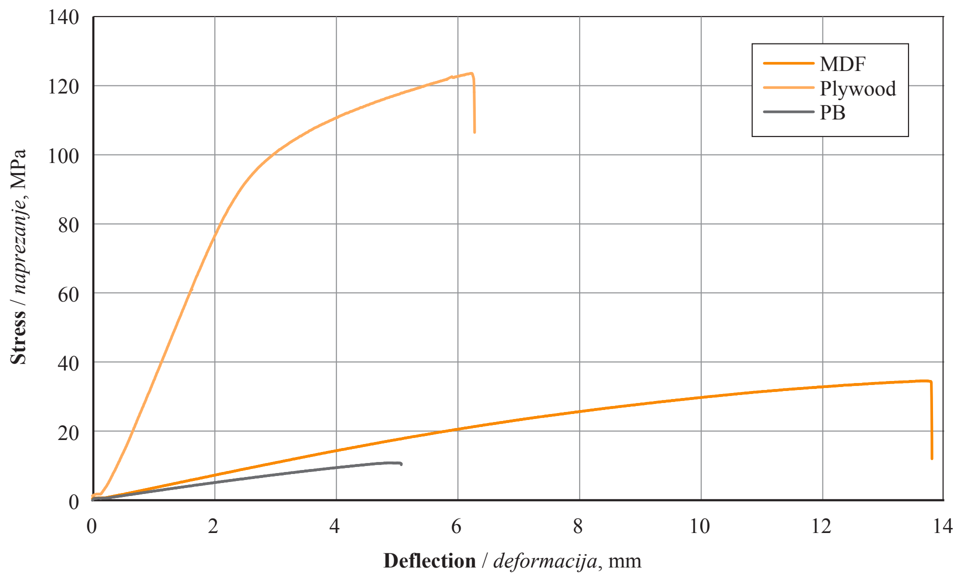


Figure 3 Average stress – deformation curves for materials tested in bending
Slika 3. Prosječne krivulje *naprezanje – deformacija* za materijale ispitane na savijanje

Table 1 Some physical and bending properties of materials tested in the study
Tablica 1. Neka fizička svojstva i svojstva na savijanja materijala ispitanih u studiji

Material *Materijal*	**Density, kg/m³** *Gustoća,* kg/m³	***MC*, %**	***E*, N/mm²**	**σ, N/mm²**	**Max. deflection at failure, mm** *Najveći progib pri lomu,* mm
PB	635	8.1	1540 (76)	11.18 (0.81)	5.07
MDF	780	8.0	3084 (80)	31.96 (1.07)	13.79
Plywood	750	11.5	10066 (919)	118 (5.65)	6.25
Foam	30		10		
P-PB-P	720		7205 (430)	53.39 (0.85)	14.5
P-MDF-P	809		7311 (247)	65.59 (8.4)	18.5
P-foam-P	432		2213 (114)	20.28 (0.81)	35

*Values in parenthesis are standard deviations / *vrijednosti u zagradama standardne su devijacije* lowed by plastic deformation. The curves of the two specimens with PB and MDF core materials were steep and had good linearity in the elastic stage. In contrast to that, the foam-core material yielded mostly parabolic curves, which is a sign of more plastic deformation. It can be concluded that layer properties are reflected in the behavior of sandwiches.

Sandwich panels with PB- and MDF-cores behaved significantly stiffer than sandwich panels with foam-cores. It is well-known that the stress-strain be-

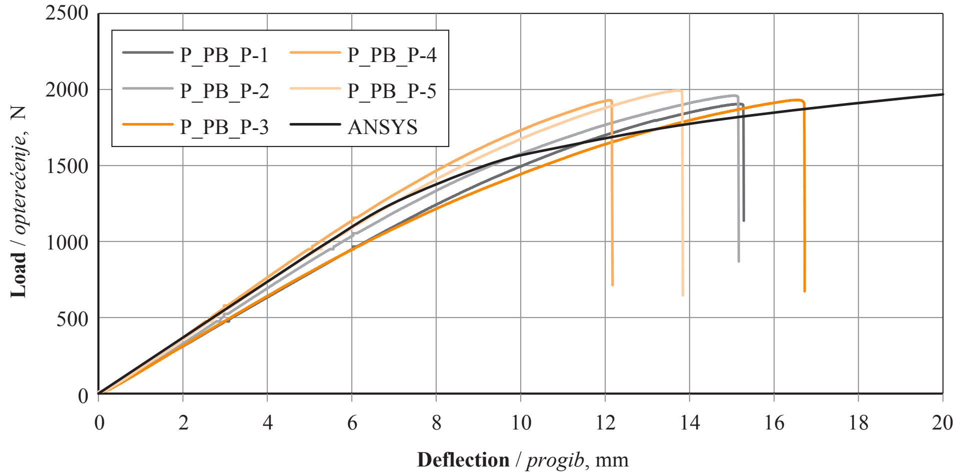


Figure 4 Load – deflection curves of PB core sandwich materials
Slika 4. Krivulje *opterećenje – progib* sendvič-materijala s PB jezgrom

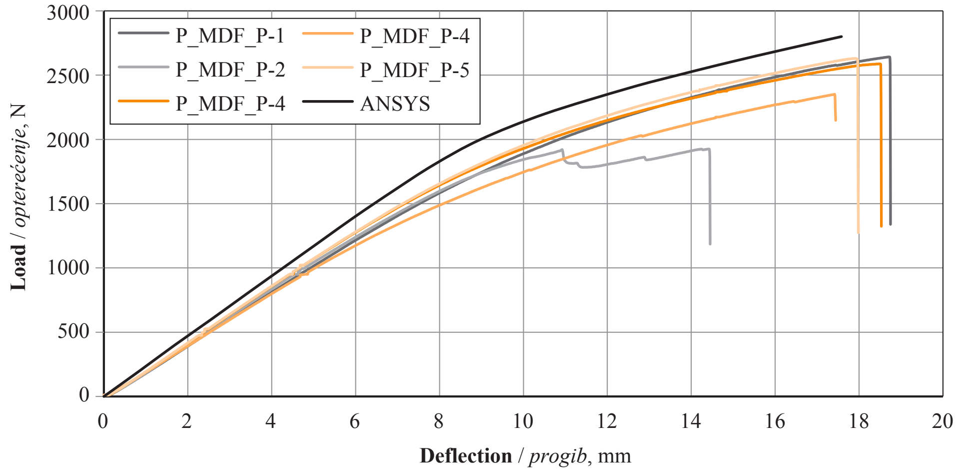


Figure 5 Load – deflection curves of MDF core sandwich materials
Slika 5. Krivulje *opterećenje – progib* sendvič-materijala s MDF jezgrom

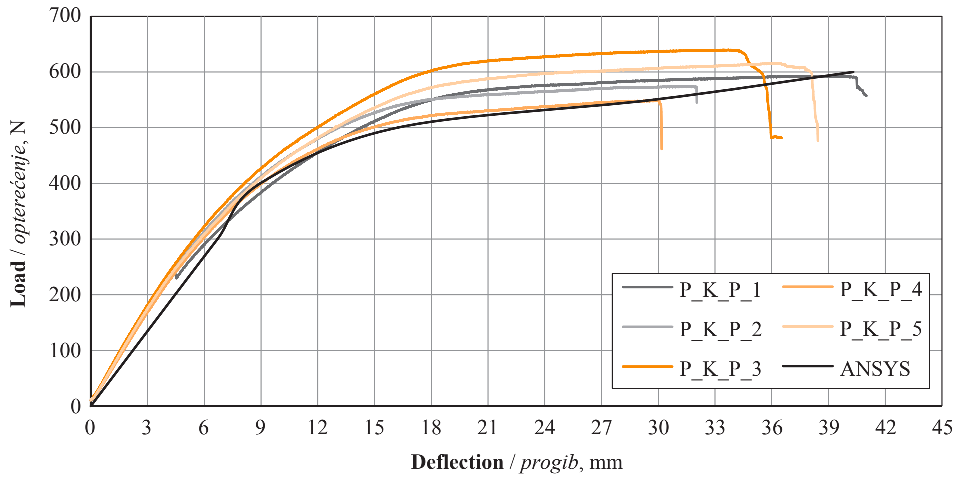


Figure 6 Load – deflection curves of foam core sandwich materials
Slika 6. Krivulje *opterećenje – progib* sendvič-materijala s jezgrom od pjene

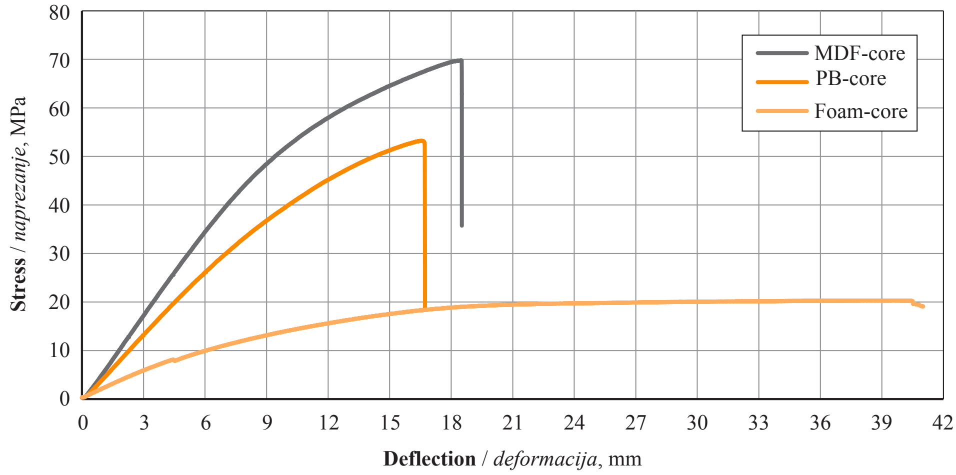


Figure 7 Comparison of bending curves of sandwich panels with different core materials
Slika 7. Usporedba krivulja savijanja sendvič-ploča s jezgrom od različitih materijala

havior of wood in compression parallel or perpendicular to grain is nonlinear (Goodman and Bodig, 1971). Consequently, bending fractures in sandwich panels made with plywood facings are expected to present non-linear load-displacement behavior. This non-linear behavior may end with a brittle fracture.

The average bending strength of sandwich panels with PB core material and plywood facings is measured as 53 MPa, while the average total deflection at the failure is determined as 13.4 mm. PB-core sandwich panels have the average bending stiffness of 7205 MPa, which is slightly lower than MDF-core sandwich panels with a bending strength of 65 MPa and a bending stiffness of 7311 MPa, The average total deflection at failure measured for MDF-core sandwich panels is 18 mm. Thickness of the core material may also contribute to the overall bending stiffness. Thus, sandwich panels made of MDF core having the same core thickness may yield much more stiffness than PB core sandwiches. This is also valid in terms of the bending strength of the MDF core sandwich panels. Foam-core sandwich panels had the greatest total deflection at the failure, while they had the lowest bending stiffness and bending strength.

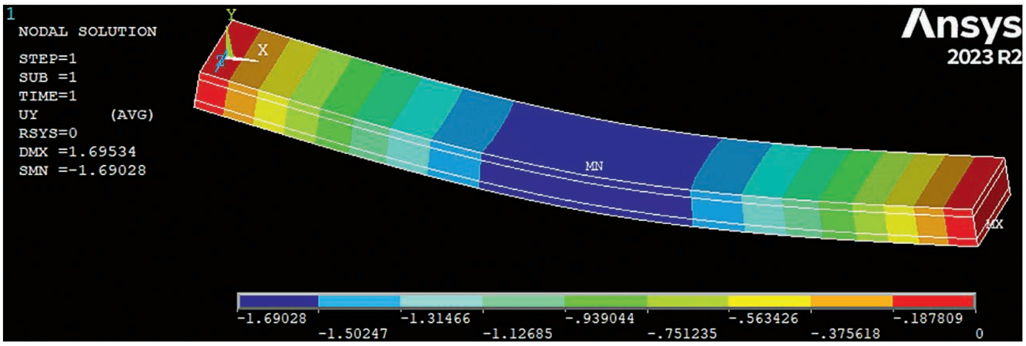
As shown in Figure 7, it is critical to note that both initial stiffness and ultimate load were obviously distinct for sandwich panels with different core materials.

A comparison of the numerical and experimental results showed that the deflection behavior of sandwich panels until failure is in good agreement with the simulation results of ANSYS (or slightly over prediction as shown for MDF core sandwiches). The numerical models assumed a perfect bond between the layers of the sandwich panels. This was confirmed by the failure types, which were never observed in the bond of the core and face layers. The numerical models are more detailed and they presented stress concentrations, which was a sign of a higher probability of failure (Figure 8).

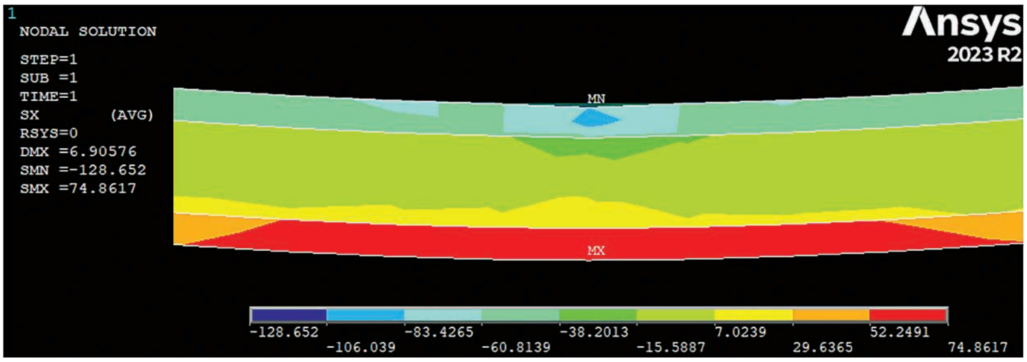
Numerical modeling of non-linear behavior was challenging because the data that would define the elastoplastic behavior of wood-based panels are not available in the literature, which significantly complicates the modeling. Using yield stress and tangent modulus of materials in numerical modeling make it possible to obtain non-linear behavior of sandwiches and more precise results.

Several studies related to the FEM modeling of sandwich panels under bending loading can be found in the literature. Most studies established good agreement between numerical models and experimental outcomes (Alade *et al.,* 2023). Some studies reported over-prediction. Since internal defects or irregularities are inevitable while using wood, over-prediction of numerical models may be somehow expected. Kljak *et al.* (2018) revealed that the use of isotropic models in the modeling of PB panels instead of a three-layer orthotropic model yields more precise results within the linear-elastic limit.

The accuracy of numerical models may depend on the type and number of the elements, geometry and loading scheme used. Solid elements may yield better prediction than plane elements, and second order elements have a high degree of accuracy than first order elements. In numerical modeling, meshing with simple elements such as plane182 (4 node) or solid 186 (8 nodes), having moderate number of elements and isotropic element properties in modeling of simple bending, may yield accurate results. Results reported by Edgars *et al.* (2017) and Kljak *et al.* (2018) support this idea. Complicated loading schemes or geometries may require the use of high order quadratic elements such as solid 186 (20 nodes), orthotropic element properties and higher number of elements. Recent investigations engaged in non-linear behavior using orthotropic properties (Kljak and Brezović 2007; Labans and Kalnin, 2014; Fang *et al.,* 2015; Smardzewski, 2019a; Mohammadabadi *et al.*, 2019; Mohammadabadi *et al.*, 2020) presented highly



a)



b)

Figure 8 Deformation (a) and stress (b) obtained using ANSYS software (DMX – maximum deformation, SMN – minimum stress and SMX – maximum stress)
Slika 8. Deformacija (a) i naprezanje (b) dobiveni primjenom ANSYS softvera (DMX – najveća deformacija, SMN – najmanje naprezanje i SMX – najveće naprezanje)

accurate results. Nevertheless, few predictive models are established to better understand the non-linear mechanical behavior of sandwich structures with wood elements. In general, elastoplastic behavior with strain hardening has also been presented in the modeling of wood joints (Serrano, 2001; Guan *et al*., 2009).

In the case of using MDF- or PB-core panels, their dominant failure type was mainly due to the failure of MDF or PB. On the contrary, those of foam-core panels were mainly due to the failure of the adhesive between the layers of plywood (Figure 9). It is well-known that particle or fiber-based wood panels are weak in shear; it is particularly true that the presence of flaws and the discrepancies in internal bond strength may contributed to the shear failure. The identical phenomena may have also contributed to the increased bending deflection during experiments. The higher shear strength of the foam materials may cause the diversion of stress concentrations from the core to the face material. Delamination or splitting that prevailed in the plywood facings supports this idea. As mentioned in the literature, the most common failure patterns for sandwich beams were shear failure, indentation, and face yield (Hao *et al*., 2018).

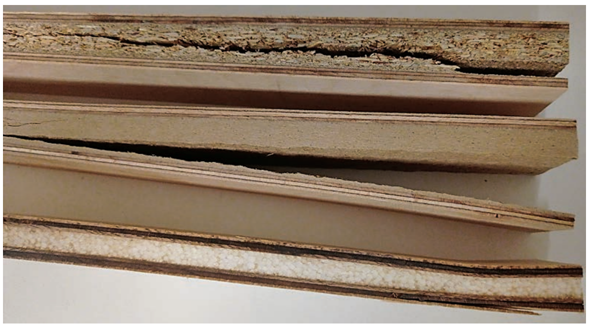


Figure 9 Failure types observed for sandwich panels constructed
Slika 9. Uočene vrste lomova na sendvič-pločama

Results indicated that stress concentration is located at the mid-part of the sandwich panels. When sandwich panels are subjected to bending, compressive stresses act on the surface while tensile stresses act on the bottom. Since the yield stresses of the materials used in the construction of the sandwiches are different, it is important to know the lower values of these stresses that will start to cause failure. Wood has lower yield stresses in compression, perpendicular directions, and shear; whichever reaches the critical level will cause the failure.

4 CONCLUSIONS
4. ZAKLJUČAK

Results of the study have shown that the type of core material has a significant effect on the bending behavior of sandwich panels with plywood facings.

Panels with the MDF core are more resistant to bending compared to panels with PB- and foam-core.

Although the foam core deflects more, it can carry the load for a long time.

Numerical models can be used successfully in the prediction of the bending behavior of the sandwich panels constructed in the study.

Numerical models can be adapted to predict the behavior of new sandwich materials with different thicknesses.

The nonlinearity of sandwich constituents was successfully defined by using yield and tangent modulus.

The suitability of the model to simulate the nonlinear behavior of sandwich panels until failure is demonstrated.

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Analyzing Growing Wood Pellet Markets in Face of Renewable Energy Demand: Making Informed Trading Decisions with Multi-Criteria Decision-Making Model

Analiza rastućih tržišta drvnih peleta u uvjetima potražnje obnovljive energije: donošenje informiranih odluka o trgovanju utemeljenih na višekriterijskome modelu odlučivanja

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ABSTRACT • *As a sustainable and cost-effective biofuel source for power generation and heating systems, wood pellets play a critical role in the renewable energy landscape. This leads to the discussion on their international trade on the edge of major global challenges such as climate change and energy security. In this paper, we focus on the wood pellets trade and analyze its growing markets by decision-making models. A hybrid multi-criteria decision-making model (MCDM) is proposed, supported by critical criteria of international trade, to trading countries' executives to make informed decisions on target markets. The model includes both criteria (value imported, trade balance, unit value, annual growth in value, CO_2 emission, logistic performance index, concentration of supplying countries) and alternatives (17 prior importing countries). It determines the weights of criteria by Criteria Importance Through Intercriteria Correlation (CRITIC) method and ranks alternatives by Additive Ratio Assessment (ARAS) technique. Based on CRITIC analysis, "concentration of supplying countries" is found as the most significant criterion. According to the results, within informed trading decisions, the top three markets for exporting countries are determined as the United Kingdom, Japan, and the Netherlands in terms of growing demand for wood pellets.*

KEYWORDS: *wood pellet; international market; biofuel trade; CRITIC; ARAS*

SAŽETAK • *Drvni peleti imaju ključnu ulogu u proizvodnji obnovljive energije kao održiv i troškovno učinkovit izvor biogoriva za proizvodnju električne energije i za grijanje. To nas dovodi do bitne rasprave o međunarodnoj trgovini u kontekstu velikih globalnih izazova kao što su klimatske promjene i energetska sigurnost. U ovom radu fokus je na trgovini drvnim peletima i analizi rastućeg tržišta primjenom posebnog modela odlučivanja. Predlaže*

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se hibridni višekriterijski model odlučivanja (MCDM) podržan kritičkim kriterijima međunarodne trgovine kako bi operativci trgovinskih zemalja donosili informirane odluke o ciljanim tržištima. Model uključuje kriterije međunarodne trgovine (vrijednost uvoza, trgovinsku bilancu, jediničnu vrijednost, godišnji rast vrijednosti, emisiju CO_2, indeks logističke učinkovitosti, koncentraciju zemalja izvoznica) i alternative (17 prethodnih zemalja uvoznica). Usto, modelom se određuju ponderi kriterija metodom njihove važnosti putem međukriterijske korelacije (CRITIC) te se alternative rangiraju tehnikom procjene omjera aditiva (ARAS). Na temelju CRITIC analize utvrđeno je da je najvažniji kriterij koncentracija zemalja izvoznica. Prema rezultatima, unutar informiranih trgovačkih odluka kao tri najveća tržišta za zemlje izvoznice u smislu rastuće potražnje drvnih peleta prepoznate su Velika Britanija, Japan i Nizozemska.

KLJUČNE RIJEČI: *drvni pelet; međunarodno tržište; trgovina biogorivom, CRITIC; ARAS*

1 INTRODUCTION
1. UVOD

The rapid growth in the world population, urbanization, and industrialization in emerging regions led to a considerable increase in the demand for energy generation and consumption. However, while fossil fuels meet 80 per cent of the current global primary energy demand used in heating, electricity, transportation and industry, they are also the cause of approximately two-thirds of greenhouse gas (GHG) emissions (UN, 2015). The relevant institutions strongly emphasize that the use of renewable energy should be increased and that the share of fossil fuels in energy consumption should be significantly reduced to combat global climate change. Therefore, renewable energy has increasingly become more important to meet the global energy demand. Gielen *et al*. (2019) demonstrated in their study that the proportion of renewable energy in the total primary energy supply can increase from 15 % in 2015 to 63 % in 2050.

Wood pellets are one of the significant renewable biofuel energies derived from woody biomass and are considered to be a promising carbon-neutral alternative to fossil fuels. According to Bioenergy Europe, wood pellets are mentioned to be a reliable and affordable solution for all sectors in the context of achieving carbon neutrality by 2050 and will contribute significantly to the decarbonization of the heating sector, which is responsible for almost half of the energy consumption (Bioenergy Europe Statistical Report, 2021). They are highly efficient, effective and cheaper energy sources with a lower moisture content and relatively high heating value compared to other types of biomass fuels; they also stand out among all renewable energy sources with ease of production technology (Proskurina *et al*., 2016). Moreover, due to their smaller volume, their storage and shipping is also more efficient (Uslu *et al*., 2008) and they are suitable for use in both local, urban, and large public areas due to their characteristics (Giacomo and Taglieri, 2019). Therefore, wood pellets have recently become an important energy carrier trad-

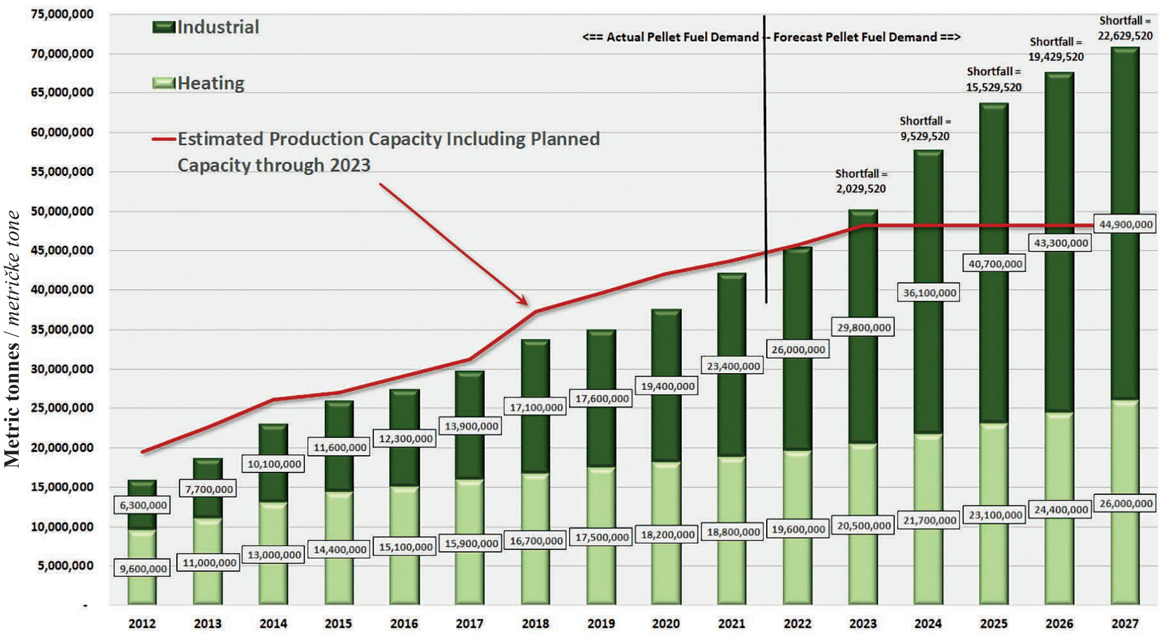

Figure 1 Global heating and industrial pellet demand with the forecast up to 2027 (Strauss (2022), Canadian BioMass, https://www.canadianbiomassmagazine.ca/2022-wood-pellet-markets-outlook/)
Slika 1. Globalna potreba za grijanjem i potražnja industrijskih peleta s predviđanjem do 2027. godine (Strauss, 2022., Canadian BioMass; https://www.canadianbiomassmagazine.ca/2022-wood-pellet-markets-outlook/)

ed on a large scale and over long distances, due to their high energy density and stable characteristics (Scarlat *et al*., 2019).

Figure 1 shows the global heating and industrial wood pellets demand with the forecast up to 2027. According to a forecast analysis by Future Market Insights (FMI), the total global demand for wood pellets, for both industrial and heating purposes, is projected to expand at a compound annual growth rate (CAGR) of 44 % during the forecast period between 2021 and 2027. However, this growth projection assumes that the production capacity will increase in parallel with the demand growth.

To meet the growing demand for wood pellets, global production totaled 1.7 million metric tons in the year 2000 (Statista, 2021), and it had surpassed 44.3 million tonnes by 2021. Europe produced roughly 25.4 million tonnes of wood pellets, accounting for the largest share of wood pellet production that year, and America followed Europe with 13.2 million tonnes of production in 2021 (Food and Agriculture Organization – FAO, 2023). The total global exports amounted to over 31.1 million tonnes, with a total value of US$ 4.7 billion. Meanwhile, the total import was 27.7 million tonnes, with a total value of US$ 50.0 billion in 2021 (FAO, 2023). Therefore, the wood pellets market appears to be developing dynamically in response to the increasing global demand for renewable energy in the face of climate change. In this sense, it is crucial to focus on wood pellets markets to create insight for both researchers and trading bodies for the future of the industry in the face of renewable energy demand.

2 LITERATURE REVIEW AND STUDY AIM
2. PREGLED LITERATURE I CILJ ISTRAŽIVANJA

Although there is an increasing interest in wood pellets markets due to the demand for renewable energy, few studies have focused on an overview of the current market, price policies and future economic expectations for several pioneer countries.

Peng *et al*. (2010) examined the current and future wood pellet market for Canada. Sikkema *et al*. (2011) provided a comprehensive overview of the current wood pellet market in Europe, including demand, supplies, market types, prices, and outlook, considering raw material supply. Goh *et al*. (2013) overviewed the wood pellet markets in various countries, including market factors and relevant policies under the discussion on global production and consumption in 2010, with a focus on the EU as the primary market. Roni *et al*. (2017) investigated the industrial-grade wood pellet market assuming potential buyers and suppliers optimize their decision independently. Jonsson and Rinaldi (2017) used economic modeling to assess the impact of gradually increasing wood pellets on global wood-based product markets. Their findings indicated that an increase in EU demand for wood pellets would result in a significant rise in imports, in addition to increasing EU production. Thran (2018) examined the global wood pellets market dynamics and traced sectoral developments in production, consumption, export/import and price patterns under the effect of policies between 2008 and 2016. Schipfer *et al*. (2020) aimed to understand the efficiency of the wood pellet market using modern trade theory. The writers analyzed the recent European market data for wood pellets used in small-scale heating systems, specifically focusing on trade flows and price developments between Italy, Austria, Germany, and France. They also examined market integration, identified potential inefficiencies, and made policy recommendations to ensure access and affordability of this renewable heating commodity in the long run based on the findings. Krivokochenko (2021) considered the current state and prospects for the wood pellet market and characterized the major trends in production, consumption and international wood pellet trade. Franco (2022) conducted a review of the literature published from 2010 to March 2020 that helped to understand the dynamics of the forest biomass supply for wood pellets production. However, these papers did not fully address the trade potential of wood pellets globally. Many studies have just focused on local or country-based production or trade potential and furthermore, no studies focused on modeling the growing wood pellet exporting markets by any decision-making models in the face of growing renewable energy demand.

Consequently, identifying target countries and focusing on growing markets is a critical issue for wood pellet trading countries to gain a competitive advantage and a significant market share in the future. This leads to the multi-criteria decision-making (MCDM) problem, which should be addressed by considering various criteria and solved using relevant MCDM methods. With this perspective in mind, the aims of this study have been determined as follows:

1. Create a multi-criteria decision-making system for wood pellets trading countries, by determining important criteria and their weights for target market selection,
2. Provide export forecasting to trading countries' executives about the priority target markets within the most rapidly growing 17 alternatives.

To achieve these aims, the methods were discussed in detail and applied for both determining the criteria and ranking the countries for export within the MCDM methods in the methodology part supported by the literature review.

3 EMPIRICAL METHODS AND DATA
3. EMPIRIJSKE METODE I PODATCI

Target market selection is seen as one of the most complex and time-consuming activities of both countries and companies, due to conflicting objectives, abundance of alternatives and diversity of criteria. For this reason, target market selection can be defined as a Multi-Criteria Decision Making problem (Aghdaie and Alimardani, 2015).

Various MCDM methods have been employed in multiple studies in recent years to assess the selection of target markets for both organizations and industries. Albadvi *et al*. (2007) applied the PROMETHEE method to select the best target market for TV in Iran. Aghdaie *et al*. (2011) utilized Fuzzy AHP and Fuzzy TOPSIS to evaluate and choose market segments. Mobin *et al*. (2014), employed Entropy, SAW, TOPSIS and VIKOR to identify markets for Iranian pistachios. Aghdaie and Alimardani (2015) used AHP and TOPSIS to elicit a suitable target market. Söyler and Yaraş (2016) applied AHP and TOPSIS methods to select the target markets for the travertine market. Ortiz-Barrios and Lopez-Meza (2016) proposed an integrated AHP-VIKOR approach for selecting the most suitable markets for prospective companies.

Tosun (2017) utilized Fuzzy VIKOR to determine the target market for fresh fruit and vegetables. Oey *et al*. (2018) evaluated the international market selection of a metal company in Indonesia using AHP and Goal Programming. Sukoroto *et al*. (2020) implemented the AHP method for target market selection of a rolling stock manufacturer in Indonesia. Zakeri *et al.* (2020) used Grey COPRAS and Grey TOPSIS to select the target market for the Iranian dairy market. Aghajani (2021) prioritized target markets using a combined method of AHP/Monte Carlo simulation and Fuzzy AHP. Yıldız and Özbek (2021) employed TOPSIS, Grey Relational Analysis and ANP to evaluate alternative sock export markets. Espinoza-Lastra *et al*. (2022) applied AHP to select the target market for the Indonesian rolling stock market. Celik and Akmermer (2022) evaluated export markets for major aquaculture products of Turkey using Fuzzy AHP and TOPSIS methods.

In this paper, a hybrid MCDM model was proposed combining CRITIC and ARAS methods to create a multi-criteria decision-making system. Since it is an objective decision-making method, the CRITIC method is used to determine the weights. The ARAS method is preferred for this study because it is easy to understand, has a short calculation time and requires few mathematical operations, but is still a reliable method. It is assumed that using the CRITIC and ARAS methods together would contribute to the literature. The analysis was conducted in three stages, including constructing the decision model, analysis, and scenario analysis as presented in the framework of the application shown in Figure 2.

The first stage of the application is to create the decision matrix, as in all MCDM problems. Evaluation criteria and alternative countries for creating a decision matrix were defined using data obtained from the international trade database. In the second stage, the CRITIC method is used for weighting the criteria objectively, and the ARAS method is applied for evaluating the top priority markets. These methods are detailed below.

3.1 CRITIC Method
3.1. CRITIC metoda

The CRITIC method has been proposed to objectively determine the importance weights of the criteria of MCDM problems. The CRITIC method was introduced to the literature in 1995 by Diakoulaki *et al*. This method is a weighting method performed by using the standard deviations of the criteria and the correlation between the criteria. The steps of the CRITIC method are as follows (Diakoulaki *et al*., 2015; Aytaç Adalı and Tus Işık, 2017);

Step 1: Creation of the Decision Matrix

In the decision matrix expressed by Eq. (1), the index i represents the alternatives and the index j repre-

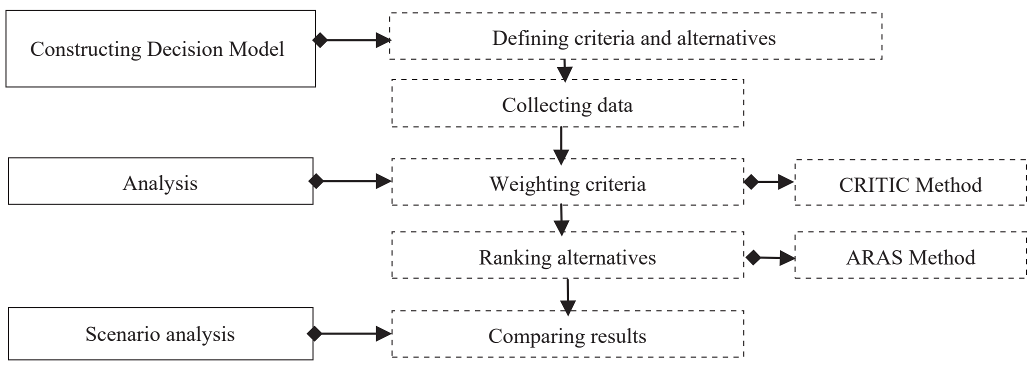

Figure 2 Application framework
Slika 2. Okvir aplikacije

sents the criteria. x_{ij}, represents the performance value of i*th* alternative in terms of j*th* criteria.

$$X = [X_{ij}]_{mxn} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}$$

i= 1,2,…m and j = 1,2,…,n) (1)

Step 2: Decision matrix is normalized by Eq. (2).

$$x_i j^* = \frac{x_{ij} - \min x_{ij}}{\max(x_{ij}) - \min(x_{ij})}$$

(i= 1,2,…m and j = 1,2,…,n) (2)

Step 3: In this step, the standard deviation of the criterion and its correlation with other criteria are included. Then the weight is calculated by Eq. (3).

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \quad (3)$$

C_j shows the quantity of information comprised in j*th* criterion settled as:

$$C_j = \sigma_j \sum_{j=1}^{n} (1 - r_{ij}) \quad (4)$$

Where σ_j represents the standard deviation of the j*th* criterion and r_{ij} is the correlation coefficient between the two criteria. This method tends to assign greater importance to criteria exhibiting a high standard deviation and weak correlation with other criteria. To be specific, a higher value of C_j means that a greater amount of information is obtained from the given criterion, so the criterion has higher relative importance for the decision problem.

3.2 ARAS Method
3.2. ARAS metoda

Zavadskas and Turskis (2010) introduced the ARAS (Additive Ratio Assessment) method as an MCDM (Multi-Criteria Decision Making) approach. This method, as outlined in their works (Zavadskas and Turskis, 2010; Zavadskas *et al*., 2010), comprises the following sequential steps.

Step 1: Formation of decision matrix: x_{ij} values are created for *m* alternatives and *n* criteria.

$$X = \begin{bmatrix} x_{01} & \cdots & x_{0j} & \cdots & x_{0n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix};$$

$i = 0, 1, \ldots, m \quad j = 0, 1, \ldots, n$ (5)

Let x_{ij} denote the performance value and x_{0j} denote the optimal value for criterion *j*. In cases where the optimal value x_{0j} j is not known, it is assigned as follows:

$x_{0j} = \max_i x_{ij}$, if maximization is preferable, (6)

$x_{0j} = \min_i x_{ij}$, if minimization is preferable.

Step 2: Creating a normalized decision matrix $(\bar{X})$w

The criteria values, which are desired to be maximized, are normalized as follows:

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_{i=0}^{m} x_{ij}} \quad (7)$$

The criteria values, which are preferred to be minimized, undergo normalization using the method illustrated below:

$$x_{ij}^* = \frac{1}{x_{ij}} \quad (8)$$

$$\bar{x}_{ij} = \frac{x_{ij}^*}{\sum_{i=0}^{m} x_{ij}^*} \quad (9)$$

Step 3: Defining weighted normalized decision matrix $(\hat{X})$

$$\sum_{j=1}^{n} w_j = 1 \quad (10)$$

$$\hat{x}_{ij} = \bar{x}_{ij} \cdot w_{ij}$$

Where the weights are denoted by w_j and $0<w_j<1$.

Step 4: The determination of optimality function values is performed through the calculation process.

$$S_i = \sum_{j=1}^{n} \hat{x}_{ij}, \quad i = 0,1,\ldots,m \quad (11)$$

Where the optimality function value of alternative *i* is represented by S_i.

Step 5: The degree of utility (K_i) for alternatives is obtained through the process of assessment.

$$K_i = \frac{S_i}{S_0}, \; i = 0,1,\ldots,m \quad (12)$$

Where the optimal value of the alternative is denoted as S_0. The K_i values, which range between 0 and 1, are sorted in ascending order, with the highest degree indicating the most favorable outcome.

3.3 Scenario analysis
3.3. Analiza scenarija

In the last stage, scenario analysis was applied to assess the impact of changes in criteria weights on the rankings and evaluate the reliability of the proposed methodology.

The application of scenario analysis serves multiple purposes: (1) validating the results derived from MCDM problems, (2) identifying the primary factors responsible for alterations in alternative rankings, and (3) ranking alternatives based on variations in criteria weights, as described by Butler *et al*. (1997). In the final phase of implementation, a scenario analysis is conducted, encompassing seven distinct scenarios. This analysis explores changes in rankings resulting from modifications in criteria weights and assesses the robustness of the proposed methodology. The outcomes obtained from the analysis are subsequently compared for evaluation.

4 EMPIRICAL RESULTS AND DISCUSSIONS
4. EMPIRIJSKI REZULTATI I RASPRAVA

4.1 Constructing decision model
4.1. Konstruiranje modela odlučivanja

In the first stage of the application, the decision matrix was created by defining evaluation criteria and alternative countries for the analysis, using data obtained from the international trade database.

In the determination of the criteria, we examined the target market analysis reports to identify the main criteria for trading decisions. In many research studies, various criteria have been used from different perspectives (Aghdaie and Alimardani, 2015; Akmermer and Celik, 2021; Özekenci, 2024). To determine the primary criteria, a survey was conducted with the export experts, who have experience in Forest industry. We also referred to the studies in the literature and checked data availability in the database. Consequently, we determined seven criteria, listed in Table 1, to evaluate potential markets.

The datasets of 6 criteria (VI, TB, UV, AG, CO_2, and COS) were obtained from TradeMap, UNdata and FAOSTAT. The criterion LPI was obtained from WorldBank. We used the Harmonized Commodity Description and Coding Systems for products to search for the data in the database. The 6-digit HS tariff Classification Number for wood pellets is 440131. All these data pertaining to the criteria were utilized in the analysis phases for the construction of the multi-criteria decision-making model.

In the second step, we determined the potential target countries. We identified the wood pellet importing countries and then evaluated them based on their con-

Table 1 Evaluation criteria
Tablica 1. Kriteriji ocjenjivanja

Criteria / *Kriterij*	**Explanation** / *Objašnjenje*
Value imported in 2022 (USD thousand) (VI) *vrijednost peleta uvezenih 2022. (tisuće USD) (VI)*	Total monetary value of pellets that a country has brought in from other countries during 2022 *Ukupna novčana vrijednost peleta koje je neka zemlja uvezla iz drugih zemalja tijekom 2022.*
Trade balance in 2022 (USD thousand) (TB) *trgovinska bilanca u 2022. (tisuće USD) (TB)*	The trade balance is equal to the difference between the value of the exports and imports. (Negative Trade Balance values are important for supplying countries. According to CRITIC and ARAS methods we take the Trade Balance data in absolute value.) *Trgovinska bilanca jednaka je razlici između vrijednosti izvoza i vrijednosti uvoza. (Vrijednosti negativne trgovinske bilance važne su za zemlje izvoznice. Prema metodama CRITIC i ARAS, uzimamo podatke o trgovinskoj bilanci u apsolutnoj vrijednosti.)*
Unit value (USD/unit) (UV) *jedinična vrijednost (USD/jedinica) (UV)*	The unit value is the quotient of the value and the quantity. It shows the average value per unit of quantity of the commercial transactions. It is not in any case a selling price of the pellets. *Jedinična vrijednost je kvocijent vrijednosti i količine. Prikazuje prosječnu vrijednost po jedinici količine komercijalnih transakcija. To nikada nije prodajna cijena peleta.*
Annual growth in value between 2018-2022 (%) (AG) *godišnji rast vrijednosti između 2018. i 2022. (%) (AG)*	The computation formula of the growth rate over five years is the following: *Formula za izračun stope rasta tijekom pet godina glasi:* $$\left(\exp\left(\frac{\sum_{i=1}^{5} i\cdot \mathrm{Ln}(v_i) - 3\cdot\sum_{i=1}^{5}\mathrm{Ln}(v_i)}{10}\right)-1\right)\cdot 100$$ Where v_i is the value of the i-th year in current US dollar. *Pritom je v_i vrijednost i-te godine izražena američkim dolarima.*
CO_2 emission (tons) (CO_2) *emisija CO_2 (tona) (CO_2)*	The amount of carbon dioxide (CO_2) released into the atmosphere by a particular source or activity, measured in metric tons. *Količina ugljikova dioksida (CO_2) ispuštena u atmosferu iz određenog izvora ili od neke aktivnosti mjerena metričkim tonama.*
Logistic Performance Index (LPI) *indeks logističke učinkovitosti (LPI)*	A measure used to assess a country's logistics performance based on six key dimensions, including customs performance, infrastructure, and timeliness of shipments. *Mjera koja se upotrebljava za procjenu logističke učinkovitosti zemlje na temelju šest ključnih dimenzija, uključujući carinsku učinkovitost, infrastrukturu i pravodobnost pošiljaka.*
Concentration of supplying countries (COS) *koncentracija zemalja izvoznica (COS)*	The concentration is based on the Herfindahl index (H). It is calculated by squaring the share of each country in the selected market and by summing the resulting numbers. Koncentracija se temelji na Herfindahlovu indeksu (H). Izračunava se kvadriranjem udjela svake zemlje na odabranom tržištu i zbrajanjem dobivenih brojeva. $$\mathrm{H} = \sum_{i=1}^{N} s_i^2$$ Where s_i is the share of the country i in the market, and N is the number of countries. *Pritom je s_i udio zemlje i na tržištu, a N broj zemalja.*

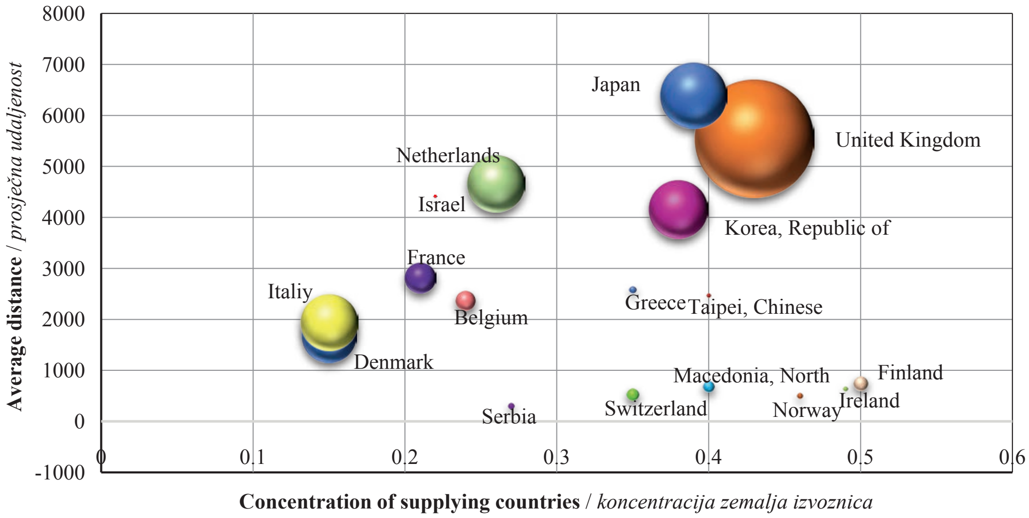

Figure 3 Importer countries
Slika 3. Zemlje uvoznice

centration of importing, the average distance from their supplying countries and their trade balance of more than one million USD Dollars in absolute value. The data was obtained from Trademap Database. The bubble map in Figure 3 shows the results of this evaluation, prompting us to determine 17 alternative countries for analysis. These countries were all included in the analysis stages for creating the multi-criteria decision-making model.

4.2 Analysis
4.2. Analiza

This stage consists of weighting the criteria and ranking the potential target markets for wood pellets. The steps of the CRITIC method are applied to weight the criteria objectively. Then the rankings of alternative countries are calculated by the ARAS method. To that end, the decision matrix of the problem is created as shown in Table 2.

Applying the Equations (1-4) to the CRITIC method, the weights of the criteria are calculated as in Table 3. In this context, the most important criterion is found as "concentration of supplying countries (COS)", whereas the least important criterion is found as "logistic performance index (LPI)".

In the subsequent phase of analysis, the ranking of countries is determined using Eqs. (5-12) based on the ARAS method. Table 4 shows the scores of the ARAS method. Considering the ranking column, the

Table 2 Decision matrix
Tablica 2. Matrica odlučivanja

Importers / *Uvoznici*	VI	TB	UV	AG	CO_2	LPI	COS
United Kingdom	1794802	1794207	217	9	364.995	3.987	0.43
Japan	562691	562547	204	54	1164.931	4.026	0.39
Denmark	525270	374074	222	0	32.078	3.992	0.15
Netherlands	499624	420581	186	91	160.938	4.019	0.26
Korea, Republic of	439379	439379	183	4	659.578	3.612	0.38
Italy	414321	410980	218	3	333.722	3.739	0.15
Belgium	159103	48568	168	-1	96.965	4.039	0.24
France	150615	120198	343	25	318.349	3.844	0.21
Finland	27297	25433	208	23	45.392	3.969	0.5
Switzerland	19176	19165	410	-3	38.950	3.901	0.35
Serbia	15482	5175	235	16	83.153	2.841	0.27
Macedonia, North	15367	15261	198	9	7.885	2.705	0.4
Norway	11222	3874	186	8	43.610	3.697	0.46
Ireland	8629	2867	349	16	37.338	3.510	0.49
Greece	7254	6136	303	-4	67.671	3.205	0.35
Taipei, Chinese	1938	1930	197	-6	286.023	3.600	0.4
Israel	1076	1076	211	34	68.269	3.308	0.22

Table 3 Weights of criteria
Tablica 3. Ponderi kriterija

VI	TB	UV	AG	CO_2	LPI	COS
0.143	0.128	0.152	0.131	0.158	0.124	0.164

Table 4 Scores of ARAS method
Tablica 4. Rezultati ARAS metode

Importers *Uvoznici*	Score (K_i) *Rezultati* (K_i)	Ranking *Rangiranje*	Importers *Uvoznici*	Score (K_i) *Rezultati* (K_i)	Ranking *Rangiranje*
United Kingdom	0.659	1	Israel	0.167	10
Japan	0.567	2	Taipei, Chinese	0.149	11
Netherlands	0.420	3	Switzerland	0.146	12
Korea, Republic of	0.341	4	Serbia	0.143	13
Italy	0.254	5	Norway	0.142	14
France	0.252	6	Belgium	0.131	15
Denmark	0.207	7	Macedonia, North	0.126	16
Finland	0.187	8	Greece	0.123	17
Ireland	0.184	9			

United Kingdom can be seen as the top priority market for wood pellets. Other prior target markets for wood pellets trading are Japan and the Netherlands.

In the concluding part of the application, we applied the scenario analysis to assess the impact of changes in criteria weights on the rankings and evaluate the reliability of the proposed methodology. Scenario analysis is utilized to evaluate the reliability of outcomes in the face of uncertainties arising from Multiple Criteria Decision Making (MCDM) problems, as indicated by Karande *et al*. (2016). In MCDM problems, decision makers often assign weights to criteria based on subjective evaluations, employing methods like AHP, ANP, and others. Consequently, conducting sensitivity analysis becomes crucial in the decision-making process to ensure accurate interpretation of the collected data.

In all scenarios, the United Kingdom, Japan, and the Netherlands consistently emerge as the foremost priority markets for wood pellets, in six out of the seven scenarios. Furthermore, Figure 4 presents a visual representation of the data.

5 CONCLUSION AND POLICY IMPLICATIONS
5. ZAKLJUČAK I UTJECAJ NA POLITIKU

Wood pellets have gained considerable attention among renewable energy sources due to their several advantages in mitigating global warming and promoting energy security. Thus, the wood pellet industry and its trading potential are growing globally. Therefore, focusing on growing markets for wood pellets has become a crucial strategic discussion for producing countries to maintain their competitive edge in renewable energy markets. In this study, we proposed a MCDM model for executives in producing countries to forecast the growing wood pellets markets in international markets. We selected seven criteria that are commonly used in international trade decisions, such as imported value, trade balance, unit value, annual growth in value, CO_2 emission, logistic performance index, and the concentration of supplying countries, and applied the CRITIC method to weigh these criteria. Then, we chose 17 alternative target countries, which are among

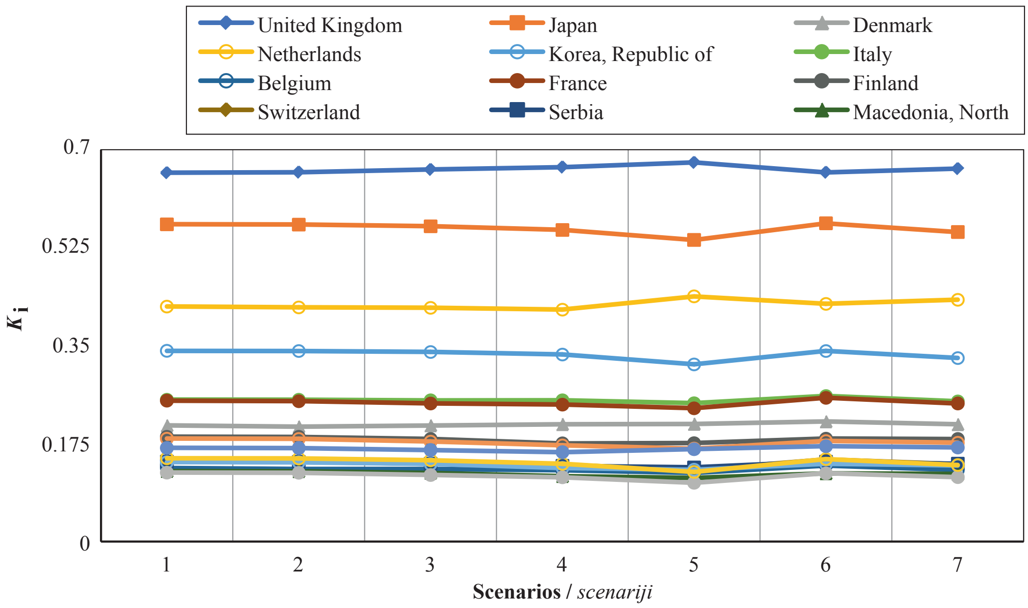

Figure 4 Scenario analysis
Slika 4. Analiza scenarijâ

Table 5 Scenario analysis
Tablica 5. Analiza scenarija

Scenarios *Scenariji*	**1**		**2**		**3**		**4**		**5**		**6**		**7**	
Weights *Ponderi*	w_1	0.143	w_1	0.128	w_1	0.152	w_1	0.164	w_1	0.143	w_1	0.143	w_1	0.143
	w_2	0.128	w_2	0.143	w_2	0.128	w_2	0.128	w_2	0.164	w_2	0.128	w_2	0.143
	w_3	0.152	w_3	0.152	w_3	0.143	w_3	0.152	w_3	0.128	w_3	0.152	w_3	0.143
	w_4	0.131	w_4	0.131	w_4	0.131	w_4	0.131	w_4	0.152	w_4	0.131	w_4	0.143
	w_5	0.158	w5	0.158	w_5	0.158	w_5	0.158	w_5	0.131	w_5	0.158	w_5	0.143
	w_6	0.124	w_6	0.124	w_6	0.124	w_6	0.124	w_6	0.158	w_6	0.164	w_6	0.143
	w_7	0.164	w_7	0.164	w_7	0.164	w_7	0.143	w_7	0.124	w_7	0.124	w_7	0.143
	K_i	**ranking**	**K_i**	**ranking**	**K_i**	**ranking**	**K_i**	**ranking**	**K_i**	**ranking**	**K_i**	**ranking**	**K_i**	**ranking**
United Kingdom	0.659	1	0.660	1	0.665	1	0.669	1	0.677	1	0.660	1	0.666	1
Japan	0.567	2	0.566	2	0.563	2	0.557	2	0.539	2	0.569	2	0.553	2
Netherlands	0.420	3	0.418	3	0.418	3	0.414	3	0.438	3	0.425	3	0.432	3
Republic of Korea	0.341	4	0.340	4	0.339	4	0.334	4	0.317	4	0.341	4	0.328	4
Italy	0.254	5	0.254	5	0.252	5	0.252	5	0.247	5	0.260	5	0.251	5
France	0.252	6	0.251	6	0.247	6	0.245	6	0.238	6	0.257	6	0.247	6
Denmark	0.207	7	0.205	7	0.207	7	0.210	7	0.210	7	0.215	7	0.209	7
Finland	0.187	8	0.187	8	0.183	8	0.175	8	0.176	8	0.184	8	0.183	8
Ireland	0.184	9	0.184	9	0.179	9	0.172	9	0.166	9	0.180	9	0.177	9
Israel	0.167	10	0.167	10	0.163	10	0.160	10	0.165	10	0.170	10	0.168	10
Serbia	0.143	13	0.142	13	0.139	13	0.135	13	0.133	11	0.143	13	0.139	11
Switzerland	0.146	12	0.146	12	0.141	12	0.137	12	0.128	13	0.147	12	0.138	12
Taipei, Chinese	0.149	11	0.148	11	0.145	11	0.139	11	0.124	14	0.147	11	0.137	13
Norway	0.142	14	0.142	14	0.139	14	0.131	14	0.128	12	0.139	14	0.136	14
Belgium	0.131	15	0.130	15	0.130	15	0.127	15	0.123	15	0.136	15	0.128	15
North Macedonia	0.126	16	0.126	16	0.123	16	0.117	16	0.114	16	0.122	17	0.121	16
Greece	0.123	17	0.123	17	0.119	17	0.115	17	0.105	17	0.122	16	0.115	17

the growing importing countries and have a trade balance of one million USD dollars in absolute value. The ARAS method was applied to evaluate and rank the top-priority markets for wood pellet trading countries. In conclusion, a scenario analysis was carried out, encompassing seven distinct scenarios, with the aim of evaluating the influence of variations in criteria weights on rankings and assessing the dependability of the proposed methodology. Therefore, we have successfully analyzed the expanding wood pellet markets in response to the demand for renewable energy, providing executives with scientifically informed trading decisions. This paper makes a significant contribution to literature as it is the first study to combine the CRITIC and ARAS methods. According to the available literature, there is a dearth of research examining the assessment of target markets for wood pellets utilizing the MCDM approach. Furthermore, this paper presents a practical method for evaluating target markets and demonstrates its application. However, this study has certain limitations pertaining to the scope of the research and the methods used. The examination is limited to 17 countries, and there are limitations in terms of the number of alternatives and the availability of data. Besides, the number of selected criteria is also limited due to the unavailability of data for some criteria. Future studies are encouraged to investigate the incorporation of supplementary criteria that could potentially impact performance in practical settings.

According to the results, the export executives of countries who want to make informed trading decisions should focus on the United Kingdom, Japan, and the Netherlands under the criteria of concentration of supplying countries. The criterion of logistics performance index does not demonstrate significance in relation to wood pellets trading. However, due to the environmental interest of wood pellets and their commitment to energy and CO_2 emission saving, the way of transportation of wood pellets should be especially considered by the trading countries. There are some significant but very limited studies in the literature discussing the management of logistics and ways of transportation of wood pellets (European Biomass Industry Association [EUBIA], 2009; Fritsche *et al.*, 2019) and considering the CO_2 emission of wood pellets in different transportation types. Researchers are advised to prioritize this significant issue in their future investigations, as it will assist executives in making informed transportation decisions amid the challenges posed by global climate change.

On the other hand, all analyses were conducted using data from the past five years, which indicated that Europe is currently the largest market for wood pellet trading. This finding is supported by company-based sectoral reports, which also suggest that Europe will continue to be the largest wood pellet market in the next five years. However, according to the sectoral reports, the Asia-Pacific region is expected to be the fastest-growing market during the forecast period (ReportLinker, 2023; Mondor Intelligence, 2023; Research and Markets, 2023; Fortune Business Insight, 2023). Therefore, in the coming years, future research can reapply a similar methodology using the Asia-Pacific countries as potential alternatives to explore the new target markets for wood pellets.

We believe that this research will not only make a significant contribution to the academic literature but also advance the knowledge of foreign trade executives in exporting countries regarding the growing market for wood pellets, ultimately supporting their capacity building. Additionally, our findings can offer new insights and understanding for enterprises, particularly in sustainably managing the energy industry with a focus on renewable energy sources.

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Image Processing Based Scrub Tester Design and Production

Dizajn i izrada uređaja za ispitivanje otpornosti površine na struganje na temelju obrade slike

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ABSTRACT • *Determining how resistant paint, varnish or coating type materials, applied to wood-based panel surfaces, are to the effects of exposure to household chemicals is important in terms of developing products and providing durable surface coating to users. Every paint or coating type product coming off the production line needs to be tested quickly, and a new direction should be given to the work based on the positive or negative results obtained. Products without quality monitoring are returned by customers due to insufficient performance, resulting in loss of time, labor and materials. In this study, an Image Processing Based Scrub Tester (IPBST) was designed and produced in order to imitate the effect of paint, varnish and coating materials on the surfaces of furniture and decoration elements used in daily life against household chemicals. Unlike its counterparts, with IPBST, the image of each sample is digitally recorded before and after the scrubbing process, thanks to the "compact photo booth" integrated into the device. Wear, color and brightness change analyses of sample images can be performed with the "Surface Flaw Analysis (SFA)" method developed using the Matlab Graphical User Interface (GUI) image processing program on a computer integrated into the device. In this way, a 4-in-1 device that can do the job of 4 devices has been provided to the relevant scientific community and industry without the need for different types of industrial test devices.*

KEYWORDS: *scrub tester; image processing technique; household chemicals; wear; color and brightness test*

SAŽETAK • *Utvrđivanje otpornosti premaza na drvnim pločama na kemikalije u kućanstvu važno je za razvoj proizvoda i osiguranje trajnosti površinskog premaza tijekom uporabnog vijeka tih drvnih proizvoda. Svaki površinski obrađen proizvod koji izlazi s proizvodne trake potrebno je brzo ispitati kako bi se proizvodnja nesmetano nastavila na temelju dobivenih pozitivnih ili negativnih rezultata. Kupci vraćaju proizvode zbog neodgovarajućih svojstava, što je posljedica nedostatka kontrole kvalitete te rezultira gubitkom vremena, rada i materijala. U ovoj je studiji dizajniran i izrađen uređaj za ispitivanje otpornosti površina na struganje zasnovan na obradi slike (IPBST) kako bi se oponašao utjecaj kemikalija u kućanstvu na lakirane površine namještaja i dekorativnih elemenata. Za razliku od drugih metoda, s IPBST-om se slika svakog uzorka digitalno snima prije i nakon procesa struganja zahvaljujući kompaktnoj fotokabini integriranoj u uređaj. Razina istrošenosti, promjena boje i svjetline uzoraka na slikama mogu se provesti metodom analize površinskih grešaka (SFA) koja je razvijena primjenom programa za obradu slike Matlab Graphical User Interface (GUI) na računalu integriranom s uređajem. Time je zainteresi-*

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ranoj znanstvenoj zajednici i industriji predstavljen uređaj koji istodobno može obavljati posao četiriju uređaja, bez potrebe za različitim vrstama industrijskih ispitnih uređaja.

KLJUČNE RIJEČI: *uređaj za ispitivanje otpornosti površine na struganje; tehnika obrade slike; kemikalije u kućanstvu; istrošenost; ispitivanje boje i svjetline*

1 INTRODUCTION
1. UVOD

To utilize wood-based panels for furniture manufacturing and interior reinforcement, it is imperative to apply coatings or paint to both the surfaces and edges of the panels.

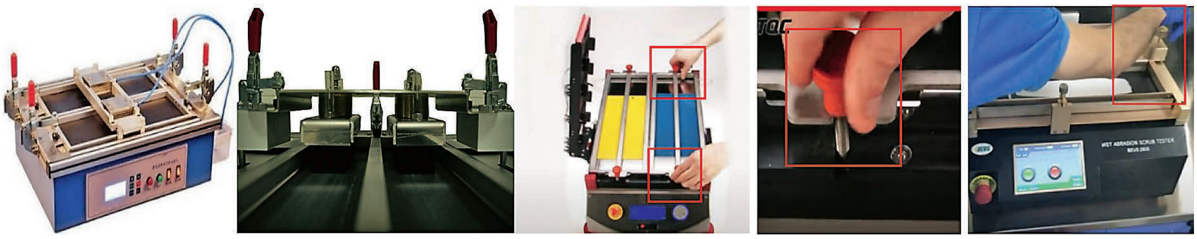
The materials applied to the panel surfaces serve various purposes, including enhancing the mechanical and physical properties of the panels, boosting the product's aesthetic value, providing a natural wood-like appearance and warmth, and ensuring consistency in color and pattern across the panel surfaces (Budakçı, 2010).

These applications, which aim to increase and protect the aesthetic value of wooden panels, deform and degrade over time depending on the performance of the materials used. In addition, the strength, interaction and quality of these materials, to which various coating, dyeing and printing techniques are applied, are effective in the rapid or slow development of the degradation process. In this context, a range of tests (brightness, hardness, roughness, color, adhesion, etc.) are conducted to evaluate the effectiveness of the protective coatings applied to the upper surfaces of wood materials or wood-based panels. Moreover, these materials undergo artificial or natural aging processes, including exposure to outdoor conditions, effects of rain or snow water, UV radiation from sunlight, accelerated salt corrosion, aging, temperature variations, household chemicals and abrasion. Consequently, various distortions can occur in the protective layers (Bayraktar and Kesik, 2022; Büşra *et al*., 2022; Özdemir *et al.,* 2018).

Nowadays, there is a wide variety of methods or devices available for testing resistance to household chemicals. In the paint / coating industry, wet scrubbing test devices are used to determine in advance the performance of a newly produced product in its environment. These devices are used to test the wear resistance of paints, varnishes and other coatings under wet conditions. Painted/coated samples are scrubbed with an abrasive pad specified in the standards, usually with a solution containing water or detergent. The weight pressure on the sample panel, scrubbing time and speed can be adjusted according to the standard principles of the selected test. After performing the accelerated aging process with scrubbing test devices, changes such as scratch depth, wear amount, color and brightness loss on the sample surfaces are measured. These measurements must be made using stereo microscope, SEM, color, brightness and roughness devices.

In prior research, Redsve *et al.* (2003) conducted cleanability tests on ceramic tiles using an Erichsen scrubbing device with a microfiber mop and two different chemical agents. Kok and Young (2014) employed a wet scrubbing test to assess the cleanability of insect residue on aircraft wing coatings, utilizing a Zeiss LSM 710 confocal laser scanning microscope and weight measurements of experimental samples. Marco *et al.* (2015) adhered to ISO 11998 standards, conducting 500 cycles of scrubbing on glass panels with chemical liquid and 3M dish washing sponges, analyzing surface changes with scanning electron microscopy (SEM). Santos *et al.* (2019) used a Leneta wet scrubbing test device to evaluate water-based paint dirt retention, employing a BYK color measuring device for assessing color differences. Helwani *et al.* (2021) employed "the BGD 526 wet scrubbing tester" to examine the brightness and washability of PVAc paint, measuring brightness according to Indonesian standard SNI 3564:2009. In the studies conducted, it was seen as a major problem that the scrubbing test devices used today cannot test the changes in the samples after the scrubbing process, cannot show any reference point and cannot produce a report and output.

In this study, "Image Processing Based Scrub Tester (IPBST)" was designed and produced in order to imitate the effect of painted or coated panels against household chemicals and to see the damage in a short time. The development of this tester received funding from the Scientific and Technological Research Council of Turkey (TUBITAK) under project number 221O551. Unlike its counterparts, digital images of each sample are recorded with the "compact photo booth" integrated into the device before and after the scrubbing process. A method named "Surface Flaw Analysis (SFA)" was developed using the Matlab GUI image processing program on a computer integrated into the device. With this method, wear, color and brightness change analyses of sample images were made possible. Thus, after the scrubbing process is applied to the sample surfaces, the amount of brightness, color and wear on the sample surfaces are determined without the need for a different testing device, and an output/report with numerical data is obtained. In this way, an innovative and original contribution to the industry has been made by reducing labor, reducing research costs and saving time.



a) b) c) d) e)

Figure 1 Working position of scrubbing head on sample surface (a, b), fixing of samples (c, d, e) (Alibaba, 2023; Mikroskopik, 2023)
Slika 1. Radni položaj glave za struganje na površini uzorka (a, b), fiksiranje uzoraka (c, d, e) (Alibaba, 2023.; Mikroskopik, 2023.)

2 CURRENT TECHNOLOGIES USED IN SCRUBBING PROCESSES
2. DANAŠNJE TEHNOLOGIJE ZA TESTIRANJE OTPORNOSTI POVRŠINE NA STRUGANJE

Wet scrubbing tester is a device used to determine the wear/aging resistance of the material surface (Figure 1a). It is a type of aging test method generally used to determine the wear/aging resistance of paint, varnish or similar coatings. A scrubbing head with an abrasion pad/brush under a certain weight pressure is moved on the coated sample surfaces prepared for testing. During this movement, a liquid is added between the sample and the etching pad. Then, the wear/aging resistance of the sample is monitored over a specific cycle and time interval according to the standards used in the study (Parvate and Mahanwar, 2019; Uytterhoeven *et al., 2002)*.

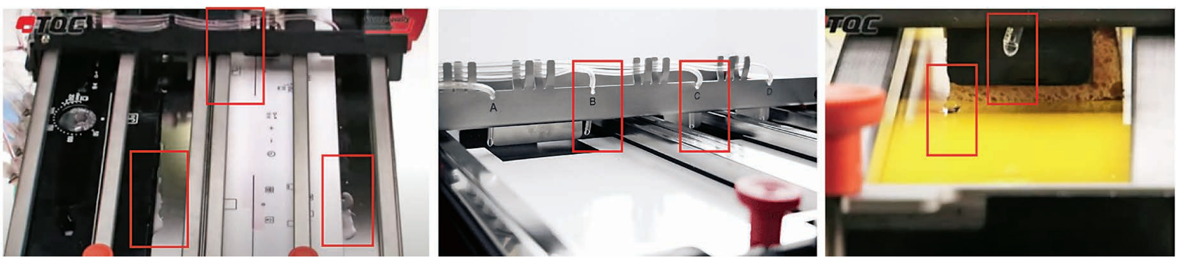
Scrub testers are used in industry to determine the quality of coating materials, evaluate the effectiveness of surface treatments, and measure the wear/aging performance of materials. It is an important test method used especially in areas such as the automotive industry, furniture industry, paint and coating industry (Smith *et al.,* 2017).

In order to carry out the resistance tests of painted/coated sample surfaces against household chemicals in the test devices as shown in Figure 1a-e, various abrasive equipment such as brush, felt, sponge pad, and sandpaper are used, and applications are carried out wet or dry. However, after the wet/dry scrubbing processes applied in these devices, it was observed that the entire sample surface area could not be aged by scrubbing. This is due to the fact that the samples placed in the device are compressed with a pressure arm coming from above to prevent them from moving during scrubbing (Figure 1c, d and e). In addition, this mechanical pressure on the sample surface causes deformations in the paint/varnish/coating film layer. This causes the chemicals used in the experiments to deform the material surfaces differently, resulting in misleading results.

In the existing scrubbing devices, it has been observed that during the back-and-forth movement of the scrubbing head during the wet scrubbing process, the chemical that should drip onto the surface often does not drip onto the sample. It was observed that the drops falling on the painted sample bounced with the force of the impact and dispersed on the device (Figure 2a, b and c). It is thought that this situation is caused by the incorrect design of the liquid flow/drip system (Figure 2a).

Another negative situation is that the platforms on which the samples seen in Figure 1.a, b and d and Figure 2a are placed cannot be adjusted parametrically. Due to this situation, researchers are forced to prepare samples according to the device.

The most important deficiency in scrubbing test devices is that these test devices only perform abrasion by wet/dry scrubbing and cannot produce a quantitative result report/output for the test samples as a result of this process. When the working principles of scrub testers are examined, it is observed that they cannot go beyond automation according to the principles of Industry 4.0 (Jeon *et al.,* 2020; Lin *et al.,* 2019).



a) b) c)

Figure 2 Liquid dropping on sample surfaces (a, b, c) (Karkimya, 2023; Satatonmall, 2023)
Slika 2. Kapanje tekućine na površinu uzoraka (a, b, c) (Karkimya, 2023.; Satatonmall, 2023.)

3 IMAGE PROCESSING BASED SCRUB TESTER (IPBST)
3. UREĐAJ ZA ISPITIVANJE OTPORNOSTI POVRŠINE NA STRUGANJE NA TEMELJU OBRADE SLIKE

In this study, IPBST was produced and designed in order to imitate the effect of materials such as coating, paint and varnish on the surfaces of furniture and decoration elements used in homes in daily life against household chemicals (Figure 3a and Figure 3b).

AutoCAD and Solidworks 3D modeling programs were used to model, project and simulate the device. Thanks to simulations made with design programs, issues that may pose problems during production and possible situations that may be encountered in the innovative aspect of the device were recognized at the design stage, and technical solutions were developed accordingly. Considering the commercial potential of the tester, its name was determined as "Image Processing Based Scrub Tester" and the abbreviation term was determined as "IPBST".

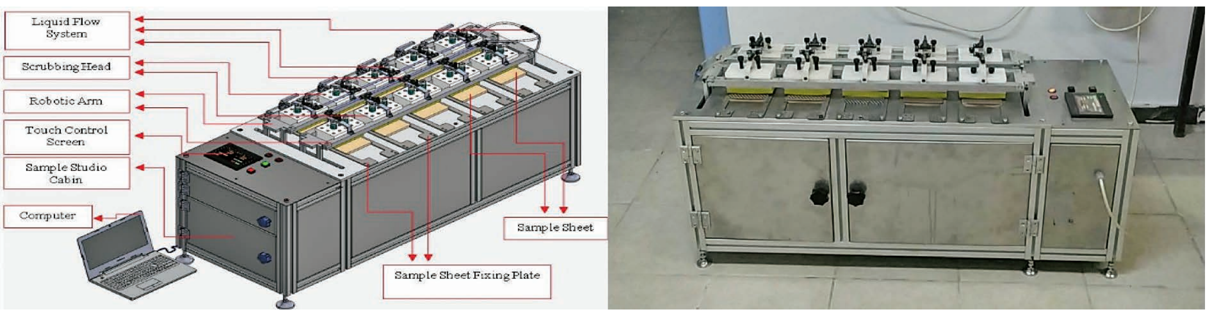
The parameters required for the tester to operate while scrubbing the sample surfaces are: Parameters that can be adjusted such as movement speed, time, revolutions, liquid flow rate. By changing the parameters in the IPBST device such as weight, scrubbing speed, number of scrubbing cycles, it is adjusted according to American Society for Testing and Materials Standard (ASTM) D2486, ASTM D3450, ASTM D4213, ASTMD 4828, German Standardization (DIN) EN 11330 and Turkish Standard (TS EN) ISO 11998 wet scrubbing standards and tests are carried out accordingly (Francone *et al.,* 2021; Uytterhoeven *et al.,* 2002).

Scrub test devices currently used in scrubbing processes cannot measure and provide numerical data on changes such as color, brightness, roughness and scratching that occur on the sample surface after physically aging the painted, varnished, coated sample surfaces with chemical liquid and abrasive pad. Experts in quality control laboratories in the industry and/or researchers in the scientific community complete the scrubbing process of the samples. Then, it is seen that researchers have to make measurements and produce data using devices such as color, brightness, roughness, stereo microscope and SEM in order to detect the changes occurring on the surface of these samples (Helwani *et al.,* 2021; Kok and Young, 2014; Marco *et al.,* 2015; Redsve *et al.,* 2003; Santos *et al.,* 2019).

IPBST was developed with the aim of performing the scrubbing process on sample panel surfaces (accelerated aging) and obtaining numerical results of the wear, color and brightness changes that occur on the material surfaces due to the scrubbing process. In this way, a new and unique tester is planned to be introduced to industry. Although IPBST is basically designed for scrubbing and aging painted and coated wooden surfaces, it also has an infrastructure that can be used for scrubbing materials such as plastic, glass and metal. Thus, the device is expected to have a very wide use in industry.

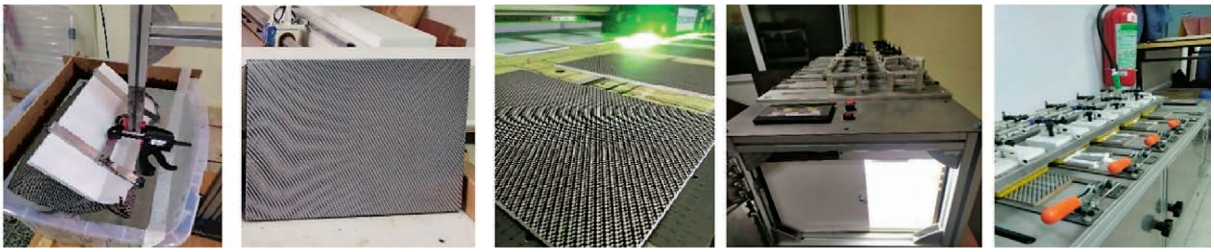
3.1 Test device working principle
3.1. Načelo rada ispitnog uređaja

The working principle of IPBST is based on TS EN ISO 11998 (2006) standard. In accordance with the standard, a scrubbing unit weighing (135±1) g in total, including a 70 g scrubbing head, a 10 g abrasive sponge pad and a 55 g weight apparatus, is contacted to the painted / varnished / coated sample surfaces. During the scrubbing process, approximately 5 ml of liquid is transferred to the surface of the painted samples by using household chemicals specified in the ASTM D1308-20 (2020) standard. The scrubbing heads execute a smooth linear motion, moving back and forth on the +Y and –Y axis at a rate of (37±2) cycles per minute, totaling 200 cycles. It has been reported in the literature that surfaces scrubbed with these parameters are very effective on wear, scratching, color, brightness and roughness values (Mermer *et al.,* 2023; Popa *et al*., 2021; Zettl, 2014). In addition, it is seen that researchers use many different brands of devices in wet scrubbing tests and perform different scrubbing processes according to many



a) b)

Figure 3 Image processing based scrubbing tester (IPBST) design (a), IPBST (b)
Slika 3. Dizajn uređaja za ispitivanje otpornosti površine na struganje na temelju obrade slike (a), IPBST (b)



a) b) c) d) e)

Figure 4 Example of WTP (a, b), example of UV printing process (c), scrubbing process application (d), IPBST compact photo booth (e)
Slika 4. Primjer vodenoga prijenosnog tiska (a, b), primjer procesa UV ispisa (c), primjena procesa struganja (d), IPBST kompaktna fotokabina (e)

standards depending on the purpose of the subject. Depending on the standards they use, it appears that they vary the scouring pad/brush, weight masses, scouring speed and duration (Cayton and Sawitowski, 2005; Shi *et al.,* 2013; Wen *et al.,* 2022).

With the IPBST, digital images are captured before and after the scrubbing process within the integrated compact photo booth to evaluate the effectiveness of protective layers on sample surfaces. After the scrubbing process, wear, color and brightness change analyses of the sample images are performed with a method called "SFA" using the Matlab GUI image processing program on the computer integrated into the device. No wet scrub tester used in the industry has such a capability. Thanks to IPBST, whose design and production has been completed, numerical data is produced based on image processing to measure the amount of wear, color and brightness of paint/coating types without using a different test device. In this way, reducing tiring manpower and saving time and equipment will provide an innovative and original contribution to the sector. The different aspects of the device produced within the scope of the research from its counterparts in the industry are presented under headings in the following sections of the study.

4 MATERIALS AND METHODS
4. MATERIJALI I METODE

4.1 Preparation of samples and scrubbing process
4.1. Priprema uzoraka i proces struganja

In order to evaluate the performance of IPBST after its production, sample parts were prepared, and preliminary studies were carried out on these samples. Various types of Medium-Density Fiberboard (MDF) panels commonly used in the furniture industry, including first-class 8 mm thick bright white PVC coated MDF, high gloss acrylic coated MDF, MDF ready-to-use laminate panels, and raw MDF panels, were used. These samples, measuring 520 mm × 310 mm, were conditioned in an air-conditioned cabinet until reaching a constant weight and reducing their moisture content to 9 to 10 %, in accordance with the Turkish Standard (TS) EN 322 (1999). A protective layer, consisting of glossy white polyurethane, acrylic, cellulosic, and water-based lacquer paint, was applied to all raw MDF panels following the ASTM D3023-98 (2017). Subsequently, these lacquered samples were acclimatized to 9 to 10 % moisture content first at room conditions and then in the air-conditioned cabinet.

Carbon fiber patterned decorative coating was applied to the sample surfaces using both water transfer printing (WTP) and ultraviolet (UV) printing methods, as depicted in Figures 4a, b, and c. These methods were cited in the references (Kaçamer, 2024; Kaçamer *et al.,* 2024; Kaçamer and Budakçı, 2023). A total of 980 samples were prepared for the experimental groups, comprising two different decorative coating types, seven different panel types, and seven different household chemical types.

Before starting the scrubbing process, digital images of the sample panels were captured using the compact photo booth integrated into the device (Figure 4d). Subsequently, these samples underwent exposure to various household chemicals using the IPBST. The scrubbing operation involved a (135±1) g scrubbing head unit in accordance with TS EN ISO 11998 (2006) standards. A 3M dish washing sponge served as the scrubbing pad. Scrubbing was carried out by the scrubbing heads executing 200 smooth linear movements, oscillating between the +Y and – Y axis, at a frequency of (37±2) cycles per minute. Household chemicals including cola, lemon juice, dishwashing liquid, bleach, acetone, and ethyl alcohol were used for scrubbing in accordance with ASTM D1308-20 (2020) standards. Each sample surface received 5 mL of these chemicals (Figure 4e).

Considering the preparatory work, the differences in the types of household chemicals used in the scrubbing process were reflected in the data obtained in the measurements. The effect of each household chemical on accelerated aging has been found to be different.

4.2 Tests
4.2. Testovi

A method named "SFA" was developed using the image processing technique and the Matlab GUI image processing program, and the wear, color and brightness changes of the recorded sample images were analyzed. In addition, Zeiss Axio Scope A1 brand stereo microscope and BYK Gardner Spektro-Guide 45/0 device (Spectro-guide sphere gloss meter, model CD-6834. BYK-Gardner GmbH, Geretsried, Germany), which are industrial testing devices, were used to test the accuracy of the SFA method. With these devices, wear (ASTM E112-13, 2013), color (ASTM D2244-21, 2022) and brightness (TS EN ISO 2813, 2014) measurements were made (Figure 5). For the wear test, coating film thicknesses were measured in micron (µm) units and then wear rates were calculated by calculating the wear rates as percentages (%). For the color test, the result was obtained by calculating the total color change (Δ*E**). For the brightness test, the percentage (%) of the numerical data taken before and after the scrubbing process on the surfaces of the sample boards was calculated.

5 RESULTS AND DISCUSSION
5. REZULTATI I RASPRAVA

The data collected in this study were analyzed using the SPSS 24 statistical package program (IBM, 2021). Pearson Correlation analysis was carried out to determine the relationship between the data of wear, color and brightness tests performed with IPBST and hand data from industrial testing devices. The findings obtained are given in Table 1.

According to the results of Table 1, a robust and statistically significant positive relationship ($P<0.01$) was determined between two different wear measurement methods, statistically 0.81, and between two different color measurement methods, statistically 0.97.

Furthermore, a strong and statistically significant positive correlation of 0.71 ($P<0.01$) was observed between the two distinct brightness measurement techniques. These correlation findings are illustrated in Figures 6a, b and c.

The result of the correlation graph given in Figure 6.a.b.c proves that the wear, color and brightness measurement method with IPBST can be used without the need for other industrial type devices.

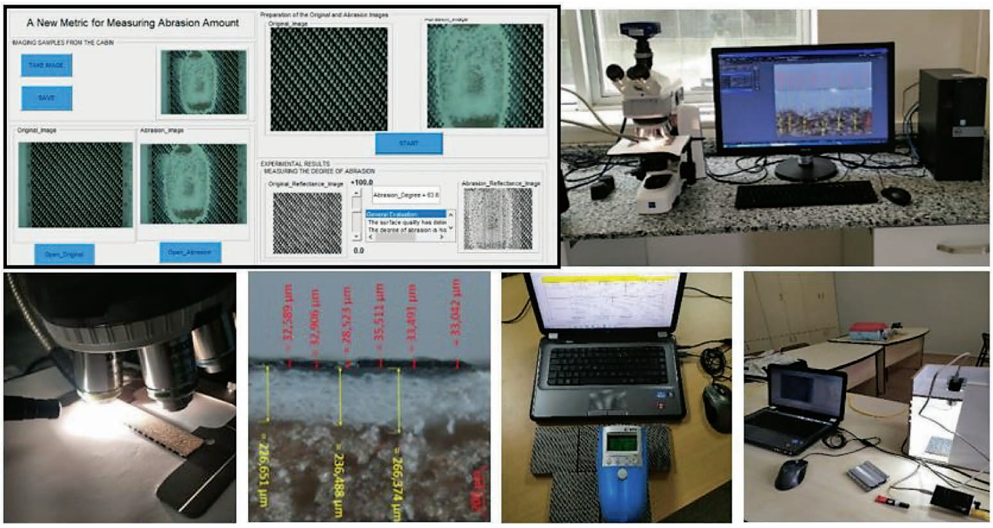
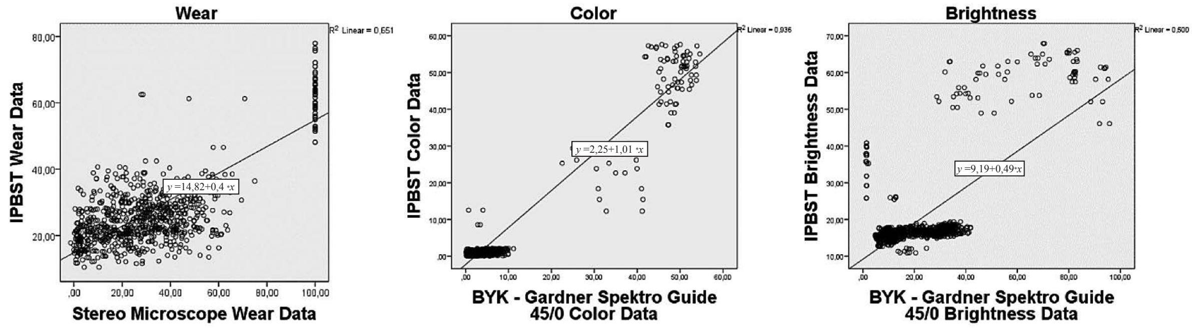


Figure 5 Wear, color and brightness tests before and after scrubbing
Slika 5. Testovi istrošenosti, boje i svjetline prije i nakon struganja

Table 1 Relationship between IPBST measurement method and measurements of industrial test devices
Tablica 1. Odnos između IPBST metode mjerenja i mjerenja industrijskim ispitnim uređajima

Measurement methods *Metode mjerenja*	**Correlation coefficient (*r*)** *Koeficijent korelacije (r)*	***P* Value** *P-vrijednost*	**Sample measurement amount (*n*)** *Broj izmjerenih uzoraka (n)*
Wear / *istrošenost* (IPBST – Stereo Microscope)	0.81	0.000*	1680
Color / *boja* (IPBST – BYK Gardner Spectro-Guide 45/0)	0.97	0.000*	1680
Brightness / *svjetlina* (IPBST – BYK Gardner Spectro-Guide 45/0)	0.71	0.000*	1680

*Significant at $P < 0.01$ / *značajno pri P < 0,01*



a) b) c)

Figure 6 IPBST and stereo microscope wear data (a), IPBST and BYK gardner spectro-guide 45/0 color data (b), correlation relationship between IPBST and BYK gardner spectro-guide 45/0 brightness data (c)
Slika 6. Korelacija podataka o istrošenosti dobivenih IPBST uređajem i podataka sa stereomikroskopa (a), korelacija podataka o boji dobivenih IPBST uređajem i uređajem *BYK gardner spectro-guide* 45/0 (b), korelacija podataka o svjetlini dobivenih uređajem IPBST i uređajem *BYK gardner spectro-guide* 45/0 (c)

6 CONCLUSIONS
6. ZAKLJUČAK

As a result of the research, the wear, color and brightness changes on the material surfaces rubbed using various household chemicals with IPBST, designed and produced within the scope of the project, were compared with different industrial test devices, and similar and positive results were identified.

İt was determined that acetone was the chemical that caused the highest abrasion of the coated sample surfaces and color changes. It was also determined that dishwashing detergent caused the greatest decrease in gloss on coated surfaces. Furthermore, it was determined that lemon juice was the chemical that caused the least damage when cleaning the surface of coated panels. In addition, after scrubbing the coated sample panel surfaces with household chemicals, the UV printed samples showed better performance in wear, color and brightness tests than the WTP applied samples.

Thanks to IPBST, an accelerated aging (scrubbing process) was performed on the material surfaces. Thanks to the IPBST and SFA method developed with the original study, the data obtained as a result of the wear, brightness and color tests were analyzed quickly. In this way, a 4-in-1 device that can do the work of 4 devices, without the need for different types of industrial test devices, was presented to the relevant scientific community and industry. The ability of IPBST to perform the scrubbing process, as well as wear, brightness and color analyses is a gain for the world of science.

SFA, an advanced image processing-based technique, has significantly advanced the ability to measure wear, color, and brightness changes in the paint and coating industry. By offering a faster and more efficient method, SFA eliminates the need for costly instrumentation traditionally required for such assessments. This method is particularly well-suited for applications in woodworking, paint, varnish, and coating industries, as well as furniture manufacturing. Its adoption is expected to facilitate new research and development initiatives, thereby contributing to innovation in these fields.

Due to the effectiveness and innovative nature of IPBST, industrial organizations and researchers involved in mass production within the paint and coating sector have achieved significant time savings and simplified processes. This advancement has enabled researchers to conduct studies on wear, color, and brightness measurement without relying on expensive equipment, leading to substantial cost reductions.

Thanks to remote sensing of PBST, it can be emphasized that it is a candidate to be a new and widely used wear, color and brightness measurement system that can provide increasing occupational safety and ease of use.

The scrubbing head weights, scrubbing pad, number of scrubbing cycles and speed of IPBST produced are designed to be changeable according to different materials and different standards. In this way, wet or dry scrubbing can be done, and new research opportunities can be provided for different studies. The hardware can be enriched by preparing a precision scale or a mechanism for micron measurement on the main body of IPBST for wear control.

Additionally, experiments can be carried out on different material surfaces (plastic, wood, metal fabric, etc.) using different types of chemicals with IPBST. In the scrubbing process, instead of a sponge, a brush, sandpaper or steel wool can be preferred. Experiments can be carried out using bacteria, virus and germ inhibiting chemicals, especially in health, food and laboratory areas where hygiene conditions are important. It may be recommended to develop and research method with different algorithms in programs such as MATLAB, OpenCV, Python to perform tests such as surface roughness, hardness and scratching with SFA.

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Design Opportunities for Added Value By-Products in Woodworking Industry

Mogućnosti dizajna nusproizvoda s dodanom vrijednošću u drvoprerađivačkoj industriji

REVIEW PAPER
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ABSTRACT • *The present work describes several possible options for using waste wood from the woodworking industry as a raw material for manufacturing design products with high value-added. In the production of plywood, as well as engineered wood products (EWP), low final yields are obtained. A large portion of wood waste consists of peeler cores, veneer pieces, large and small pieces with defects, cut pieces, shavings, etc. This study offers the author's approach to the use of this raw material, as the planning, design and fabrication were carried out in laboratory conditions. The resulting products have the necessary physical and mechanical properties that satisfy the needs of both the furniture and construction industries. The information presented could be a foundation for introducing and implementing the products described in the industry.*

KEYWORDS: *cut pieces; peeler cores; construction materials; EWP*

SAŽETAK • *U radu se opisuje nekoliko mogućnosti iskorištavanja otpadnog drva iz drvoprerađivačke industrije kao sirovine za izradu dizajnerskih proizvoda visoke dodane vrijednosti. U proizvodnji furnirskih ploča i kompozitnog drva (EWP) ostvaruju se niski profiti. Velik dio drvnog otpada čine drveni valjci preostali od ljuštenja trupaca, komadi furnira, krupni i sitni komadi drva s greškama, odresci, strugotine i dr. Ovo istraživanje nudi autorski pristup iskorištavanju te sirovine jer su planiranje, projektiranje i izrada obavljeni u laboratorijskim uvjetima. Dobiveni proizvodi imaju fizička i mehanička svojstva koja su zadovoljavajuća i za industriju namještaja i za građevnu industriju. Na temelju prezentiranih informacija, proizvodnja opisanih proizvoda moći će se implementirati u industriju.*

KLJUČNE RIJEČI: *odresci; drveni valjak preostao od ljuštenja trupca; konstrukcijski materijali; EWP*

1 INTRODUCTION
1. UVOD

Wood is a widely accessible building material, used from the earliest years of human existence. At the same time, there is a global trend of continuously increasing consumption of this natural material. This leads to a decrease in wood resources, and from an unlimited resource it becomes more and more limited due to the reduction of forested areas. The qualities of wood are well known. It is probably the only building material that can be renewed naturally within a human

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generation. The need for various types of wood and derivatives of their products will continue to increase due to the heightened demand from the market. As environmentally friendly materials with the necessary physical and mechanical properties, they are finding increasing application not only in the construction and furniture industries, but also in transport.

In order to overcome the shortage of wood raw material worldwide, measures are being taken in several main directions – search for new raw material sources, reducing wood waste during processing, more complete application of the waste in other efficient productions, and closing the wood use cycle with zero waste.

2 GLOBAL WOOD CONSUMPTION
2. SVJETSKA POTROŠNJA DRVA

An interesting fact is the predictions of the Global Forest Products Model (GFPM) for wood consumption by 2050. During this period, consumption is expected to reach 3.124 billion m^3 of wood raw material, an increase of about 37 % compared to the wood consumption recorded in 2020 (2.286 billion m^3). The use of round assortments for the production of solid wood materials is expected to increase by about 0.5-0.9 billion m^3 by 2050 (FAO, 2022). According to forecasts made by FAO (2022), the production of wood composite panels is expected to experience the largest growth by 2050, nearly +102 % for veneer/plywood and +72 % for particleboard and MDF, respectively. Moreover, consumption of solid wood and EWP intended for the construction industry is expected to increase from 41 to 123 million m^3 by 2050.

The utilization of solid wood materials in different regions around the world by 2020 is presented in Figure 1.

The chart shows the highest consumption in countries from East Asia, Europe, and North America (Figure 1). These three regions account for approximately 82 % of global consumption, considering that they represent only 36 % of the world's population.

The displayed values for the utilization of solid wood and wood-based panels in different regions of the world for the period from 1965 to 2030, as shown in Table 1, reveal interesting dependencies.

The presented results show that the consumption of both EWP and composite wood panels worldwide is expected to increase. The production growth is anticipated to be the highest in the Russian Federation, Eastern Europe, and South America. The utilization is projected to rise in Africa, Asia, and the Pacific region. Consumption of wood in developed countries is expected to be significantly more moderate due to rational and comprehensive utilization of wood resources in these regions (State of the World's Forests, 2009).

3 BY-PRODUCTS IN WOODWORKING
3. NUSPROIZVODI U OBRADI DRVA

The intensive growth in the demand for various types of wood-based products, as well as the expansion of the spheres of its consumption and processing, inevitably leads to an increase in timber harvesting in the forests. The consumption of timber from forest areas will continue to rise due to the growing market needs. It should not be forgotten that forests as ecosystems

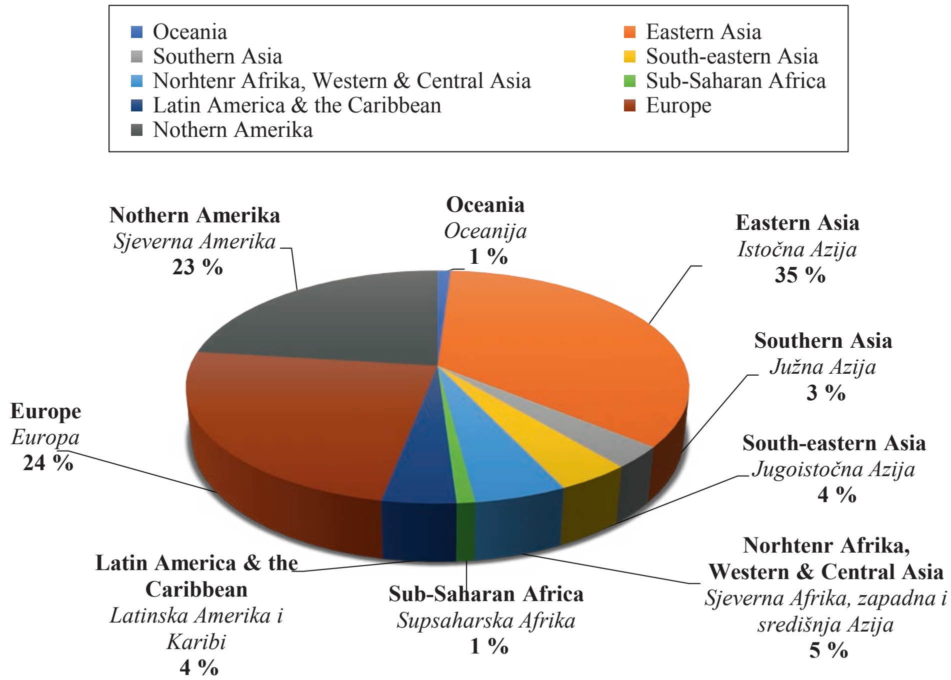

Figure 1 Global consumption of primary treated wood by region in 2020 (FAO, 2022)
Slika 1. Svjetska potrošnja drva u primarnoj proizvodnji po regijama 2020. (FAO, 2022.)

Table 1 Consumption of solid wood and wood-based panels for the period 1965 - 2030 (State of the World's Forests, 2009)
Tablica 1. Potrošnja cjelovitog drva i drvenih ploča za razdoblje 1965. – 2030. (State of the World's Forests, 2009.)

Region *Regija*	**Production and consumption of sawnwood** *Proizvodnja i potrošnja piljene građe*					**Production and consumption of wood-based panels** *Proizvodnja i potrošnja drvenih ploča*				
	Amount (million m³)/ *Iznos (milijuni* m³*)*									
	Actual *Stvarno*			**Projected** *Planirano*		**Actual** *Stvarno*			**Projected** *Planirano*	
	1965	**1990**	**2005**	**2020**	**2030**	**1965**	**1990**	**2005**	**2020**	**2030**
Africa / *Afrika*	3	8	9	11	14	1	2	3	4	5
Asia and the Pacific / *Azija i Pacifik*	64	105	71	83	97	5	27	81	160	231
Europe / *Europa*	189	192	136	175	201	16	48	73	104	129
Latin America and the Caribbean *Latinska Amerika i Karibi*	12	27	39	50	60	1	4	13	21	29
North America / *Sjeverna Amerika*	88	128	156	191	219	19	44	59	88	110
Western and Central Asia *Zapadna i Centralna Azija*	2	6	7	10	13	0	1	5	11	17

perform increasingly important, water conservation, protective, climate-regulating, sanitary-hygienic, aesthetic, and other useful functions. Therefore, our efforts and scientific research urgently need to focus on searching for the most rational utilization of both the wood and the waste raw materials in its processing. According to data from the Bulgarian Executive Forest Agency (2020), in Bulgaria, the age structure as well as the average tree diameter have significantly decreased over a period of several years. This, in turn, is associated with increasing difficulty in obtaining solid wood materials with the necessary dimensional and quality characteristics. This trend of shortage of medium and large building timber for industrial needs is observed not only in Bulgaria, but also in other countries around the world. (Warde, 2006; Nazir *et al.*, 2018; Alberdi *et al.*, 2020; Odppes *et al.*, 2021).

3.1 Waste wood in production of EWP
3.1. Drvni otpad u proizvodnji EWP-a

As mentioned above, one of the largest consumers of large and medium-sized construction timber are woodworking companies producing solid wood materials and engineered wood products (EWP), as well as manufacturing rotary veneer for plywood. There is a significant amount of waste in the form of caps, cut-outs, offcuts, shavings, etc. during the initial cutting of round wood for solid wood materials. Their percentage share is directly dependent on a number of factors, such as: dimensional and quality characteristics of the raw material; specification of the finished product; technical characteristics of woodworking machines, and many others (Campbell, 2013; Heräjärvi *et al.*, 2004; Hernandez *et al.*, 2005; Starkova, 2004; Trichkov and Koynov, 2016 Trichkov and Koynov, 2018). With the continuation of the technology and further processing of the solid wood materials to obtain EWP, the same go through a number of technological operations, in which the wood consumption in the form of cut pieces with the presence of defects, cuts, shavings, etc. significantly increases (Figure 2).

According to data from wood processing companies in Bulgaria, in the production of EWP, in some cases, the final quantitative yields reach only up to 20-30 % (Koynov *et al.*, 2023). As the diameter of the round wood decreases, and therefore its quality, the percentage of waste increases inversely proportional. Several authors have conducted studies on the influence of the quantity, size, and number of defects in the wood on the physical and mechanical properties of the final products (Koman *et al.*, 2013; As *et al.*, 2006; Kaiser, 2020; Wright *et al.*, 2019; Montero *et al.*, 2015). It follows that

Figure 2 Cut pieces with presence of EWP manufacturing defects
Slika 2. Odresci s greškama u proizvodnji kompozitnih ploča

the presence of numerous defects in the wood, specifically knots, sharply reduces the mechanical properties of the solid wood materials. With this raw material, if the low-quality wood is removed from the high-quality one, then the final quantitative yields are greatly underestimated. Waste wood in the form of cuttings, large and small cut pieces, shavings, sawdust, etc., is mainly used for saturating them in technological chips for subsequent production of wood-based panels, pellets, and as a raw material for burning.

The problem of their utilization is that there is a lack of adaptation of modern technologies in the woodworking industry. Several authors have focused their research in this direction, searching for options for more rational application of this waste raw material (Pandey, 2022). Many proposals have been examined for optimal use of wood waste in products with high value-added. For example, studies in Finland have been carried out (Cai *et al*., 2013) on the implementation of new products in textiles, chemicals, biofuels, and plastic substitutes, based on wood. Studies in Japan have found that every year there are about 15 million m^3 of wood waste from the furniture industry, of which over 90 % have found application in the production of wood-based panels and as a raw material for burning (Hiramatsu *et al*., 2002).

Now, there is not enough information based on which to implement a precise and clear approach for optimal utilization of waste wood. It is necessary to search for more opportunities to use it as optimally as possible in the production of EWP. This goal is driven by the fact that production capacities on a global scale will continue to increase due to the growing consumption of such products. It is imperative to search for options for the utilization of waste wood not only in the aforementioned ways but also as a basis for obtaining high value-added products that meet the needs of consumers. Globally, opportunities are being sought for a more sustainable and circular economy (Bowyer *et al*., 2023), which requires taking into account various aspects, such as their impact on the environment and human health, as well as their practicality and economic feasibility.

3.2 Waste wood in plywood production
3.2. Drvni otpad u proizvodnji furnirskih ploča

Another major consumer of large and medium-sized construction timber is plywood production. The technological process is associated with significant raw material losses, which come in the form of veneer pieces during and after log peeling, cutting, trimming, slicing, and last but not least – peeler cores. According to data from leading manufacturers in Bulgaria, the final quantitative yields do not exceed 47-49 %. They are also directly dependent on the dimensional and quality characteristics of the peeled timber. Peeler cores are an inevitable by- product obtained in the process of log peeling (Figure 3). Their percentage ratio (1-30 %) is directly dependent on both the diameter of the logs and the technical characteristics of the peeling machine (Syafii and Novari 2021; Fonseca, 2005; Melo *et al*., 2014).

The diameter of the peeler cores varies within different limits. It mainly depends on the technical characteristics of the peeling machines, but the wood species of the raw material also has an influence. According to data from some global veneer producing companies (Tolko Industries Ltd; Thebault group; Welde - The Wood Company, etc.), the diameter of the obtained peeler cores ranged from 80 to 140 mm. Modern technologies provide an opportunity for spindleless peeling, where the diameter of the peeler cores can be reduced to 30-40 mm. It should be noted that in the central zone of the wood (the first 5 to 20 annual rings), there is a large percentage of juvenile wood, which leads to very low physical and mechanical properties of the wood (Yang, 1994; Zobel, 1998). In its first years of growth, the tree produces so-called juvenile wood, which is the area of the stem extending outward from the heartwood. This wood is prone to cracking, splitting and easy destruction, which lowers its quality and economic characteristics. Studies on the mechanical properties of juvenile wood show that its hardness and strength are 50-70 % lower compared to mature wood (Barbour, 2003; Hernandez *et al*., 2005).

Figure 3 Peeler cores from poplar wood
Slika 3. Središnji valjci preostali nakon ljuštenja drva topole

For this reason, peeling the logs to a minimum diameter of the peeler cores on the one hand increases the quantitative yield of the veneer, but on the other hand, it can lead to a deterioration of its quality. Results from industrial studies show that a large portion of veneer pieces obtained with minimal peeling of the peeler cores diameter (up to 30 mm) are discarded after drying up to 7-8 %. The reasons for this are the formation of large cracks, splitting, or structural damage. Another drawback is the appearance of a "striped" texture on the face side during the drying process. Rough calculations show that, when reducing the peeler cores from 100 to 30 mm, only about 5-10 % of the veneer pieces from this zone are suitable for plywood production after drying. The rest go into chippers to be processed into technological chips.

According to data from global veneer-producing companies (Tolko Industries Ltd), the quantity of veneer with an average diameter of 80-85 mm can reach up to 3 million pieces per year. Information from other companies (Thebault group) shows that the number of veneer pieces obtained within a year is smaller, around 500 thousand pieces, which is still a significant amount of wood raw material. Depending on the wood species, some of the veneer finds application as: stakes for trees; wine stakes; for agricultural production; in gardening; fence posts, signs, as well as for the production of pallets, packaging, etc. The remaining quantity is crushed into technological chips for use in the production of composite panel materials or as raw material for pellets, briquettes, and burning (Torgovnikov and Vinden, 2014; Darzi *et al*., 2020; Ross *et al*., 2005; Wolfe *et al*., 2000).

From the above, it becomes clear that the sectors in which veneer is used are significantly limited. The manufactured products have limited applications, low value-added, and short longevity due to the mentioned shortcomings of this wood. Therefore, it is necessary to explore different options for the most optimal and rational utilization of by-products obtained in the woodworking industry. Conditions should also be created to form final products with the highest possible value-added, having the necessary physical and mechanical properties to meet consumer needs.

4 OPPORTUNITIES FOR PRACTICAL APPLICATION OF CUTTING PIECES WITH DEFECTS AS A RAW MATERIAL FOR MANUFACTURING DESIGN PRODUCTS

4. MOGUĆNOSTI PRAKTIČNE PRIMJENE ODREZAKA S GREŠKAMA KAO SIROVINE ZA IZRADU DIZAJNERSKIH PROIZVODA

During the technological process of producing glued products from solid wood, a large percentage of waste is generated. The dimensions and quantity of these wastes depend directly on the specification of the final product and the quality characteristics of the raw material. For the purpose of our research (Koynov *et al*., 2023), panels of glued solid wood using large waste pieces with defects were obtained. Selected cut pieces with the same thickness and width but varying length, depending on the size of their defects, were used. The cross-sections of these large waste pieces have a shape close to ideal geometry, as the obtained lamellae were pre-treated on four sides. The methods of gluing and forming three types of proposed solid wood panels are described in detail in Koynov *et al*., 2023. The dimensions of the cut pieces with defects can be smaller than those used in the mentioned paper, but they must be produced from lamellae with the same cross-sections. This condition guarantees their potential for creating a technology for combining and gluing them lengthwise. In the described paper, PVA: "*Moment Wood Express*" was used as an adhesive, but other fast-drying and two-component adhesives can also be applied (Lubis *et al*., 2022; Savov *et al*., 2022).

The results of testing some of the more important physical and mechanical properties clearly showed that these products can find various applications as load-bearing structural elements, enclosing structures, as well as in the furniture industry. Depending on the selected type of panel, the average values of modulus of elasticity (MOE) ranged from 2982 to 5580 N/mm^2, and modulus of rupture (MOR)- from 8.8 to 28.6 N/mm^2 (Koynov *et al*., 2023).

The possibility of using waste wood from EWP to obtain a final product for the needs of the furniture industry is presented in Figure 4a.

The production technology was presented, as well as the possibility of potential applications of these products as a raw material for the manufacturing of a design product intended for furnishing homes and offices (Figure 4b).

After removing the high-quality from the low-quality wood in the production of EWP, all the waste has the same cross-sectional dimensions but different lengths. In order to produce the final product, initially, large wastes were stuck together in the foreheads by smoothing until obtaining a lamella of the desired length (Figure 4a-1). After forming and subsequent mechanical processing, the lamellae were glued together along the edge (Figure 4a-2). Finally, panels of glued solid wood of the desired width were obtained (Figure 4a-3), (Koynov *et al*., 2023).

In the present version (Figure 4b), a final product - coffee table with overall dimensions of the tabletop: 560 mm × 560 mm × 35 mm and a height of 430 mm, was manufactured. The legs of the table were of the "hairpin" type, hand-made from rebar and subsequently painted. The surface of the tabletop was

a)

b)

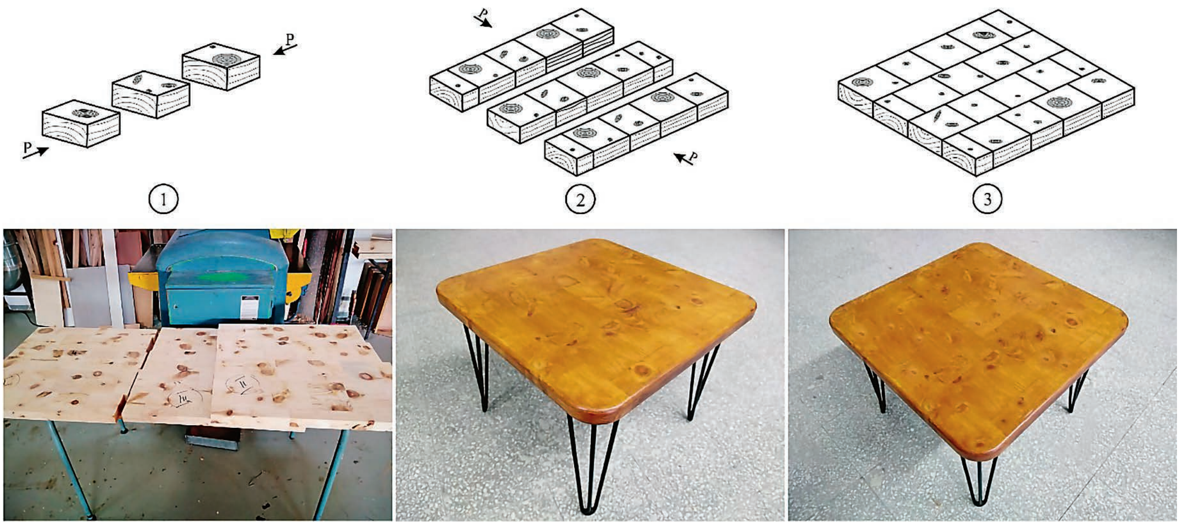

Figure 4 Technology for obtaining glued panels from solid wood from waste and potential application for the final product (Koynov *et al*., 2023)
Slika 4. Tehnologija izrade lijepljenih ploča od otpadnoga cjelovitog drva i mogućnosti njihove primjene za izradu finalnog proizvoda (Koynov i sur., 2023.)

further refined. Depending on the choice of varnish and the client's preference, the prominence of the defects can either be clearly accentuated or slightly concealed.

Utilizing waste wood in this way allows for the formation of laminated panels from solid wood with final dimensions that meet the demand. They can be used in the furniture industry as kitchen countertops, exterior and interior doors, furniture doors, tabletops, and many other products. The presence of numerous defects, including falling knots, holes, gaps, cracks, etc., certainly deteriorates the external and aesthetic appearance. For this reason, the laminated panels from waste wood can be veneered, thus not only hiding the negative impact of the defects but also enhancing the mechanical properties of the products (Koynov *et al*., 2023).

The proposed method for obtaining final products from waste wood not only allows for the utilization of this wood but also saves some technological operations. Firstly, the solid wood materials for EWP production were previously dried to a final moisture content of 8-9 %, which is also the moisture content of the waste wood. Secondly, before removing the defects, the lamellae were previously four-sided planed, resulting in cut pieces with a proper geometric shape, including parallelism between the sides and perpendicularity between the sides and their ends. Thirdly, the steps mentioned so far facilitate the possibility of bonding them by planing. Fourthly, when matching the waste wood end to end, it is not necessary to cut finger-joints, which on the one hand saves this technological operation, on the other hand reduces the cost of cutting teeth, and finally reduces the amount of bonding material (Koynov *et al*., 2023).

5 DESIGN APPROACH FOR USING PEELER CORES AS A RAW MATERIAL FOR OBTAINING HIGH VALUE-ADDED PRODUCTS

5. DIZAJNERSKI PRISTUP ISKORIŠTAVANJU DRVENIH VALJAKA PREOSTALIH NAKON LJUŠTENJA TRUPACA KAO SIROVINE ZA DOBIVANJE PROIZVODA VISOKE DODANE VRIJEDNOSTI

Plywood manufacturing is another industry in the woodworking sector and a major consumer of softwood. In the technological process of peeling the logs for veneer, peeler cores are inevitably produced. Several authors have conducted research on the more rational utilization of this raw material, but as a whole, the proposed options do not provide the opportunity for their use in the industry, due to some specific features (Darzi *et al*., 2020; Wolfe *et al*., 2000; Piao *et al*., 2013; Torgovnikov and Vinden, 2014). In one case, the peeler core sections have been used in the core layers in composite laminated wood panels (Darzi *et al*., 2020). The presented products have significantly good mechanical properties, but glued solid wood, cross-laminated timber (CLT), as well as various types of plywood for the face layers have been used. By applying these materials, the cost of the final product will significantly increase. Other authors (Wolfe *et al*., 2000) present the possibility of using peeler cores in cylindrical form as fasteners in the construction industry. The disadvantages of this raw material listed above are a prerequisite for numerous defects in structural elements, such as distortion, warping and, last but not least, a shorter life cycle of operation. Piao *et al*., 2013 Piao *et al*., 2013 have conducted experiments on direct finger-

a)

b)

c)

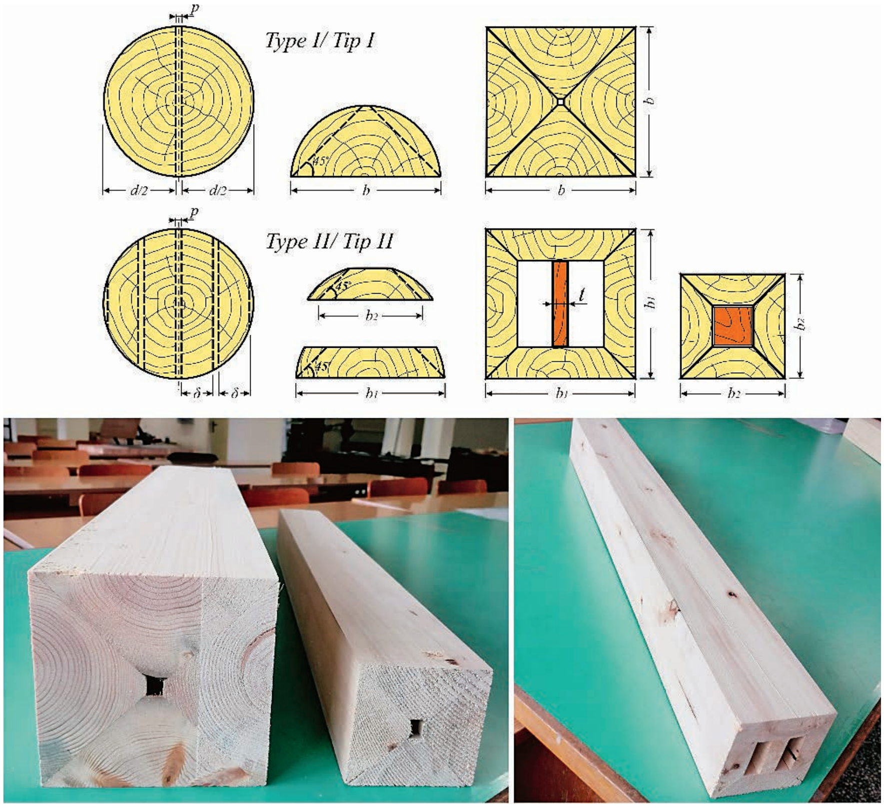

Figure 5 Variants for producing glued beams with a hollow cross-section from sawmill wood (Koynov and Valyova, 2022)
Slika 5. Varijante proizvedenih lijepljenih greda od piljenog drva sa šupljim poprečnim presjekom (Koynov i Valyova, 2022.)

joint splicing along the peeler cores length in their cylindrical form. The established mechanical properties are satisfactory, but again, conditions for subsequent defects in the final products are created.

Some of the main reasons of defects in peeler cores, when used in cylindrical form are: the wood in the central zone of the tree has reduced mechanical properties and many stresses; presence of heartwood; large difference in early and late wood; annual rings with large width and irregular shape. All this will inevitably lead to warping or twisting of peeler cores when applied in their cylindrical form. It is necessary to search for options for their optimal cutting with minimal labor, energy, and wood consumption, in order to minimize the impact of the listed deficiencies.

In our previous research, our efforts were oriented towards these issues (Koynov and Valyova, 2022; Koynov *et al*., 2022; Koynov *et al*., 2024a; Koynov *et al*., 2024b). We were looking for options to obtain high value-added products that would find application in both the furniture and construction industries. One of the proposed methods had several variants for longitudinal cutting of peeler cores and gluing the lamellae in order to produce beams with a hollow cross-section (Figure 5a). In this case, the diameter of the peeler cores is directly dependent on the dimensional cross-sections of the glued beams.

In the presented method - *Type I* (Figure 5a), the peeler cores were initially cut longitudinally into the two semicircles. The resulting materials were notched at an angle of 45°, thus forming cross-sections close to that of an isosceles triangle. Finally, the same were combined into a glued beam, the direction of the annual rings being oriented so that there was a correct radial cut on each side of the beam.

In method - *Type II* (Figure 5b), the peeler cores were initially cut longitudinally into four boards of equal thickness. To achieve maximum quantitative yield, the same were notched at an angle of 45° to trapezoidal cross-sections. Two peeler cores make it possible to join two hollow beams, but one of them will have a cross-sectional area exceeding the cross-section of the peeler core. Cutting methods and established quantitative yields for different peeler cores cuttings are described in detail by Koynov and Valyova, 2022.

Three types of bonded beams with hollow cross-sections were obtained as final products in laboratory conditions (Figure 5c). Some of the basic physical and mechanical properties on the beams were determined, but subsequent experiments with the necessary number of beams from each series were conducted for more accurate and comprehensive results.

Other variants for optimal cutting of the peeler cores in order to manufacture glued laminated timber (GLT) are presented by Koynov *et al*., 2022; Koynov *et al*., 2024b. Three methods for bonding characterized by the trapezoidal cross-sections of the lamellae form-

a)
b)

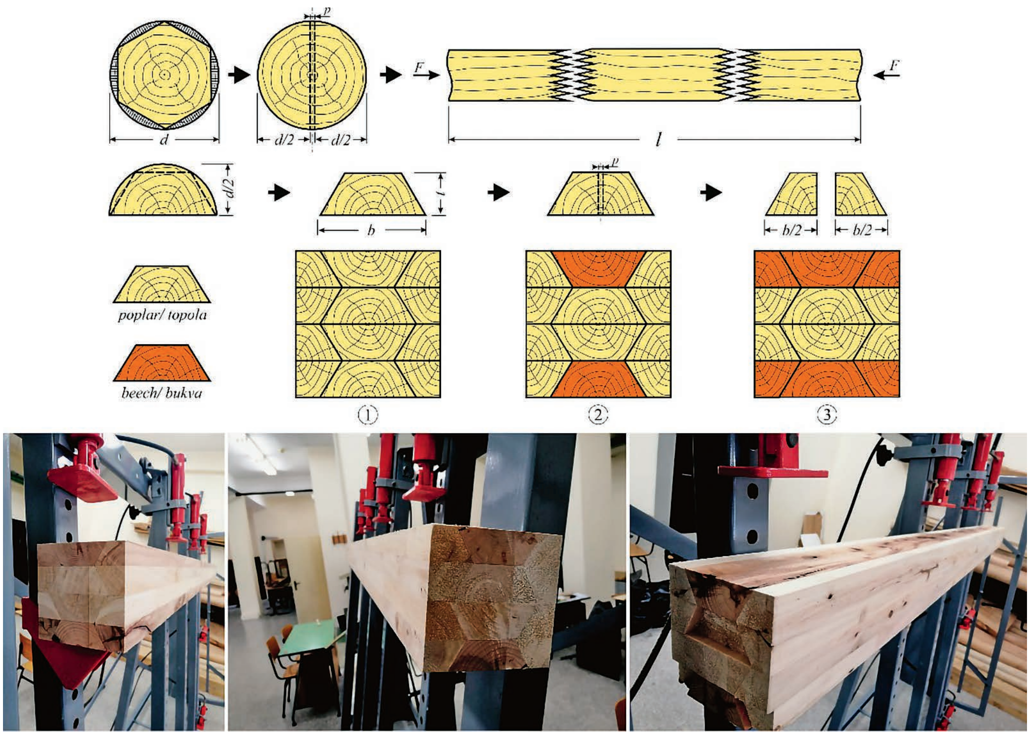

Figure 6 Glued-laminated timber manufactured from peeler cores (GLPC) with different percentages of trapezoidal cross-section lamellae from beech and poplar wood (Koynov *et al*., 2024b)
Slika 6. Lijepljeno lamelirano drvo proizvedeno od središnjih valjaka preostalih nakon ljuštenja trupaca (GLPC) s različitim postotcima lamela trapeznog presjeka od drva bukve i topole (Koynov i sur., 2024b)

ing in the construction package were proposed. The latter were made of beech and poplar wood with different percentage share. Peeled veneer is mainly obtained from the above wood species in Bulgaria. The cutting methods and subsequent technological operations are described in detail in the papers.

Laboratory bonded hybrid beams from glued-laminated timber manufactured from peeler cores (GLPC), as well as the technology for their production, are presented in Figure 6b.

The purpose of this study was to determine the effect of the amount of beech wood on the physical and mechanical properties of glued beams produced from peeler cores.

Laboratory bonded GLPCs were manufactured by different combinations of poplar and beech: 100 % poplar (Figure 6a-1); 25 % beech/ 75 % poplar (Figure 6a-2) and 50 % beech / 50 % poplar (Figure 6a-3).

The shape of the lamellae cross-sections was chosen based on the minimal wood consumption when cutting the peeler cores (Koynov *et al*., 2022). The established results for the physical and mechanical properties of these products clearly indicate that they can be easily used as structural beams in the construction industry. With different percentages of beech and poplar, the MOE results showed values ranging from 8062 to 10985 N/mm^2. The average values of MOR were in the range of 35 to 57 N/mm^2. The density of the glued beams is very low (425 - 544 kg/m^3). The results conclusively showed that these beams meet strength classes *GL* 32*c* and *GL* 32*h* (Koynov *et al*., 2024b).

A variant for utilizing the peeler cores as a core layer to produce hybrid plywood was developed. The technological process was described in detail by Koynov *et al*., 2024a. Three options for different quantities and thicknesses of peeler core sections to form the final product were proposed. The results for density-to-strength ratio after establishing the physical and mechanical properties of the hybrid plywood from all series showed a clear dependence. In this case, the most optimal variant was obtained with 80 % filling of the core layer with peeler core sections. The MOE results ranged from 2312 to 3088 N/mm^2, and the MOR- from 10.7 to 17.9 N/mm^2. The density of the hybrid plywood is close to that of very light-weight panels (304 and 378 kg/m^3). Overall, these products can find applications not only in furniture, but in some cases also in the construction industry (Koynov *et al*., 2024a).

Several coffee tables have been produced as final product options shown in Figure 7b. The selected item is based on the dimensional characteristics of the laboratory press used for gluing.

On the one hand, the aim of the present study was to rationally use peeler cores to produce hybrid plywood, and on the other hand, to determine the influence of the washer amount on the physical and mechanical parameters of the final products.

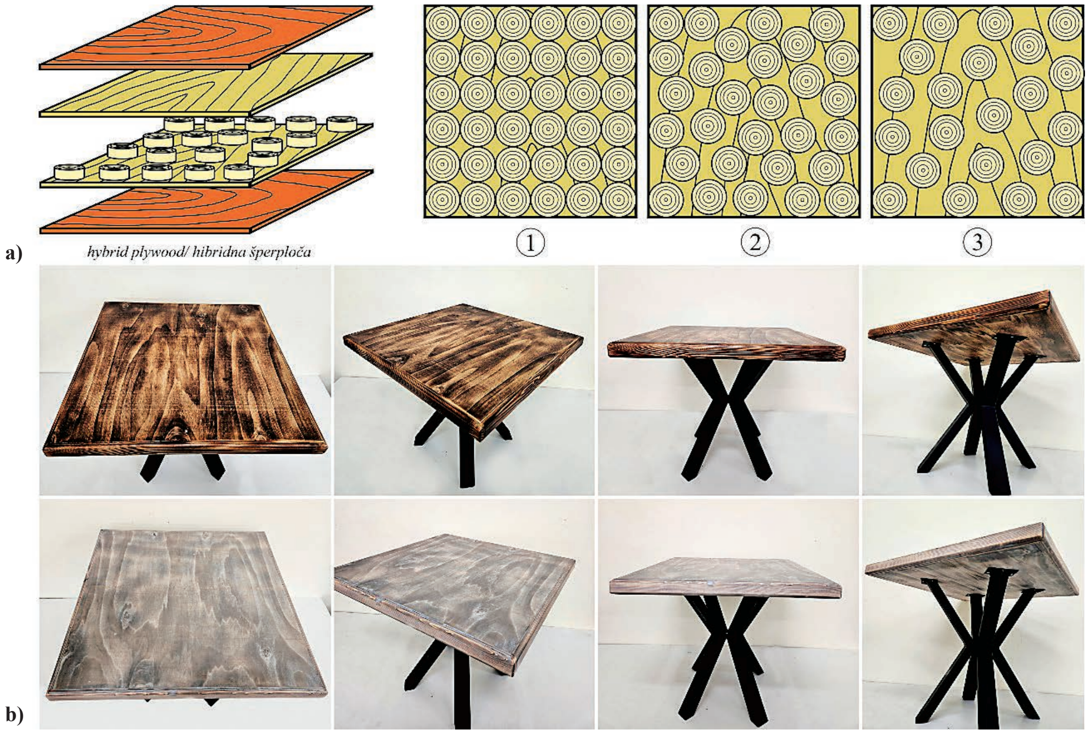

Figure 7 Laboratory produced tables from hybrid plywood (Koynov *et al*., 2024a)
Slika 7. Laboratorijski proizvedeni stolovi od hibridne furnirske ploče (Koynov i sur., 2024a)

In the first case, the veneer sheets were filled to the maximum with washers from peeler cores in the intermediate layer of the hybrid plywood or the so-called 100 % (Figure 7a-1). All washers were stacked tightly together with as few gaps as possible between them. The maximum number of washers reached 36 pieces. In the second case, the goal was to reduce the amount of washers to approximately 80 % of the maximum number, i.e. 29 pieces (Figure 7a-2). The amount of washers in the last version was reduced to 60 % or 22 pieces (Figure 7a-3), (Koynov *et al*., 2024a).

The dimensions of the coffee tabletop were 600 mm × 600 mm × 40 mm with a height of 450 mm (Figure 7b). The legs were once again hand-made and painted in the desired color. The tabletops were formed from five-layer hybrid plywood with minimal use of veneer sheets (4 pieces). Poplar veneer sheets were used for the face. With minimal additional processing and surfacing of the top layer, a significantly improved aesthetic appearance is achieved, resembling that of valuable wood species. The main point in this specific case is the use of waste raw material in the form of peeler core sections, which on one hand act as fillers in the core layer, and on the other hand, due to their size, can easily adjust the desired final thickness of the panel. By increasing the number of veneer sheets, the strength characteristics will significantly increase, but the goal of this study was to achieve a product with good physical and mechanical properties as well as an aesthetically pleasing appearance while minimizing the use of high-quality raw materials.

6 CONCLUSIONS
6. ZAKLJUČAK

The conducted review presents optimal opportunities for utilizing waste in the woodworking industry to obtain high value-added products. The proposed options for final products obtained from waste wood in the woodworking industry can find applications in both the furniture and construction industries. These products can be used for both decorative and non-structural elements, as well as for structural components. They have very good characteristics in terms of density to strength properties. Research in this direction should continue to provide the final products ideally tailored to the needs of consumers. On the other hand, their manufacturing should involve minimal wood consumption, optimal labor and energy expenditure, as well as technological efficiency.

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Risks of Carcinogenic Pollution in Wood Industry within European Regulations

Rizici kancerogenog onečišćenja u drvnoj industriji prema europskim propisima

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ABSTRACT • *Many materials used in wood industry are considered to have carcinogenic or mutagenic effects, which is a health risk for workers in production. Carcinogenic chemical compounds, apart from causing cancer, also pose a great risk for human health in other terms like respiratory issues, skin irritation, allergic reactions, congenital abnormalities in women, visual impairments, immune system and neurological disorders, hormonal imbalances, etc. Carcinogenic pollution in the wood industry is associated with activities related to the emission of wood dust, production of panel materials, drying and steaming of wood, sharpening tools, the activities of handling glues, paints, varnishes, coatings, wood preservatives, exposure to fossil and biofuel exhaust gases, and many others. The purpose of this paper was to present the carcinogenic substances to which workers in the wood industry are professionally exposed, to present previous research and currently valid regulations and protection measures in the EU. By reviewing the sources, it can be concluded that, although legislation often requires clearly defined etiological factors, scientists agree that the understanding of the relationship between occupational exposures and cancer is not yet complete and that occupational carcinogenic factors are considered occupational exposures if a significant number of workers were exposed to significant levels.*

KEYWORDS: *occupational health; carcinogens; wood dust; formaldehyde; nanoparticles*

SAŽETAK • *Smatra se da mnogi materijali koji se upotrebljavaju u drvnoj industriji imaju kancerogene ili mutagene učinke koji su zdravstveni rizik za radnike u proizvodnji. Osim što uzrokuju rak, kancerogeni kemijski spojevi ujedno su veliki rizik za ljudsko zdravlje u smislu drugih tegoba kao što su respiratorni problemi, iritacija kože, alergijske reakcije, kongenitalne abnormalnosti u žena, oštećenje vida, bolesti imunološkog sustava i neurološki poremećaji, hormonska neravnoteža itd. Kancerogeno onečišćenje u drvnoj industriji povezano je s procesima vezanima za mehaničku obradu drva i emisiju drvne prašine, proizvodnju pločastih materijala, sušenje i parenje drva, oštrenje alata, rukovanje ljepilima, premazima i sredstvima za zaštitu drva, izloženošću ispušnim plinovima od fosilnih goriva i biogoriva te s mnogim drugim procesima. Cilj ovog rada bio je prezentirati kancerogene tvari kojima su profesionalno izloženi radnici u drvnoj industriji, prikazati rezultate dosadašnjih istraživanja te dati uvid u trenutačno važeće propise i mjere zaštite u Europskoj uniji. Iako zakonodavstvo često zahtijeva jasno definirane etiološke čimbenike, pregledom literaturnih izvora može se zaključiti da se znanstvenici slažu kako*

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odnos između profesionalne izloženosti i karcinoma još nije potpuno razjašnjen te da se izloženost profesionalnim kancerogenim čimbenicima smatra profesionalnom izloženošću kada je znatan broj radnika bio izložen povišenim razinama onečišćenja.

KLJUČNE RIJEČI: *zdravlje na radu; kancerogene tvari; drvna prašina; formaldehid; nanočestice*

1 INTRODUCTION
1. UVOD

The activity of wood processing emits numerous pollutants into the working environment, including those classified as mutagens and carcinogens, posing a serious risk to the worker's health. According to the Proposal for a Directive of the European Parliament and of the Council amending Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work, at the end of 2016 the European Commission launched a proposal to reduce the limit values for 13 carcinogenic substances, considering the fact that annually 53 % of work-related deaths are attributed to cancer. In 1981 the International Agency for Research on Cancer (IARC) listed occupational risks associated with the wood industry, including nasal cancer, nasopharyngeal cancer, laryngeal cancer, lung cancer, stomach cancer, hematopoietic and lymphoreticular cancer (IARC, 1981). In addition to emitted wood dust, some chemical compounds related to wood products and wood processing also pose a carcinogenic risk to human health. Formaldehyde is released during the drying and steaming of wood and production of wood-based panels (chipboards, medium-density fiberboard and plywood, etc.). Also, carcinogenic formaldehyde is slowly being released in the occupational area during the lifetime of wood-based panels (for example particleboards and MDF) formaldehyde (IARC, 1995; IARC, 2012a; Beane Freeman *et al*., 2009). Combustion of fossil fuels to drive vehicles and devices, obtain energy or drive a chainsaw, releases toxic gases not only into the surrounding air but also into the working environment. There is also metal dust from wear and sharpening of hard metal tool blades that contain carcinogenic substances such as tungsten carbides and cobalt (Wild *et al*., 2009; IARC, 2022). Numerous nanomaterials are used to improve the properties of wood and wood surfaces, the most common being nanoTiO_2, nanoSiO_2 and nanoAg (IARC 2010; Aschberger *et al*., 2011). Carcinogenic heavy metal compounds (lead, cadmium, chromium, nickel) are not completely banned but restricted in wood preservatives, paints, coatings or varnishes, and can be used in products under certain conditions (restorations,

Table 1 Sources of carcinogenic and/or mutagenic substances in wood industry
Tablica 1. Izvori kancerogenih i/ili mutagenih tvari u drvnoj industriji

Source / *Izvor*	**Carcinogenic substances** / *Kancerogene tvari*
Mechanical wood processing / *strojna obrada drva*	Wood dust / *drvna prašina*
Wood-based panels, wood drying and streaming *ploče od drvnog materijala, sušenje i parenje drva*	Formaldehyde / *formaldehid*
Fossil fuel exhaust gases, biofuel combustion *ispušni plinovi od fosilnih goriva*	Benzene / *benzen* Benzo[α]pyrene / *benzo[α]piren* Xylene / *ksilen;* Toluene / *toluen*
Biofuel combustion *izgaranje biogoriva*	Dioxins and furans / *dioksini i furani* Benzo[α]pyrene / *benzo[α]piren*
Tool sharpening *oštrenje alata*	Tungsten carbides and cobalt dust *prašina volframovih karbida i kobalta*
Wood preservatives, paints and varnishes *sredstava za zaštitu drva, boje i lakovi*	Heavy metals (Lead, Cadmium, Chromium, Nickel) *teški metali (olovo, kadmij, krom, nikal)*
Paints and varnishes *boje i lakovi*	Hexamethylene diisocyanate / *heksametilen diizocijanat* Polychlorinated Biphenyls (PCBs) / *poliklorirani bifenili (PCB)* Xylene / *ksilen;* Toluene / *toluen* Nanoparticles / *nanočestice*
Resins *smole*	Acrylonitrile / *akrilonitril* Epoxy resins hardeners – epichlorohydrin *učvršćivači epoksidnih smola – epiklorohidrin*
Fungicides and insecticides *fungicidi i insekticidi*	CCA salts (copper, chromium and arsenic oxides) *CCA soli (bakar, krom i arsenovi oksidi)* Arsenic and arsenical compounds / *arsen i njegovi spojevi* Creosote oil / *kreozotno ulje* Coal-tar oil / *ugljenokatransko ulje* Pentachlorophenol / *pentaklorofenol*

works of art). Among epoxy resin hardeners, epichlorohydrin is classified as a carcinogen, while there is insufficient evidence for diaminodiphenyl sulfone and glycidyl ethers. Acrylic resins (acrylonitrile) probably carcinogenic in humans, as well as Polychlorinated Biphenyls (PCBs), Toluene and Xylene, are used in paints and varnishes (IARC, 1981; EU-OSHA, 2014, Regulations NN148/2023). Carcinogenic fungicides and insecticides, CCA salts (copper, chromium and arsenic oxides), arsenic and arsenical compounds, creosote oil and coal-tar oil and pentachlorophenol have limited use in industrial plant and professional use. Asbestos tremolite was banned for production and market in 2006. It was previously used in paper production, in talc production as coating pigment, in furniture production as filler in melamine-formaldehyde glues and in carpentry as insulator, flame retardant. Mineral oil, which is used as a solvent for chlorophenols in sawmills, is also carcinogenic in humans (IARC, 1981; EU-OSHA, 2014, Regulatins NN148/2023). Table 1 shows the most common carcinogenic substances, from the above sources, whose carcinogenic and/or mutagenic influence on human health has been investigated and scientifically proven, as well as their sources in the wood industry.

The aim of the work is to present the previous research on the most significant carcinogenic substances that are produced in the wood industry and their characteristics related to certain health risks as well as norms and regulations providing protective measures.

2 RISKS OF OCCUPATIONAL EXPOSURE TO WOOD DUST
2. RIZICI OD PROFESIONALNE IZOŽENOSTI DRVNOJ PRAŠINI

In 1995, the IARC stated that wood dust, especially dust from hard wood species, generally causes significant health problems. Separated wood particles are classified as carcinogenic substances and can cause many types of cancer especially those related to the respiratory system, sinonasal adenocarcinomas (Siew *et al*., 2017; Soćko, 2021), nasopharyngeal cancer (Beigzadeh *et al*., 2019; Meng *et al*., 2020) and lung cancer (Scarabelli *et al*., 2021; Matrat *et al*., 2019). European Directive 2017/2398 on the protection of workers from the risks related to exposure to carcinogens or mutagens at work prescribes an Occupational Exposure Limit (OEL) of 2 mg/m^3 for 8-hours exposure to inhalable hardwood dusts. European wood processing facilities use beech wood and oak wood as their raw material in large quantities and according to Hausen (1981), respiratory cancers are prevailing among workers who deal with these wood species. In the wood processing industry, separation of wood particles is inevitable during mechanical processing. According to Kauppinen *et al.* (2006) about 3.6 million workers in the EU are exposed to inhalable wood dust, about 16 % of workers are exposed to mass concentrations of inhalable wood particles of up to 5 mg/m^3 and 25 % of workers to mass concentrations of up to 2 mg/m^3. According to the Health Council of the Netherlands (2000), 1 of 250 workers would be a victim of nasal cancer while being exposed to a wood dust concentration of 5.8 mg/m^3 during their working life of 40 years. Scheeper *et al.* (1995) also explain higher wood dust exposure caused by a poor solution or lack of an exhaust ventilation system connected to the machines. Similarly, Čavlović *et al.* (2022) noticed that the wood dust exposure was lower than the level of increased risk (2 mg/m^3) at workplace near the CNC machine connected to a quality central suction machine. While researching the effect of wood moisture content and average chip thickness during routing operation on rubberwood, Ratnasingam *et al*. (2009) concluded that higher wood moisture content and lower average chip thickness, which can be achieved by manipulating the rotational speed of the cutting tool, results in a significant reduction of airborne wood dust emission. Studying different materials like medium density fibreboard (MDF) and plywood, Welling *et al.* (2009) concluded that sanding MDF produces much higher dust emissions than sanding pine and birch plywood. Wood sanding produces the smallest wood dust particles that remain airborne for longer periods of time and pose greater health risks (Beljo-Lučić *et al.*, 2011). According to Thorpe and Brown (1995), mean aerodynamic diameter of a wood dust particle is inversely proportional to the mentioned density and hardness of wood. They concluded that overall wood dust produced by the coarsest sandpaper was negligibly higher than that of a finer grade sandpaper.

There are two hypotheses that explain why wood dust could cause sinonasal adenocarcinoma. The first possible explanation for the cause of the sinonasal cancer are inhalable potentially carcinogenic substances like tannins, aldehydes and other chemicals that are being used in the wood industry. The second explanation might be the inhalation of wood dust particles that are smaller than 5 μm and intervene with normal mucosa function, which leads to a higher risk of cancer (Elwood, 1981). Nylander *et al.* (1993) concluded in their paper that workers in the furniture industry have the highest risk of developing nasal cancer induced by wood dust among all other workers in the wood processing industry. Furthermore, wood dust could be the cause of other tumors in the lungs, stomach and the above-mentioned types of cancer because wood dust can easily come into contact with these organs.

3 RISKS OF EXPOSURE TO OTHER CANCIROGENS
3. RIZICI OD IZLOŽENOSTI OSTALIM KANCEROGENIM TVARIMA

3.1 Formaldehyde
3.1. Formaldehid

In 1995, IARC classified formaldehyde as a Group 1 carcinogen for humans. Apart from exposure through inhalation, formaldehyde can be absorbed through the skin or ingested (Protano *et al*., 2022). Formaldehyde is a chemical compound that is naturally found in wood composition. Cellulose, hemicelluloses and lignin are the main components of wood and according to Schäfer and Roffael (2000) formaldehyde can be formed out of the mentioned components, just as from wood extractives. The amount of formaldehyde is very small but still occurs and is traceable in solid wood. The emission of formaldehyde from solid wood is dependent on its pH value and temperature. With increased temperature and heating wood for a longer period, the amount of formaldehyde emission is increased. This process is usually conducted when wood is being dried, where apart from formaldehyde other volatile organic compounds are released (Cronn *et al*., 1983). European Directive 2019/983 on the protection of workers from the risks related to exposure to carcinogens or mutagens at work prescribes an OEL of 0.37 mg/m^3 for 8-hours exposure to formaldehyde. In the wood industry, synthetic resins are mostly used in the production of wood-based panels. It is important to mention that 95 % of all wood adhesives used in wood-based panel production are based on formaldehyde. Adhesives that are being used in industry today are phenol-formaldehyde (PF), melamine-formaldehyde (MF), melamine-urea-formaldehyde (MUF) and lastly urea-formaldehyde (UF), which is the most used synthetic resin (Pizzi *et al*., 2020). Particleboard, medium-density fiberboard and plywood are widely used in furniture production, flooring industry, i.e., multi-layered parquetry, construction industry, etc. Airborne formaldehyde is released in living spaces and the level of exposure to formaldehyde depends on various factors like temperature, humidity and ventilation rate (Liu *et al*., 2015). In 2012, IARC stated that there was enough epidemiological and toxicological evidence that formaldehyde could be a cause of nasopharynx tumors and limited evidence for nasal sinus tumors. Newer reports indicate possible leukaemia induction by formaldehyde (Beane Freeman *et al*., 2009).

3.2 Benzene and benzo[α]pyrene
3.2. Benzen i benzo[α]piren

Among the many polycyclic aromatic hydrocarbons (PAHs), benzene and benzo[α]piren stand out as carcinogens and mutagens. Exposure to benzene and benzo[α]piren at work in the wood processing and forestry sectors is associated with fossil combustion sources, i.e. biofuels. Chainsaw workers are exposed to risks not only in a forest, but also in the industrial facilities, in closed environments, when cutting down logs to preferred lengths. Apart from chainsaw use, transporting devices, like forklifts, loaders or trucks with grapple loaders, running on internal combustion engines and fossil fuels are also often used in the wood industry. In wood processing companies and power plants, the consumption of wood fuel (solid biomass) for energy production is increasing, and thus the emission of pollutants from industrial furnaces from the combustion of wood fuel, among which is benzo[α]piren. Moreover, due to the incomplete combustion of fuel, there is the formation of floating particles smaller than 2.5 µm (PM 2.5) that adsorb toxic chemical compounds such as PAH shorter aromatic chains (Simoneit, 2002). Also, residential use of coal and wood as a source of thermal energy increases the emission of benzo[α]piren (Guerreiro *et al*., 2014).

Polycyclic aromatic hydrocarbons (PAHs) are organic compounds made of multiple aromatic rings known to be the cause of mutations in DNA. Santesson (1897) noticed benzene toxicity to blood forming organs. Infante *et al.* (1977) described five times increased risk of leukaemia caused by occupational benzene exposure. In 2012, IARC stated that there was sufficient evidence for benzene to cause acute myeloid leukaemia and limited evidence for acute lymphocytic leukaemia, chronic lymphocytic leukaemia, etc. Apart from leukaemia which is the most common type of cancer caused by benzene, lung cancer, kidney cancer, nasal cavity and oesophagus cancer and other less common types of cancer were reported. European Directive 2022/431 on the protection of workers from the risks related to exposure to carcinogens or mutagens at work prescribes an OEL of 0.66 mg/m^3 for 8-hours exposure to benzene (OEL of 1.65 mg/m^3 is valid from 5 April 2024 until 5 April 2026). Benzo[α]piren is lipophilic, which makes it able to penetrate the cell membrane without any difficulty (Petrulis and Perdew, 2002). The chemical process in a cell and its nucleus is carried out causing DNA to mutate and eventually start a cancer (Kucab *et al*., 2015). Damage to the human DNA can lead to specific mutations that lead to cancer (Cooper, 2000). An example of prolonged exposure to benzo[α]piren and its bad influences on the human body is the mutation of the TP53 tumor suppressor genes (Krais *et al*., 2016).

3.3 Dioxins and furans
3.3. Dioksini i furani

Dioxins are a group of chemical compounds out of which 17 isomers are considered to be toxic and mutagenic. Dixons belong to a group of 75 polychlorinated dibenzo-p-dioxins and 135 polychlorinated dibenzofurans. Combustion of wood and wood processing generates emission of dioxins, which represents a great danger to human health because dioxin can accumulate in fat tissues (Lavric *et al*., 2004). Schatowitz *et al.* (1994) concluded that dioxin annual emissions during the combustion of natural wood were not significantly increased, while the combustion of waste wood, such as wood chips coming from the demolition of buildings, greatly increased dioxin emissions. A wide range of different inorganic compounds are used for wood treatment like salts that improve fire-resistant properties (Richards and Zheng, 1991). Chromated copper arsenate, copper boron azole, etc. improve wood resistance to microbial and fungal degradation (Humprey, 2002). The addition of inorganic compounds affects the emissions of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans. According to the research conducted in 2007 by Tame *et al*., combustion of wood with improved properties by preservatives produces higher levels of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans, and hence they strongly advise not to use impregnated wood as a source of thermal energy in households. It is possible to reduce the production of dioxins in wood combustion by adding sulphur or nitrogen-containing agents. Furthermore, it is important to prevent particles of burned biomass from reaching the atmosphere using filters and particle removers. Before filtering the particles, good conditions for effective combustion contribute to lower dioxin emissions (Lavric *et al*., 2004).

3.4 Hard metal dust
3.4. Prašina tvrdih metala

Hard metals are widely used in wood industry; they represent a material that is bound together with cobalt or nickel (Santhanam, 1992). Apart from hard metals, metallic carbides are also commonly used. Tungsten carbide is the most widespread metallic carbide in wood industry. Such hard metals and metallic carbides are used for the production of wood cutting tools. Common exposure to metal dust in wood industry occurs while doing the maintenance and resharpening of hard-metal tools. The IARC (2006) states that the levels of exposure to metal dust are much lower during their use than during their manufacture. However, grinding of the tools and blades while sharpening and doing maintenance release cobalt in the air at a concentration of several hundred micrograms per cubic meter (Mosconi *et al.*, 1994). Metal dust, especially cobalt metal, is classified as "probably carcinogenic to humans" following the testing on animals (IARC, 2022). Furthermore, the study of tungsten conducted by Wild *et al.* (2009) in hard-metal factories shows increased risk of lung cancer among workers.

3.5 Nanoparticles
3.5. Nanočestice

Natural wood is an effective structural material, but it is not durable and stable. To ensure its stability and durability, wood is treated with coatings and chemical treatments (Unger *et al.*, 2001). Nanoparticles are used as treatments to improve wood properties. De Filpo *et al.* (2013) described the prevention of fungal growth by submerging wood samples in a solution of titanium dioxide (TiO_2). NanoTiO_2 helped to prevent the decay through its photo-catalytic activity. Using nano zinc oxide (ZnO) treatments, Clausen *et al.* (2010) managed to contribute to a significant decrease in wood greying. ZnO is a strong ultraviolet absorbent, meaning that it reduces the UV radiation effect and lignin decay, which gives wood its natural colour. Chemical reagents like nano copper oxide (nanoCuO), which was confirmed to be effective against fungi by Aguayo *et al.* (2021), are also commonly used. Nano silica dioxide (nanoSiO_2) is used to improve the properties of paints used in wood surface treatments. Paints with the addition of SiO_2 showed improved water repellence, scratch resistance, antimicrobial properties and durability (Kaiser, 2013). Nano silver is commonly used in furniture production because of its antimicrobial properties (van Broekhuizen, 2012). According to van Broekhuizen (2012), nanomaterials do not have a common effect on health, moreover every nanomaterial has its own unique influence on human health. Van Broekhuizens summary suggests that nanoTiO_2 is the most common nanomaterial used in furniture production. According to IARC (2010), nanoTiO_2 is possibly carcinogenic to humans and could pose a slightly increased risk of lung cancer. NanoSiO_2 and nanoAg are the second most used nanomaterials in furniture production, but lack of evidence and research leads to a bad understanding of their health effects. Inflammation is the most frequently studied health effect of nanomaterials, which leads to cell death or scar-tissue forming dominantly in lungs that could result in a cancer (Aschberger *et al*., 2011).

4 CONCLUSIONS
4. ZAKLJUČAK

Researching the literature, it can be observed that there is a lack of studies that explain why wood dust is considered directly carcinogenic. Further studies should emphasize their investigation of the effects of the chemical composition of wood dust on human health, and the correlation of the effect with the size of the wood dust particles. Scientific knowledge is applied in the development of the best available techniques for reducing the emission of carcinogenic substances in the working environment of the wood industry and its general environment. Apart from wood dust being a carcinogen, wood industry workers are faced with chemical compounds that represent a great health concern as well. Protection should be provided to workers and citizens who might be affected by the harmful carcinogenic sources generated by wood industry activities. European legislative bodies are trying to prevent workers from getting cancer at work through legislative action, not just guidelines, by finalizing the Carcinogens and Mutagens Directive (CMD). In order to ensure a safer working and ambient environment around industrial plants and residential areas, regulations and safety protocols need to be applied to reduce the source of air pollution, especially carcinogens and mutagens.

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Historical Application of Dovetail Corner Joints with Practical Example

Povijesni pregled primjene kutnih spojeva *lastin rep* s primjerom izrade spoja

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ABSTRACT • *This paper presents the most common traditional dovetail joints used in furniture making in past centuries, which are among the almost forgotten skills, practiced today by only a relatively small number of restoration workshops. The paper deals with the basic joints used in the restoration of furniture and traditional woodworking (houses, churches, temples, etc.) for the purpose of protecting rich cultural heritage. The history of furniture making is also the history of the art of making joints. In restoration, knowledge of these joints facilitates and accelerates the dating of furniture pieces to be restored. For this reason, the aim of this paper is to present an overview of the use of dovetail joints. The decorative effect of these joints and their constructive ingenuity certainly deserve more attention and research. A historical review of the development of traditional dovetail corner joints demonstrates the importance of the skill of crafting joints that stand the test of time and survive to this day. With the development of art, the joints became more and more decorative, but also of higher quality to withstand the various stresses that occur when furniture is used. Practical examples of making traditional dovetail corner joints are used to show how important it is to preserve the craftsmanship of these traditional joints from being forgotten, which is necessary when restoring furniture and other historical structural components made of wood such as ceilings, floors and altars.*

KEYWORDS: *traditional joint; dovetail corner joint technique; dovetail solid wood elements; restauration; furniture*

SAŽETAK • *U radu su prikazani najčešći tradicionalni spojevi nazvani lastin rep koji su se primjenjivali u izradi namještaja tijekom prošlih stoljeća, a čija je izrada danas gotovo zaboravljena vještina, koja se prakticira samo u relativno malom broju restauratorskih radionica. Prikazani su osnovni spojevi koji se primjenjuju pri restauraciji namještaja i tradicionalnoj obradi drva (kuće, crkve, hramovi itd.) radi zaštite bogate kulturne baštine. Povijest izrade namještaja ujedno je i povijest umijeća izrade drvenih spojeva. Poznavanje drvenih spojeva pri restauraciji olakšava i ubrzava datiranje namještaja koji se restaurira. Stoga je cilj ovog rada prikazati povijesni pregled primjene spojeva lastin rep. Dekorativni učinak tih spojeva i njihova konstruktivna domišljatost svakako zaslužuju veću pozornost i detaljnije istraživanje. Povijesni pregled razvoja tradicionalnih kutnih spojeva tipa lastin rep pokazuje važnost vještine izrade spojeva koji odolijevaju vremenu i primjenjuju se do danas. S razvojem umjetnosti spojevi su postajali sve dekorativniji, ali i sve kvalitetniji kako bi izdržali različita naprezanja što su nastajala tijekom uporabe namještaja. Praktični primjeri izrade tradicionalnih kutnih spojeva tipa lastin rep dat će doprinos*

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očuvanju umijeća izrade tih spojeva od zaborava, što je iznimno važno za restauraciju namještaja i drugih povijesnih strukturalnih elemenata izrađenih od drva poput stropova, podova i oltara.

KLJUČNE RIJEČI: *tradicionalni spoj; tehnika kutnog spoja lastin rep; elementi od punog drva lastin rep; restauracija; namještaj*

1 INTRODUCTION
1. UVOD

Joinery, the basis of woodworking, is a sophisticated blend of art and engineering (FPL 2010); strong joints will contribute to its longevity, while the design and craftsmanship enhance its beauty (Rogowski, 2002).

By observing wooden objects created in different historical periods, Fairham (2010) has analysed the handmade joints used to connect wooden elements over the centuries, which allowed for a firm joining of wood without the need for metal nails, particularly in handmade furniture and restoration.

There are many interesting joints that master carpenters have made with their acquired skills. This paper will provide an overview of the dovetail joint, which has clearly fascinated woodworking craftsmen throughout the centuries and continues to do so today. From simple to more complex versions, the dovetail joint has both, its functional simplicity and its explicit decorativeness. Of great significance is the fact that this joint bears witness to the history of the first great civilisations; it could even be said that it is "encapsulated in the history of mankind" with its tails and pins. The development of this simple but sophisticated combination and its variations is truly fascinating and goes far back into the history of crafting wooden objects.

In furniture making, it is necessary to create a structural system that justifies the durability and contributes to the aesthetics of the object itself (Hoadley, 2000). Joints, as a traditional segment of historical furniture, provide historians, conservators, restorers, curators and other related professions with information about the furniture itself, which is the subject of their interest.

Although there is a wide variety of joints, it is usually the dovetail that is of primary importance in furniture making. It is one of the most durable joints, whether it is a through dovetail joint, a full-blind joint or another type, which often reflects the quality of the workmanship and the mastery of the joints.

The dovetail joint got its name because of its resemblance to the shape of a bird's tail. This joint, which takes its name from the shape of the outstretched dovetail, has an unusual strength and rigidity that enables it to withstand repetitive strain in different directions (Bajalo, 1957; Coppola, 1993). A dovetail joint is extremely strong and is used to join two pieces of wood, usually the fronts and sides of drawers or the corners of chests (De Cristoforo, 1992).

In this paper, the importance and craftsmanship of handmade joints in woodworking will be explored, with a particular focus on the dovetail joint, which is a symbol of quality in traditional two-piece joinery. Additionally, as a practical supplement to literature review, the handmade creation of dovetail joints will be demonstrated, as well as bonding techniques including box joint, mitered-through dovetail, half-blind mitered dovetail and half-blind dovetail.

The aim of the paper is to highlight the importance of these joints today in the production of solid wood objects, especially in restoration, where the aesthetic and artistic component is very important in addition to functionality, and the craftsman's skill is required in the production process. Understanding the evolution of the described compounds will help readers appreciate how much woodworking technology and construction methods have advanced in the production of objects of artistic and historical value.

2 FROM CRAFT TO SYMBOLISM: LEGACY OF TRADITIONAL WOODEN JOINTS
2. OD OBRTNIŠTVA DO SIMBOLIZMA: KULTURNO NASLJEĐE TRADICIONALNIH SPOJEVA ZA DRVO

Through comprehensive literature research, the historical, structural and aesthetic value of traditional wooden joints will be explained, particularly in furniture making, their role in maintaining durability and beauty and their symbolic association with human skill and history.

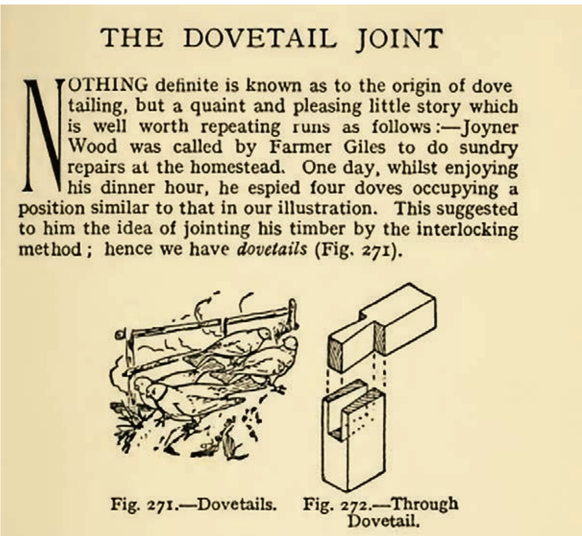
In this article, the literature was selected according to the criteria of the basic principles of conservation and restoration of wooden objects. The experience of conservators and European institutes, that train students in conservation and restoration all over the world, has been used. The literature in this paper is mostly from older publications, which is entirely understandable given the historical nature of the subject. Recent publications are either reprints or reiterate established information about wood joints, with a particular focus on the dovetail joint.

Kirby (2001) describes wood joined so that it cannot be split lengthwise. Most joints require some form of mechanical reinforcement to withstand the force exerted on the object (Morić, 1995). Therefore, even though a properly glued joint is stronger than the wood fibres themselves, the adhesive will hardly withstand the forces acting on the joint when the furniture is in use. In addition to this property that provides strength, it is also very decorative (Rogowski, 2002). Whether crafted from a special, expensive wood, or a less expensive one, this joint is extremely attractive due to the contrast created by the different orientation of wood fibres (Banister, 1896). The construction of an object consisting entirely of wooden elements and wooden connecting elements certainly has a striking visual appeal (Granić, 1964). The characteristics of traditional joints are aesthetics, durability, and strength (Bierling, 1989; Pieresca,1992)

The small, subtle imperfections of the wood and the patina that inevitably comes with age inspire the observer to reflect and meditate on time, transience and the inherent imperfection of life. On the other hand, joints speak of perfection, the desire for enhanced performance, the precision of the cut and the final stroke of the chisel. An object crafted or built without other aids lasts longer because it harmonises with nature. The use of other materials to fix the wood disrupts the natural synergy.

2.1 A brief historical overview of development of dovetail corner joints
2.1. Kratki povijesni pregled i razvoj spoja *lastin rep*

One of the first joints that is often seen in old photos of antique furniture is a plain butt joint reinforced with a dovetail insert. (Figure 1). Edwards (2012) states that most high-quality antique furniture had a dovetail joint in its construction, which was so


THE DOVETAIL JOINT

NOTHING definite is known as to the origin of dove tailing, but a quaint and pleasing little story which is well worth repeating runs as follows:—Joyner Wood was called by Farmer Giles to do sundry repairs at the homestead. One day, whilst enjoying his dinner hour, he espied four doves occupying a position similar to that in our illustration. This suggested to him the idea of jointing his timber by the interlocking method; hence we have *dovetails* (Fig. 271).

Fig. 271.—Dovetails. Fig. 272.—Through Dovetail.

Figure 1 Image showing tails of four doves (left) from which a wooden joint (right) was created (Fairham, 1910)
Slika 1. Prikaz repova četiriju golubica (lijevo) na temelju kojih je kreiran drveni spoj (desno) (Fairham, 1910.)

effective that it was used for centuries and continues to be used today in the manufacture of unique pieces, as well as in the restoration of furniture. For thousands of years, this joint has been made by the hands of master carpenters who used small precision saws and hand-forged chisels to finish the joints. Tails on one side and pins on the other, were precisely measured and manufactured to fit perfectly into a joint. Once the joint is completed, the individual pieces of wood become a single body of beauty and strength that can endure for centuries (Forest Products Laboratory, 2010).

Carpentry is the craft of joining wood, and in the context of structural connections, this term "traditionally" refers to wood-wood connections that are linked together by geometries that can provide the interlocking and friction necessary to transfer loads between elements while maintaining rigidity. Heritage structures with wood-wood connections can be found worldwide and date back hundreds or thousands of years depending on the locality (van Nimwegen and Latteur, 2023).

Many traditional techniques are millennia old, like Tibetan building techniques that date back 4500 years, and centuries-old timber structures like the Potala Palace and Jokhang Temple that still stand today (Guo *et al*., 2021). Structures with Dou-gong brackets, a common joint dating back as far as 770 BC, can still be found throughout heritage timber buildings in China, Korea, and Japan (Arlet, 2021). Egyptian archaeological sites have been known to exhume millennia old woodworking tools like hand saws, chisels, and mallets alongside artworks depicting carpenters using these tools (Lucas, 1934). This method can already be recognised in the Egyptian era in the furniture in which mummies were buried, in the pyramids and in the furniture built for the Chinese emperors (Janson, 1997). The dovetail dates back to the time of Ancient Egypt (1st Dynasty), 3000 BC at the latest, as it was found on various pieces of furniture, coffins and ivory from this period (Nicola *et al*., 2008). The earliest examples of this joint can be traced back to furniture that was kept together with mummies in ancient Egypt, as well as in the tombs of Chinese emperors and in Indian temples (Banister, 1896).

In his Ten Books of Architecture (25 BC), the Roman architect Vitruvius reports on methods of roof beam construction, including the use of "dovetail dowels". It is obvious that the compound was also used in construction, which can be seen in Roman buildings, where it appears in the manufacture of various pieces of furniture as well as in building structures. Vitruvius (1st century BC) mentions the use of a securicla (hatchet), i.e. a dovetail, in his discussions on the construction and methods of assembling roof beams. Although the observation of the transition from the Roman era to

Figure 2 Dovetail joints shown on the chest in the painting The Death of the Virgin, Dürer, 1506. (Reprinted from Hutchison (1990) with permission of Princeton University Press)
Slika 2. Spoj *lastin rep* prikazan na škrinji s Dürerove slike *The Death of the Virgin*, 1506. (preuzeto iz: Hutchison, 1990., uz suglasnost Princeton University Pressa)

the Middle Ages is very delicate and complex, it is clear that different variants of the dovetail continued to appear during this period (Charlish, 1976).

Early types of dovetail joints were quite large, even unwieldy, often additionally fastened with nails due to the tools that existed at the time. As the fineness of the tools changed, so did the joints become finer and neater (Welsh, 2011).

There is some evidence of dovetail chests in England from early times. A monk who was present when the tomb of St. Cuthbert (who died in 687 but was reburied several times) was opened in 1104 noted that one of the chests containing the mortal remains was made of jagged planks joined in different directions (Eames, 1977). Contemporary European art also provides us with visual representations of the use of the dovetail (Pischel, 1975).

The paintings by Dürer (Hutchison, 1990) along with a chair and a chest from 1506 (Danube School, 1522, Figure 2), show the common application of this joint in wooden furniture and other everyday items. It can be concluded, from the literature, that the development of this joint was a process of improving structural solutions over the centuries.

A development in the production of chests and small decorative caskets can be recognised in Italy in the 14th century (Figure 3), although the joints are often concealed by external decorations.

Figure 3 Dovetail corner joints on the chest from 14th century (https://tinyurl.com/297vu8of)
Slika 3. Spoj *lastin rep* na bočnim stranama škrinje iz 14. stoljeća (https://tinyurl.com/297vu8of)

The joint mentioned was already used in antiquity, but it was not widely used until the 16th century, when the art of furniture making emerged as a distinct craft, separate from carpentry or woodworking. Originally this joint was made by hand, cut with a small saw and a chisel and glued with animal glue (Kumar, 2021).

English cabinetmakers began using dovetail joints on walnut furniture in the mid-17th century and continued to do so until the end of the 19th century when they were machine-made, particularly in the Edwardian period (Roe, 1902).

The secretary cabinet shown in Figure 3a, dating from around 1780, was made by a good countryside cabinetmaker. The dovetail on the side of the drawer was executed in the same way as the joint of the top and side boards (Melchert, 2003).

Dubarry de Lassale (2022) describes the evolution of dovetail crafting during the Empire and Restoration periods, spanning from 1804 to 1830, when the number of dovetail lines on commodes increased to seven (Figure 4).

This joint was most prominent and widely used in the making of drawers during the 19th century (Oats, 2021). It was revolutionary in every respect, resulting in numerous changes, which in this case required an increased need for the manufacture of furniture, especially furniture with drawers (Rivers, 2003). It was precisely for this reason that numerous patents were created, i.e. mechanical machines that could address this challenge. These various patents found the most fertile ground on the new continent, where between 1833 and 1900 numerous inventors registered 106 inventions of dovetailing machines (Reynolds, 1873). Over time, they evolved to become more refined and smaller with an increased number of pins, and their evolution reached its peak in the 19th century. There were no fixed rules for craftsmanship, it depended mainly on the craftsmen, their skills and the type of workshop they belonged to. In the larger workshops, there were masters who specialised only in the production of tenons (Arnston, 1965). This need gave rise to the art of making joints. In terms of furniture, it is necessary to establish a structural sys-

a) b) c) d)

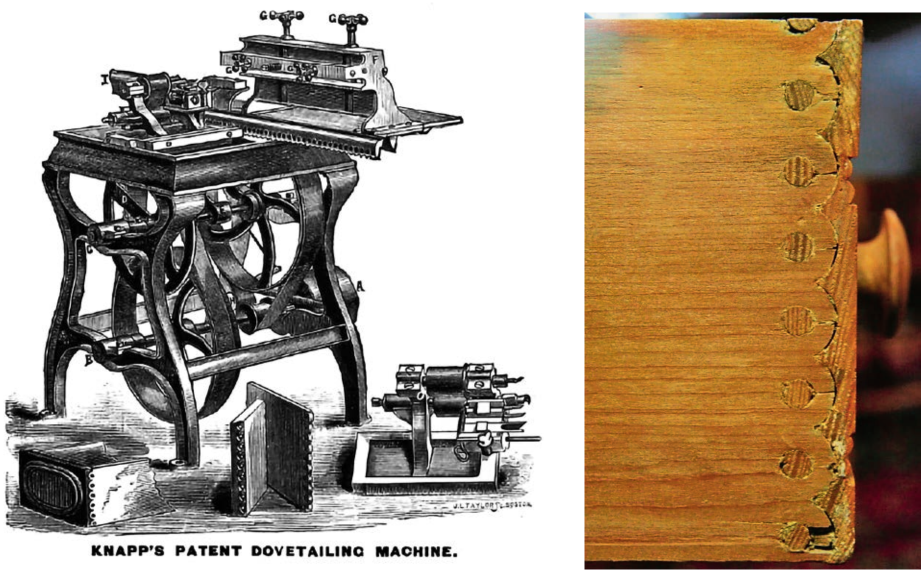
Figure 4 Display of dovetail joint in different countries: a) joint between the back and side panel of a chest, England, 1780 (https://tinyurl.com/2d72mlj8); b) drawers of a chest, Italy, 1825 (https://tinyurl.com/2636bz97); c) side panel of a chest, France, 1780 (https://tinyurl.com/2xmv9py4); d) wall joint in a wooden house, Croatia, 1902 (Živković, 2013)
Slika 4. Prikaz spoja *lastin rep* iz različitih država: a) spoj leđne i bočne strane škrinje, Engleska, 1780. (https://tinyurl.com/2d72mlj8), b) ladice škrinje, Italija, 1825. (https://tinyurl.com/2636bz97), c) bočna strana škrinje, Francuska, 1780. (https://tinyurl.com/2xmv9py4), d) spoj zidova na drvenoj kući, Hrvatska, 1902. (Živković, 2013.)

tem that justifies the durability and enhances the aesthetics of the piece.

As it evolved over the past 150 years, this joint has become an important factor in determining the age of an object. The dovetail joint model reveals a lot about the furniture and the period in which it was made. The craftsman's dexterity and skill are evident and reveal whether an object was made by hand or by machine. Until 1870, handmade joints were common all over the world. The date of manufacture of antique furniture can be estimated by examining the dovetail joint. If the joint was cut by hand, that indicates that it is a pre-1880 piece, and a more primitive cut usually means that a piece is from an earlier period (Mercer, 1929).

In the 1870s, inventors in America developed the first commercial machine for industrial production of furniture, which did not gain much popularity outside America and Canada. The so-called round style dovetail was produced, which is commonly found in furniture from the late Victorian period (Aronson, 1965) (Figure 5a).

The development of technologies that enabled faster manufacturing and mass production in this area followed in the 1890s, also in America. This marked the beginning of mass production of furniture for the rapidly growing upper middle class (Arnston, 1965). Machine-made joints are just as durable and long-lasting as those made by hand, but every cut is exactly the same, with no deviation, which is not the case with hand-made joints. That became the standard in furniture production in America from 1890 - until today. If you have an antique piece of furniture that features drawers with a curious-looking half-circle joint, you can be almost certain that it was made in a North American factory between 1871 and 1900. While it came to be known as the Knapp Joint, the joint is also variously



a) b)

Figure 5 a) Dovetailing machine (American Artisan, 1871), b) example Knapp dovetail (https://tinyurl.com/2c96woqf)
Slika 5. a) Stroj za izradu zubaca (American Artisan, 1871.), b) primjer spoja izrađenog Knappovim strojem (https://tinyurl.com/2c96woqf)

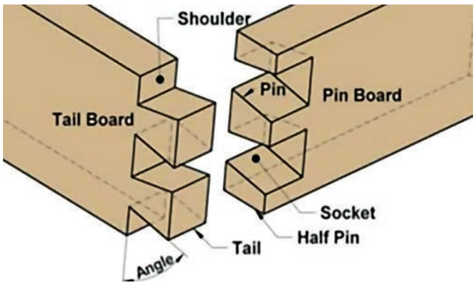


Figure 6 Mitered-through joint with marked details (https://tinyurl.com/23rcy6wb)
Slika 6. Spoj s otvorenim zupcima i označenim detaljima (https://tinyurl.com/23rcy6wb)

Figure 7 Robust miter joint (https://tinyurl.com/22ebx3l9)
Slika 7. Robusni spoj *lastin rep* (https://tinyurl.com/22ebx3l9)

described by its appearance: the pin and cove, scallop and dowel, scallop and peg, pin and scallop, and half-moon (Figure 5b)

Why the (rather brief) departure from dovetails? By the second half of the 19th century, most furniture in America was made by machines in industrialised factories—with the exception of fine drawers. Though people were patenting machines that could produce dovetails (106 patents for the like applied for between 1833 and 1900!), no one had yet developed an appealing way to cut more than one uniform pin and tail at a time (See the Burley & Putman Dovetailing machine, patent nos. 12,122 and 26,647).

From simple carpentry to sophisticated decorative joints, from basic construction techniques to the highest standards in furniture making - dovetail joints represent the history of furniture making, wood construction and production. This open miter joint was crafted in wood construction/carpentry, using a "dovetail" shape that is projected onto wood designed to fit wood of equal size. (Figures 6, 7).

There is a great deal of literature attesting to the importance of handmade joints, especially dovetails. The joint is still interesting today because of its aesthetic and mechanical properties, and not only in restoration (Bullar, 2013; Bridgewater *et al*., 2014; Fleming 2020).

The master carpenters were not overly satisfied with this type of joint, as the adhesive properties, i.e. the adhesion of the veneer to the joint, were not adequate when the veneer was applied. Other types of joints such as "half-blind mitered joint" and "secret mitered joint" have arisen from this need (Jones and Lutes, 1993).

2.2 Crafting traditional joints: tails and pins (teeth)
2.2. Izrada tradicionalnih spojeva: repovi i igle (zupci)

2.2.1 Materials for making dovetail joints
2.2.1. Materijali za izradu spojeva *lastinim repom*

Dovetail joints are very common in carpentry due to their strength and aesthetic value. They were mostly used to join pieces of wood together at an angle to make solid wood furniture (Jackson *et al*., 1996). The wood used for these joints must be sufficiently strong, stable and resistant to bending. Research by Hoadley (2013) has shown which types of wood are traditionally used to make dovetail joints.

Oak is the best known and most valued timber material for the manufacture of dovetail joints due to its exceptional strength, stability and durability.

Ash is also very popular for the production of dovetail joints due to its strength and flexibility, slightly softer than oak used in furniture construction and very impact resistant.

Walnut is a wood that is used for the production of high-quality furniture. Due to its fine texture and beautiful colours, walnut wood is highly valued in joinery, especially for making dovetail joints in furniture of high aesthetic and artistic value in restoration.

Pine is a softwood that is used for dovetail joints when the high strength of hardwood is not required.

Yew is a very resistant and stable wood used for precise joints, especially in the manufacture of antique furniture. It is wear resistant and has a beautiful texture that lends itself to fine detailing in dovetail joints.

Larch, the hardest wood species among conifers with a density of 590 kg/m^3 (when dry), medium strength, which enables the cutting of precise joints. Resistant to moisture and rot, aesthetically and decoratively interesting due to the fineness of the rings and the colour. When choosing the type of wood for dovetail joints, the key criteria are strength, resistance to cracking, and stability to retain shape over time. Dovetail joints provide high joint strength, support loads, and require great precision in manufacturing, which is crucial for the longevity and stability of furniture.

In this paper, handmade creation of dovetail joints will be demonstrated. For that purpose, larch wood was used, which was sawn from larger logs with bark to the appropriate dimensions, after calculating the size and number of teeth.

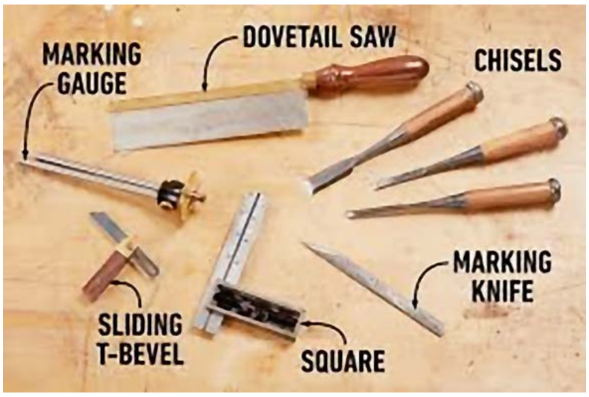


Figure 8 Dovetail tool (https://tinyurl.com/256zlqyf)
Slika 8. Alat za izradu spoja *lastin rep* (https://tinyurl.com/256zlqyf)

Figure 9 Captain Vlaho Podic's sea chest from 1871, dovetail corner joints
Slika 9. Pomorska škrinja kapetana Vlaha Podića iz 1871, kutni spoj *lastinim repom*

2.2.2 Hand tools for making dovetail joints
2.2.2. Ručni alati za izradu spoja *lastin rep*

After selecting the type of wood, it is necessary to choose the appropriate tools for manually making joints (Moxon, 2013). Specific hand tools are recommended for making dovetail joints, as they allow for precise shaping and the creation of a strong joint. The main tools (Glennon, 2018) used for this type of joint are: hand saws for precise cutting of wood according to the required dimensions of the joint; fine saws for precise cutting along thin lines, ensuring that the joints are accurate; a flat chisel for removing excess material and precisely shaping the joints; a specialised chisel with a thin blade for shaping the interior of the joint and detailed wood sculpting, especially in narrow and precise joint spaces; a wooden or rubber mallet for striking the chisel to shape the details of the joint; a marking gauge for marking the depth of the cut; a marking knife for exact marking of the cut line; clamps for fixing wooden pieces; a combination square and dovetail marker; scrapers for smoothing and levelling the joint surfaces; and files and fine planers for fine finishing of the joint, removing sharp edges, or precisely adjusting the joint dimensions (Figure 8).

2.2.3 Making and use of dovetail joints today
2.2.3. Izrada i upotreba spojeva napravljenih *lastinim repom* danas

The production and use of dovetail joints still plays an important role in modern woodworking, especially in the production of high-quality furniture, individual pieces and in the restoration of antiques. Today, CNC (computer numerically controlled) machines are often used to produce precise joints that speed up production and ensure high accuracy (https://tinyurl.com/2beapzom)

However, many craftsmen still prefer to produce dovetail joints by hand due to their aesthetic appeal and symbolic value. Dovetail joints are still widely used in furniture making, especially for the construction of drawers and boxes, as they offer exceptional stability and durability. These joints help to distribute weight evenly and prevent damage, which is crucial for the long-term performance of furniture (Conover, 2009.)

The use of these joints imparts a traditional aesthetic to furniture, enhancing its overall visual appeal. In some cases, the joints are intentionally left exposed as a decorative feature.

Reviewing the literature, it is surprising how frequently the dovetail joint is depicted and described. It can be concluded that this joint was not used solely for its aesthetic appeal, as noted in the literature, but also for its durability, stability, and functionality. Restored objects dating from the 18th and 19th centuries are predominantly inlaid and polished, with some even featuring polychrome surfaces, yet all share the structural characteristic of dovetail joints. It is well understood how challenging surfaces with inlays and intricate patterns can be. Even after so many years, these objects remain stable and retain their significant artistic value, thanks to the dovetail connection provided the necessary stability and strength to the entire structure.

The marinet chest from 1871 has a painting on the entire surface, which has remained sufficiently stable because the dovetail joint connecting front and side panels (Figure 9, orange markings on the right-hand side of the picture) not only enhances the aesthetic impression of the chest but also ensures the construction of the period and the painting on the surface. This shows that the dovetail joint is durable, reliable, strong and stable for objects of historical value. Therefore, the preservation of these joints is unquestionable, even if they are not attached to the fronts but to the inside, as the example in Figure 10. The drawers of a chest of drawers from the 19th century, which is completely veneered and polished, retain the stability of the entire body and thus the aesthetically refined surface. The

a) b)

Figure 10 Drawers of a chest: a) drawer front, b) drawer back
Slika 10. Ladica škrinje: a) prednja strana b) stražnja strana

dovetail joint is part of the historical heritage and there is a need to demonstrate its importance as the most important constructive element of a wooden object cultural heritage.

There would be movement in the supporting elements, leading to instability in the painted and inlaid surfaces of wooden objects, as seen in paintings from the 19th century. The importance of the dovetail joint lies not only in its historical significance but, more importantly, in its structural function.

Today, dovetail joints are frequently employed in the restoration of antiques, where preserving traditional techniques is considered crucial. They are also commonly used in the luxury market, where superior craftsmanship and long-lasting durability are essential.

3 ART OF DOVETAIL JOINTS: A PRACTICAL EXPLORATION OF TRADITIONAL HANDCRAFTING
3. UMJETNOST SPOJEVA *LASTINIM REPOM*: PRAKTIČNO ISTRAŽIVANJE TRADICIONALNE RUČNE IZRADE

Based on the knowledge of the historical development, a practical example of the production of the dovetail joints has been presented. The importance of preserving the tradition of handcrafting techniques is demonstrated from the selection of the type of wood used to make the joints and the tools used to make the joints by hand, to the determination of the pattern dimensions, number of patterns, determination of the size, arrangement and spacing of the teeth of dovetail joint. The wood was sourced from the remnants of previously used larch boards, measuring 37 cm × 45 cm × 5 cm. These were used to create a handmade box joint, beveled foundation dovetail, semi-blind beveled dovetail, full blind dovetail, and dovetail joint. The bark was removed from the wood, and the resulting samples were sawed in half in both directions. The pieces were then glued together to a dimension of 16 cm × 16 cm. This procedure was carried out with 12 samples. The materials used for crafting the dovetail joints included simple hand tools: a saw, chisel, hammer, and measuring and drawing tools.

3.1 Methodology for making a dovetail joint
3.1. Metodologija izrade spoja *lastin rep*

Determining the size, arrangement, and spacing of the teeth in a dovetail joint (the so-called “tooth joint”) requires precise planning to ensure that the joint is strong, aesthetically pleasing, and functional. Based on examples from the literature, the following is an overview of the process for making a dovetail corner joint, accompanied by illustrations: divide the end of one piece into six equal divisions. Use a doventail template and pencil to mark on the tails shade the areas to be removed. Mark the lines across the top and down the other side. Place the wood in the vice at a slight angle, so that sawing is vertical (straight down). Take care to saw on the waste wood side of the lines (which will be removed after making each „tooth“) using a doventail saw. Use a coping saw to remove the waste wood, cutting just above the depth line between each tail. The blade of the coping saw may need turning sideways (Figure 11).

Analysing the literature for standard guidelines for tooth size, it was determined that the height of the tooth should be between 1/3 and 1/2 the thickness of the wood, the width of the tooth should be approximately 1/2 to 2/3 the width of the wood, and the number of teeth in a dovetail joint will depend on: the dimension of the joint (the number of teeth increases with larger joint dimensions; smaller joints may have 4-6 teeth, while larger joints may have 8 or more), the function of the joint (depending on the load, the number of teeth will be greater to increase the strength of the joint; for lighter loads, fewer teeth may be needed), and aesthetics (in fine wooden objects, the number of teeth may be fewer, while in more massive structures such as boxes and drawers, it may be greater).

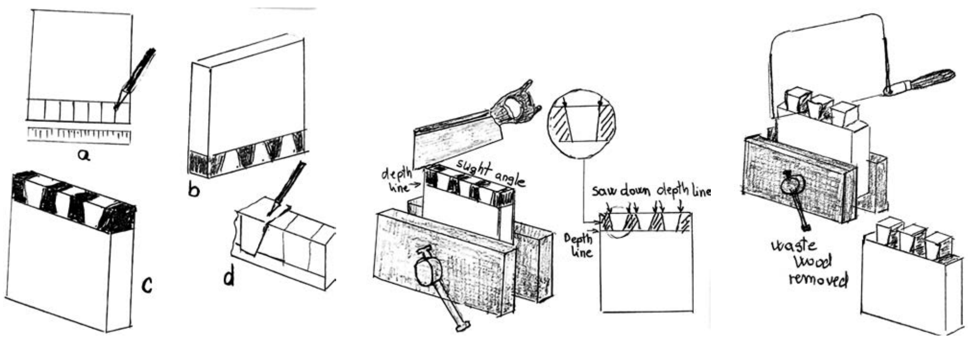


Figure 11 Making a dovetail join
Slika 11. Izrada spoja *lastin rep*

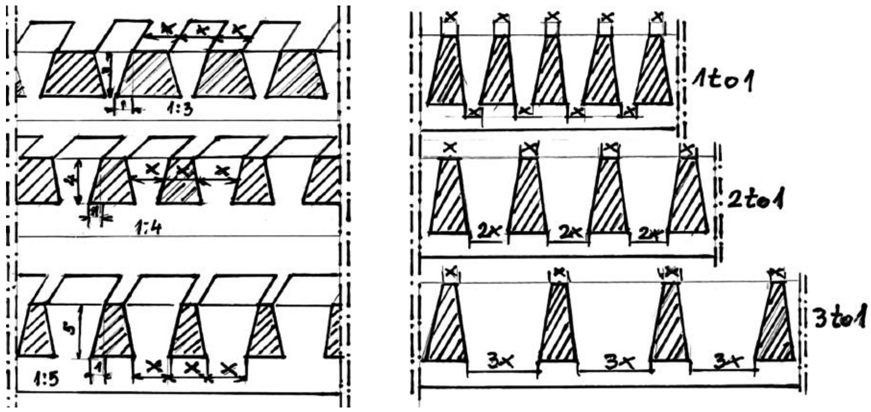


Figure 12 Different ratios in dovetail joint
Slika 12. Različiti omjeri u spoju *lastin rep*

The recommended distance between the teeth is 1.5 to 2 times the width of the tooth (for example, if the width of the tooth is 10 mm, the distance between the teeth should be about 15-20 mm).

The angle between the teeth in a dovetail joint is about 7° to 14° (a smaller angle means a tighter joint, making it more difficult to create; a larger angle makes it easier to make the joint, but reduces its strength).

Proper sizing, placement, and spacing of teeth in a dovetail joint are critical for creating durable, functional, and decorative joints. Although parameters can be adjusted depending on the specific application and desired strength, ensuring the proper balance between height, tooth width, and spacing will allow for optimal results. The practicality and visual appeal of the "dovetail" in tenon joints are determined by the angle of the cut. The proportions and angles tell us a lot about the master as well as the degree of sophistication of the construction (Figure 12). The earliest ratio of the joints was usually 1:1 (<45°). In the early 17th and 18th centuries, the ratio was 1:2 or 1:3, which shows a not very sophisticated but nevertheless practical technique (Jones and Lutes, 1993).

It is generally recognised that the 1:5 (11°) or 1:6 (9.5°) ratio is the strongest version of the joint and the one most commonly used. Any ratio exceeding this,

Figure 13 Through dovetail, 1:5 (https://tinyurl.com/26lyt3am)
Slika 13. Spoj otvorenim *lastinim repom*, 1:5 (https://tinyurl.com/26lyt3am)

Figure 14 Half-blind dovetail, 1:8 (https://tinyurl.com/28xv4f2w)
Slika 14. Spoj poluzatvorenim *lastinim repom*, 1:8 (https://tinyurl.com/28xv4f2w)

such as 1:7 or 1:8 (7°), as we can see on furniture designs from the end of the 18th century, represents an exaggeration both in terms of construction and functionality (Figure 13 and 14). All variants and types of joints are originally made by hand, chisel or saw, or a combination of these. Written markings are often visible as a guide for the craftsman when measuring and cutting, and small irregularities in the size and spacing of the cuts are common. The value of skill in crafting these joints is undeniable, so this paper will demonstrate the manual production of tenon-dovetail joints.

4 PRACTICAL EXAMPLES: HAND-MADE DOVETAIL CORNER JOINTS
4. PRAKTIČNI PRIMJERI: RUČNA IZRADA SPOJA *LASTIN REP*

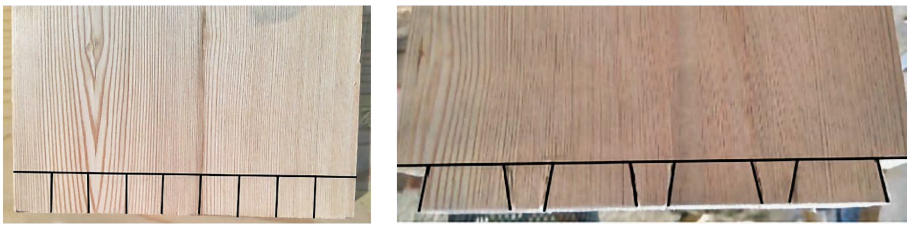
Based on historical records research, this paper offers a brief account of the process of making tenons with traditional hand tools, such as saws and chisels, which requires unique skills of craftsmen.

The process of crafting tenons begins with the selection of high-quality wood that has a uniform texture and fibres. In addition to selecting the wood, it is also important to determine the size of the tails and pins by measuring and marking them accurately.

After measuring and marking (Figure 15 and 16), several cuts were made within the marked lines using a saw, ensuring that removing the marked parts with a chisel would not cause the fibbers to be pulled out or the wood to crack. The wood on which the teeth are made is additionally reinforced with two boards; black arrows indicate one on the back, at the height of the teeth, and the other along the bottom line, corresponding to the depth of the teeth (Figure 14a and 14b). The reason for the additional reinforcement is to provide resistance to the force of the chisel impact and prevent damage when making the teeth. After finishing one side halfway with the chisel, the board needs to be turned over, and the rest should be removed with the chisel, repeating the process. The reason for not chiselling all the way through on one side is that it could cause the wood to crack, and this method avoids that. The result is a clean and neat joint (Figure 14c).

In this example of making semi-open oblique teeth, the height of the teeth is 1/3 shorter than the thickness of the wood, because the second part extends up to 2/3 the thickness of the wood (Figure 17). When making furniture, this joint is placed at the front side, (e.g., for a drawer).

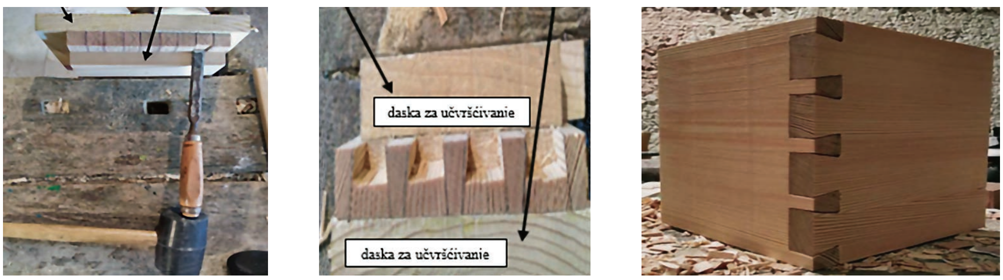
Making a joint with hidden teeth is a process where the teeth cannot be seen from the outside. This joint is used in the production of finely polished furniture. When making this joint, 1/3 of the height of the wood is removed, but not the entire thickness - only 2/3 of it. Then, lines are drawn on the resulting face, along which oblique teeth are made. These teeth are cut at an angle of 45°, so that when they are subsequently joined with the other part, an angle of 90° is formed, and the joint itself remains hidden (Figure 18).



a) b)

Figure 15 Marking patterns for making dovetail corner joints: a) straight teeth of a dovetail joint, b) angled teeth of a dovetail joint

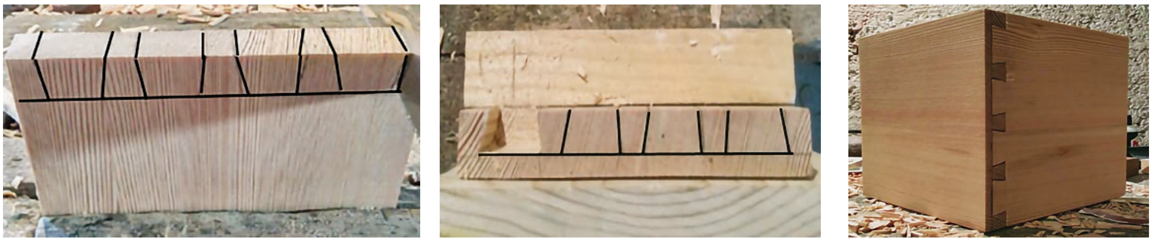
Slika 15. Oznake pri izradi kutnih spojeva *lastin rep*: a) ravni zupci spoja *lastin rep*, b) kosi zupci spoja *lastin rep*



a) b) c)

Figure 16 A mitered-through dovetail: a) marking out, black arrows indicate auxiliary panels used to secure the joint, b) hand crafting, c) final joint

Slika 16. Otvoreni spoj *lastin rep*: a) označivanje: crne strelice označuju pomoćne ploče koje služe za učvršćivanje spoja, b) ručna izrada, c) izrađeni spoj



a) b) c)

Figure 17 Crafting a semi-blind mitered dovetail: a) marking out, b) crafting, c) final joint
Slika 17. Izrada poluzatvorenog spoja *lastin rep*: a) označivanje, b) izrada, c) izrađeni spoj

a) b) c)

Figure 18 Crafting a full-blind dovetail: a) marking out, b) crafting c) final joint
Slika 18. Izrada zatvorenog spoja *lastin rep*: a) označivanje, b) izrada, c) izrađeni spoj

Dovetail as reinforcement is another useful application of this joint element. It is used to strengthen and secure a wooden joint on a flat surface that is reinforced with a dovetail insert that prevents the joined surface from coming loose. Reinforcement is used in the production of tabletops, larger altar surfaces with carved boards, floors and wall panelling. With a cut, the wood is sawed in half. A dovetail shape is carved into the resulting pieces (Figure 19), which will eventually be joined with a piece of wood in the shape of a dovetail.

The art of making the above-mentioned traditional joints, which can be traced back through history, is particularly interesting in workshops for the restoration of furniture and other historical wooden components (ceilings, floors, altars).

The results of handmade dovetail joints in a restoration workshop, based on the literature, show that they still have the same importance in the manufacture of solid wood furniture today, after centuries of use.

5 CONCLUSIONS
5. ZAKLJUČAK

Traditional joints in furniture making have evolved over the centuries with no major variations in production, except that they have become more precise and finer in execution. Drawings and calculations from the literature are used to show how the traditional joints are made using simple tools, saws and chisels. It is obvious that the joint has been used for centuries because of its properties: Strength and stability, durability, aesthetics, preservation of tradition and acquired skills. This paper emphasises the importance of preserving traditional methods and their application in today's world of cultural heritage preservation and presents an

a) b) c)

Figure 19 Crafting of a dovetail joint: a) elements, b) making a groove, c) final joint
Slika 19. Izrada spoja *lastin rep*: a) elementi, b) izrada utora, c) izrađeni spoj

example of the production of open, semi-open and concealed dovetails, focusing on the name of the joint corner dovetail. In the restoration of wooden objects, the dovetail joint is still the most common today, and knowledge of the development and skills involved in making the said joint is necessary for students studying conservation and restoration. It can be concluded that this joint was not used solely for its aesthetic appeal, as noted in the literature reviewed for this paper, but also for its durability, stability, and functionality. Over the last 30 years, there have been fewer and fewer students in woodworking schools. The skills that master carpenters had in the manual production of joints in solid wood are rarely passed on to students. It is therefore particularly important that traditional joints continue to be made by hand so that they can be used in the restoration of wooden objects in the future.

Today we admire master carpenters who were inspired by their own culture, historical influences and the beauty of nature and the materials that nature gave them, creating works of art with their own hands and simple tools. In addition to the external beauty, there is the skill and knowledge of the masters, who have passed on their furniture-making expertise from generation to generation and perfected the execution of dovetail joints. However, the harmony of the creation conceals the complexity of the joint itself. Nothing can replace the elaborate joining technique, neither in terms of aesthetics nor design, and especially not in terms of the quality of the workmanship. From today's perspective, one can only admire the ingenuity, virtuosity and patience of master craftsmen in the production of solid wood furniture.

Although dovetail joints offer undeniable advantages such as exceptional strength, durability and aesthetics, they are not without drawbacks. The production of dovetail joints requires a high level of precision and craftsmanship, making them very demanding and sometimes time-consuming. Furthermore, the process can be slow and requires a lot of patience due to the manual labour required, which can be a challenge in today's industrial production, which is focused on speed and efficiency. Furthermore, while the joint is extremely strong, it is sensitive to changes in humidity and temperature, which can lead to deformation if not done properly or if unsuitable materials are used. Despite these disadvantages, the dovetail joint is still a symbol of high quality in furniture construction and has its place in modern restoration practise, where it is still used in the restoration of historical wooden objects.

Examples shown in Figure 9 and 10 confirm all the listed properties of the dovetail joint with particular emphasis on the durability, hardness, elasticity and stability of wooden objects from the University wood restoration workshop.

From today's perspective, it can be concluded that joints such as the dovetail joint are still essential for the preservation of cultural heritage, but that it is important to balance them with innovation to ensure the longevity of these skills in a modern context.

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