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Mahadi Mussa*, Lamesa Abara, Misganaw Wale, Tsegaye Wubushet, Samson Waktole, Getachew Mezgebu, Getachew Desalegn, Daniel Gebeyehu[1]

Development of Laminated Bamboo Lumber from Lowland Bamboo (*Oxytenanthera abyssinica*) Culms Grown in Pawe, Ethiopia

Izrada lamelirane građe od stabljika nizinskog bambusa (*Oxytenanthera abyssinica*) uzgojenoga u Paweu, Etiopija

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ABSTRACT • *The aim of this paper was to develop laminated bamboo lumber (LBL) from the two-culm position of Oxytenanthera abyssinica (O. abyssinica) and to examine its basic physical and mechanical characteristics. Samples of lowland bamboo (O. abyssinica) culms were selected and harvested from Pawe Agricultural Research Center site, Pawe, Ethiopia. Three-ply LBL samples were fabricated using urea formaldehyde resin, and then sample specimens were prepared from the fabricated LBL, and the selected basic properties were tested including density, static bending, impact bending and hardness strengths. The result depicted the mean values of density (863 kg/m³), modulus of elasticity (15743 N/mm²), modulus of rupture (149 N/mm²), impact bending strength (18633 Nm/m²), and side hardness (3145 N) obtained in the fabricated LBL of O. abyssinica culm. The results revealed that density and the tested mechanical properties in this study were significantly affected by culm position in the culm height, with the exception of the impact bending, which was not affected by culm position. Superior density and strength performances were observed in the middle position of bamboo compared to the bottom position. The laminated bamboo lumber produced from O. abyssinica culm has the potential to be utilized as a substitute for wood material in building and other end products.*

KEYWORDS: *culm position; density; hardness; modulus of elasticity; modulus of rupture*

SAŽETAK • *Cilj ovog rada bio je napraviti lameliranu građu od bambusa (LBL), i to od dva dijela stabljike Oxytenanthera abyssinica (O. abyssinica), i ispitati njezina osnovna fizička i mehanička svojstva. Uzorci stabljike nizinskog bambusa (O. abyssinica) odabrani su i ubrani s lokacije Poljoprivrednoga istraživačkog centra Pawe u Paweu u Etiopiji. Troslojni uzorci LBL-a izrađeni su upotrebom urea formaldehidne smole te su ispitana ova osnovna svojstva: gustoća, čvrstoća na savijanje, čvrstoća na udarce i tvrdoća. Za lameliranu građu od stabljike bambusa dobivene su ove srednje vrijednosti: gustoća 863 kg/m³, modul elastičnosti 15 743 N/mm², modul loma*

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149 N/mm², čvrstoća na udarce 18 633 Nm/m² i bočna tvrdoća 3145 N. Rezultati su pokazali da na gustoću i ostala testirana mehanička svojstva znatno utječe položaj uzorka s obzirom na visinu stabljike, osim na čvrstoću na udarce. Izrazito bolje vrijednosti gustoće i čvrstoće uočene su u uzoraka uzetih sa sredine stabljike u usporedbi s uzorcima s njezina donjeg dijela. Lamelirana građa proizvedena od bambusove stabljike može biti zamjena za drvni materijal u graditeljstvu i za proizvodnju drugih gotovih proizvoda.

KLJUČNE RIJEČI: *položaj na stabljici; gustoća; tvrdoća; modul elastičnosti; modul loma*

1 INTRODUCTION
1. UVOD

Bamboo is classified under the taxonomic groups of the Bambusoideae subfamily and the Gramineae family. According to Vorontsova *et al*. (2016) and Srivaro (2018), bamboo species are naturally found throughout the world's tropical, subtropical, and mid-temperate regions. All over the world, there are around 1,600 bamboo species under 90 genera covering about 36 million hectares (Khalil *et al*., 2012; Vorontsova *et al*., 2016). The most widespread non-timber forest product in Africa, especially in eastern Africa, is wild bamboo. Ethiopia is one of the East African countries that are home to two native indigenous bamboo species, *Oldeania alpina* and *Oxytenanthera abyssinica* with a combined total area of over 1.47 million hectares (Zhao *et al*., 2018). It was also reported that more than 850,000 ha is covered by the lowland bamboo (*O. abyssinica*) (Zhao *et al*., 2018).

Despite bamboo abundance in Ethiopia, it has not been extensively utilized in high quality products. Recently, it has been used for rural housing, fencing, firewood, rudimentary furniture, crafts, mats, household utensils, and other low-value products (Monaco, 2019). They are mostly used in their round culm shape, which requires less complex processing. Consequently, the sector provides low economic returns to farmers and other actors along the bamboo industry's value chains (Monaco, 2019). Although bamboo is native to many countries, it is employed as a structural building material. For instance, bamboo has historically been utilized in Asia for low-rise structures, footbridges with small spans, long-span roofs, and construction platforms (Anokye *et al*., 2016).

The growing demand for wood and wood products has resulted in a decline in forest products in Ethiopia. Because of this, bamboo must be creatively developed to replace those slow-growing hardwoods for both structural and nonstructural uses. Due to its fast growth rate, rapid renewable energy, low embodied energy, wide availability, and versatile uses, bamboo has garnered significant attention recently as a sustainable building material (Rittironk and Elnieiri, 2008; Sulastiningsih and Nurwati, 2009; Mahdavi *et al*., 2011). It also shares similarities with structural wood products in terms of physical and mechanical properties.

Bamboo is the world's fastest-growing plant on the earth, reaching a maximum height of 15–30 meters in about two to four months, and growing up to 100 centimeters in a single day (Liese, 1987). In contrast to most softwood and hardwood tree species, which have rotations of 10–50 years, bamboo has a maturity age of roughly 3–7 years for construction and furniture uses and a short rotation life that may be harvested in 3-5 years (Desalegn and Tadesse, 2014). In comparison to a stand of hardwood tree species of a similar size, bamboo not only replenishes quickly but also releases twice as much oxygen into the atmosphere and consumes three times as much carbon dioxide (Akarsu *et al*., 2012). Comparing bamboo structural use to other typical construction materials like steel and concrete, the quantitative lifespan study of bamboo had less adverse environmental impact (van der Lugt *et al*., 2006).

Bamboo culms have been utilized recently in many different engineering projects, such as scaffolding, fiber-reinforced composites, columns, beams, rafters, and bridges (Sharma *et al*., 2015; Kelkar *et al*., 2020). Mahdavi *et al*. (2011) stated that the geometric configuration of the bamboo material, along with the presence of nodes within its culm, hinders its potential for development as a construction material and further into other products. The bamboo culm structure is difficult to use in structural parts (beams and columns) and generally where flat surfaces are required. Moreover, pins cannot be inserted into bamboo culms due to their low shear resistance, which makes it difficult to build larger structures that require connections. Additionally, compared to the internode culm region, bamboo nodal structures often exhibit lower mechanical qualities (compressive strength and tension strength), and its physical and mechanical attributes vary along the culm positions. Many scholars (Zakikhani *et al*., 2014; Li *et al*., 2016; Huang *et al*., 2018; Xuan *et al*., 2021) reported that these characteristics differ significantly based on the species, climatic conditions, soil type, age, density, silvicultural practices, etc. Consequently, it has been of interest to make bamboo available in forms more appropriate for its existing structural use.

Laminated Bamboo Lumber (LBL), typically made as a board with a rectangular cross-section, was developed as a result of this desire. LBL is an engineered bamboo product made by bonding bamboo materials in different shapes and sizes (such as strips, strands, and mats) with glue to create boards or sheets with rectangular cross sections that resemble lumber (Sinha *et al*., 2014; Sun *et al*., 2020). According to earlier research, the material's qualities are similar to those of wood and engineered wood products (Xiao, 2016; Sharma *et al*., 2017). To ascertain the physical and mechanical characteristics of the material to be used in construction and other end products, validation testing is necessary, just like with other non-conventional materials (Sharma *et al*., 2021).

Like raw bamboo culms, many factors such as species, climatic condition, location site, harvesting method, age, density, moisture content, and culm position, etc. can affect the mechanical and physical characteristics of LBL (Huang *et al*., 2018; Dauletbek *et al*., 2022). In Ethiopia, there is little use of bamboo culms for engineered bamboo because of inadequate knowledge and technology. As a result, the objective of this work was to create LBL from lowland bamboo (*O. abyssinica*) in two culm locations and test their physical and mechanical characteristics.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Sampling site description
2.1. Zemljopisni položaj uzorkovanja

The lowland bamboo (*O. abyssinica*) culms were collected from the Benishangul Gumuz Regional State of Ethiopia's Pawe Agricultural Research Center site. It is located 575 km from Addis Ababa. The mean annual temperature and annual rainfall precipitation of the site were 24 °C and 788 mm, respectively. The latitude and longitude of the site were 11°18'40''−11° 19' 29''N and 36°24'2''−36°25'27''E, respectively.

2.2 Selection and harvesting of bamboo culm samples
2.2. Odabir i prikupljanje bambusovih stabljika

The matured culms of 4-year-old lowland bamboo (*O. abyssinica*) were selected and harvested at about 20 – 30 cm above the ground using a machete and axe. The harvested lowland bamboo sample culms were sectioned into three positions (Figure 1a) along the axial direction (bottom, middle, and top), but since its top position was thin and not suitable to split, only the bottom and middle positions were used for this study. The average diameter of the culm at breast height and bamboo height were 7 cm and 6 m, respectively. After that, the bamboo culms were moved to the laboratory of the Forest Products Innovation Center of Excellence (FPICE) for further process evaluation.

2.3 Fabrication of laminated bamboo lumber (LBL) from *O. abyssinica*
2.3. Izrada lamelirane građe od bambusa (LBL) *O. abyssinica*

The collected lowland bamboo (*O. abyssinica*) culms from each position (bottom and middle) were split into 2 cm width strips by using manual bamboo splitters (Figure 1b) and hammers. The strips were dried to 12 % moisture content level in a conventional kiln-dryer (Figure 1d). A thicknesser machine was used to remove the inner portion and the outside waxy/silica layer simultaneously from the split and dried strips, resulting in a rectangular cross-section size of 20 mm × 7 mm (Figure 1e). Eventually, strips devoid of defects were chosen to create laminated bamboo lumber (LBL) of *O. abyssinica*.

Figure 1 LBL manufacturing process: Bamboo culm harvesting and sectioning (a), culm splitting (b), split strips (c), kiln drying strips (d), plaining strips (e), and clumping strips which is glued with UF resin (f)
Slika 1. Proces proizvodnje LBL-a: a) prikupljanje i rezanje bambusovih stabljika, b) cijepanje stabljika, c) cijepanje traka, d) sušenje traka u peći, e) ravnanje traka, f) lijepljenje traka UF smolom

Urea-formaldehyde (UF) in powdered form was purchased from the local market and used for the manufacture of laminated bamboo lumber. This UF resin is manufactured by Sprea Misr Company in Egypt. It has pH value of 8.0 – 9.0 and characteristics of fast curing, low toxicity and high strength, which is excellent for wooden materials such as wood-based panels, furniture, load bearing constructions, and wooden building products. To attain a 50 % solid content, the powdered UF resin was gradually added to water at a 1:2 ratio. Throughout the resin preparation process, constant stirring was done to prevent coagulation. During the LBL fabrication process, UF resin was applied on the dried bamboo culm strips manually using a brush. Layers of adhesive-coated strips were layered on top of layers of unglued strips. The strips were put together with the grains running parallel to one another. The strips were clamped together and left for 24 hours at room temperature (20-25 °C) (Figure 1f). Although the exact pressure was not measured, the sufficiency of the pressure was visually evaluated using glue squeeze-out and continuous interfacial surface contact. After 24 hours, the assembled strips were removed and cured for four days. The final measurements of 2.1 cm × 4 cm × 100 cm (thickness, width, and length, respectively) were obtained by trimming all the sides of the fabricated LBL samples. Finally, twelve 3-ply LBL sample boards were made in order to get specimens ready for studies on their physical and mechanical characteristics.

2.4 Determination of physical properties
2.4. Određivanje fizičkih svojstava

2.4.1 Moisture content (*MC*)
2.4.1. Sadržaj vode

The specimens were prepared from the fabricated LBL panels with a dimension of 20 × 20 mm^2 and length of 30 mm. Moisture content (*MC*) of the sample board was evaluated based on oven drying method according to the procedure ISO 13061-1:2014. The test specimens were first weighed using a digital weighing balance to ensure accuracy of 0.01 g, and then oven-dried at 103 °C. The specimens were kept in the oven until they attained the target constant weight. The following equation was used to compute and determine the moisture content of LBL of lowland bamboo:

$$Moisture\ content\ (\%) = \left(\frac{m_g - m_{od}}{m_{od}}\right) \cdot 100 \quad (1)$$

Where m_g – green weight of the specimen in gram, and m_{od} – oven-dry weight of the specimen in gram.

2.4.2 Density
2.4.2. Gustoća

Determination of density was conducted based on the procedure ISO 13061-2:2019. Density was determined using volumetric measurement method. The manufactured LBL panels were used to prepare a sample with dimensions of 20 mm × 20 mm × 30 mm. Specimen blocks were reweighed to determine the oven-dried weight after being oven dried at 103 °C until a consistent weight was reached. The following equation was used to calculate and find the density of LBL:

$$Density\ (kg/m^3) = \frac{W}{V} \quad (2)$$

Where W – specimen weight at test in kg, V – specimen volume at test in m^3.

2.4.3 Shrinkage
2.4.3. Utezanje

Specimens representing two culm heights were prepared from LBL of *O. abyssinica* culm with a dimension of 20 mm × 20 mm and length of 30 mm for determination of tangential, radial, longitudinal and volumetric shrinkages. The specimens were subjected to an oven drying process at (103±2) °C after the weight and dimensions were assessed with an analytical balance and digital caliper, respectively, yielding measurements with a precision of 0.001g and 0.001 mm. Until a consistent weight was achieved, the specimen weight and dimensions were measured repeatedly and recorded. The ISO 13061-13:2024 and ISO 13061-14:2016 standards were used to evaluate shrinkage. The percentage of shrinkage was determined using the following equation.

$$Shrinkage\ (\%) = \left(\frac{D_i - D_f}{D_i}\right) \cdot 100 \quad (3)$$

Where D_i – specimen initial dimension before oven-dry in mm, and D_f – specimens final dimension after oven-dried in mm.

2.5 Determination of mechanical properties
2.5. Određivanje mehaničkih svojstava

2.5.1 Static bending
2.5.1. Čvrstoća na savijanje

The static bending (*MOE* and *MOR*) of this study was determined based on ISO 13061-3:2014 standard technique. Specimens with dimension of 20 mm × 20 mm × 300 mm were prepared from each culm portion for determination of *MOE* and *MOR*. The specimens were subjected to center loading on the Universal Testing Machine, type FM2750 (Figure 2). The specimen was loaded at a rate of one millimeter per minute in its center, with support at both ends. The following equations were used to determine *MOE* and *MOR* based on this test:

$$MOE\ (N/mm^2) = \frac{P^1 \cdot L^3}{4 \cdot d^1 \cdot b \cdot h^3} \quad (4)$$

$$MOR\ (N/mm^2) = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot h^2} \quad (5)$$

Figure 2 Universal testing machine (UTM) for static bending test
Slika 2. Ispitivanje čvrstoće na savijanje uz pomoć univerzalnog uređaja za mehanička ispitivanja

Where *MOE* – modulus of elasticity, *MOR* – modulus of rupture, P^1 – load at the limit of proportionality in N, *P* – maximum load in N, *L* – span length in mm, and *d* – deflection at the limit of proportionality.

2.5.2 Impact bending strength
2.5.2. Čvrstoća na udarce

Impact bending strength was determined based on the ISO 13061-10:2017 standard technique. Specimens with dimensions of 20 mm × 20 mm × 300 mm were prepared from each culm portion for testing the impact bending strength. The specimens were set up on a pendulum hammer, type of Impact bending Testing Machine model PW5-S. The test machine force plate was used to read the joule value whereas the load was applied to the center. The impact bending strength was computed from the following equation.

$$Impact\ strength\ (\mathrm{Nm/m^2}) = \frac{P}{b \cdot h} \quad (6)$$

Where *P* – Joule value in Nm, *b* – specimen width in mm, *h* – specimen thickness in mm.

2.5.3 Hardness
2.5.3. Tvrdoća

According to Forest Products Laboratory (2010), the force needed to embed an 11.3 mm ball with half of its diameter into the wood is used to determine the hardness of wood. This information is collected using the Janka technique. Specimens with dimensions of 20 mm × 20 mm × 45 mm were cut from each designated portion for hardness strength testing. Hardness strength was determined based on the procedure of ISO 13061-12:2017 using universal testing machine.

2.5.4 Experimental design and statistical analysis
2.5.4. Postavke eksperimenta i statistička analiza

This study was carried out with a completely randomized design (CRD). To investigate the physical and mechanical characteristics of the fabricated LBL panels, twelve replications for each parameter with a single factor (culm height with two levels) were taken into consideration. The statistical software package for social science (SPSS) version 24 was used to analyze the data. The data were analyzed using descriptive statistics and one-way analysis of variance (ANOVA).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Physical properties of LBL
3.1. Fizička svojstava LBL-a

3.1.1 Moisture content
3.1.1. Sadržaj vode

According to the statistical analysis of variance (Table 1), the culm portion did not significantly affect the *MC* of the LBL at tests (Table 1), despite a decrease of *MC* percentage from the bottom to the middle portion. The *MC* percentage found in LBL fabricated from the bottom portion was 10.87 % and the middle portion was 9.82 % (Figure 3a). The mean value of *MC* at the test found in LBL ranges from 7.31 % to 12.59 %, which is in the range of the minimum *MC* allowed by ASTM for laminated board products. Many scholars reported the *MC* percentage of LBL panels in the range of 8 % to 16 % (Table 4).

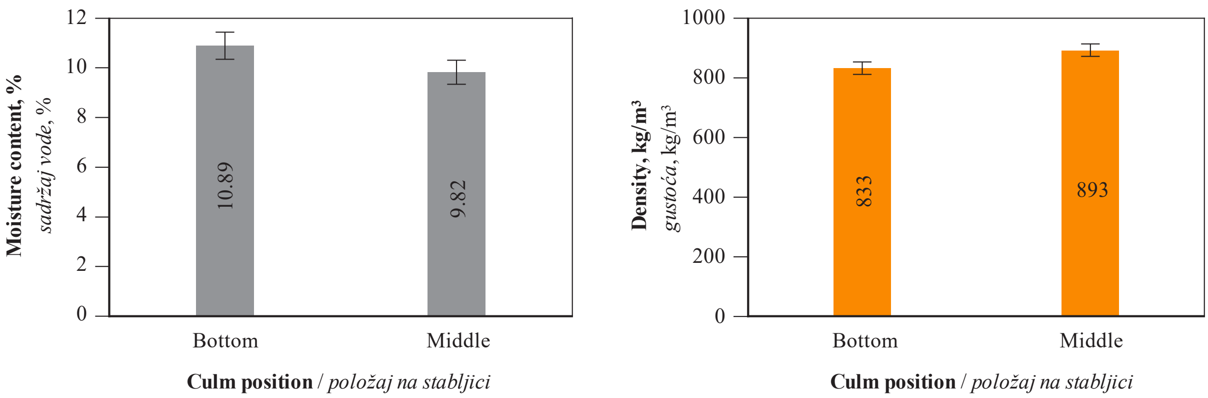

Figure 3 Moisture content (a) and density (b) variation of LBL within culm position
Slika 3. Varijacija sadržaja vode (a) i gustoće (b) LBL-a s obzirom na položaj na stabljici s kojega je uzorak uzet

3.1.2 Density
3.1.2. Gustoća

The result depicted that the culm portion significantly affected the density of the LBL at the test (Table 1). The density value obtained at the test of LBL fabricated from the middle portion was 892.80 kg/m^3, which is significantly greater than from the bottom portion (833.31 kg/m^3) (Figure 3b). The variation trend of this finding was similar to the trend reported in the raw bamboo *O. abyssinica* culms (Kelemwork, 2012).

Regardless of the variation along the culm height, the mean density of LBL fabricated from *O. abyssinica* culm varies from 778 to 926 kg/m^3 with an average value of 863 kg/m^3. The density value of the LBL found in this study was higher than the raw bamboo/original *O. abyssinica* of air-dried density (805 kg/m^3) as reported by INBAR (2019), which is increased by 7.20 % compared to the raw bamboo culm. Similarly, Kelemwork (2012) also reported basic density ranges from 532 kg/m^3 to 658 kg/m^3 for the raw *O. abyssinica* pole, which is a lower value than that obtained in this study in the LBL of *O. abyssinica* culms. Similar density variation was obtained for both raw bamboo strips and LBL along the culm portion of *Dendrocalamus brandisii* (Kelkar *et al*., 2020). According to Sulastiningsih *et al*. (2016), the variation of density between the LBL and its raw bamboo is due to density of the component, the adhesive, and the pressing process used during fabrication process of LBL. They also state that the process of compaction that occurred during the compressing phase is impacted by glue. The trend to this finding reported in LBL manufactured from moso bamboo (*Phyllostachys pubescens*) was denser than in its raw bamboo culms and the variation was due to press treatments during the manufacture of LBL that results in an increased value of density (Nugroho and Ando, 2001). On the other hand, the mean density of this finding, which is 863 kg/m^3, was greater than the density of cross laminated timber (CLT) of red oak and Southern pine tested at 12 % moisture content with mean vlues of 748 kg/m^3 and 562 kg/m^3, respectively (Omotayo *et al.*, 2024). Furthermore, the Gluelam density of *Pinus merkusii* (360 kg/m^3) and *Anthocephalus cadamba* (0.73 kg/m^3) were lower than the density of this finding obtained in LBL of *O. abyssinica* culm (Diza Lestari *et al*., 2018).

The density of this finding was greater than the density (730 kg/m^3) of 3-ply LBL manufactured from the giant bamboo *Guadua bamboo* (Correal *et al*., 2010). In contrast, higher density (940 kg/m^3) than this finding was reported for LBL manufactured from *Phyllostachys pubescens* (Nugroho and Ando, 2001). This difference may be associated with the species and thicknesses of the manufactured LBL panels. According to Manik *et al*. (2022), the density and mechanical characteristics of LBL observed an increment in line with the increased number of layers of the same thickness.

The density of LBL obtained was higher than that of the following solid lumber species in Ethiopia: *Eucalyptus globulus* (780 kg/m^3), *Eucalyptus camaldulensis* lumber (853 kg/m^3), *Pinus patula* (450 kg/m^3), *Juniperus procera* (540 kg/m^3), *Pouteria adolfi-friederici* (600 kg/m^3), *Hagenia abyssinica* lumber (560 kg/m^3), and *Pinus patula* (450 kg/m^3) (Desalegn *et al*., 2012; 2015).

3.1.3 Shrinkage
3.1.3. Utezanje

A major element affecting the use of bamboo culms as a raw material is shrinkage. The statistical analysis showed that the culm portion did not show significant effects on the tangential, radial, longitudinal, volumetric shrinkages of the LBL fabricated from lowland bamboo culm (Table 1).

3.2 Mechanical properties of LBL
3.2. Mehanička svojstva LBL-a

3.2.1 Modulus of elasticity (*MOE*)
3.2.1. Modul elastičnosti (*MOE*)

The results showed that the bending stiffness or *MOE* was significantly (P < 0.05) influenced by the culm position (Table 2). The *MOE* increased with the increasing of bamboo height from the base to the mid-

Table 1 Statistical analysis of variance for physical properties of LBL fabricated from *O. abyssinica* culms
Tablica 1. Statistička analiza varijance za fizikalna svojstva LBL-a izrađenoga od stabljika *O. abyssinica*

Parameters *Parametri*	***DF***	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednji kvadrat*	***F* value** *F-vrijednost*	***Pr* (>*F*)**
Density / *gustoća*	1	21237.930	21237.930	29.969	0.000***
MC	1	6.848	6.848	3.694	0.068^{ns}
TS	1	0.704	0.704	3.201	0.870^{ns}
RS	1	0.540	0.540	1.269	0.272^{ns}
LS	1	0.015	0.015	2.611	0.120^{ns}
VS	1	0.390	0.390	0.498	0.488^{ns}

***significant at P < 0.001, **significant at P < 0.01, *significant at P < 0.05, ^{ns}not significant at P > 0.05, *TS* – tangential shrinkage, *RS* – radial shrinkage, *VS* – volumetric shrinkage
****značajno pri P < 0,001, **značajno pri P < 0,01, *značajno pri P < 0,05, ns – nije značajno pri P > 0,05, TS – tangentno utezanje, RS – radijalno utezanje, VS – volumno utezanje*

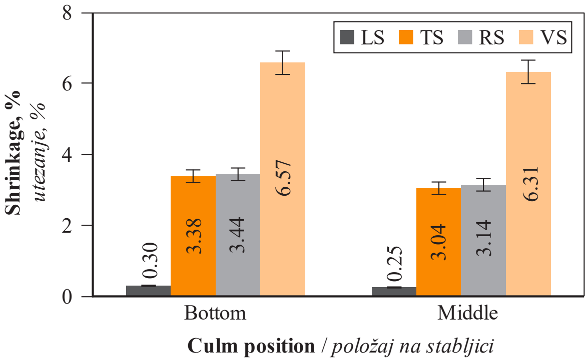

Figure 4 LBL shrinkages variation along the culm position of *O. abyssinica* (TS – tangential shrinkage, RS – radial shrinkage, LS – longitudinal shrinkage and VS – volumetric shrinkage)
Slika 4. Varijacije utezanja LBL-a duž stabljike *O. abyssinice* (TS – tangentno utezanje, RS – radijalno utezanje, LS – uzdužno utezanje, VS – volumno utezanje)

dle position. The mean value of *MOE* found in LBL produced from the middle position (16558 N/mm²) was significantly greater than that from the bottom (14929 N/mm²) position of *O. abyssinica* culms (Table 2). The *MOE* values reported in the original or raw bamboo of *O. abyssinica* culms (Kelemwork, 2012) exhibited a similar tendency of variation to this finding. The variation along the culm height of the bamboo might be associated with the anatomical characteristics of the bamboo culm. Siam *et al*. (2019) observed that the *MOE* of bamboo was impacted by the increased density with culm height from the base towards the top. They also noted that the higher number of vascular bundles along the culm height followed the increasing tendency of *MOE*.

Regardless of the variation along the culm height, the overall mean value of *MOE* for LBL was 15743 N/mm² (Table 3). In a previous study on the original *O. abyssinica* pole with node, Kelemwork (2012) found the average value of *MOE* (9099 N/mm²) and without node (11293 N/mm²) grown at Pawe, Ethiopia. On the other hand, the mean value of *MOE* obtained in this study of LBL was increased by 73 % and 39 % when compared to the original bamboo with node and without node, respectively. A similar significant difference was observed in LBL and raw bamboo strips reported in other bamboo species of *Dendrocalamus brandisii* (Kelkar *et al*., 2020).

The overall average value of *MOE* (15743 N/mm²) was higher than *MOE* (10000 N/mm²) of 3-ply LBL manufactured from *G. apus* (Sulastiningsih and Nurwati 2009). In addition, the value of *MOE* (14163 N/mm²) of LBL manufactured from *O. alpina* culms (Kariuki *et al*., 2014) is lower than this finding of *MOE* (15743 N/mm²). Furthermore, *MOE* of this study is higher than 4-ply LBL manufactured from *Phyllostachys pubescens* culms reported by Mahdavi *et al*. (2012). Similar to density, this variation may be associated with the type of species, number of layers, thickness of strips/ panels, type of resin applied. Compared to lumber derived from commercially recognized timber species in Ethiopia, the *MOE* value found in this study was greater than that of *Prunus africana* (12070 N/mm²), *Eucalyptus globulus* (11655 N/mm²), *Cordia africana* (6996 N/mm²), and *Cupressus lusitanica* (6145 N/mm²) (Desalegn *et al*., 2015). Omotayo *et al.* (2024) reported that the mean *MOE* of cross laminated timber (CLT) of red oak and Southern pine was 13,238 N/mm² and 9,406 N/mm², respectively. These values are lower than the *MOE* of this finding obtained in LBL of *O. abyssinica* (15743 N/mm²). On the other hand, the *MOE* value reported for Gluelam of *Pinus merkusii* (5500 N/mm²) and *Anthocephalus cadamba* (10600 N/mm²) were lower than the *MOE* of this finding obtained in LBL of *O. abyssinica* culm (Diza Lestari *et al*., 2018).

3.2.2 Modulus of rupture (*MOR*)
3.2.2. Modul loma (*MOR*)

The result showed that the bending strength/ *MOR* was significantly ($P < 0.01$) affected by culm position (Table 2). The value of LBL fabricated from the middle position was (164 N/mm²), which is greater than that from the bottom position (134 N/mm²) of *O. abyssinica* culms. The increased value of *MOR* from the bottom to the middle position was reported for the raw/original *O. abyssinica* pole (Kelemwork, 2012). A similar variation of the trend to this finding was reported for LBL fabricated from other bamboo species of *Bambusa vulgaris* (Ojo *et al*., 2018).

Table 2 Statistical analysis for mechanical properties of LBL fabricated from *O. abyssinica* culms
Tablica 2. Statistička analiza mehaničkih svojstava LBL-a izrađenoga od stabljika *O. abyssinica*

Parameters *Parametri*	**DF**	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednji kvadrat*	***F* value** *F-vrijednost*	**Pr (>*F*)**
MOE	1	15916959	15916959	6.462	0.0186*
MOR	1	5370	5370	10.99	0.00315**
Impact bending / *čvrstoća na udarce*	1	20417	20417	2.786	0.109ns
Hardness / *tvrdoća*	1	6273038	6273038	37.33	0.000***

***significant at $P < 0.001$, **significant at $P < 0.01$, *significant at $P < 0.05$, ns not significant at $P > 0.05$
****značajno pri P < 0,001, **značajno pri P < 0,01, *značajno pri P < 0,05, ns – nije značajno pri P > 0,05*

Table 3 Average mechanical properties of LBL along the culm height of *O. abyssinica*
Tablica 3. Prosječna mehanička svojstva LBL-a duž stabljike *O. abyssinica*

Culm position *Položaj na stabljici*	***MOE***, **N/mm²**	***MOR***, **N/mm²**	**Impact bending, Nm/m²)** *Čvrstoća na udarce,* Nm/m²	**Hardness, N** *Tvrdoća,* N
Bottom / *donji dio*	14929±1584[b]	134±26[b]	18604±113[a]	2634±481[b]
Middle / *srednji dio*	16558±1555[a]	164±17[a]	18663±43[a]	3657±324[a]
Total / *ukupno*	15743±1746	149±26	18633±89	3145±658

Note: Within the same column, mean values denoted by a different superscript letter show a significant difference at $P < 0.05$.
Napomena: srednje vrijednosti označene različitim slovima unutar istog stupca pokazuju značajnu razliku pri P < 0,05.

The overall mean value of *MOR* for LBL fabricated from *O. abyssinica* culms was 149 N/mm² (Table 3). The *MOR* obtained in this study was 8 times higher than that of the original lowland bamboo poles without nodes and 18 times higher than that of bamboo poles with nodes grown at Pawe, Ethiopia (Kelemwork, 2012). A similar difference to this finding was reported between *MOR* of LBL and its raw bamboo strips of *Dendrocalamus brandisii* (Kelkar *et al*., 2020). This finding was greater than the *MOR* (111.03 N/mm²) of LBL produced from giant bamboo Guadua (Correal *et al*., 2010). Similarly, the value of *MOR* (95.1 N/mm²) reported for 3-ply LBL of *Gigantochloa apus* was lower than *MOR* (149 N/mm²) obtained in this study (Sulastiningsih and Nurwati, 2009). Furthermore, the *MOR* value obtained in this study was higher than 4 ply LBL of *Phyllostachys pubescens* as reported by Mahdavi *et al*. (2012). The value of *MOR* (149 N/mm²) of this result was greater than *MOR* of commercially well-known and endangered wood species of Ethiopia such as *Cordia africana* (64 N/mm²), *Cupressus lusitanica* (64 N/mm²), and *Juniperus procera* (87 N/mm²) (Desalegn *et al*., 2015). This indicates that LBL fabricated from *O. abyssinica* culms has a potential to substitute these commercial timber species as alternative raw material. Omotayo *et al*. (2024) reported that the mean *MOR* of cross laminated timber (CLT) of red oak and Southern pine was 52.77 N/mm² and 36.21 N/mm², respectively. These values are lower than the *MOE* of this finding obtained in LBL of *O. abyssinica* (149 N/mm²). On the other hand, the mean *MOR* values reported for Gluelam of *Pinus merkusii* (46.10 N/mm²) and *Anthocephalus cadamba* (86.20 N/mm²) were lower than the MOE of this finding obtained in LBL of *O. abyssinica* culm (Diza Lestari *et al*., 2018).

3.2.3 Impact bending
3.2.3. Čvrstoća na udarce

The resistance that wood specimens provide to abrupt shocks is known as impact bending. According to the statistical analysis of variance, there was no significant ($P > 0.05$) effect of culm portion on the impact bending strength (Table 2). The strength of impact bending of LBL fabricated from the middle position (18663 Nm/m²) was insignificantly higher than that from the bottom position (18604 Nm/m²) of *O. abyssinica* culms (Table 3). The overall mean value of impact bending found in this study was 18633 Nm/m². The impact bending strength value of glulam bamboo manufactured from *B. vulgaris* is reported in the range of 0.75 to 1.98 MPa (Ogunsanwo *et al*., 2019).

The result of this finding was considerably higher than that of solid lumbers of commercially known timber species in Ethiopia; for instance, the impact bending strength of *Cupressus lustanica* (5888 Nm/m²), *Pinus patula* (5187 Nm/m²), *Eucalyptus saligna* (12873 Nm/m²) and *Grevillea robusta* (18094 Nm/m²) (Desalegn *et al*., 2012; 2015). This indicates that the LBL fabricated from *O. abyssinica* culms has a potential to substitute these commercial timber species as alternative raw material in Ethiopia.

3.2.4 Hardness
3.2.4. Tvrdoća

The hardness was shown to be significantly ($P < 0.001$) influenced by the culm height (Table 2). The mean variation of hardness found in LBL fabricated from the middle position (3657 N) was greater than the LBL fabricated from the bottom position (2634 N) of lowland bamboo culm. Regardless of the variation along the culm height, the overall mean value of hardness found in LBL fabricated from *O. abyssinica* culm was 3145 N (Table 3). The result of this finding was considerably higher than that of LBL fabricated from other bamboo species of *Phyllostachys aurea* with a hardness value of 1,647 N (Rusch *et al*., 2019). Nonetheless, higher than this finding was reported in LBL fabricated from other species of bamboo *Guadua angustifolia* Kunth with hardness in the range of 5000-6500 N (Correal *et al*., 2014). The variation of this finding compared to other findings may be due to the difference of bamboo species and the species of this finding. Correal *et al*. (2014) noted that the value of hardness in LBL differed significantly among the species of bamboo culms. The mean values of hardness obtained in this study were higher than those of solid lumber of commercially well-known tree species of Ethiopia, such as *Pinus patula* (2179 N), and *Cupressus lustanica* (2761 N) (Desalegn *et al*., 2015).

Table 4 Average physical and mechanical characteristics of the manufactured LBL compared to specimens examined in earlier research studies of LBL, PSL, and LVL
Tablica 4. Prosječna fizička i mehanička svojstva proizvedenoga LBL-a u usporedbi s uzorcima ispitanim u dosadašnjim istraživačkim studijama LBL-a, PSL-a i LVL-a

Species *Vrsta*	**Product** *Proizvod*	**Number of ply** *Broj slojeva*	**Specimens size, cm** *Veličina uzorka, cm*	***MC*, %**	**Density, kg/m³** *Gustoća, kg/m³*	***MOE*, N/mm²**	***MOR*, N/mm²**	**Impact bending, Nm/m²** *Čvrstoća na udarce,* Nm/m²	**Hardness, N** *Tvrdoća,* N
*Oxytenanthera abyssinica**	LBL	3	2.1×2×100	7.31–12.59	863 (40)	15743 (1746)	149 (26)	18633 (89)	3145 (658)
Gigantochloa apus[a]	LBL	3	-	13.07 (1.2)		10000	95.1 (9.7)	-	-
Guadua bamboo[b]	LBL	-	-	9.0 (2.0)	756 (2.8)	13821 (5.8)	112 (8.6)	-	-
Yushania alpina[c]	LBL	-	-	<12	-	14163	91	-	-
Phyllostachys pubescens[d]	LBL	4	3.5[d]×5.08×76.2	15.81 (5.5)	-	9300 (594)	76.5 (4.58)	-	-
Phyllostachys aurea[e]	GLB	-	-	9.47	770	12746	99.40	-	1647
Guadua angustifolia Kunth[f]	GLB	-	-	8.33-11.90	741	12720	103	-	5000-6500
Eastern species[g]	PSL	-	2.54×2.54×40.64	-	-	11600	90.3	-	-
Phyllostachys pubescens Mazel[h]	LVL	-	2.54×2.54×40.64	-	-	11000	93.5	-	-
Moso bamboo (*Phyllostachys pubescens*)[i]	LBL	-	-	10.6	-	8870	111.5	-	-
G. apus	LBL	-	-	11.74 (0.80)	0.80 (0.02)	6,967.86	42.81	-	-

Note: LBL – laminated bamboo lumber, PSL – parallel strand lumber, LVL – laminated veneer lumber, GLB – glued laminated bamboo.
Napomena: LBL – lamelirana građa od bambusa, PSL – građa od lijepljenih traka furnira, LVL – lamelirana furnirska građa, GLB – lamelirani lijepljeni bambus.
[a]Sulastiningsih and Nurwati, 2009; [b]Sulastiningsih and Nurwati, 2009; [c]Kariuki1 *et al*., 2014; [d]Mahdavi *et al*., 2012; [e]Ni *et al*., 2016; [f]Correal *et al*., 2014; [g]Mahdavi *et al*., 2011; [h]Nugroho and Ando, 2001; [i]Chen *et al*., 2020; [j]Sumardi *et al*., 2022

4 CONCLUSIONS
4. ZAKLJUČAK

The physical and mechanical properties of LBL fabricated from the bottom and middle positions of lowland bamboo (*O. abyssinica*) culms have been studied. Density, MOE, MOR, impact bending and hardness tests indicate that LBL fabricated from upper position of *O. abyssinica* culm has superior properties when compared with LBL fabricated from the lower position of *O. abyssinica* culm. The density and mechanical properties found in LBL have been shown to be much higher than those of normal structural timber in Ethiopia and other countries, whereas compared to other laminated bamboo products, the manufactured LBL may be regarded as having average density and mechanical qualities. Compared to other wood species, shrinkage was less pronounced in radial and tangential directions; as a result, LBL may be regarded as dimensionally stable material. According to the present study, LBL can potentially be used as a substitute material for wood and wood-based products. The tested physical and mechanical properties of LBL obtained in this study fulfilled the minimum requirement of D60 strength class for hardwoods in BS 5268-2 standard for timber structural applications. Further research is recommended to examine other characteristics of the product, such as its bonding strength, biological resistance, fastener holding capability, and a connecting system.

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Determination of Bending Resistance and Modulus of Elasticity in CLT, Wood Materials and Wood Laminated Materials

Određivanje čvrstoće na savijanje i modula elastičnosti CLT-a, drvnih materijala i drvnih lameliranih materijala

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ABSTRACT • *In this study, test samples were prepared from CLT, wooden materials and wooden laminated materials, and bending strength and elasticity modulus values were determined. All samples were prepared using Scots pine (Pinus sylvestris L.) timber as the wood species and PVAc glue as the adhesive. Four-point bending test was applied to the test samples in two different directions, vertical and parallel to the glue line. Flexural and elastic modulus values were examined. The highest bending strength and elasticity modulus values were found in wood laminated material and the lowest in solid wood material. The average values of bending strength and modulus of elasticity were found to be higher in the direction parallel to the glue line than in the direction vertical to the glue line. As a result of the study, it can be said that CLT and wooden laminated materials can be used as an alternative to solid materials, which are frequently used as building and frame construction furniture materials.*

KEYWORDS: *CLT; wood laminate; wood material; bending resistance; elastic modulus*

SAŽETAK • *U ovom istraživanju ispitni su uzorci pripremljeni od CLT-a, masivnog drva i drvnih lameliranih materijala te su određeni čvrstoća na savijanje i modul elastičnosti. Svi uzorci pripremljeni su od drva običnog bora (Pinus sylvestris L.) i PVAc ljepila. Ispitni uzorci savijani su u četiri točke u dva različita smjera, okomito i paralelno s lijepljenim spojem. Ispitane su vrijednosti modula savijanja i modula elastičnosti. Utvrđeno je da drvni lamelirani materijali imaju najviše, a masivno drvo najniže vrijednosti čvrstoće na savijanje i modula elastičnosti. Prosječne vrijednosti čvrstoće na savijanje i modula elastičnosti bile su veće u smjeru paralelnom s lijepljenim spojem nego u smjeru okomitom na taj spoj. Kao rezultat istraživanja može se reći da se CLT i drvni lamelirani materijali mogu upotrebljavati kao alternativa materijalima od masivnog drva, koji se često rabe u graditeljstvu i izradi okvira namještaja.*

KLJUČNE RIJEČI: *CLT; drvni lamelirani materijal; masivno drvo; čvrstoća na savijanje; modul elastičnosti*

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1 INTRODUCTION
1. UVOD

Wood has been one of humanity's oldest and most indispensable materials throughout history. This valuable resource provided by nature is used in many different fields for both aesthetic and functional purposes. Modern processing techniques, particularly laminated wood and cross-laminated timber (CLT), have further expanded the use of wood and established a significant place among construction materials.

In recent years, the use of CLT and laminated wood materials as alternatives to solid materials has become increasingly widespread. Numerous studies have been conducted on the use of CLT materials in regions with high seismic risk. (Asiz and Smith, 2009; Ceccotti *et al*., 2013; Dujic and Zarnic, 2005; Gavric, 2013)

Laminated wood is created by combining multiple layers of wood to produce durable and aesthetically pleasing products. These products are commonly used in furniture, across all areas of the construction industry, as well as in interior cladding and flooring. On the other hand, cross-laminated timber (CLT) has revolutionized the construction sector with its structural advantages, finding applications in large buildings, bridges, and prefabricated structures. The potential of these materials to offer sustainable building solutions presents a significant opportunity in today's environmentally friendly construction practices.

CLT has emerged as a versatile prefabricated material for flooring, roofing, and wall systems, gaining traction in construction across Austria, Germany, and North America (Fredriksson *et al*., 2015; Karacabeyli and Douglas, 2013). This innovative panel system traces its roots back to the 1990s in the Swiss cities of Lausanne and Zurich. However, it was not until 1996 that a significant industrial-academic collaboration in Austria led to its advancement and wider adoption (Schickhofer *et al*., 2009; Espinoza *et al.*, 2016).

CLT is an innovative engineered wood product that typically comprises three to nine layers of dimensioned lumber, arranged perpendicular to one another, similar to the layers of veneer in plywood. This unique configuration enhances its structural integrity and stability. CLT has gained traction in prefabricated construction, serving as effective wall, floor, and roofing elements across residential, commercial, and non-residential buildings. Its potential is particularly noteworthy in the realm of tall timber structures, offering a sustainable and efficient alternative in modern architecture (Mohammed *et al*., 2012).

In Europe, the predominant raw materials for constructing CLT are structural C24-grade spruce and pine, with densities ranging from 420 kg/m³ to 500 kg/m³ at 12 % moisture content. In contrast, U.S. standards set by ANSI restrict the use of lumber for CLT to species with a minimum density of 350 kg/m³. As CLT continues to gain traction in industry, it is crucial to explore the potential of alternative and lower-density wood species that are not specified in ANSI/APA PRG 320. Investigating these materials could expand the versatility and sustainability of CLT panels, allowing for innovative applications in construction.

CLT is an engineered wood panel composed of layers of lumber, typically ranging from 20 to 60 mm in thickness, that are laminated orthogonally to the grain direction. This configuration enhances its strength and stability, allowing it to effectively support loads in various directions (Schmidt and Griffin, 2009).

Recently, CLT has gained significant traction in Europe as a preferred material for both interior and exterior applications, particularly in high-rise construction, due to its versatility and sustainability (Gagnon and Pirvu, 2011). CLT panels serve as essential load-bearing components in walls, floors, and roofs, contributing to the overall structural integrity of buildings (Popovski *et al*., 2012).

CLT serves as a fundamental component in constructing heavy timber structures for mid- to high-rise buildings. Its benefits as a building material encompass factory prefabrication, ease of installation, lightweight nature, exceptional strength, solid structural integrity, superior thermal insulation, and long-lasting durability (Que *et al*., 2017; Wang *et al*., 2017)

In CLT production, adhesives are selected and applied based on the specific requirements of the intended use and the environmental conditions. For example, polyurethane (PU) adhesives are used for moist environments and high durability, phenolic adhesives for moisture and high temperatures, EPI (Emulsion Polymer Isocyanate) adhesives for moisture and high durability, and MDA (Melamine Diisocyanate) adhesives. Polyvinyl Acetate (PVA) adhesives are used for low-cost, non-toxic, and easy application. This composition exhibits remarkable stiffness and strength in all directions, making it highly durable. The primary raw materials for producing this panel are sourced from the Pinus genus, combined with phenol-resorcinol-formaldehyde adhesive (Gagnon and Pirvu 2011; Karacabeyli and Douglas 2013; Buck *et al*., 2016).

Recent research has focused on key properties such as bending strength, shear strength (Okabe *et al*., 2014; Fredriksson *et al*., 2015; Espinoza *et al*., 2016; Lu *et al*., 2018), and elastic limit (Gsell *et al*., 2007; Gulzow *et al*., 2011), highlighting their significance in enhancing performance and application potential.

In this study, solid wood, laminated wood, and CLT were produced from the same tree species. The decision to conduct such a test was made to better understand the performance of CLT in different usage scenarios. While CLT is typically used for walls, floors, and other structural elements, this test aimed to examine its different load-bearing capacities and properties. Additionally, the test was carried out to provide data for future potential applications of CLT, contribute to product development and innovation processes, and gain a deeper understanding of its mechanical properties.

This study aimed to investigate the effects of forces applied on wooden materials, specifically CLT and laminated wooden materials, commonly used in the construction and furniture industries. We compared the bending strength and modulus of elasticity of these materials under different force applications – both perpendicular and parallel to the glue line. The objective was to assess how these variables, including the type of material and the direction of the applied forces, influence bending and elastic modulus values. By understanding these relationships, we can select materials that are best suited for specific applications, optimize their use based on the expected force directions, and ultimately enhance the durability and longevity of the products.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wooden material
2.1. Drvni materijal

All test samples were made from Scots pine (*Pinus sylvestris* L.), sourced from commercial suppliers (Bag Kerestecilik, Karabuk, Turkey). The average density of the wood was measured at 0.45 g/cm³. Scots pine, a common choice in the wooden construction industry, was specifically selected for this study due to its availability from the Eastern Black Sea region in Turkey. The test specimens were chosen based on the TS 2470 (1976) standard. Selection criteria included uniformity of natural color, smooth fiber texture, absence of knots, heartwood consistency, and lack of reaction wood, as well as the absence of fungal and insect damage. This careful selection ensured the suitability of the specimens for further processing.

2.2 Polyvinyl acetate D4 (PVA D4) adhesive
2.2. Polivinilacetatno D4 (PVA D4) ljepilo

PVA D4 is an odorless, nonflammable adhesive ideal for a wide range of wood bonding applications, including veneering and laminating. Manufactured to meet BS EN204 category D4 and DIN 68602 standards, it is suitable for both internal and external uses. This adhesive performs well in cold temperatures and cures quickly, ensuring ease of application without damaging cutting tools. For optimal results, the adhesive must be applied to only one surface, using a recommended amount of 150–200 g/m². The application process follows the TS 3891 standard, ensuring consistent quality. PVA D4 has a density of 1.1 g/cm³, a viscosity of 13–18 Pa·s, and a pH value between 2.0 and 3. For jointing, a pressing time of 30 minutes is advised for cold processes, while hot pressing at 60 °C should last 5 minutes, maintaining a humidity level of 6–15 %. After hot pressing, materials should be kept until they reach normal temperature for optimal bonding results.

2.3 Preparation of test samples
2.3. Priprema ispitnih uzoraka

The solid material used for control test samples was made from Scots pine (*Pinus sylvestris* L.) wood. The wood was cut to dimensions of 1900 mm × 100 mm × 100 mm and stored at a temperature of (20 ± 2) °C and a humidity of (65 ± 5) % until it reached a constant weight. The average moisture content (MC) of the first control sample was determined to be (12 ± 0.5) % according to TS 2471 (2005) standard.

The length of the laminations used in the production of CLT and laminated wood samples was 2000 mm, and their thickness was prepared to be 14 mm. In the laminated wood preparation, the lamination layers were glued parallel to each other, while the CLT lamination layers were bonded to each other at a 90-degree angle. The samples were laminated using PVAc adhesive, in accordance with the TS EN 408+A1 (2015) standard, to create a 5-layer laminated wood element. Finally, the resulting structural laminated wood elements were cut to dimensions of 1900 mm × 100 mm × 100 mm.

2.4 Density
2.4. Gustoća

The density of the Solid, Cross-Laminated Timber (CLT), and Wood Laminate samples was determined in accordance with the TS EN 408+A1 (2015) standard. The air-dried density (δ) was calculated using the following Eq. 1:

$$\rho = M / V \text{ (g/cm}^3\text{)} \tag{1}$$

Where, M is the air-dried mass (g) and V is the air-dried volume (cm³).

2.5 Bending test method
2.5. Metoda ispitivanja savijanjem

The bending strength test applied a 4-point load method on specimens aligned both parallel and vertical to the glue line. This test was conducted in the Karabük University Safranbolu Vocational School Laboratory using a SHIMADZU universal testing device, such as a SHIMADZU AGS-X series model, with a measuring capacity generally ranging from 0.1 N to 50 kN. According to TS EN 408+A1 (2015), bending strength and modulus of elasticity were measured. A total of 60 test specimens, each measuring 100 mm × 100 mm ×

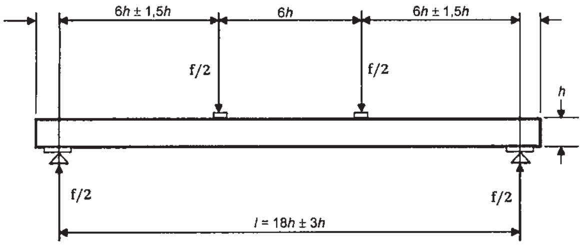

Figure 1 Bending strength and elasticity module test assembly
Slika 1. Postav ispitivanja čvrstoće na savijanje i modula elastičnosti

Figure 2 Four-point bending test setup
Slika 2. Postavljanje ispitivanja savijanja u četiri točke

1900 mm, were prepared – 30 for each loading direction and laminated type. The support distance was set to 18 times the specimen height, as illustrated in Figure 1, while Figure 2 depicts the experimental setup.

The 4-point bending test is an experiment used to determine a material bending strength and modulus of elasticity. The sample is fixed on two parallel supports, equipped with two symmetrical loading points. The deformation of the material is measured as a result of the applied loads. This test is commonly used in materials science and engineering to examine the durability of structural materials. The test setup is shown in Figure 2.

The average value of the deformation of two displacement transducers was used for the analysis of the results. The *MOE* and *MOR* were determined by substituting the test results into equarions 2 and 3, respectively.

$$MOR = \frac{3 \cdot P_{max} \cdot (L-S)}{2 \cdot b \cdot h^2} \qquad (2)$$

Where, *MOR* is the bending strength (N/mm²), P_{max} is the maximum applied load (N); *L* is the span of the CLT (mm); *S* is the distance between the loading points (mm); *b* is the width (mm); *h* is the thickness of CLT (mm)

$$MOE = \frac{\lambda^3 \cdot (F_2 - F_1)}{b_1 \cdot h_1^3 \cdot (W_2 - W_1)} \cdot \left[\left(\frac{3a}{4\lambda} \right) - \left(\frac{a}{\lambda} \right)^3 \right] \qquad (3)$$

In bending tests, the modulus of elasticity in bending (*MOE*) is calculated using the following parameters: *MOE* (N/mm²) – modulus of elasticity in bending; *l* (mm) – span length between supports; b_1 (cm) – width of the cross section being tested; h_1 (cm) – depth of the cross section being tested; *a* (mm) – distance from the loading position to the nearest support; ΔF (N) – change in load between two points on the regression line, where the correlation coefficient is 0.99 or better (i.e., $F_2 - F_1$); ΔW (mm) – change in deformation corresponding to the change in load (i.e., $W_2 - W_1$) and λ – represents the elastic modulus constant.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Flexural strength
3.1. Čvrstoća na savijanje

Statistical evaluation of the results regarding the bending strength of CLT and laminated wood materials and solid wood materials is given in Table 1, and the results of multiple variance analysis are given in Table 2.

According to Table 1, the results of the four-point bending strength tests indicate clear differences in the average values of laminated wood, CLT and solid wood materials. This test was conducted to determine the bending strength of each material, and the results allow for a comparison of the mechanical properties of these three materials.

First, the test results for laminated wood materials generally show high strength, while the strength of CLT is also at a noteworthy level. In contrast, solid wood materials typically have lower average values compared to laminated and CLT. It is believed that these differences are related to the manufacturing techniques and structural properties of the materials. To assess whether the differences between the groups are statistically significant, a multiple variance analysis (ANOVA) was performed (Table 2).

According to the results of the variance analysis, the material type and the interaction between material type and load application direction were found to be statistically significant. However, the direction of load application (to the adhesive line) was found to be insignificant.

Deformation types are presented in Figures 4 and 5. Under the load applied perpendicular to the adhesive line, the deformation of the prepared laminate is first observed in the bottom lamella. In contrast, when the load is applied parallel to the adhesive line, deformation is observed simultaneously across all the lamellae that make up the laminate. The Duncan test was conducted to determine the significance level between groups (Table 3). The results of the Duncan test indicate that the differences between the groups are statistically significant.

3.2 Flexural modulus of elasticity
3.2. Modul elastičnosti pri savijanju

The comprehensive statistical evaluation of the results regarding the bending modulus of elasticity of CLT and laminated wood materials, as well as solid

Table 1 Four-point bending strength results of the test samples (N/mm²)
Tablica 1. Rezultati čvrstoće na savijanje u četiri točke (N/mm²)

Force direction *Smjer sile*	**Material type** *Vrsta materijala*	***X*min.**	***X*ort.**	***X*max**	**Std.**
Parallel to the glue line *paralelno s lijepljenim spojem*	Solid wood materials (no glue) / *masivno drvo (bez ljepila)*	75.10	77.50	79.90	3.028
	CLT	76.50	78.90	81.30	4.229
	Wood laminated / *lamelirano drvo*	88.50	90.90	93.30	3.143
Vertical to the glue line *okomito na lijepljeni spoj*	CLT	77.20	79.60	82.00	4.926
	Wood laminated / *lamelirano drvo*	79.60	82.00	84.40	3.916

Table 2 Four-point bending strength results of test samples (N/mm²)
Tablica 2. Rezultati čvrstoće na savijanje u četiri točke (N/mm²)

Sources of variance *Izvori varijance*	**S.D**	**Total of squares** *Ukupno kvadrata*	**Mean squares** *Srednja vrijednost kvadrata*	***F* Value** *F-vrijednost*	**Chance of error *P*<0.05** *Vjerojatnost pogreške P<0,05*
Material type *vrsta materijala*	2	900.033	450.017	31.511	.000
Force direction *smjer sile*	1	112.067	112.067	7.847	.007
M.T. × F.D.	2	286.433	143.217	10.028	.000
Error / *greška*	54	771.200	14.281		
Total / *ukupno*	60	396378.000			

wood materials, is presented in Table 4. Additionally, the results of the multiple variance analysis conducted to examine the differences among these materials are provided in Table 5.

According to Table 4, the results obtained from the four-point bending tests aimed at determining the modulus of elasticity reveal significant average differences among laminated wood, CLT and solid wood materials. This test serves as an important method for establishing the modulus of elasticity for each type of material, facilitating a comprehensive comparison of their mechanical properties.

First, the results indicate that laminated wood materials generally exhibit high strength, which can be attributed to their engineered nature and the advantages of their layered structures. Similarly, CLT also demonstrates a remarkable level of strength, which can be said to arise from its cross-laminated structure that enhances stability and load-bearing capacity. In contrast, the average modulus of elasticity values for solid wood materials tend to be lower compared to both laminated wood and CLT. This difference may stem from the inherent characteristics of solid wood, such as natural variations in density and grain structure.

The observed discrepancies in mechanical properties are believed to be influenced by the distinct manufacturing techniques and structural attributes of each material. Laminated wood is typically produced by bonding layers of wood together, which enhances its mechanical performance. CLT, on the other hand, increases durability through the cross-lamination of its layers. To determine whether the differences among the groups are statistically significant, a multiple variance analysis (ANOVA) has been conducted (Table 5).

Table 3 Duncan results regarding the effects of material type on bending strength (N/mm²)
Tablica 3. Duncanovi rezultati utjecaja vrste materijala na čvrstoću na savijanje (N/mm²)

Material type / *Vrsta materijala*	***X*ort.**	**H.G**
Solid wood materials / *masivno drvo*	77.50	A
CLT	79.25	B
Wood laminated / *lamelirano drvo*	86.45	B

The results of the variance analysis conducted to determine the bending modulus of elasticity indicate that both the material type and the interaction between material type and load application direction are statistically significant ($p<0.05$). However, it was found that the direction of load application (relative to the adhesive line) is not significant ($p<0.05$). To further investigate the differences among the groups, a Duncan test was conducted, which determined the significance levels between the groups (Table 6). The results of the Duncan test indicate that there are statistically significant differences between the groups.

3.3 Fracture types
3.3. Vrste loma

The wood (control), laminated wood, and cross-laminated timber materials exhibited different types of fractures under loading. The test samples fractured between both load arms and support points. These fractures indicate that the prepared samples were appropriately designed for the purpose of the experiment and that the obtained values are valid. The type of fracture observed in the wood material samples is presented in Figure 3; the fracture type observed in the laminated wood material is shown in Figure 4; and the fracture

Table 4 Results of modulus of elasticity of test samples in four-point bending (N/mm²)
Tablica 4. Rezultati modula elastičnosti ispitnih uzoraka pri savijanju u četiri točke (N/mm²)

Force direction *Smjer sile*	**Material type** *Vrsta materijala*	***X*min.**	***X*ort.**	***X*max**	**Std.**
Parallel to the glue line *paralelno s lijepljenim spojem*	Solid wood materials (No glue) *masivno drvo (bez ljepila)*	10676.66	10919.90	11163.14	268.921
	CLT	11268.86	11512.10	11755.34	270.451
	Wood laminated / *lamelirano drvo*	12248.36	12491.60	12734.84	545.978
Vertical to the glue line *okomito na lijepljeni spoj*	CLT	11479.06	11722.30	11965.54	466.022
	Wood laminated / *lamelirano drvo*	11528.36	11771.60	12014.84	387.458

Table 5 Results of variance analysis regarding the effects of material type and force direction on bending modulus of elasticity values
Tablica 5. Rezultati analize varijance utjecaja vrste materijala i smjera sile savijanja na modul elastičnosti

Sources of variance *Izvori varijance*	***S.D***	**Total of squares** *Ukupno kvadrata*	**Mean squares** *Srednja vrijednost kvadrata*	***F* Value**	**Chance of error *P*<0.05** *Vjerojatnost pogreške P<0,05*
Material type *vrsta materijala*	2	14,793,676.933	7,396,838.467	50.252	.000
Force direction / *smjer sile*	1	433,160.067	433,160.067	2.943	.092
M.T. × F.D.	2	2,379,760.133	1,189,880.067	8.084	.001
Error / *pogreška*	54	7,948,549.600	147,195.363		
Total / *ukupno*	60	8,038,346,878.0			

Table 6 Results of Duncan test regarding the effects of material type on elasticity modulus in bending (N/mm²)
Tablica 6. Rezultati Duncanova testa utjecaja vrste materijala na modul elastičnosti pri savijanju (N/mm²)

Material type / *Vrsta materijala*	***X*ort.**	**H.G**
Solid wood materials / *masivno drvo*	10919.90	A
CLT	11617.20	B
Wood laminated / *lamelirano drvo*	12131.60	C

type observed in the cross-laminated timber material is illustrated in Figure 5.

In the examples of wooden materials, it was observed that the effects of force initiated capillary action from the midpoint of both supports and progressed inward. During the initial phase of the test, the displacement increased linearly with the applied force. However, at the point of fracture (at maximum loading), while the displacement continued to increase, the force exhibited a decline.

In laminated wood samples subjected to forces, distinct differences have been observed between the fracture characterization under perpendicular forces to the adhesive line and that under parallel forces. In samples perpendicular to the adhesive line, wide-angle fractures occur, while narrow-angle fractures are ob-

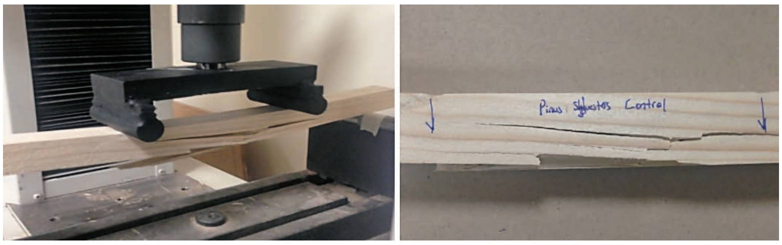

Figure 3 Type of fracture observed in wood material
Slika 3. Vrsta loma uočena na masivnom drvu

Figure 4 Type of fracture observed in laminated wood material
Slika 4. Vrsta loma uočena na lameliranom drvu

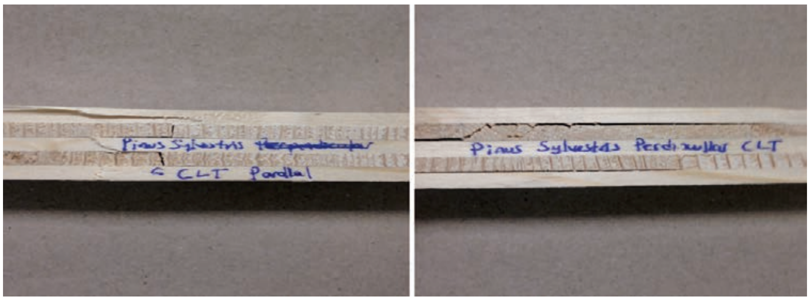

Figure 5 Type of fracture observed in CLT
Slika 5. Vrsta loma uočena na CLT-u

served in samples parallel to the adhesive line. In the samples subjected to perpendicular forces, it has been determined that the fracture starts from the lower layer and progresses towards the inner sections, meaning that the initial fracture occurs in the bottom laminate. In the parallel samples, the fracture occurs between the wood laminates and the adhesive layers.

In cross-laminated timber materials, failure primarily occurs as the annual rings of the laminates in the middle layer separate from one another. The fracture angle has been observed to be wide in samples parallel to the glue line, while it is narrow in samples perpendicular to the glue line.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, solid wood materials, cross-laminated timber (CLT), and laminated wood materials, which are frequently used in the construction and furniture industries, were compared in terms of their bending strength and elastic modulus values. Four-point bending tests were applied to the test samples, with forces applied in two different directions: perpendicular and parallel to the glue line. The results obtained from the experimental work led to the following conclusions:

When examining the results of the four-point bending tests, it was observed that the highest value was obtained for the laminated wood material in the direction parallel to the glue line. This can be attributed to the alignment of the laminates in the same direction and the resistance of the adhesive layer against bending. The lowest bending resistance was observed in solid wood. It was also noted that the adhesive and laminates used in CLT and laminated wood materials enhanced their resistance to bending.

According to the results of the Duncan test, higher values were obtained in the direction parallel to the glue line when considering the applied force direction. This finding suggests that when the material is used as a structural or furniture skeleton component, the forces it will be subjected to, will be independent of the point of application and parallel to the glue line, which would yield better results.

It was observed that the adhesive and laminates bonding the layers of CLT and laminated wood materials provided high bending strength, and there were no issues with the adhesive bonding area.

Average values for bending strength and elastic modulus were found to be higher in the direction parallel to the glue line compared to the direction perpendicular to the glue line. In conclusion, it can be stated that CLT and laminated wood materials can be used as alternatives to solid wood materials, which are frequently used in construction and as furniture materials in framed structures.

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The Influence of Exchange Rate on Performance of Furniture Industry: The Case of Turkey

Utjecaj tečaja na uspješnost industrije namještaja: primjer Turske

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ABSTRACT • *In this study, the effect of the effective exchange rate on the industrial production index, capacity utilization rate, import and export of the furniture products sector was investigated. The analysis covers the period from 2007 to 2023, and the data consists of month observations. Since some of the variables are non-linear and not stationary at the same level, nonlinear autoregressive distributed lag limit test (NARDL), which takes into account asymmetric effects, was used as a method. According to the results of the research, it has been determined that in the short term, downward movements in the effective exchange rate increase the capacity utilization rate of the furniture sector with a significance of 5 %, while upward movements in the effective exchange rate decrease the industrial production index of the furniture sector with a significance of 1 %. Additionally, the downward movements in the effective exchange rate negatively affect the export of furniture products in the long term, while it positively affects the import of furniture in the short term.*

KEYWORDS: *effective exchange rate; foreign trade; capacity utilization rate; industrial production index; furniture sector*

SAŽETAK • *U ovom je radu istražen utjecaj efektivnog tečaja na indeks industrijske proizvodnje, stopu iskorištenosti kapaciteta te na uvoz i izvoz u sektoru namještaja. Analiza obuhvaća razdoblje od 2007. do 2023. godine, a podatci se sastoje od mjesečnih opažanja. Budući da su neke varijable nelinearne i nisu stacionarne na istoj razini, primijenjen je nelinearni autoregresivni distribuirani test vremenskih ograničenja (NARDL) koji uzima u obzir asimetrične učinke. Prema rezultatima istraživanja, utvrđeno je da silazna kretanja efektivnog tečaja povećavaju stopu iskorištenosti kapaciteta sektora namještaja u kratkom roku, sa značajnošću od 5 %, dok uzlazna kretanja efektivnog tečaja smanjuju indeks industrijske proizvodnje sektora namještaja, uz značajnost od 1 %. Osim toga, silazna kretanja efektivnog tečaja dugoročno negativno utječu na izvoz namještaja, dok kratkoročno pozitivno utječu na njegov uvoz.*

KLJUČNE RIJEČI: *efektivni tečaj; vanjska trgovina; stopa iskorištenosti kapaciteta; indeks industrijske proizvodnje; sektor namještaja*

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1 INTRODUCTION
1. UVOD

The manufacturing sector plays a catalytic role in the modern economy. This sector is a pathway for trade expansion, a source of competitiveness and a major contribution to exports and productivity growth. Additionally, the added value of the manufacturing sector has the highest economic multipliers because of its relationship with the industrial production sectors (mining and agriculture) and sub-service sectors.

The furniture sector in Turkey is included in the manufacturing industry and is classified under Code 31: Furniture Manufacturing according to NACE Rev. 2 classification (Anonymous, 2023a). The Turkish furniture sector is one of the important sectors of our country in terms of its capacity utilization rate, the number of employees it employs, its production volume and its contribution to the national economy.

Capacity utilization in the Turkish furniture sector may vary depending on factors such as demand in the sector, production volume and the performance of businesses. The annual average capacity utilization rate of the Turkish furniture manufacturing sector has been above 71 % in the last 9-year period, excluding 2020. The average capacity utilization rates of the furniture industry in Turkey were 77.3 % in 2022, 75.9 % in 2023 and 75.6 % in 2024. (Anonymous, 2023a; CBRT, 2024).

The Turkish furniture industry is generally dominated by SMEs, but the numbers of medium and large-scale enterprises have also been increasing in recent years. Turkey's furniture production capacity is quite high and is at a level that can feed both the domestic and foreign markets. The furniture sector in Turkey is concentrated in certain regions where the market and/or forest products are concentrated. Important furniture production regions are listed as follows: Istanbul, Ankara, Bursa (İnegöl), Kayseri, İzmir and Adana according to their share in total production (Anonymous, 2021; Anonymous, 2023b). Furniture production in Turkey reached 12 billion dollars in 2023. The furniture sector, which is expected to grow by an average of 10 % annually until 2030, is expected to reach approximately 29 billion dollars. The furniture industry plays a significant role in supporting the global economy. Moreover, it positively affects the general employment situation in the country by creating numerous job opportunities. The Turkish furniture sector provides direct and indirect employment to approximately 245000 people. (Damlayıcı and Arslan, 2024; Anonymous, 2024; TURKSTAT, 2023).

Turkey's revenue from furniture exports has increased by reaching over 5 billion dollars in 2023. Thus, Turkey has become the 11th largest furniture exporter in the world. Turkey has an important position in furniture exports, especially to European countries and the Middle East. The share of this sector in total exports was 2 % in 2023. Turkish Furniture sector import was 906 million dollars in 2022, and in 2023, it increased by 17 % compared to the previous year and reached 1 billion 67 million dollars. The furniture sector in Turkey has been one of the sectors with a foreign trade surplus since 2001 (TradeMap, 2023).

There are several macroeconomic factors that can affect the performance of the manufacturing sector. One of these factors is the exchange rate (Mlambo and McMillan, 2020). The exchange rate is a way of measuring the monetary competitiveness of a country. Since changes in the exchange rate tend to create a multiplier effect on macroeconomic variables, it is one of the important macroeconomic indicators used in determining the performance level of an economy. The depreciation or appreciation of the exchange rate, which is an important economic variable, affects the performance of all sectors of the economy, especially the manufacturing sector (Omolola *et al*., 2023). A decrease in the exchange rate causes a decrease in that country's exports and an increase in imports from foreign countries. As a result, there is an outflow of funds from the domestic economy and the amount of resources that domestic companies can use to invest and grow decreases. The increase in the exchange rate makes the country more attractive to foreign investment and makes its products more competitive in the international market. As a result, foreign companies tend to invest more in the country and increase local demand for goods and services (El Aboudi *et al*., 2023).

There are studies in the literature on the effects of exchange rate and effective exchange rate on foreign trade, capacity utilization rate and industrial production index with the help of the Linear Autoregressive Distributed Lag (ARDL) and the Nonlinear Autoregressive Distributed Lag (NARDL) approaches. Eren Sarıoğlu (2013) tried to determine the effect of real exchange rate change on the exports of chemical, automotive, electrical-electronics and iron-steel sectors with ARDL approach. It was found that the exchange rate change did not have a significant effect on the exports of the sectors within the scope of the study. Tutueanu (2015) investigated the dynamic effect of exchange rate on the trade balance of forest products (fibreboard, particleboard and pulp) in Romania. As a result of the study, it was observed that the exchange rate will affect Romania's pulp trade balance in the short term but will have no significant effect in determining the trade balance of fibreboard and particleboard in both the short and long term. Saraçoğlu *et al*. (2018) stated that the effects of exchange rate and exchange rate uncertainties on exports and imports vary depending on the sector. Habibi (2019) investigated the effect of exchange rate on industrial production in various sectors in the United States. According to research results, although exchange rate movements have short-term linear effects on electricity production in the United States, exchange rate movements have no effects on mining and production of energy materials. Simonyan (2020) showed that in both the long and short term, the exchange rate has an asymmetric effect on export and import prices in Turkey using NARDL approach. Bıtrak (2021) examined the effect of some macroeconomic variables on cellulose (pulp) imports. According to the findings of the study, it was determined that increases in the exchange rate negatively affected cellulose imports in the long term. Uche and Nwamiri (2022) stated that positive movements in exchange rates lead to lower output levels in the short term, whereas negative movements does not have any significant effect on productivity levels. Moreover, positive or negative changes in the exchange rate cannot be expected to have a significant impact on productivity in the economy in the long term. In the study conducted by Sylvanus *et al*. (2023), the effect of exchange rates on the agricultural industry was investigated in Nigeria. It was also determined that exchange rates affect agricultural capacity utilization. Hong Nga *et al*. (2024) denoted that although exchange rate movements significantly affect imports in Vietnam, it has an insignificant effect on exports in Vietnam.

The purpose of this research is to examine the effects of increases and decreases in the effective exchange rate on the capacity utilization rate, industrial production index and foreign trade in the furniture sector. In this context, the research questions (RQ) can be defined as follows:

RQ1: How the changes in effective exchange rate influence the capacity utilization rate in the furniture sector?

RQ2: How the changes in effective exchange rate influence the industrial production index in the furniture sector?

RQ3: How the changes in effective exchange rate influence the export in the furniture sector?

RQ4: How the changes in effective exchange rate influence the imports in the furniture sector?

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Capacity utilization rate, industrial production index, import and export values were used as selected indicators for the purpose of analyzing the relationship between effective exchange rate and selected indicators in the furniture sector. As seen in Table 1, effective exchange rate, capacity utilization rate and industrial production index data were obtained from the Central Bank of the Republic of Turkey (CBRT) Data Distribution System (EVDS), while export and import values of the wood and wood products sector were obtained from the TradeMap web address. The analysis covers monthly data from 2007 to 2023. All analyses were performed by taking the natural logarithm of all data except the capacity utilization rate.

Four different models were established to investigate the relationship between the effective exchange rate and the capacity utilization rates, industrial production indices and foreign trade (import and export) values of companies operating in the furniture sector.

NARDL 1: $CUR=\beta_1*InEER+\varepsilon$

NARDL 2: $IPI=\beta_2*InEER+\varepsilon$

NARDL 3: $IMP=\beta_3*InEER+\varepsilon$

NARDL 4: $EXP=\beta_4*InEER+\varepsilon$

Considering the determined targets and the results of the linearity tests, the NARDL test was selected as the analysis technique. The NARDL technique provides a dynamic framework that allows us to simultaneously test asymmetric and nonlinear relationships between variables (Shin *et al*., 2014). In this technique, it is not necessary for all variables to be stationary at

Table 1 Variables used in the study
Tablica 1. Varijable promatrane u istraživanju

Variables *Varijable*	**Descriptions** / *Opis*	**Symbols** *Simboli*	**Database** *Baza podataka*
Effective exchange rate *efektivni tečaj*	The effective exchange rate is a weighted average of a country's currency relative to a basket of other major currencies (Krugman and Obstfeld, 2003).	EER	CBRT
Capacity utilization rate *stopa iskorištenosti kapaciteta*	Capacity utilization is a ratio of the current level of output to full level of output, or capacity (Corrado and Mattey, 1997).	CUR	CBRT
Industrial production index *indeks industrijske proizvodnje*	The Industrial Production Index is an indicator that allows for the comparative tracking of the industrial sector's condition, reflecting the increase or decrease in production activities over the years (Koç *et al.*, 2016)	IPI	CBRT
Import / *uvoz*	Import is the process of goods produced in other countries being bought by buyers in the domestic market (Yurdakul, 2014).	IMP	TradeMap
Export / *izvoz*	Export is the sale of goods that are in free circulation within the country to a foreign country (Yurdakul, 2014).	EXP	TradeMap

the same level for cointegration. Another advantage of this technique is that short-term and long-term coefficients can be modeled simultaneously. Lastly, NARDL permits one to capture the dynamic effect of both upward and downward movements in an explanatory variable (ie. exchange rate) on a particular dependent variable (Adekunle *et al*., 2019; Mesagan *et al*., 2022). The NARDL method includes the following steps (Pesaran *et al*., 2001; Shin *et al*., 2014; Göksu and Balkı, 2023):

Step 1: Stationarity Test of Variables

First of all, it is necessary to determine whether the time series is stationary. For this purpose, tests such as ADF, PP, and KPSS are used. Moreover, the variables should be I(0) and/or I(1) but not I(2).

Step 2: Decomposition of the Independent Variable

The positive (X^+) and negative (X^+) changes of the independent variable are decomposed.

$$X_t^+ = \sum_{j=1}^{t} \max(\Delta X_j, 0);\ X_t^- = \sum_{j=1}^{t} \min(\Delta X_j, 0)$$

Step 3: Determine the Appropriate Lag Length

Optimal lag lengths are determined according to criteria such as LR, FPE, AIC, SIC, HQ. This step is valid for both dependent and independent variables.

Step 4: Estimate the NARDL Model

The model is generally set up as follows:

$$\Delta Y_t = \alpha + \sum_{i=1}^{p} \theta_i \, \Delta Y_{t-i} + \sum_{j=0}^{q} (\theta_j^+ \Delta X_{t-j}^+ + \theta_j^- \Delta X_{t-j}^-) + \lambda_1 \Delta Y_{t-i} + \lambda_2 \Delta Y_{t-i}^+ + \lambda_3 \Delta Y_{t-i}^- + \varepsilon_t$$

Step 5: Bound Test

If there is a long-term relationship, it is tested with the Bounds Test (Pesaran *et al*., 2001) and the test is performed with the F-statistic.

Step 6: Calculation of Long and Short Term Coefficients

Long term coefficients are calculated as $\frac{-\lambda_2}{\lambda_1}$ and $\frac{-\lambda_3}{\lambda_1}$. Also, short-term dynamics are evaluated based on lagged differences.

Step 7: Asymmetry Tests

Wald tests are conducted for short- and long-run symmetry. H_0 hypotheses of short- and long-term asymmetries are as follows.

Long-term asymmetry: H_0: $\frac{-\lambda_2}{\lambda_1} = \frac{-\lambda_3}{\lambda_1}$

Short-term asymmetry: H_0: $\theta_j^+ = \theta_j^+$

If H_0 is rejected, there are asymmetric effects.

Step 8: Diagnostic & Stability Tests

The following tests are used to test the validity and robustness of the estimations:

Autocorrelation: Breusch-Godfrey test

Heteroskedasticity: White or Breusch-Pagan test

Normality: Jarque-Bera test

Functional Form Test: Ramsey-RESET test

Model stability: CUSUM and CUSUMSQ graphics

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

First, Wald linearity test was performed to determine whether the variables used in the analysis were linear. The results obtained from the Wald linearity test are given in Table 2. When the Walds linearity test results in Table 2 are examined, it is determined whether the capacity utilization rate, import and export series of the furniture sector are linear, while the effective exchange rate and industrial production index series are non-linear. Since some variables to be included in the analysis are non-linear, an econometric method that allows the analysis of non-linear series should be preferred in the study.

Determining whether the series are stationary and the degree of stationarity is also very important in choosing the method to be used in the analysis. In this context, the stationarity of the series used in the analysis was investigated with the Augmented Dickey-Fuller (ADF) and Philipps-Perron (PP) tests. The results obtained from the stationarity tests are given in Table 3.

As shown in Table 3, the EER variable is not stationary at the level, and it has become stationary at the first difference. The CUR and EXP variables are stationary at the level of 1 % according to both unit root tests. While the IPI and IMP variables become stationary at the first difference at the level of 1 % according to the ADF unit root test, they are stationary at the level of 1 % according to the PP unit root test. Thus, all the variables used in the analysis are either stationary at the level or become stationary at the first difference. The absence of any variable becoming stationary at

Table 2 Wald linearity test results
Tablica 2. Rezultati Waldova testa linearnosti

Effective exchange rate (EER) *Efektivni tečaj*		**Capacity utilization rate (CUR)** *Stopa iskorištenosti kapaciteta*		**Industrial production index (IPI)** *Indeks industrijske proizvodnje*		**Import (IMP)** *Uvoz*		**Export (EXP)** *Izvoz*	
Constant	39.4*	Constant	-0.01	Constant	43.2*	Constant	193	Constant	47.1
EER(-1)	-25.7*	CUR(-1)	2.16	IPI(-1)	-28.9*	IMP (-1)	-48.6	EXP(-1)	-14.6
EER^2(-1)	6.02*	CUR^2(-1)	-2.94	IPI^2(-1)	6.92**	IMP^2(-1)	4.26	EXP^2(-1)	1.59
EER^3(-1)	-0.45*	CUR^3(-1)	1.87	IPI^3(-1)	-0.53**	IMP^3(-1)	-0.12	EXP^3(-1)	-0.05

*, **, and *** indicate 10 %, 5 %, and 1 % significance levels, respectively
, ** i * označavaju razinu značajnosti od 10 %, 5 % i 1 %*

Table 3 Stationarity test results
Tablica 3. Rezultati testa stacionarnosti

	ADF		PP	
	Level	First difference	Level	First difference
lnEER	0.299	- 9.389***	0.375	- 11.27***
CUR	- 5.279***	-	- 5.362***	-
lnIPI	- 0.539	- 6.142***	- 3.681***	-
lnIMP	- 2.799*	- 22.46***	- 4***	-
lnEXP	- 3.476***	-	- 4.784***	-

*, **, and *** indicate 10 %, 5 %, and 1 % significance levels, respectively
, ** i * označavaju razinu značajnosti od 10 %, 5 % i 1 %*

Table 4 Lag lengths of NARDL models
Tablica 4. Duljine zaostajanja NARDL modela

	Lag	LogL	LR	FPE	AIC	SIC	HQ
NARDL 1	0	305.13		0.0001	-3.047	-3.013	-3.033
	1	793.37	961.76	1.25e-06	-7.913	-7.814	-7.873
	2	804.36	21.43	1.17e-06	-7.984	-7.818	-7.917
	3	815.57	21.64*	1.09e-06*	- 8.056*	- 7.824*	- 7.962*
	4	817.32	3.34	1.11e-06	-8.033	-7.735	-7.913
NARDL 2	0	24.149		0.0027	- 0.223	- 0.19	- 0.209
	1	473.84	885.82	3.11e-05	-4.702	-4.603	-4.662
	2	489.57	30.673	2.77e-05	- 4.82	-4.654	-4.753
	3	509.58	38.605*	2.35e-05*	- 4.981*	- 4.749*	- 4.887*
	4	512.22	5.034	2.39e-05	-4.967	-4.669	-4.846
NARDL 3	0	-29.987		0.005	0.321	0.355	0.335
	1	484.12	1012.72	2.81e-05	-4.805	-4.706	-4.765
	2	508.36	47.26	2.29e-05	-5.009	-4.843	-4.942
	3	520.45	23.338*	2.11e-05*	- 5.09*	- 4.858*	- 4.996*
	4	521.81	2.581	2.17e-05	-5.063	-4.765	-4.943
NARDL 4	0	- 325.31		0.092	3.29	3.323	3.303
	1	183.72	1002.7	0.00057	-1.786	-1.687	-1.746
	2	193.42	18.908	0.00054	-1.843	-1.678	-1.776
	3	205.48	23.268*	0.0005*	- 1.924*	- 1.693*	- 1.831*
	4	208.88	6.489	0.000503	-1.918	- 1.62	-1.798

* indicates the lag length selected by the criterion; LogL – Log-Likelihood; LR – Likelihood Ratio; FPE – Final Prediction Error; AIC – Akaike Information Criterion; SIC – Schwarz Information Criterion; HQ – Hannan-Quinn Criterion
** označava duljinu zaostajanja odabranu kriterijem; LogL – log-vjerojatnost; LR – omjer vjerojatnosti; FPE – konačna pogreška predviđanja; AIC – Akaikeov informacijski kriterij; SIC – Schwarzov informacijski kriterij; HQ – Hannan-Quinnov kriterij*

second or higher orders and the fact that some of the variables are linear and some are non-linear indicates that the variables used in the analysis are in a suitable form for the NARDL model in terms of stationarity and linearity. Then, suitable lag lengths were determined for the NARDL models. Accordingly, for all four models, the appropriate lag length was identified as three lags. The detailed information about the suitable lag lengths for the NARDL models is shown in Table 4.

Then, it was denoted that the models would be predicted with the NARDL technique. The prediction results of the models found with the NARDL method is given in Table 5.

Before providing information about the results obtained in the first model, it should be noted that the capacity utilization rate series show a structural break in the period 2015 – 2020. Within this framework, a dummy variable was added to the model in order to explain and correct the breakage. Based on the results obtained from the NARDL l model, in the long term, it was observed that changes in the effective exchange rate do not significantly affect the capacity utilization rate of firms operating in the furniture manufacturing industry. The main reasons why changes in the effective exchange rate do not significantly affect the capacity utilization rate of firms in the furniture sector in the long term may be as follows: high domestic input use, demand being the determinant, firm strategies developed against exchange rate changes, structural characteristics of the sector, and the balancing effects of export advantages. However, it was observed that the dummy variable added to the model positively affected the capacity utilization rate with a significance level of 5 %. Additionally, it was observed that in the short term, positive movements in the effective exchange rate did not significantly affect the capacity utilization

Table 5 NARDL test results
Tablica 5. Rezultati NARDL testa

	Short run coefficients (Std. Error)		Long run coefficients (Std. Error)		NARDL bound tests	
NARDL 1	ΔInEER (+)	- 0.028	ΔInEER (+)	- 0.097	F- Statistic	10.519*
		(0.05)		(0.174)		
	ΔInEER (-)	0.24**	ΔInEER (-)	0.075	10 %	LB =3.588
		(0.094)		(0.103)		UB =4.605
	CUR (-1)	0.708*	Dummy	0.029**	5 %	LB = 4.203
		(0.049)		(0.012)		UB = 5.32
	ECT (-1)	- 0.292*			1 %	LB =5.62
		(0.045)				UB =6.908
NARDL 2	ΔInEER (+)	-1.315*	ΔInEER (+)	0.112	F- Statistic	20.046*
		(0.477)		(0.267)		
	ΔInEER (-)	- 0.168	ΔInEER (-)	- 0.253	10 %	LB =2.474
		(0.12)		(0.18)		UB =3.312
	ΔInIPI(-1)	0.335*	Dummy	0.115*	5 %	LB = 2.92
		(0.068)		(0.036)		UB = 3.838
	ECT (-1)	- 0.665*			1 %	LB =3.908
		(0.066)				UB =5.044
NARDL 3	ΔInEER (+)	- 1.772*	ΔInEER (+)	- 0.523	F- Statistic	3.743***
		(0.566)		(1.56)		
	ΔInEER (-)	1.134*	ΔInEER (-)	- 0.277	10 %	LB = 3.26
		(0.436)		-1.076		UB = 4.247
	ΔInIMR(-1)	- 0.364*			5 %	LB = 3.94
		(0.064)				UB = 5.043
	ECT (-1)	- 0.122*			1 %	LB = 5.407
		(0.036)				UB = 6.783
NARDL 4	ΔInEER (+)	- 0.356	ΔInEER (+)	-1.334	F- Statistic	4.84**
		(0.218)		(0.976)		
	ΔInEER (-)	- 0.117	ΔInEER (-)	- 0.81***	10 %	LB =3.588
		(0.392)		(0.467)		UB =4.605
	ΔInEXP (-1)	- 0.432*	Dummy	- 0.43**	5 %	LB =4.203
		(0.081)		(0.177)		UB =5.32
	ECT (-1)	- 0.267*			1 %	LB =5.62
		(0.06)				UB =6.908

*, *, **, and *** indicate 10 %, 5 %, and 1 % significance levels, respectively; ECT – Error correction term
, ** i * označavaju razinu značajnosti od 10 %, 5 % i 1 %; ECT – oznaka za korekciju pogreške*

rate, whereas it was observed that the negative movements in the effective exchange rate increased the capacity utilization rate with a significance level of 5 %. Negative EER movements increase capacity utilization because export demand can rise quickly, firms can respond by increasing output, and higher profitability and competitiveness can drive short-term production increases. Positive EER movements have no effect because: input cost savings can take time to influence output, import competition and demand substitution can do not materialize quickly, and production planning can be rigid in the short term. Yenigün and Azizi (2022) reported that the exchange rate positively affects the capacity utilization rate. One-period lagged values of the capacity utilization rate have a significant and positive impact on the capacity utilization rate. In other words, a negative change in the capacity utilization rate one period ago negatively affects the current capacity utilization rate, whereas a positive change one period ago positively affects the current period. Finally, shocks occurring in the capacity utilization rate are quickly dampened with a coefficient of approximately -0.292.

There is also a structural break in the industrial production index series. In this context, a dummy variable was added to the model. According to the results obtained from the NARDL 2 model, in the long term, both positive and negative movements in the effective exchange rate do not have a significant impact on the industrial production index, as well as the dummy variable positively affected the industrial production index with a significance level of 1 %. In the long run, both appreciation and depreciation of the effective exchange rate tend to lose their power to influence industrial production significantly. This can due to a combination of structural adjustments, policy responses, strategic firm behavior, and the dominance of other macroeconomic factors that drive industrial output over time. Additionally, it was determined that in the short term, positive movements in the effective exchange rate had a negative effect on the industrial production index with a significance level of 1 %, whereas negative changes in the effective exchange rate did not have a significant effect on the industrial production index. The negative effect of a positive movement in the exchange rate on industrial production in the short term can be attributed to factors such as reduced export demand, increased competition from imports, and challenges in quickly adjusting production strategies. Meanwhile, negative changes in the exchange rate did not have a significant impact, potentially because the positive effects on export competitiveness could outweighed the costs of higher import prices, or the impact on input costs was manageable. These dynamics can suggest that industries in this particular context may be more sensitive to appreciation-induced external market shifts than to depreciation-induced internal cost pressures. One-period lagged values of the industrial production index have a significant and positive impact on the industrial production index. Finally, shocks occurring in the capacity utilization rate are quickly dampened with a coefficient of approximately -0.665.

According to the results obtained from the NARDL 3 model, in the long term, both positive and negative movements in the effective exchange rate do not have a significant impact on the import of furniture products. This may be because of market adaptation, contractual stability, hedging practices, and persistent consumer demand. Exchange rate changes may cause short-term price adjustments, but they may not significantly alter the volume of furniture imports over time due to these balancing and structural effects. Additionally, in the short term, increases and decreases in the effective exchange rate have a negative and positive impact on the import of furniture products, respectively, with a significance level of 1 %. In the short term, this is because appreciation of the effective exchange rate can have a positive effect on import volumes by making imported furniture cheaper, whereas depreciation of the effective exchange rate can have a negative effect by making imports more expensive. These effects can be mainly driven by price sensitivity, consumer behavior, import financing costs, and the absence of long-term hedging mechanisms, all of which can cause furniture imports to react quickly and visibly to exchange rate movements. One-period lagged values of the imports of furniture products have a significant and negative impact on the imports of furniture products with a significance level of 1 %. In other words, if one-period lagged values of the import are positive, they affect the current furniture import negatively, and if one-period lagged values of the import are negative, they affect the current import negatively. Finally, shocks occurring in the import are quickly dampened with a coefficient of approximately -0.122.

There is also a structural break in the furniture exports series. In this context, a dummy variable was added to the model. According to the results obtained from the NARDL 4 model, both upward and downward movements of the effective exchange rate do not significantly affect furniture exports in the short term. In the short term, both appreciation and depreciation of the effective exchange rate may not significantly affect furniture exports because: export contracts may be fixed in advance, production and logistics are inflexible in the short term, currency risks are often hedged, and demand for furniture exports is relatively inelastic and brand- or quality-driven. These factors may ensure that exchange rate movements do not quickly translate into changes in export volume, resulting in statistically insignificant short-term effects on furniture exports. In the long term, negative movements in the effective exchange rate negatively affect the export of products with a significance of 10 %. In the long term, currency depreciation (negative EER movement) may have a significant negative effect on exports due to a combination of rising production costs from imported inputs, macroeconomic instability, reduced investment and innovation, inflationary pressures, and loss of international trust and market share. Thus, even though depreciation is expected to support exports, its adverse side effects may dominate in the long run, particularly in economies with structural weaknesses or limited export competitiveness. The result of the research conducted by Bilgin (2020) is compatible with the result of this study. Bilgin (2020) said that the depreciation of the local currency caused an increase in furniture sector exports. One-period lagged values of the furniture export have a significant and negative impact on the furniture export with a significance level of 1 %. In other words, if one-period lagged values of the export are positive, they affect the current furniture export negatively, and if one-period lagged values of the export are negative, they affect the current export negatively. Finally, shocks occurring in the export are quickly dampened with a coefficient of approximately -0.276.

After presenting the results of the econometric forecasts, diagnostic tests were conducted to measure the robustness of the forecasts. The results of the diagnostic tests are given in Table 6.

F tests and Ramsey Reset tests regarding the validity and stability of the forecasting show that all four forecastings made with the NARDL method are valid and stable forecasting. According to the results obtained from Breusch Godfrey Lagrance Multiplier (BG LM) and Breusch Pagan Godfrey (BPG) tests, it was

Table 6 Robustness checks
Tablica 6. Provjere robusnosti

	NARDL 1	NARDL 2	NARDL 3	NARDL 4
R^2	0.6019	0.7917	0.7687	0.9095
Adjusted R^2	0.5896	0.7864	0.7616	0.9025
F-Statistic	48.89 (0.000)	148.27 (0.000)	107.48 (0.000)	130.57 (0.000)
Log-Likelihood	415.16	106.27	117.96	149.21
Ramsey Reset	0.332 (0.7404)	1.065 (0.288)	0.914 (0.3618)	1.671 (0.1909)
BG LM	1.97 (0.14) HAC	0.004 (0.9959)	0.326 (0.7224)	2.75 (0.06)HAC
BPG	1.18 (0.32) HAC	1.094 (0.3651)	0.502 (0.8065)	2.77 (0.00)HAC
Jarque – Bera	11344 (0.00) HAC	20.61 (0.0000)	16.84 (0.0002)	21.59 (0.00)HAC

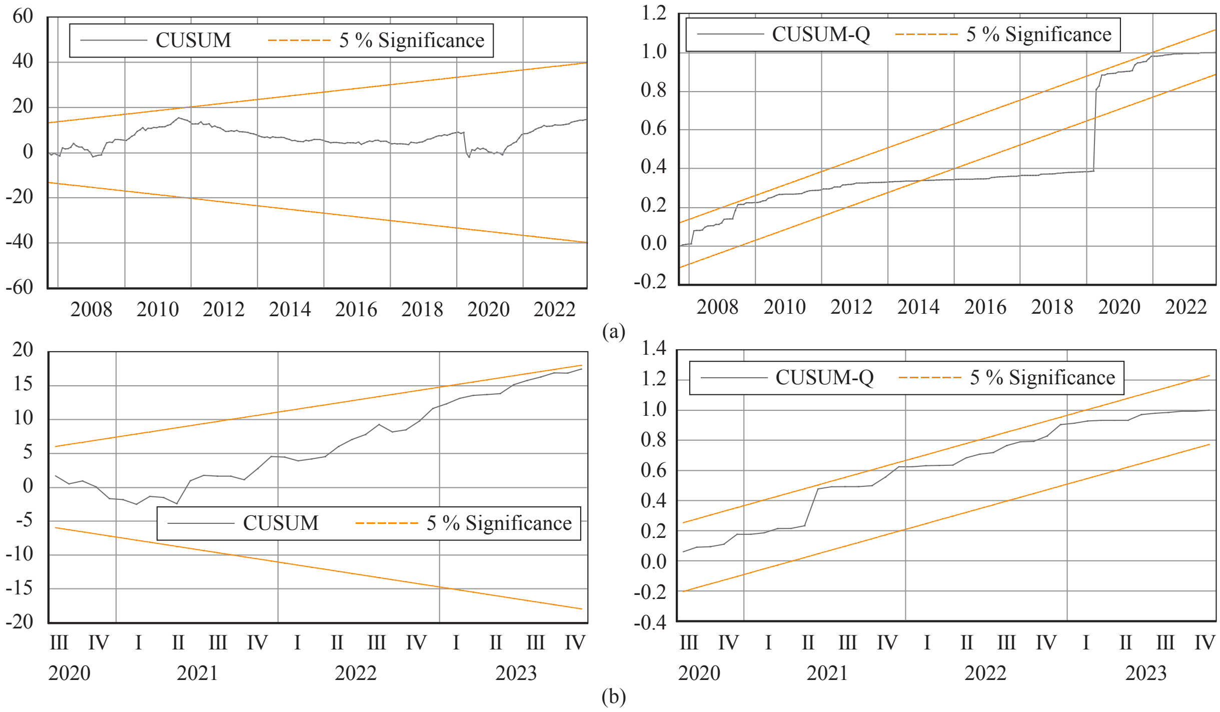

Figure 1 outcome of NARDL 1 cusum and cusum-q tests without dummy variables (a) and with dummy variables (b)
Slika 1. Rezultat NARDL 1 *cusum* i *cusum-q* testova bez lažnih varijabli (a) i s lažnim varijablama (b)

determined that there was no heteroscedasticity and autocorrelation problem in NARDL-2 and NARDL-3 models. Additionally, it was observed that there was a heteroscedasticity and autocorrelation problem in NARDL-1 and NARDL-4 models; therefore, the heteroscedasticity and autocorrelation consistent (HAC) variance-covariance matrix was used in NARDL-1 and NARDL-4.

To determine the stability of ARDL models, Cusum and Cusum-Q graphs, which examine structural breaks in variables using reversible error terms, were used. When Figures 1, 2 and 4 are examined, it is seen that there is a structural break in the variables with a significance of 5 % according to the Cusum-Q test. It is seen that the structural break disappears when a dummy variable is added. When Figure 3 is examined, it is seen that the long-term coefficients of the variables in the ARDL 3 model move between critical values. In other words, it is seen that no dummy variable is used in the model, and the long-term coefficients of the variables are stable.

4 CONCLUSIONS
4. ZAKLJUČAK

This study examines the relationship between the upward and downward movements in the exchange rate and some indicators in the furniture products sector in the long and short term. According to the results of linearity and stationarity analysis in this study, it was concluded that the NARDL method is the most appropriate method to determine how the changes in the exchange rate affect the furniture sector.

As a result of the analysis, it has been determined that there is a structural break in the capacity utilization rate, industrial production index and exports of the furniture sector. Structural breaks refer to radical and permanent changes in the capacity utilization rate, industrial production and exports in the furniture sector.

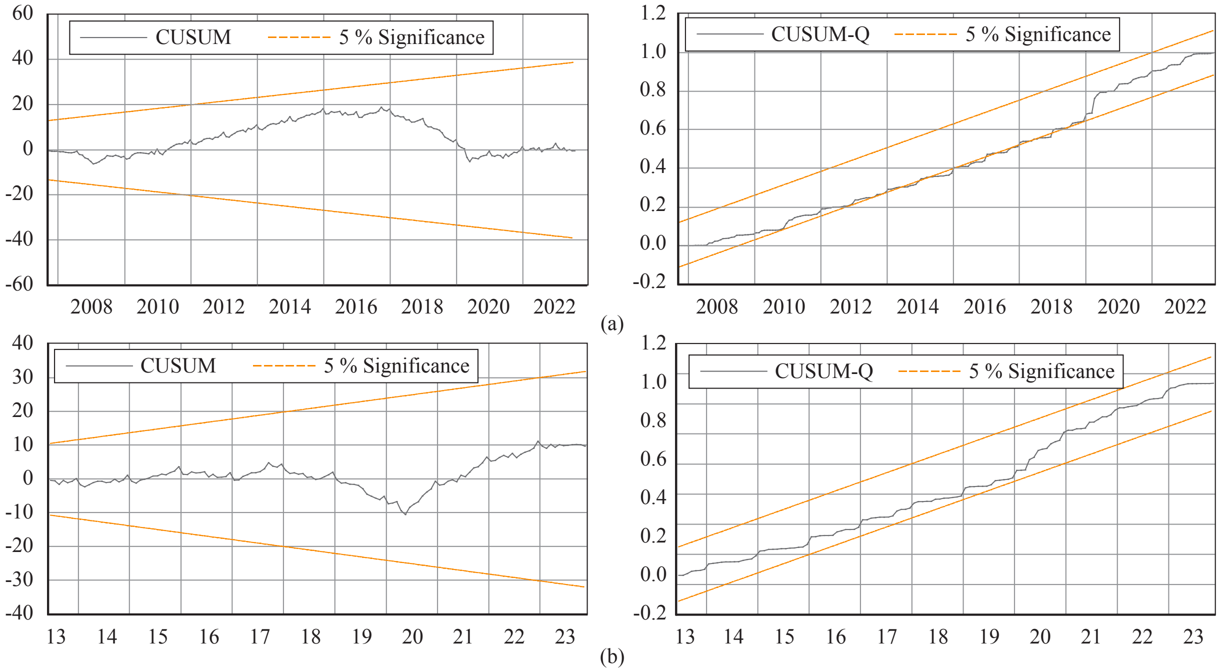

Figure 2 Outcome of NARDL 2 cusum and cusum-q tests without dummy variables (a) and with dummy variables (b)
Slika 2. Rezultat NARDL 2 *cusum* i *cusum-q* testova bez lažnih varijabli (a) i s lažnim varijablama (b)

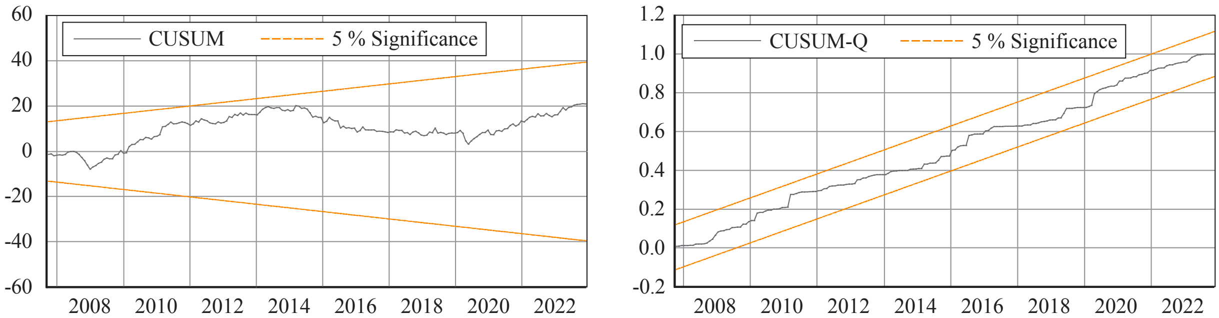

Figure 3 Outcome of NARDL 3 cusum and cusum-q tests
Slika 3. Rezultat NARDL 3 *cusum* i *cusum-q* testova

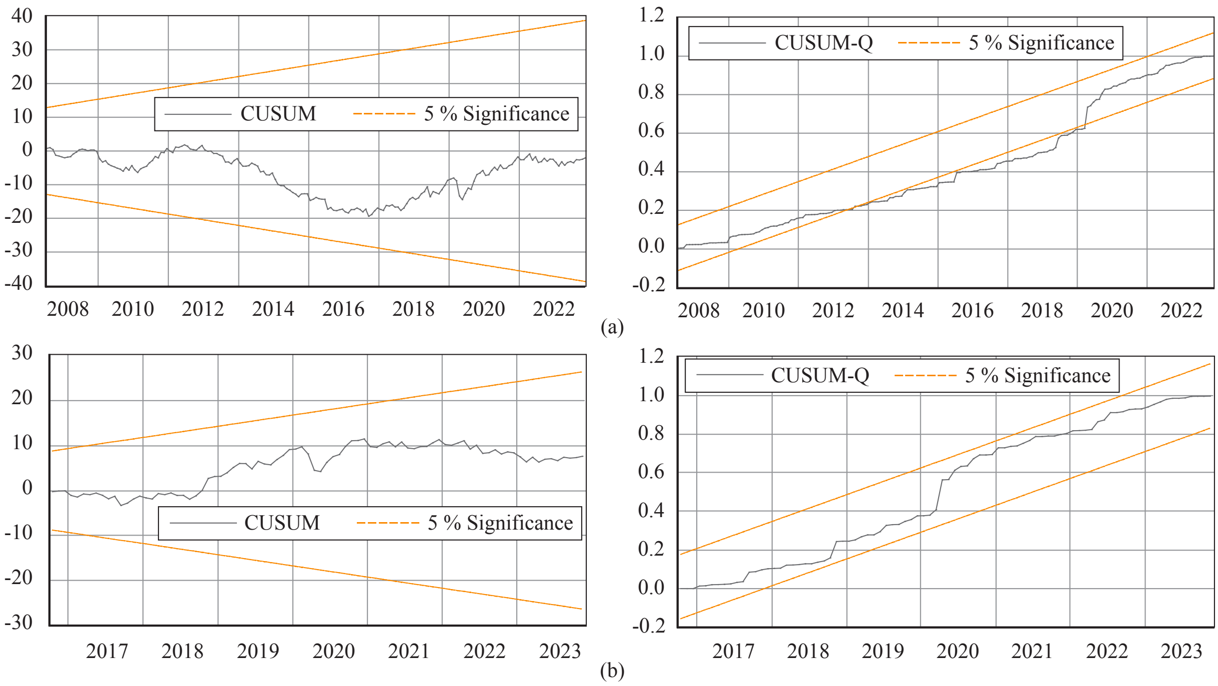

Figure 4 Outcome of NARDL 4 cusum and cusum-q tests without dummy variables (a) and with dummy variables (b)
Slika 4. Rezultat NARDL 4 *cusum* i *cusum-q* testova bez lažnih varijabli (a) i s lažnim varijablama (b)

Such changes indicate that the current structure and functioning of the sector is no longer the same as before. While the break in the capacity utilization rate and industrial production index started in 2015, the break in exports started in 2014. In addition, all the breaks ended in 2020. Due to this break, a dummy variable was added to the capacity utilization rate, industrial production index and export variables. Following the 2008 Mortgage Crisis, the US central bank, the FED, implemented quantitative easing by reducing policy interest rates from 5.25 % to 0.25 %. This process continued until the end of 2015, and the US central bank began increasing interest rates at the end of 2015. This situation affected Turkey's foreign trade, as it did all countries in the world, and thus also the production volume of sectors with foreign trade activities in the Turkish economy. Additionally, in the world economy, where there was dollar abundance during the period in question, the relevant abundance gradually ended with the FED's interest rate increases compared to the 2008-2015 period. This also affected the effective exchange rate. Therefore, it can be said that the source of the breaks detected in the Cusum and Cusum-Q tests of our study was the FED's interest rate increases during the period in question. However, it would not be realistic to say that such long-term breaks are only due to the FED's interest rate increases. In this context, the coup attempt, political instabilities and exchange rate shocks experienced in Turkey may also have caused the breaks to spread over a long period. Based on this, the source of these breaks may be factors outside Turkey, but the reason why the breaks are so long-lasting may be due to Turkey's own dynamics. While this dummy variable positively affects the capacity utilization rate and industrial production index of the furniture sector, it negatively affects furniture exports. When the relationship between the exchange rate and the capacity utilization rate is analyzed, in the short term, there is a direct proportion between the appreciation of the Turkish lira and the capacity utilization rate of the furniture industry. Considering the relationship between the effective exchange rate and the industrial production index of the furniture sector, the depreciation of the Turkish lira negatively affects the industrial production index of the furniture sector. Considering the relationship between the effective exchange rate and foreign trade of furniture products, when the Turkish lira loses value, furniture product imports decrease, and when it gains value, it increases. In the long term, the appreciation of the Turkish lira significantly reduces the export of furniture products. These situations are consistent with our theoretical expectations. In the short term, the appreciation and depreciation of the Turkish lira do not significantly affect the export of furniture products. It is theoretically expected that the appreciation of the Turkish lira will significantly reduce the exports of furniture products, and the depreciation of the Turkish lira will significantly increase the exports of furniture products, but it is seen that the results obtained on the subject do not coincide with theoretical expectations. As a result, the exchange rate is an external variable that seriously affects the indicators of the furniture sector. Therefore, it is necessary to follow economic policies that will minimize exchange rate fluctuations.

There are many studies in the literature on the effect of exchange rate and exchange rate volatility on foreign trade, but there is a limited number of studies on the effect of both the exchange rate on foreign trade on a sectoral basis and on the capacity utilization rate and industrial production index. There is no study on this subject, especially for furniture products. In this context, this study will contribute to the literature.

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Sustainable Management of Wood Residues: Challenges of Recycling, Combustion and Environmental Impact

Održivo gospodarenje drvnim ostatcima: izazovi recikliranja, spaljivanja i utjecaja na okoliš

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ABSTRACT • *In the quest for climate neutrality, the importance of sustainability and the reuse of wood waste are becoming crucial. To determine how wood waste is managed by wood and wood-based panel plants, the research aimed to focus particularly on energy recovery contribution. The research was based on quantitative data analysis obtained through computer-assisted telephone interviews. The results showed that over 57 % of respondents declared that they combusted waste to recover energy, which causes immediate CO_2 emissions, instead of enabling long-term storage in wood-based products. Further research analyzed the emissions produced by combustion of the selected products: MDF boards and softwood and hardwood pellets. Laboratory tests showed that the incineration of MDF boards resulted in the emission of a number of harmful substances, which pose a threat to health and the environment. In contrast, burning pellets does not generate toxic compounds, but it still leads to the release of CO_2. Research findings indicate the need for further research into the cascading wood utilization strategy, focusing on the use of wood waste in the material cycle instead of the energy cycle in order to understand and promote the EU's sustainable development goals throughout the wood industry.*

KEYWORDS: *wood waste; toxic substances; medium-density fiberboard; pellet; biomass; supply chain*

SAŽETAK • *U postizanju klimatske neutralnosti ključnu važnost ima održivost i ponovna uporaba drvnog otpada. Kako bi se utvrdilo na koji način tvornice za proizvodnju drvnih ploča gospodare drvnim otpadom, istraživanje je bilo posebno usredotočeno na proizvodnju energije od drvnog otpada te se temeljilo na kvantitativnoj analizi podataka dobivenih putem računalno potpomognutih telefonskih intervjua. Rezultati su pokazali da je više od 57 % ispitanika izjavilo da otpad spaljuju radi proizvodnje energije, posljedica čega su neposredne emisije CO_2, umjesto da ga dugoročno skladište u drvnim proizvodima. U daljnjim istraživanjima analizirane su emisije nastale spaljivanjem odabranih proizvoda: MDF ploča te peleta od mekoga i tvrdog drva. Laboratorijska ispitivanja pokazala su da spaljivanje MDF ploča rezultira emisijom niza štetnih tvari koje su prijetnja za zdravlje i okoliš. Nasuprot tome, izgaranjem peleta ne nastaju otrovni spojevi, ali se ipak oslobađa CO_2. Rezultati upućuju na potre-*

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bu daljnjeg istraživanja kaskadne strategije iskorištavanja drva, posebice drvnog otpada u materijalnom umjesto u energetskom ciklusu kako bi se razumjeli i promovirali ciljevi održivog razvoja EU-a u cijeloj drvnoj industriji.

KLJUČNE RIJEČI: *drvni otpad; otrovni spojevi; MDF; peleti; biomasa; opskrbni lanac*

1 INTRODUCTION
1. UVOD

Wood is one of the most suitable renewable raw materials. Its key value is recognized from both an economic and environmental point of view. Based on FAO reports, the trend of increasing global timber supply has been observed (FAO, 2020). Within the past two decades, the global timber supply increased by over 20 %. This growth is estimated to continue in the following decades of the 21st century. The main factor that influences the growth in demand for raw wood material is the increase in the world's population. As the world's population grows, there is an increase in the demand for wood in various areas of the timber industry as well as in households.

One of the most popular wood utilizations is fuelwood (sometimes firewood). Among the earliest applications of wood were its uses in building and as a fuel source (Rhodes, 2018). According to Eurostat (Eurostat, 2023), in 2022 approximately 25 % of total wood production in the European Union was used as fuelwood. In some countries fuelwood production is a major direction of wood production, i.e. Netherlands – 78.5 %, France – 50.7 % or Lichtenstein – 50 %. This phenomenon is due to the great heating value of wood. In general, the heating value depends mainly on wood species and moisture content, but it is commonly well-known that burning wood is a good source of heat or power. In Poland, 21 % of households use wood for any heating purpose, while 11 % use it as a primary commodity for dwelling heating (GUS, 2023). Unfortunately, the side effect of energy/heat production from burning wood is wood smoke, which consists of particulates and gases that negatively affect human health. The effect of wood smoke on people and the environment was widely studied (Heibati *et al*., 2025; Naeher *et al*., 2007; Ward and Lange, 2010). However, this problem is gradually being minimized by the introduction of clean air programs in both cities and villages throughout the World to improve air pollution control (Wang *et al*., 2024).

Another argument in the discussion of the legitimacy of wood combustion is the question of what wood should be used for energy production, so as not to compete with its use in other wood industries. Wood biomass, such as forest residues, wood processing residues or construction and municipal waste, can be recycled and reused. The work has proven that forest residues from Scots pine (*Pinus sylvestris* L.), which are usually burned after shredding, can be used as a raw material for particleboard manufacturing with increased mechanical strength (Pędzik *et al*., 2022).

Pellet production should be based on the use of wood waste that cannot be reintroduced into the material cycle, rather than full-grade wood. The production of pellets from forest residues from thinning stands of Mediterranean pine (*Pinus halepensis* Mill. and *Pinus pinaster* Aiton) is uneconomical, and pellets produced from debarked logs of larger diameter show the highest quality, while pellets produced from branches have lower quality (Lerma-Arce *et al*., 2017). Therefore, the priority should be to use wood waste that is no longer suitable for further processing for pellet production. Such reasonable wood management is called wood cascading, a concept that allows for maximum use of wood in material applications, with an indication of energy use at the end of utilization. This concept becomes more and more popular both in research and industry (Jarre *et al*., 2020). Cascading wood and a reverse supply chain would allow the long-term use of wood, which, despite being a renewable resource, has a long renewal cycle. In addition, it would allow carbon dioxide to be sequestered rather than, as in the case of incineration, immediately released into the atmosphere along with other harmful substances.

In this context, it is worth highlighting the measures taken by the European Union to reduce carbon emissions by promoting the alternative, more sustainable use of wood. The climate package is based on two key objectives: reducing greenhouse gas emissions in the EU by 55 % by 2030 compared to 1990 levels and achieving climate neutrality for the climate and the environment by 2050 (European Commission, 2018; Köhl *et al*., 2021). One of the priority areas of action remains the reduction of carbon dioxide emissions, including those resulting from the energy use of wood through combustion (Brodny and Tutak, 2020). One of the key elements of the European Green Deal is the promotion of timber construction. The use of wood in the construction and fitting out of buildings promotes long-term carbon storage, which contributes to the reduction of greenhouse gas emissions (Mazur and Winkler, 2025). The strategic implementation of technologies focused on the use of wood waste in sustainable production processes is becoming crucial for promoting responsible environmental management (Pelyukh *et al*., 2025). Therefore, the effective management of wood waste, its recycling and reuse in the construction sector is a key element in reducing the carbon footprint and promoting a circular economy (European Commission, 2021). At the same time, this emphasizes the need for optimized logistics and transportation strategies that enable an efficient management of wood raw materials at every stage of the supply chain.

In Poland, around 15 % of total round wood production is used for fuelwood (Eurostat, 2023). In an era of growing demand for wood, which is necessary to produce building materials, wood-based panels and other industrial products, efficient wood waste management is becoming a key challenge. Burning full-value wood solely for its high energy value leads to an irretrievable loss of raw material that could be used in further production. Therefore, the purpose of the article was to determine how wood waste and residues are managed by wood plants, what part of it goes to recycling and what part is used for energy recovery. In addition, emissions from the combustion of wood products and pellets were analyzed, which is important for assessing the environmental impact of the process. The second aim of this study was to understand what substances may be emitted when material such as MDF is ignited, e.g. in the event of a building or furniture fire.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The research was carried out based on a multi-step study on wood biomass supply chain, which consists of literature review with the focus on group interviews (Kawa, 2023) and originally published methods (Dubisz and Kawa, 2023). The study was based on a dataset provided by a specialized research agency, which conducted computer-assisted telephone interviews based on a questionnaire and interview script prepared by the research team. The main topic of investigation consisted of wood waste management in the wood and furniture industries – what types of residues are generated and how they are processed in practice.

The sample was selected through stratified random sampling, with the population limited to companies involved in processing or transporting wood waste, producing wooden products, and recycling wood materials. Out of 12,000 potential participants, 3,800 were contacted, but only 300 companies agreed to take part in the study, resulting in a success rate of 8 %. The sample is representative of a population of up to 50,000 entities with a margin of error of 5.64 % (Raosoft, 2025). Participation in the interview was restricted to respondents with experience in the wood industry, particularly biomass. Two screening questions were used to ensure this. Respondents were asked whether the company they worked for dealt with wood waste, wood materials or post-consumer wood (waste from used wood products) and whether they had any knowledge of such waste, including its generation, processing, collection or transport. Positive answers to both questions were required for the respondent to qualify for the study.

Given the survey data obtained, in a further step, it was decided to test the presence of toxic substances in two combusted wood wastes – medium-density fiberboards (MDF) and pellets. MDF boards are commonly used in many branches of economy, including the furniture and building industry. In general, this material is commonly known as hard to recycle and burn due to its structure and presence of toxic substances. Pellets are made from the sawdust of softwood and hardwood and are one of the most common ways of utilization in the wood industry. Measurements using a cone calorimeter from Fire Testing Technology Ltd. were conducted in accordance with ISO 5660-1, 2015. This calorimeter enables accurate measurements of relevant flammability parameters, which are essential for understanding the fire risks associated with different materials. Samples were placed horizontally against the cone heat sink and exposed to a 35 kW/m^2 heat flux. At least three measurements were taken for each material. To investigate the formation of gaseous combustion products, the tube furnace (Purser furnace) method was employed to simulate fire conditions, following ISO/TS 19700, 2016. Samples of the test materials were placed in a quartz mold and inserted into a furnace. The samples were then heated to 350 °C with an airflow of 2 dm^3/min (poor ventilation) and to 650 °C with an airflow of 10 dm^3/min (good ventilation). The test run was considered valid only if the initial air velocities were correct according to the ISO standard and the selected steady-state conditions were maintained for at least 5 minutes during the test. The sampling procedure for the chromatograph coupled with a mass spectrometer was described in an earlier publication (Mizera *et al*., 2024).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In the context of wood waste management in the wood and furniture industry, it is crucial to determine what types of residues are generated in production processes and to define their uses. The research carried out included the following waste groups: wood residues from agriculture and forestry (e.g., wood chips), post-production residues (e.g., particles, wood-based panel residues) and post-consumer wood. Such categorization of waste utilization is part of the wood cascading concept (Besserer *et al*., 2021; Jarre *et al*., 2020), especially in terms of size of the wood waste production in

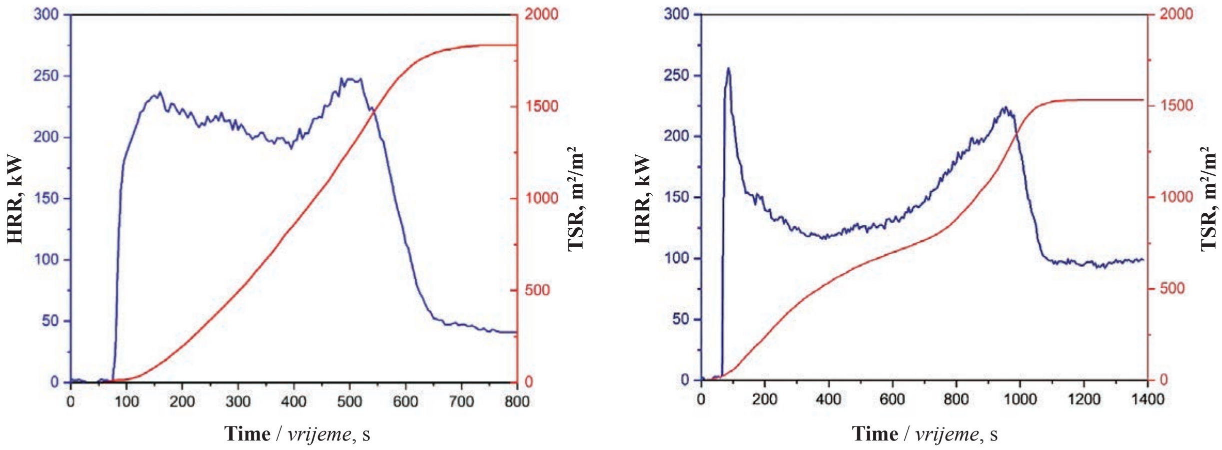

Figure 1 Representative heat release rate (*HRR*) and total smoke release (*TSR*) curves of a) pellet and b) medium-density fiberboard
Slika 1. Reprezentativne krivulje brzine oslobađanja topline (*HRR*) i ukupnog oslobađanja dima (*TSR*): a) spaljivanjem peleta, b) spaljivanjem MDF ploča

Europe (Garcia and Hora, 2017), i.e., Germany produces around 11 million tons of wood waste (Burnard *et al*., 2015; Sommerhuber *et al*., 2015) and is the biggest wood waste producer in the whole Europe, followed by France, United Kingdom, Italy and Finland (Garcia and Hora, 2017). In the first part of the study, we conducted and analyzed a survey on wood waste management of wood and furniture industries in volunteer companies. In general, the utilization of the wood waste is a combination of recycling, energy recovery, and disposal processes (de Souza Pinho *et al*., 2023; Hossain and Poon, 2018). An analysis of the answers regarding waste management methods indicates that most waste ends in combustion with energy recovery or is transferred to external companies for energy production, which confirms the worldwide trends described in the literature (Elginoz *et al*., 2024; Farjana *et al*., 2023). The three most numerous groups participating in the research, namely sawmills, furniture manufacturers and manufacturers of joinery, declare that 52 %, 65 % and 55 %, respectively, combust waste or transfer it for energy recovery. Although this approach allows for effective biomass management and a reduction in landfill waste, from a wood cascading concept point of view, incineration should be considered a last resort in the context of environmental strategies. Wood plays an important role as a carbon (CO_2) store, and its rapid combustion contributes to the accelerated emission of stored carbon dioxide into the atmosphere. To further investigate the environmental impact of burning different wood products, a laboratory study simulating fire conditions was conducted.

Testing the flammability of materials using a cone calorimeter is a crucial method for assessing their behavior under combustion conditions. The heat release rate (*HRR*) is a key parameter that indicates the amount of heat released by a material over a specific period. A higher heat release rate correlates with an increased risk of fire spreading (Mizera *et al*., 2023). Another significant phenomenon during combustion is the emission of smoke, which consists of the gaseous phase of liquid or solid products resulting from incomplete combustion. Smoke emission is an extremely important parameter due to its toxicity and the reduced visibility it causes (Hu and Wang, 2020). Increased emissions of toxic substances in the air are harmful on many levels, both to humans, animals and the environment as a whole (Lelieveld *et al*., 2015; Ram Mahala, 2024). Figure 1 summarizes the representative *HRR* and total smoke release (*TSR*) curves for the tested pellet and MDF.

The nature of the *HRR* curves indicates the presence of two distinct peaks. During wood combustion tests, two peaks typically occur: one at the initial stage of combustion and the second just before the flame extinguishes. The initial peak is primarily caused by the formation of a char layer, which reduces heat output and gas emissions. Following this first peak, the heat release rate stabilizes. As combustion continues, a second increase in the heat release rate occurs due to heat accumulation within the sample (Xu *et al*., 2015). The combustion of the MDF lasted longer than that of the tested pellet. The maximum peak heat release rate (*pHRR*) for the MDF was 244 kW/m^2, occurring 85 seconds into the measurement. For the pellet, the *pHRR* value was slightly lower at 242 kW/m^2, but this peak appeared later, at 485 seconds into measurement. In contrast, the TSR values were 1542 m^2/m^2 for the MDF and 1834 m^2/m^2 for the pellet.

Volatile gas-phase products emitted during the combustion of the test materials were identified using a Purser furnace in conjunction with a gas chromato-

Table 1 List of products identified in fire effluents released during ~5 min steady-state periods during different fire stages
Tablica 1. Popis proizvoda identificiranih u otpadnim vodama ispuštenim tijekom ~5 minuta stabilnog stanja u različitim fazama gorenja

Detected products (products exceeding 1 %) *Utvrđeni spojevi (spojevi kojih je više od 1 %)*	**CAS No.**	**Amounts** / *Količina*, %			
		Pellet		**MDF**	
		350 °C	**650 °C**	**350 °C**	**650 °C**
COx. NOx. H_2O	-	5.11	100.00	7.02	66.29
Oxalic acid	64-19-7	2.84		2.25	
Glycolaldehyde	141-46-8	1.16			
Acetic acid	64-19-7	2.84		2.25	
Benzene	71-43-2				1.18
Furfural	98-01-1	2.55		1.75	
2-Furanmethanol	98-00-0	2.56		2.57	
2(5H)-Furanone	497-23-4	1.26		2.40	
2-Hydroxy-2-Cyclopenten-1-one	10493-98-8	1.52			
5-Methyl-2-Furancarboxaldehyde	620-02-0	2.09			
3-Methoxy-Pyridine	7295-76-3			1.13	
Benzoniltrile	100-47-0				1.88
Phenol	108-95-2			1.11	3.00
Hexanoic acid	142-62-1	1.19			
3-Methyl-1.2-Cyclopentanedione	765-70-8	1.25		3.13	
2.5-Furandicarboxaldehyde	823-82-5	1.21			
2-Methoxy-Phenol	90-05-1	6.64		10.79	
Maltol	118-71-8	1.19			
Naphthalene	91-20-3				10.87
Creosol	93-51-6	9.66		9.36	
5-Hydroxymethylfurfural	67-47-0	1.21			
4-Ethyl-2-methoxy-Phenol	2785-89-9	3.80		6.21	
2-Methoxy-4-vinylphenol	7786-61-0	3.43		3.47	
2-Methoxy-4-propyl-Phenol	2785-87-7			1.34	
Biphenyl	92-52-4				1.08
Acenaphthylene	208-96-8				5.18
Dibenzofuran	132-64-9				1.74
1-Isocyan-naphthalene	1984-04-9				1.12
(2H)-Acenaphthylene	2235-15-6				1.44

graph coupled with a mass spectrometer. Table 1 summarizes the products obtained during the combustion and thermal decomposition of both pellet and MDF.

The pyrolysis and combustion of the studied materials produce products similar to those from wood decomposition. At 350 °C, the main substances in the emitted gases and vapors included creosol, 2-methoxyphenol, 4-ethyl-2-methoxyphenol, and 2-methoxy-4-vinylphenol. Creosol, a phenolic aromatic compound found in wood creosote, is known to irritate the eyes and skin. Other compounds present in smaller amounts were oxalic acid, acetic acid, furfural, 2-furanomethanol, and several others. Furfural, derived from biomass through xylose hydrolysis and dehydration in lignocellulose, contains an aldehyde group and a conjugated double-bond system within its furan ring (Sun *et al.*, 2024). It is toxic to the respiratory tract and irritates the eyes and respiratory system. Maltol vapor, a natural substance found in pine tree bark and needles, was also detected during pellet combustion (Cai *et al.*, 2023). In contrast, phenol was released during the flameless decomposition of wood-based panels.

In the case of complete combustion, the number of identified products was significantly lower. For the pellet, no products other than carbon and nitrogen oxides were detected. MDF characteristically has a high calorific value, which makes it well-suited for energy generation (Ali *et al.*, 2024). However, in the case of MDF, several compounds were identified, including benzene, benzonitrile, phenol, naphthalene, biphenyl, acenaphthylene, dibenzofuran, 1-isocyan-naphthalene and (2H)-acenaphthylene. These compounds can irritate the respiratory system and eyes, as well as lead to skin lesions. Additionally, naphthalene and its derivatives, biphenyl and dibenzofuran, are highly toxic to aquatic environments. Furthermore, benzene is a known carcinogen, and naphthalene is also suspected of having carcinogenic properties.

The combustion of pellets mainly emits nitrogen compounds and carbon dioxide, making it relatively clean in terms of chemical composition. In contrast, the combustion of MDF boards generates many harmful and irritating substances due to the presence of adhesives, resins and other additives used in their production. The emission of toxic gases in the event of a building fire poses a significant risk to health and the environment, which emphasizes the importance of research into the safety of materials used in the furniture and construction industries. Although pellets are much less harmful than MDF in terms of toxic emissions, burning them still releases CO_2 into the atmosphere. Carbon dioxide, which could remain locked in wood-based products during the natural cycle, is immediately released during the combustion process. Despite the fact that wood pellets are still considered carbon-neutral due to the equilibrium between carbon dioxide released upon combustion and carbon dioxide absorbed during biomass cultivation, their net carbon footprint is notably lower than that of fossil fuels (Mortadha *et al*., 2025; Pradhan *et al*., 2018). In terms of MDF, advanced incineration technologies and strict emission controls are needed to address the specific challenges of MDF waste (Ali *et al*., 2024). Ongoing research focuses on optimizing processes and minimizing environmental impacts. Therefore, it is crucial to promote methods that use wood more efficiently, extending the time of carbon sequestration rather than its immediate emission.

4 CONCLUSIONS
4. ZAKLJUČAK

The results of the survey and laboratory tests clearly confirm the need for well-planned wood waste management and emphasize the importance of choosing methods of wood waste management that minimize the negative impact on the environment. The analysis showed that 57 % of respondents declared that wood and wood-based waste generated in their plants is combusted or used for energy recovery, which contributes to the rapid emission of CO_2 into the atmosphere, instead of allowing for its longer sequestration by producing wood-based products.

Additional laboratory tests of two selected wood wastes have shown that burning pellets made from hardwood and softwood results in relatively low nitrogen oxide and carbon emissions but still contributes to the release of CO_2 that could be retained in the material cycle. Despite the common perception of wood pellets as a clean bioenergy source owing to their low toxic emissions, the findings suggest that their climate impact from CO_2 release requires consideration when assessing their contribution to EU climate neutrality.

On the other hand, MDF boards, which contain adhesives, varnishes and other chemicals used in their production, lead to the emission of toxic compounds such as benzene, benzonitrile, phenol, naphthalene, biphenyl, acenaphthylene, dibenzofuran, 1-isocyan-naphthalene and (2H)-acenaphthylene. These substances can pose a serious threat to human health, i.e. cause cancer, and to the environment by pollution of water, air and soil, especially in the event of a fire in buildings or furniture containing MDF.

Therefore, it is crucial to find more sustainable methods of waste wood management. Waste MDF boards and other composite materials should be recycled or processed in alternative ways instead of being incinerated. At the same time, the production of pellets should be based exclusively on clean wood waste that is no longer suitable for reuse, for example, in the production of particleboard or as a filler in thermoplastics. At the same time, research findings indicate the need for further research into the use of pure wood waste in the material cycle instead of the energy cycle, as long as the quality of the material allows for reuse. The research results also emphasize the importance of using safe building and furniture materials that will not generate toxic substances that pose a threat to human health and the environment in the event of a fire.

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The Influence of PLA and CMC Coatings on Mechanical and Physical Properties of Recycled Packaging Papers

Utjecaj PLA i CMC premaza na mehanička i fizička svojstva recikliranoga ambalažnog papira

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ABSTRACT • *In this study, the effect of polylactic acid (PLA) and carboxymethyl cellulose (CMC) coatings on the mechanical and physical properties of recycled packaging papers was investigated. Paper samples were produced according to the TAPPI T205-SP-02 standard using waste office paper and old corrugated cardboard. The physical and mechanical properties including Cobb values, burst index, tensile index, ring crush test (RCT), corrugated medium test (CMT), and corrugated crush test (CCT) were analyzed. Additionally, the chemical structure of the coated and uncoated papers was studied using Fourier-transform infrared spectroscopy (FTIR). CMC-coated papers exhibited significantly higher RCT, CMT, and CCT values compared to the uncoated samples. Furthermore, PLA hydrophobic characteristics significantly reduced water absorption, as reflected by lower Cobb values in coated samples. The combined PLA-CMC coating substantially enhanced both barrier and mechanical properties compared to uncoated samples. FTIR analysis confirmed chemical modifications in the cellulose matrix as a result of the coating process. These results confirmed that coating of the recycled packaging papers with combined CMC and PLA is a viable approach to improve their strength and water resistance, thereby supporting their potential use in sustainable packaging applications.*

KEYWORDS: *recycled papers; barrier properties; plastic alternatives; biodegradable; mechanical properties*

SAŽETAK • *U ovoj je studiji istražen utjecaj premaza od polilaktične kiseline (PLA) i karboksimetil-celuloze (CMC) na mehanička i fizička svojstva recikliranoga ambalažnog papira. Uzorci papira proizvedeni su prema standardu TAPPI T205-SP-02 iskorištenjem otpadnoga uredskog papira i staroga valovitog kartona. Analizirana su fizička i mehanička svojstva, uključujući Cobbove vrijednosti, indeks probijanja, vlačni indeks, tlačnu čvrstoću prstena (RCT), tlačnu čvrstoću papira s valovitom srednjicom (CMT) i tlačnu čvrstoću valovitog papira (CCT). Dodatno, kemijska struktura premazanoga i nepremazanog papira proučavana je uz pomoć Fourierove infracrvene spektroskopije (FTIR). Papiri premazani CMC-om pokazali su značajno više vrijednosti RCT-a, CMT-a i CCT-a od nepremazanih uzoraka. Nadalje, hidrofobna obilježja PLA-a znatno su pridonijela smanjenju upijanja vode, što se odražava nižim Cobbovim vrijednostima premazanih uzoraka. Kombinirani PLA-CMC premaz znatno*

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je poboljšao hidrofobna i mehanička svojstva u usporedbi s nepremazanim uzorcima. FTIR analiza potvrdila je kemijske modifikacije u celuloznoj matrici kao učinak procesa premazivanja. Ti su rezultati potvrdili da je premazivanje recikliranih ambalažnih papira kombinacijom CMC-a i PLA-a održiv pristup za poboljšanje njihove čvrstoće i otpornosti na vodu, što upućuje na njihovu potencijalnu upotrebu u održivim postupcima pakiranja.

KLJUČNE RIJEČI: *reciklirani papiri; zaštitna svojstva; alternative plastici; biorazgradivost; mehanička svojstva*

1 INTRODUCTION
1. UVOD

The growing environmental issues associated with plastic consumption highlight the essential requirement to substitute traditional plastics with eco-friendly and biodegradable alternatives.

Due to their high durability and resistance to degradation, plastics can persist in the environment for hundreds of years, contributing to long-term pollution of terrestrial and aquatic ecosystems. Microplastics, which result from the fragmentation of larger plastic items, have been detected in oceans, soils, and even in human tissues, raising serious concerns about their potential toxicological impacts (Andrady, 2011). Additionally, the production of plastics relies heavily on fossil fuels, which exacerbates carbon emissions and accelerates climate change. Among various candidates, paper-based packaging has emerged as a promising solution due to its low cost, renewable origin, biodegradability, recyclability, and lightweight nature. Consequently, extensive efforts have been focused on utilizing paper as a sustainable packaging material (Gällstedt *et al*., 2005).

One critical limitation of paper is its intrinsic hydrophilicity, resulting from the abundance of hydroxyl groups in cellulose, which compromises its performance under humid conditions. Consequently, enhancing the moisture resistance of paper without undermining its recyclability has become a focal point in sustainable packaging research. (Taboada Rodrigues *et al*., 2013). Furthermore, due to increased environmental regulations, which limit the utilization of wood-derived resource, packaging papers are made from 80 – 100 % recycled fibers (Cicekler *et al*., 2024). Papers made from recycled fibers exhibit lower mechanical strength and moisture resistance compared to those produced from virgin fibers. Therefore, if recycled papers are to be used as packaging materials, their properties must be seriously reinforced. In recent years, considerable attention has been directed toward the development of coatings that improve the barrier and mechanical properties of paper while maintaining its environmental compatibility. (Cicekler *et al*., 2024). However, many conventional coating materials are derived from synthetic plastics, which have negative impact on the biodegradability and recyclability of paper. This has led to growing interest in the development and utilization of bio-based coatings (Mazhari Mousavi *et al*., 2017; Taboada Rodrigues *et al*., 2013).

Various sustainable and biodegradable materials have been investigated as substitution of synthetic polymer coatings (Taboada Rodrigues *et al*., 2013; Kunam *et al*., 2024). Polylactic acid shows excellent barrier properties, effective film-forming capabilities, and strong interactions with cellulosic materials due to its semi-hydrophilic character (Sundar *et al*., 2020; Taboada Rodrigues *et al*., 2013; Kamthai and Magraphan, 2018; Rivero *et al*., 2017). The previous studies showed that the PLA coated paper has good barrier properties against water and water vapor. Nonetheless, its inherent brittleness restricts its application in flexible packaging (Zhang *et al*., 2020).

To overcome this problem, various solutions including the utilization of plasticizers, additives, combining with other polymers, and optimization of crystallization conditions have been proposed (Cabedo *et al*., 2006). One of the materials that can improve the properties of polylactic acid is carboxymethyl cellulose, which has suitable properties for papermaking due to the presence of cellulose in its structure and its ability to disperse fibers and reduce their flocculation.

CMC is produced by introducing the carboxymethyl groups along the cellulose chain. CMC has been used in textiles, cosmetic and food industries (Mazhari Mousavi *et al*., 2017). It is inexpensive and readily available (Chen *et al*., 2016; Mazhari Mousavi *et al*., 2017; Kamthai and Magraphan, 2018).

Due to its excellent film-forming ability, water retention properties, and high solubility, CMC is widely used as a surface-sizing agent, coating binder, and wet-end additive in the papermaking industry. (Beghello *et al*., 1997; Blomstedt, 2007). It not only improves the mechanical integrity of paper but can also mitigate the stiffness of PLA, enhancing its flexibility. (Kamthai and Magraphan, 2018).

Chen *et al*. (2015) investigated the biocomposites prepared from PLA and CMC by ionic assembly. They found that the biocomposite formed a transparent and uniform coating layer after casting. Both the modulus of elasticity and the maximum degradation temperature of PLA/CMC composites increased with the decrease in molecular weight of PDMAEA. Although the combination of polylactic acid (PLA) and carboxymethyl cellulose (CMC) has been previously explored in the development of composite materials, their application as a coating system for packaging paper has not yet been thoroughly investigated. Considering the advantageous properties of both substances as potential coating agents, this combination may offer a promising and sustainable alternative for enhancing the performance of recycled paper-based packaging.

Therefore, the present study aims to investigate the effects of PLA, CMC, and their combination as surface coatings on recycled packaging papers. The primary objective is to evaluate their influence on key mechanical properties and water resistance, with the broader goal of identifying eco-friendly coating strategies suitable for industrial applications in sustainable packaging.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

PLA (commercial grade 4042D; Mw = 154.8 kg/mol) was purchased from Rayan Polymer Arta Co. (Iran). Carboxymethyl cellulose (CMC) with a molecular weight of 250,000 g/mol and a degree of substitution (DS) of 1.2 was obtained from Ovj Azma Plast Co. (Iran). Methylene dichloride (CH_2Cl_2, analytical grade) was used as the solvent and supplied by Ghatran Chimi Tajhiz (Iran). Waste office paper (WOP) and old corrugated cardboard (OCC) served as sources of recycled paper fibers.

2.2 Manufacturing of recycled paper
2.2. Proizvodnja recikliranog papira

Paper samples were prepared using a 50:50 ratio of OCC and WOP, as well as 100 % OCC. The fibers were processed in a pulper, and sheets were formed according to the TAPPI T205 SP-02 standard, with a grammage of 127 g/m².

2.3 Preparation and application of coatings
2.3. Priprema i nanošenje premaza

To prepare the PLA coating, 1g of PLA was dissolved in 100 mL of chloroform and stirred continuously at 40 °C for 12 hours. The CMC solution was prepared by dissolving 1 % (w/v) CMC in distilled water under stirring at 600 rpm for 3 hours at room temperature. For the composite coating (PLA-CMC), equal volumes of the prepared PLA and CMC solutions were mixed gently to ensure uniform dispersion before application. All coatings were applied using a 4-bar laboratory coater, with a fixed blade gap of 50 µm, at a drawdown speed of 30 mm/s. The coatings were applied on the surface of papers manufactured in sequentially two layers. The coated samples were then dried in a vacuum oven at 30 °C for 24 hours (Sundar *et al*., 2020). Table 1 outlines the experimental plan.

Table 1 Experimental design and sample coding
Tablica 1. Postavke eksperimenta i označavanje uzoraka

Sign of treatment *Oznaka tretmana*	**Kind of coating** *Vrsta premaza*	**Kind of fibers** *Vrsta vlakana*	
		100 % OCC (1)	**50 %-50 % OCC+OWP (2)**
Control- 1	Uncoated	1	
Control -2	Uncoated	2	
PLA-CMC-1	PLA+CMC	1	
PLA-CMC-2	PLA+CMC	2	
PLA-1	PLA	1	
PLA-2	PLA	2	
CMC-1	CMC	1	
CMC-2	CMC	2	

OCC – Old corrugated cardboard; WOP – Waste office paper; PLA – Polylactic acid; CMC – Carboxymethyl cellulose. The coding system includes fiber composition and coating type for each treatment group.
OCC – stari valoviti karton; WOP – otpadni uredski papir; PLA – polilaktična kiselina; CMC – karboksimetil celuloza. Sustavom označavanja obuhvaćen je sastav vlakana i vrsta premaza za svaku skupinu tretmana.

2.4 Measurement of paper properties
2.4. Mjerenje svojstava papira

All samples were conditioned at 25 °C and 65 % relative humidity for 24 hours prior to testing. Physical and mechanical properties of coated and uncoated papers were then evaluated using standardized procedures.

Water absorption capacity was measured using a Cobb apparatus according to the TAPPI T441 standard (Cobb test, 30 seconds).

Tensile index and burst index were determined according to ISO 5256-1:1979 and TS 3123 EN ISO 2759, respectively.

Ring Crush Test (RCT), Corrugated Medium Test (CMT), and Corrugated Crush Test (CCT) values were assessed based on TAPPI T822-om-16, T809-om-17, and T824-om-14.

2.5 FTIR analysis of coated papers
2.5. FTIR analiza premazanih papira

The chemical structure of coated papers was characterized using Fourier-transform infrared (FTIR) spectroscopy to detect changes in functional groups caused by surface coatings. The measurements were performed on a PerkinElmer System 2000 spectrometer (Waltham, MA, USA), scanning in the range of 400 – 4000 cm^{-1} at a spectral resolution of 4 cm^{-1}.

2.6 Statistical analysis
2.6. Statistička analiza

The impact of coating on paper properties was analyzed using one-way ANOVA. Duncan's multiple range test was used to determine significant differences in paper properties between treatments.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 2 presents the statistical analysis of the coated and uncoated paper samples, demonstrating that all coating treatments significantly influenced paper properties at a 99 % confidence level ($p \leq 0.01$). Duncan's multiple range classification results are presented in Table 3.

The statistical analysis confirms that PLA and CMC coatings significantly enhance the properties of recycled packaging paper ($p \leq 0.01$). Water absorption, determined by Cobb testing, showed a notable reduction across coated samples, with PLA-CMC-2 exhibiting the lowest absorption (82.33 g/m²) versus the uncoated control (105.67 g/m²). This indicates improved moisture resistance due to PLA hydrophobic barrier and CMC surface modification effects. Mechanical strength indicators including burst index, tensile index, and compression resistance (RCT, CMT, and CCT) increased significantly in all coated samples relative to the control groups.

The highest tensile strength was observed in PLA-CMC-2 (41.82 N), significantly surpassing the control (27.73 N), highlighting the role of coatings in enhancing fiber bonding and structural integrity.

The improvements in RCT, CMT, and CCT further support the effectiveness of these coatings in strengthening recycled paper. Higher compression strength values, particularly in CCT (6.03 in PLA-CMC-2 vs. 3.48 in the control), indicate better resistance to stacking and mechanical stress, essential for packaging applications. The combination of PLA and CMC produced the most favorable results across both mechanical and barrier property evaluations. The complementary nature of PLA hydrophobicity and CMC bonding ability created a synergistic effect that improved performance significantly.

Wei *et al*. (2019) and Kamthai and Magaraphan (2018) also observed similar interactions, highlighting how hydrogen bonding and molecular compatibility between PLA and CMC can reinforce structural cohesion and flexibility in coated substrates.

3.1 Water absorption resistance
3.1. Otpornost na upijanje vode

Figure 1 illustrates the effect of coating on Cobb values. The highest water resistance was observed in PLA-1 samples (100 % OCC coated with PLA), whereas the highest water absorption occurred in the Control-1 sample (uncoated 100 % OCC paper). The superior water resistance of PLA-coated samples is attributed to the hydrophobic nature of PLA. Papers coated with a combination of PLA and CMC showed significantly lower Cobb values as compared to uncoated samples. These findings align with Taboada-Rodriguez *et al*. (2013), who reported that PLA coatings drastically reduce water absorption in paper.

Table 2 Statistical analysis of properties of paper samples
Tablica 2. Statistička analiza svojstava uzoraka papira

Properties *Svojstva*	**Sum of squares** *Zbroj kvadrata*	**Mean squares** *Srednja vrijednost kvadrata*	**Df (within groups)** *Df (unutar grupa)*	***F***	**Sig**
Cobb test	3358.36	305.31	11	21.894	0.000
Burst	10536.306	957.846	11	8.365	0.000
Tensile	5.429	0.494	11	8.113	0.000
RCT	8133.889	739.444	11	8.082	0.000
CMT	15041.222	1367.384	11	5.099	0.000
CCT	10536.306	957.846	11	8.365	0.000

Table 3 Average values and Duncan's multiple range classification of properties of paper samples
Tablica 3. Prosječne vrijednosti i Duncanova klasifikacija s višestrukim rasponima za svojstva uzoraka papira

Properties *Svojstva*	**Control-1** *Kontrolna skupina-1*	**Control-2** *Kontrolna skupina-2*	**PLA-CMC-1**	**PLA-CMC-2**	**PLA-1**	**PLA-2**	**CMC-1**	**CMC-2**
Cobb test	105.67 (d)	93 (c)	78.67 (b)	82.33 (bc)	67.67 (a)	74.33 (ab)	74 (ab)	79.67 (b)
Burst	1.93 (d)	1.93 (d)	2.01 (b)	2.04 (a)	2.01 (b)	1.99 (c)	1.98 (c)	1.97 (c)
Tensile	27. 73 (d)	27.76 (d)	36.55 (ab)	41.81 (a)	32.34 (bcd)	30.85 (cd)	33.9 (bc)	29.98 (cd)
RCT	1.63 (ab)	1.61 (d)	1.74 (e)	1.72 (c)	1.79 (b)	1.77 (e)	1.85 (a)	1.83 (ab)
CMT	1.86 (a)	1.88 (a)	1.71 (ab)	1.76 (ab)	1.31 (c)	1.51 (bc)	1.86 (a)	1.9 (a)
CCT	3.48 (d)	3.92 (c)	5.25 (b)	6.03 (a)	5.24 (b)	5.47 (bc)	5.23 (b)	5.6 (bc)

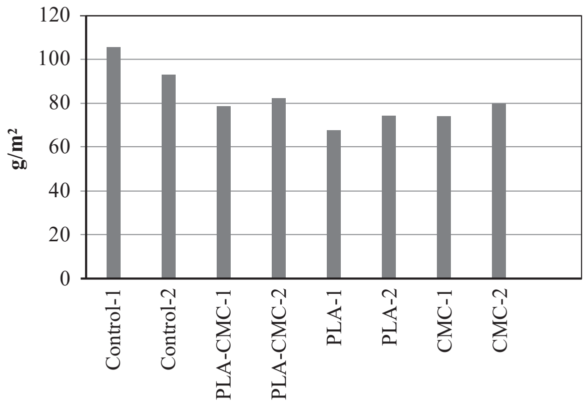

Figure 1 Effect of coating on Cobb values of paper
Slika 1. Utjecaj premaza na Cobbove vrijednosti papira

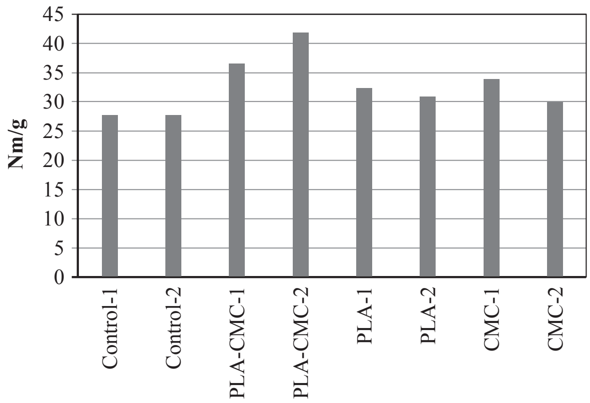

Figure 3 Effect of coating on tensile index of paper
Slika 3. Utjecaj premaza na vlačni indeks papira

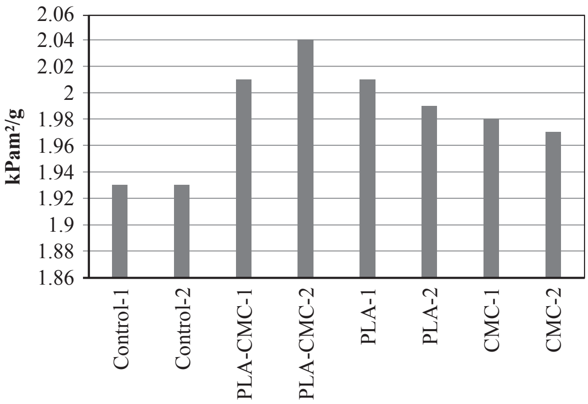

Figure 2 Effect of coating on burst index of paper
Slika 2. Utjecaj premaza na indeks probijanja papira

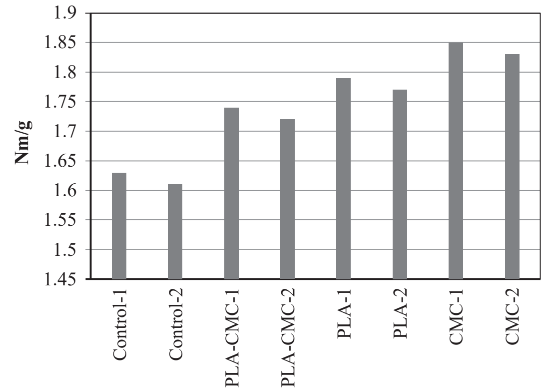

Figure 4 Effect of coating on RCT index of paper
Slika 4. Utjecaj premaza na RCT indeks papira

3.2 Burst index
3.2. Indeks probijanja

Figure 2 shows the burst index results. The highest burst index was observed in PLA-CMC -2 samples, suggesting that the combined coating enhances paper strength.

Improvement of burst index of PLA-CMC-coated packaging paper can be attributed to the synergistic effect of these materials, which leads to enhance fiber bonding, stress distribution, and structural integrity. PLA forms a strong, continuous film that condenses fibers and improves cohesion, while CMC enhances adhesion and flexibility through hydrogen bonding, reinforcing the paper network by reducing weak points, as outlined by Mazhari Mousavi (2017). Consequently, these properties lead to a stronger, coated paper with a higher burst index.

3.3 Tensile index
3.3. Vlačni indeks

Figure 3 shows the tensile index values of the papers. Coated samples have higher tensile index values as compared to uncoated papers. The highest tensile index was observed in PLA-CMC-2 (50 % OCC + 50 % WOP coated with PLA-CMC). These results are in accordance with a previous study, which revealed that PLA coatings improved the tensile index by approximately 33 % (Abuzeid *et al*., 2017). The improvement of tensile index is related to the presence of carboxyl groups in CMC, which can enhance fiber bonding (Laine *et al*., 2003; Kamthai and Magraphan, 2018).

The results of the Cobb, burst, and tensile tests reveal interrelated improvements in the paper performance characteristics. The reduction in water absorption (Cobb test) contributes to maintaining fiber integrity and bonding, which directly enhances mechanical properties such as burst and tensile strength. This interdependence indicates that the coatings not only provide a moisture barrier but also synergistically strengthen the fiber network, leading to comprehensive enhancement of both barrier and mechanical functions of the recycled paper (Laine *et al*., 2003).

3.4 Ring crush test (RCT) index
3.4. Ispitivanje indeksa tlačne čvrstoće prstena (RCT)

As shown in Figure 4, coated papers have increased RCT values. The highest RCT value was related to CMC-1 (100 % OCC coated with CMC).

CMC acts as a dry-strength additive, forming hydrogen bonds with cellulose fibers, which increases fiber-to-fiber interaction and improves the overall mechanical integrity of the paper (Beghello *et al*., 1997; Blomstedt *et al*., 2007). Additionally, CMC enhances fiber swelling and flexibility, allowing better fiber entanglement, which contributes to higher resistance against compressive forces (Laine *et al*., 2003). CMC also helps in fiber surface modification, improving stress distribution and reducing weak points within the paper matrix (Mazhari Mousavi *et al*., 2017).

3.5 Corrugated medium test (CMT) index
3.5. Ispitivanje indeksa čvrstoće papira s valovitom srednjicom (CMT)

Figure 5 demonstrates that CMC-1 samples had the highest CMT index. However, PLA coatings resulted in a decrease in CMT values. The relationship between CMT strength and paper stiffness has been established in previous studies (Chen *et al*., 2001; Cicekler *et al*., 2024). The addition of CMC improves tensile, tear, and surface strength while reducing roughness (Beghello *et al*., 1997).

One of the limitations of PLA is its brittleness and reduced toughness, which is why various studies have attempted to improve its toughness by adding different materials. (Reisi Pour *et al*., 2018).

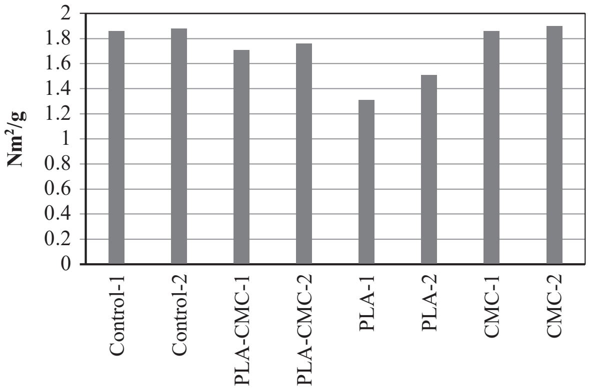

Figure 5 Effect of coating on CMT index of papers
Slika 5. Utjecaj premaza na CMT indeks papira

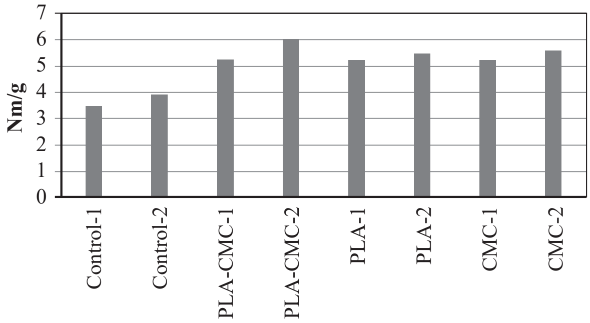

Figure 6 Effect of coating on CCT index of papers
Slika 6. Utjecaj premaza na CCT indeks papira

3.6 Corrugated crush test (CCT) index
3.6. Ispitivanje indeksa tlačne čvrstoće valovitog papira (CCT)

Figure 6 illustrates that PLA-CMC-2 samples exhibited the highest CCT index, while Control-2 had the lowest. The combination of fibers led to improved CCT performance. CCT values are primarily influenced by moisture absorption (Cicekler *et al*., 2024).

Overall, the results indicate that CMC coating has a significant positive impact on improving the quality of recycled packaging paper. CMC can improve fiber strength due to its hydroxyl groups, which promote hydrogen bonding between water and fibers (Enoki, 1999).

Previous studies have shown that PLA coating effectively reduces water absorption while improving the tensile and burst strength of paper (Sundar *et al*., 2020). It is obvious that PLA coating improves packaging paper performance (Rivero *et al*., 2017). The combined use of PLA and CMC as a coating can lead to superior results as compared to individual PLA coating, because of the improved flexibility of PLA when combined with CMC.

3.7 Chemical structure of coated papers
3.7. Kemijska struktura premazanih papira

Figure 7 shows the FTIR spectra of recycled paper coated with PLA, CMC, and their combination. Characteristic absorption bands were observed in the regions of 2800 – 3500 cm^{-1} and 550 – 1650 cm^{-1}, which are typical for cellulosic substrates due to the presence of hydroxyl, carbonyl, and alkyl groups.

A broad and intense band near 3374 cm^{-1} corresponds to the stretching vibration of the O–H bond, confirming the presence of hydroxyl groups in the cellulose structure (Manandhar *et al*., 2022). In CMC-coated papers, intensity increased at 1410 and 1319 cm^{-1} is associated with O–H and C–H stretching, while absorption peaks at 1107 and 1039 cm^{-1} represent C–O stretching vibrations typical of polysaccharides (Rozali *et al*., 2015).

For PLA-coated samples, a distinct absorption peak at 1755 cm^{-1} corresponds to the stretching vibration of the carbonyl (C=O) group in the ester linkage, a key functional group in polylactic acid. A minor but noticeable shift in the C=O stretching band from 1755 cm^{-1} to approximately 1740 cm^{-1} in PLA-coated samples also supports the successful incorporation of carboxyl functional groups, consistent with previous literature (Rivero *et al*., 2017).

Enhanced absorption bands at 2996 and 2945 cm^{-1} are attributed to asymmetric and symmetric C–H stretching vibrations of methyl groups. Additionally, a peak at 1187 cm^{-1} indicates C–O stretching in ester bonds (Singla *et al*., 2012).

In samples coated with both PLA and CMC, evidence of intermolecular hydrogen bonding is observed through the shift of the O–H/N–H stretching band to ~3420 cm^{-1}, along with increased intensity and peak narrowing. These spectral changes confirm the formation of hydrogen bonds between the PLA matrix and the CMC molecules. Notably, the intensity of this peak is lower in pure PLA, suggesting the addition of CMC enhances hydrogen bonding interactions (Wei *et al*., 2019).

These spectral changes suggest that hydrogen bonding and molecular interactions between PLA,

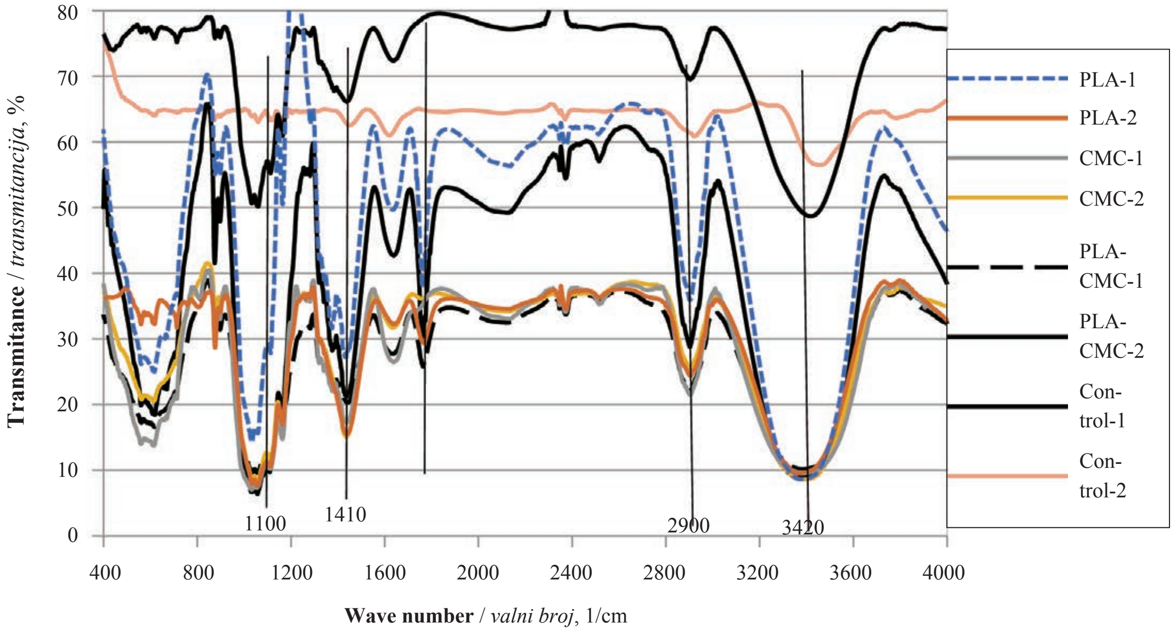

Figure 7 FTIR of paper samples with different coating materials
Slika 7. FTIR uzoraka papira s različitim premaznim materijalima

CMC, and cellulose fibers enhance interfacial adhesion, which likely contributes to the improved mechanical integrity observed in coated samples. The shift and intensity changes in the O–H and C=O regions correlate with increased fiber bonding and reduced water permeability, confirming the functional role of the coatings in modifying paper performance.

The combined use of PLA and CMC as a coating can lead to superior results as compared to individual PLA coating. Recent studies support the claim that incorporating carboxymethyl cellulose (CMC) into polylactic acid (PLA) matrices enhances the flexibility and mechanical performance of the resulting composite. Specifically, Kamthai and Magaraphan (2015) demonstrated that CMC derived from bagasse improved the toughness of PLA-based films. Their FTIR analysis revealed new absorption bands indicative of hydrogen bonding between the hydroxyl groups of CMC and the ester groups of PLA, suggesting intermolecular interactions that contribute to greater flexibility and reduced brittleness. Similar findings were reported by Khalil *et al*. (2020), where PLA–CMC blends exhibited enhanced elongation at break and tensile strength, attributed to improved dispersion and interaction of CMC within the PLA matrix.

In another study, films composed of PLA and sodium carboxymethyl cellulose (NaCMC) designed for pH-responsive applications showed higher swelling capacity and mechanical resilience. FTIR spectra confirmed structural modifications and new interaction bands between PLA and CMC components, further validating the compatibility and synergistic behavior of the blend. Collectively, these findings confirm that the addition of CMC can alter the physical structure of PLA by increasing its amorphous regions and enabling more flexible polymer chains, which are critical for packaging and coating applications where improved ductility is needed.

4 CONCLUSIONS
4. ZAKLJUČAK

This study evaluated the impact of PLA, CMC, and PLA–CMC composite coatings on recycled packaging papers made from OCC and WOP fibers. Papers were produced using two fiber compositions including 100 % OCC and a 50-50 proportion of OCC and WOP.

PLA coatings reduced water absorption due to their hydrophobic characteristics, while CMC improved mechanical integrity, particularly in compression-related properties such as RCT, CMT, and CCT. The combined PLA–CMC coating exhibited the highest values for tensile and burst indices, indicating a synergistic interaction that optimized both flexibility and strength.

The results indicate that carboxymethyl cellulose enhances the flexibility of PLA, leading to better overall paper performance. Additionally, papers made from pure OCC fibers showed better mechanical strength due to the presence of lignin, which increases fiber cohesion.

The innovative combination of polylactic acid (PLA) and carboxymethyl cellulose (CMC) for recycled paper coatings presents a suitable approach to enhancing mechanical and physical properties. This unique blend offers significant potential for industrial applications in sustainable and biodegradable packaging materials, providing an eco-friendly alternative to conventional coatings. Future research should focus on optimizing the coating formulation and process parameters to facilitate large-scale production, as well as evaluating the long-term durability and performance of these coatings under real-world conditions.

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YOLOv7-Driven Visual Inspection System for Edge Banding Defects in Panel Furniture

YOLOv7 sustav vizualnog pregleda grešaka rubnih traka pločastog namještaja

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ABSTRACT • *Current quality inspection of edge banding in panel furniture heavily relies on manual screening, which is labor-intensive, subjective, and inefficient. To address this challenge, we propose a YOLOv7-based visual inspection system by integrating machine vision and deep learning. A dataset containing 1,887 images of six defect types (e.g., open glue, chipping, uneven trimming) was constructed, with annotations generated via LabelImg. Data augmentation strategies (rotation, scaling, cropping) were applied to enhance model robustness. The YOLOv7-Tiny model achieved a mean average precision (mAP) of 74.8 % at 57.63 FPS, outperforming traditional methods and demonstrating superior speed-accuracy trade-offs. Experimental results on real-time industrial camera data validated the system's capability to detect defects with high precision (82.1 %) and recall (75.4 %). This framework significantly reduces production costs and provides a scalable solution for automated quality control in furniture manufacturing.*

KEYWORDS: *panel furniture; quality inspection; YOLOv7; machine vision*

SAŽETAK • *Današnja kontrola kvalitete rubnih traka pločastog namještaja uvelike se oslanja na ručnu provjeru, što je radno intenzivno, subjektivno i neučinkovito. Kako bismo riješili taj problem, predlažemo sustav vizualne kontrole utemeljene na YOLOv7 sustavu koji integrira strojni vid i duboko učenje. Izrađen je skup podataka koji sadržava 1887 slika šest vrsta grešaka (npr. vidljivo ljepilo, krhotine, neravnomjerno obrezivanje) s napomenama generiranim putem LabelImga. Primijenjene su strategije proširenja podataka (rotacija, skaliranje, izrezivanje) kako bi se poboljšala robusnost modela. Model YOLOv7-Tiny postigao je prosječnu preciznost (mAP) od 74,8 % pri 57,63 FPS, nadmašivši tradicionalne metode i pokazavši superiorne kompromise brzine i točnosti. Eksperimentalni rezultati podataka dobivenih industrijskom kamerom u stvarnom vremenu potvrdili su sposobnost sustava da otkrije greške s visokom preciznošću (82,1 %) i opozivom (75,4 %). Taj okvir znatno smanjuje troškove proizvodnje i daje skalabilno rješenje za automatiziranu kontrolu kvalitete u proizvodnji namještaja.*

KLJUČNE RIJEČI: *pločasti namještaj; kontrola kvalitete; YOLOv7; strojni vid*

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1 INTRODUCTION
1. UVOD

Edge banding plays a pivotal role in modern panel furniture manufacturing, contributing not only to the aesthetics of the furniture but also to the durability and structural integrity of the finished product. However, the edge banding process is often accompanied by problems such as collapsing edges, glue leakage, and uneven trimming, which can directly affect both the appearance and the functionality of the furniture (Lu *et al*., 2021). These defects are especially critical as they compromise the consumer's perception of quality and can lead to premature product degradation (Xiong *et al*., 2023a). The global panel furniture market was valued at $210 billion in 2022, and as consumer expectations continue to rise, there is a growing demand for stringent quality control throughout the production process. Traditional defect detection methods, predominantly relying on manual labor, are not only labor-intensive but also prone to subjectivity. In the furniture industry in China, for instance, manual inspection accounts for 30-40 % of the total production cost (Li *et al*., 2021), with defect escape rates exceeding 15 % due to human fatigue and inconsistent inspection standards (Wang *et al*., 2022).

In response to these challenges, recent advances in machine vision and deep learning have significantly revolutionized industrial quality inspection, particularly in defect detection. Machine vision technology, which leverages cameras and computational tools to visually inspect products, has been widely adopted across industries for its ability to perform automated, objective assessments (Wang *et al*., 2023; Peng *et al*., 2025). Early research on industrial defect detection relied heavily on classical machine learning algorithms such as Support Vector Machines (SVM) and Random Forests for defect classification (Czimmermann *et al*., 2020). However, these methods faced limitations when it came to detecting complex surface defects, particularly in materials like wood, which exhibit intricate texture variations (Xiong *et al*., 2023b). The advent of deep learning frameworks, particularly Convolutional Neural Networks (CNNs), marked a turning point by enabling automatic feature extraction and significantly enhancing detection accuracy (Alzubaidi *et al*., 2021).

For instance, Faster R-CNN, a popular deep learning-based model, achieved a mean average precision (mAP) of 71.5 % in solid wood defect detection (Fan *et al*., 2019), while YOLOv4 demonstrated real-time defect detection capabilities for structural wood with a speed of 52 FPS (Wang *et al*., 2021). However, while these models show great promise, research specific to edge banding defect detection remains sparse. Existing methods are often limited by two significant challenges: the trade-off between speed and accuracy and the scarcity of high-quality training data. Many studies prioritize accuracy at the expense of real-time performance, which makes them impractical for high-speed production lines (Redmon *et al*., 2016). Furthermore, the lack of public datasets focused on edge banding defects often leads to training on small sample sizes, making models susceptible to overfitting (Tao *et al*., 2022).

To address these challenges, this study introduces the first YOLOv7-Tiny-based visual inspection framework designed specifically for edge banding defect detection. The proposed method offers several innovative contributions:

a. A curated dataset of 1,887 images covering six distinct defect types (e.g., glue leakage, chipping), with data augmentation techniques including rotation and scaling to increase model robustness.

b. The deployment of the YOLOv7-Tiny model, which incorporates optimized anchor boxes and RepVGG modules, achieving a mAP of 74.8 % at a real-time detection speed of 57.63 FPS. This performance surpasses previous models such as YOLOv4 (68.2 % mAP) and Faster R-CNN (71.5 % mAP).

c. A real-time industrial camera integration system validated across four production lines, significantly reducing defect escape rates to below 5 %.

Beyond these practical contributions, the present study also makes several academic advancements. First, it represents the first systematic effort to construct a large-scale dataset specifically targeting edge banding defects, thereby alleviating the long-standing problem of limited training samples in this domain. Second, by combining data augmentation strategies with a lightweight YOLOv7-Tiny architecture, the study demonstrates a feasible approach for achieving both high detection accuracy and real-time performance, providing a reference model for the digital transformation of small- and medium-sized furniture enterprises. Finally, from a broader perspective, the proposed framework contributes to the academic literature by offering a transferable methodological paradigm for defect detection in high-texture-complexity materials such as wood. This not only advances the theoretical understanding of defect detection in challenging visual contexts but also opens new avenues for cross-material and cross-industry applications of deep learning in manufacturing quality control.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Test samples and tools
2.1. Ispitni uzorci i alati

2.1.1 Test sample
2.1.1. Ispitni uzorci

To minimize the influence of subjective factors, the board samples were selected randomly, adhering to established statistical principles to ensure they are representative of the overall production. The sampling process took into account various factors, including the diversity of production batches, production lines, and production times. This approach ensured that all critical features of the product appearance were sufficiently covered, enabling comprehensive inspection. The following methodology was applied:

a. Sample Size and Selection Method: The total number of samples selected was 500, with 400 samples allocated for training the network model and 100 samples reserved for validating the model performance. Samples were randomly chosen from four different production lines, all equipped with automatic edge banding machines. To account for variability, samples were taken at intervals of 2 hours and 10 days, with 20 samples selected from each batch.

b. Recording of Sample Information: Detailed information for each sample was systematically recorded, including production date, batch number, model, specifications, and other relevant attributes, in line with the established sampling methodology. This comprehensive data logging ensured transparency and traceability throughout the testing process.

c. Appearance Quality Inspection: The samples were then sent to the laboratory for appearance quality testing, adhering to the specific testing items and standards defined in Table 1. The inspection followed objective, scientific, and rigorous principles to evaluate the visual and structural quality of the edge banding.

2.1.2 Tools and equipment
2.1.2. Alati i oprema

The following tools and equipment were employed for the testing process:

a. Edge Banding Equipment: The Himile KAL 350 automatic straight-line edge banding machine was used for applying edge banding to the board samples.

b. Defect Detection Tools: A vernier caliper, tape measure, spirit level, and low magnification glass were used for initial defect inspection, measurement, and assessment of edge banding quality.

c. Test Equipment: The testing was conducted using an industrial camera system, and the data processing was performed on a computing system running the Windows operating system, with an RTX 3060Ti-12G graphics card to facilitate high-performance computing. The deep learning framework employed for model development and testing was Pytorch, and the programming language used was Python.

2.1.3 Machine vision and YOLOv7 algorithm
2.1.3. Strojni vid i YOLOv7 algoritam

Machine vision, a technology rooted in computer theory, has become an essential tool for detecting and quantifying surface defects in products (Zhu *et al*., 2023). Since its introduction, machine vision has been widely applied in industrial defect detection to describe the fundamental components of a visual surface defect detection system, including the image acquisition module, image processing module, image analysis module, data management system, and man-machine interface (Yu *et al*., 2024; Golnabi *et al*., 2007). These modules collectively enable the processing of images captured by machine vision, which are then trained using deep learning frameworks to facilitate production testing (Ren *et al*., 2024).

Machine vision systems offer several advantages over traditional image acquisition methods. They use a single camera to perform multiple tasks simultaneously, enabling rapid and efficient detection of both stationary and moving objects (Sheng *et al*., 2024). Furthermore, machine vision can analyze various image types, such as text, lines, and graphics, while recognizing diverse attributes, including color, shape, contrast, and texture. Another significant benefit of machine vision is its ability to track the movement and changes of objects, thus enabling dynamic detection and analysis (Zhang *et al*., 2024). The combination of image processing and machine learning techniques allows for the precise identification, location, measurement, and detection of objects, thus enabling automation and intelligence in industrial applications (Wang *et al*., 2021).

Building upon man, deep learning has further enhanced surface defect detection. Deep learning technologies, particularly Convolutional Neural Networks (CNNs), allow for more efficient and accurate identification of object features, distinguishing abnormal features from typical ones (Zhang *et al*., 2021). Unlike traditional machine learning techniques, which rely on manual feature extraction, deep learning autonomously extracts relevant features from images. The YOLO (You Only Look Once), a prominent target detection model, integrates classification, localization, and detection within a single framework (Redmon *et al*., 2016). It calculates the bounding box coordinates of the target and the probability of each category in the image, significantly improving computational efficiency and enabling real-time detection in production environments (Li *et al*., 2024).

YOLOv7 is designed to enhance both detection speed and accuracy. The network architecture consists of three primary components: the input layer, the backbone layer, and the neck & head layers. The input image is first preprocessed into a 640×640×3 format before being passed through the backbone network, which extracts features. These features are further processed by the neck & head layers to generate detection results. YOLOv7 employs advanced convolutional structures such as RepVGG to improve feature extraction and analysis. The specific network architecture is shown in Figure 1.

To further enhance detection performance, the Anchor-based method and structural modifications, such as expanded feature channels and additional model branches, are employed to improve the network's reasoning speed. The network also introduces the Extend-Elan module to optimize learning capabilities by controlling gradient paths and capturing more feature details. YOLOv7 offers several model variants based on different requirements. In this study, the YOLOv7-Tiny model was used to evaluate its defects in edge banding plates.

2.2 Principle and process
2.2. Načelo i proces
2.2.1 Standards for inspection of appearance quality
2.2.1. Standardi za kontrolu kvalitete izgleda

In recent years, there has been an increasing focus within the furniture industry on both the production process and the environmental sustainability of products. Consequently, stringent control over production quality is essential to ensure the final product meets the required standards for both functionality and aesthetics (Zhou *et al*., 2024). When establishing standards for the appearance quality of edge panels, it is important to consider various factors such as material composition, structural characteristics, physical and mechanical properties, durability, and environmental impact.

The inspection standards are derived from a combination of national, industry-specific, and enterprise-specific guidelines. Key national standards include GB/T 3324-2017 "General Technical Conditions for Wood Furniture," GB/T 4897-2015 "Fiberboard," and T/CNFPIA 3016-2021 "Quality Requirements for Wood-Based Customized Household Panel Edge." These standards specify the criteria for evaluating the appearance quality of wood-based panels, outlining the testing methods and evaluation techniques. Industry standards, based on national guidelines, account for the distinct characteristics of various industries, while enterprise-specific standards address the unique requirements of individual manufacturers. In addition to these formal standards, factors such as production cost, market demand, and product use must also be considered when formulating inspection criteria.

The assessment of edge banding appearance quality can generally be divided into two main methods: qualitative and quantitative. Qualitative methods include visual inspection, equipment-based inspections, and comprehensive inspection methods, while quantitative methods encompass hardness measurements, dimensional analysis, and optical testing (Xiong *et al*., 2023). These combined approaches allow for a comprehensive evaluation of the product's appearance quality.

Surface quality inspection in the wood industry is particularly challenging due to the variability in wood

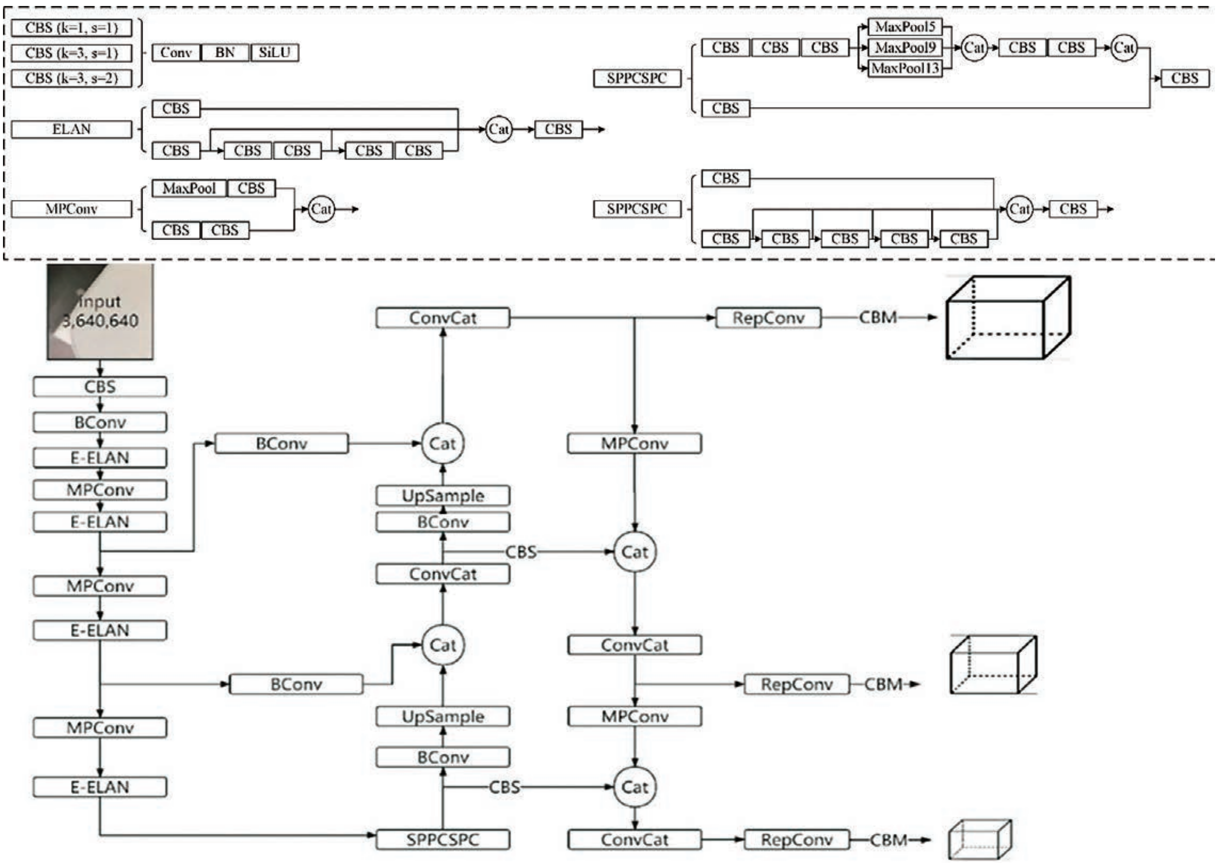

Figure 1 YOLOv7 network architecture diagram
Slika 1. Dijagram YOLOv7 mrežne arhitekture

Table 1 Appearance quality inspection items and standards of edge banding plate
Tablica 1. Stavke kontrole kvalitete izgleda i standardi za rubne trake na ploči

Serial No. *Serijski broj*	**Test items** / *Ispitivane stavke*	**Test standard** / *Standard ispitivanja*
1	Edge banding colors and specifications *boje i specifikacije rubnih traka*	Consistent with production and process requirements *u skladu sa zahtjevima proizvodnje i procesa*
2	Trim roughness, wave pattern, trim gloss *hrapavost obrubljivanja, valoviti uzorak, sjaj obrubljivanja*	No scratching sensation when touched by hand, 30 cm sight distance in natural light, cannot be seen visually under normal vision *nema osjećaja hrapavosti pri dodiru rukom, vidljivost s udaljenosti 30 cm na prirodnom svjetlu, ne može se vizualno vidjeti golim okom*
3	Finished size *konačna veličina*	Size error after banding ≤ 0.5mm *pogreška veličine nakon obrubljivanja ≤ 0,5* mm
4	Shortage of walking edge *nedostatak ruba*	Shortage, walking edge maximum width between (0.15~0.2) mm *nedostatak ruba, maksimalna širina ruba između (0,15~0,2)* mm
5	Seam allowance *dodatak za obrub*	Edge end allowance ≤ 0.1mm *dodatak za kraj ruba ≤ 0,1* mm
6	Edge banding glue line *linija ljepila za rubnu traku*	The maximum width of the edge banding line ≤ 0.1 mm, the maximum length is less than or equal to 10 mm, and not more than 3 places within 100 mm *maksimalna širina linije rubne trake ≤ 0,1* mm, *maksimalna duljina manja je ili jednaka 10* mm *i ne na više od tri mjesta unutar 100* mm
7	Pinholes, slits *rupice, prorezi*	Continuous pinhole maximum width ≤ 0.1 mm and maximum length ≤ 100mm, not more than 3 on any one side *kontinuirana rupica maksimalne širine ≤ 0,1* mm *i maksimalne duljine ≤ 100* m; *ne više od tri na bilo kojoj strani*
8	Cleaner separator marks *tragovi čistača*	The width of the print on the surface of the board after banding is ≤10mm *širina otiska na površini ploče nakon obrubljivanja je ≤ 10 mm*
9	Appearance Quality *kvaliteta izgleda*	Board surface cleanliness (residual glue, stains, etc.) and appearance defects (black spots, pen marks, scratches, etc.) width <0.6mm *čistoća površine ploče (ostatci ljepila, mrlje itd.) i nedostatci izgleda (crne mrlje, tragovi olovke, ogrebotine itd.) širine < 0,6* mm
10	Rounded corners *zaobljeni kutovi*	Thin edge does not allow scratching hands, edge banding with thick edge on both sides of the inverted R1 ~ 1.5 arc *tanki rub sprečava grebanje ruku; obrubljivanje debelim rubom s obje strane obrnutog luka R1 ~ 1,5*

shape and background texture, as well as the stringent compatibility standards that must be met. To overcome the challenge of limited training samples, machine vision-based deep learning approaches are increasingly being used to leverage transfer learning. Target detection networks are employed to identify and categorize defects in the surface of edge banded components.

Before applying machine vision technologies to the surface inspection of edge-banded components, it is essential to define the specific production processes and characteristics of these components. The assessment of edge banding panel appearance quality requires the establishment of clear evaluation items, standards, and inspection criteria. Once these criteria are set, the appearance quality of the panels can be quantified and assessed based on the data collected. An overview of the inspection items and their corresponding standards is presented in Table 1.

2.2.2 Data set training
2.2.2. Treniranje skupa podataka

In order to address the challenges associated with defect detection, a comprehensive dataset of 1,887 images was collected during the production of edge banded panels. The preprocessing of the dataset followed a series of systematic steps to ensure the quality and uniformity of the data. The initial step involved cropping the images to remove irrelevant regions, followed by resizing all images to a consistent resolution of 640×640 pixels. To enhance the model's robustness and reduce the risk of overfitting, data augmentation techniques such as rotation, translation, and scaling were applied. These transformations helped improve the model's ability to generalize across a wider range of defect scenarios. Some of the results after processing are shown in Figure 2.

The labeled dataset was created using the LabelImg annotation tool, and the process is shown in Figure 3, ensuring that each image contained the necessary details, including the precise location, type, and extent of defects. This annotation process enabled the creation of bounding boxes around each defect, which were then used to train the deep learning model.

The training data set was used to train the YOLOv7 model, utilizing the Pytorch deep learning framework. The input image size for training was fixed

Figure 2 Some image samples after preliminary processing
Slika 2. Primjeri slika uzoraka nakon preliminarne obrade

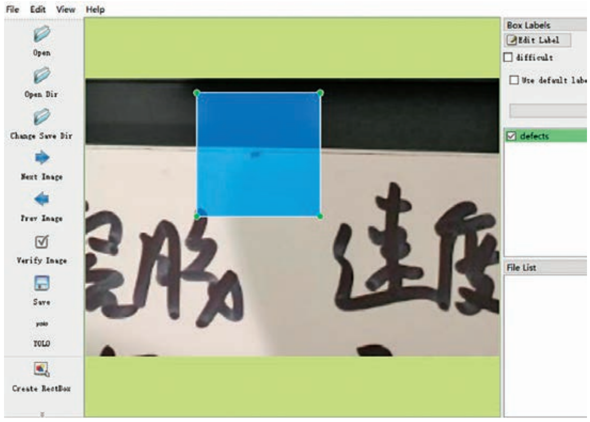

Figure 3 LabelImg process diagram
Slika 3. Procesni dijagram LabelImg

at 640×640 pixels to maintain consistency and facilitate efficient processing. During training, the initial learning rate was set at 0.001, with a batch size of 20 and a total of 500 iterations. Weight decay was applied with a coefficient of 0.001 to prevent overfitting. The Adam optimizer was employed to update the model's weights, and the Leaky ReLU activation function was used to enhance the model's non-linearity.

Throughout the training process, the learning rate was dynamically adjusted, decreasing to 0.0001 after 400 iterations to ensure convergence as the model approached optimal performance. The training continued for 500 iterations, after which the model achieved sta-

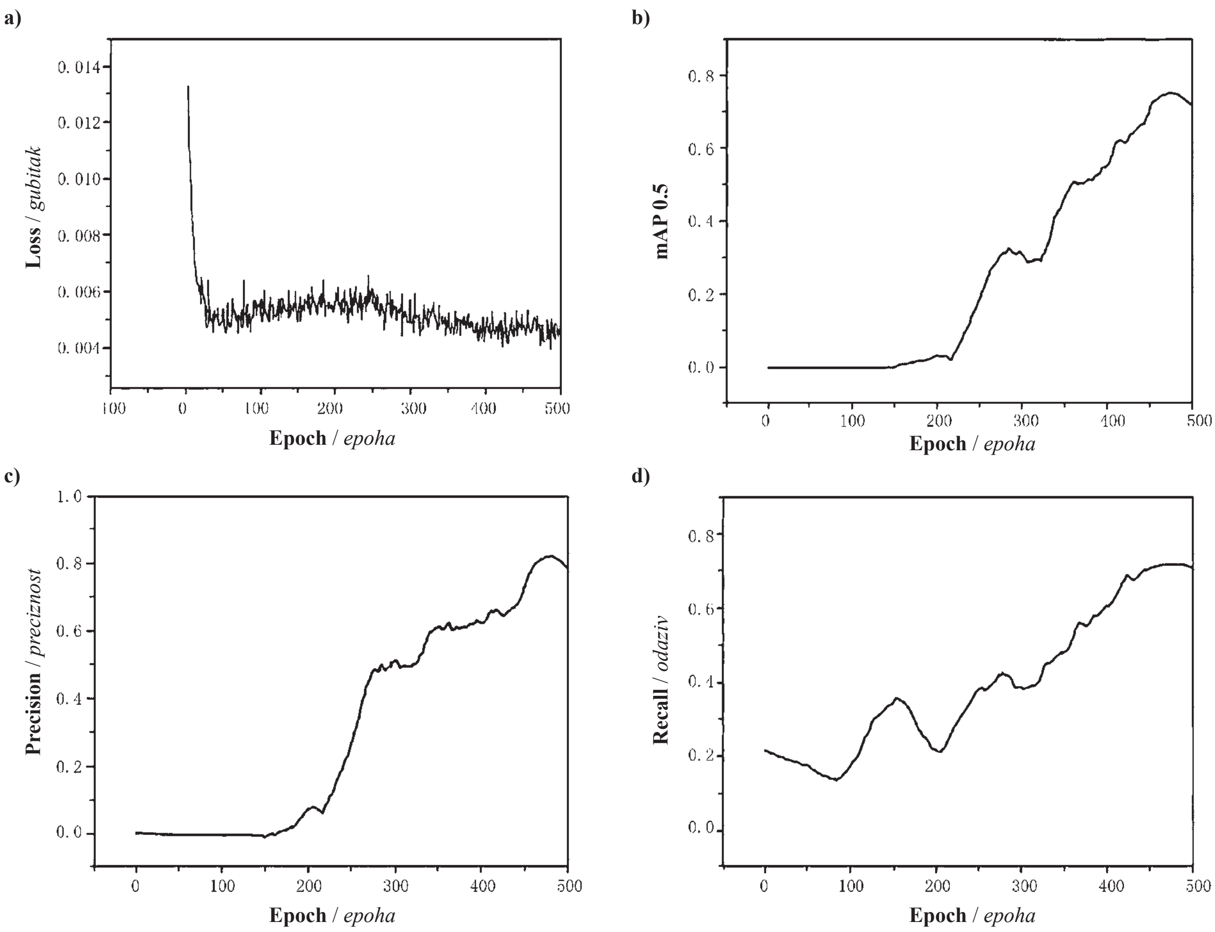

Figure 4 Model performance analysis a) loss value, b) recall rate, c) accuracy rate (precision rate), d) average precision mean
Slika 4. Analiza performansi modela: a) vrijednost gubitka, b) stopa opoziva, c) stopa točnosti (stopa preciznosti), d) prosječna srednja vrijednost preciznosti

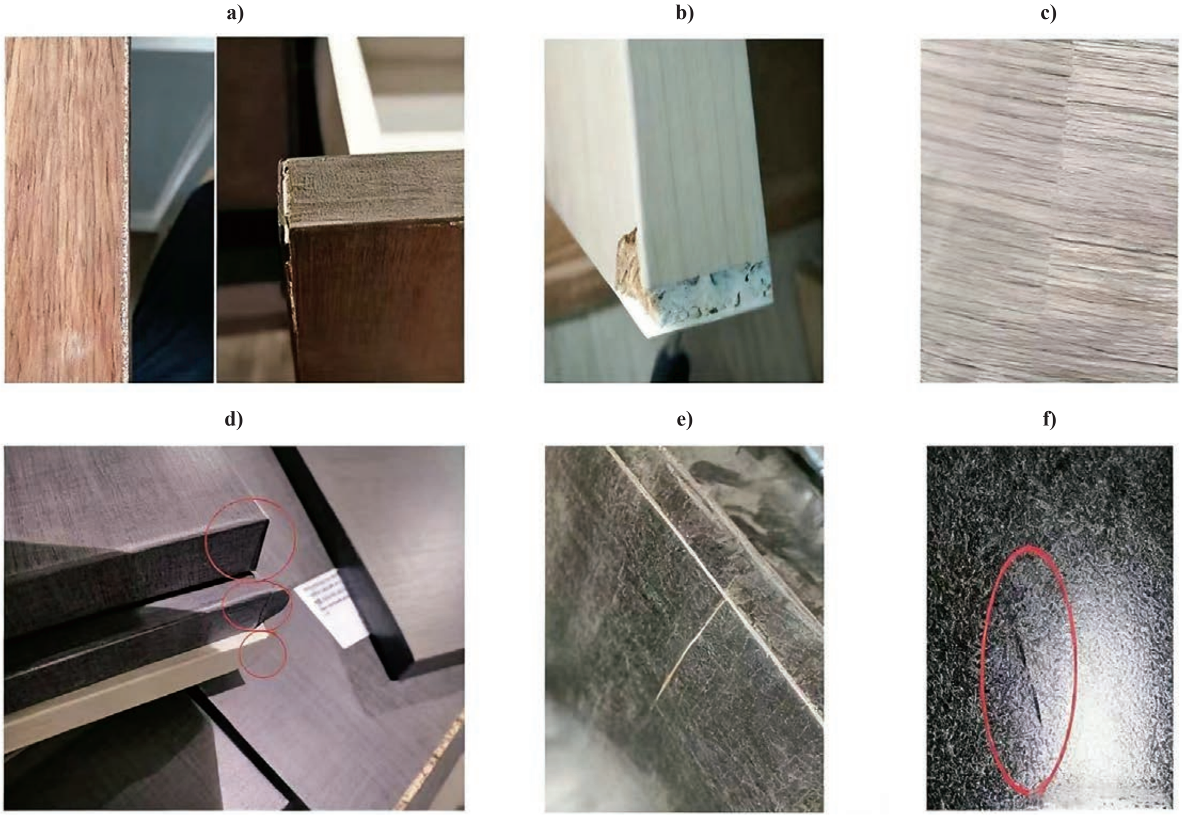

Figure 5 Several common types of edge defects: a) unglue, b) shortage, c) chipping, d) uneven trimming, e) glue line, residual glue, f) edge indentation
Slika 5. Nekoliko uobičajenih grešaka ruba: a) odljepljivanje, b) nedostatak rubne trake, c) krhotine, d) neravnomjerno obrezivanje, e) neuredna linija lijepljenja, ostatci ljepila, f) udubljenje ruba

bility in its performance metrics. The training process was closely monitored through the visualization of key metrics, such as loss values, recall rate, accuracy, and average precision, using TensorBoard, and the visualization results are shown in Figure 4. The visualization of these metrics helped assess the model's learning progress and provided insights into potential areas for further optimization. As can be seen in Figure 4, the loss value decreases as the number of iterations increases, and at 500 iterations, the loss value < 0.004, the recall rate is stable at 75.4 %, and the final accuracy rate and average precision of the model are stable at 82.1 % and 78.4 % on average. From the above evaluation metrics, the network model meets the expectation after training through the defective set.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Common appearance defects
3.1. Uobičajene greške izgleda

The detection of appearance defects in edge banding panels was carried out based on the categories outlined in Table 1. Six representative defect types were identified and classified, including unglued areas, shortages, chipping, uneven trimming, glue lines, and indentation, as shown in Figure 5. Each defect type was analyzed to determine its characteristics and impact on the overall appearance quality of the edge banding.

The decision process for categorizing defects involved a comprehensive analysis of the color, texture, shape, and boundary characteristics of the defects, ensuring that each defect was accurately identified and labeled during the image annotation process. These defect categories are vital for the subsequent training of the model and the evaluation of its detection capabilities.

3.2 Data set validation
3.2. Validacija skupa podataka

The performance of the trained model was evaluated using real-time data obtained from an industrial CCD camera during the production process. The model was tested on a set of images taken directly from the production line to assess its ability to detect defects under practical conditions. The detection threshold was set at a confidence level of 0.50, meaning that only predictions with a confidence score higher than 50 % were considered valid. The detection effect is shown in Figure 6.

The model's ability to detect the six types of defects was analyzed by comparing the predicted results with ground truth annotations. As shown in Figure 6, the model demonstrated high accuracy in identifying defects such as unglue, shortage, chipping, uneven

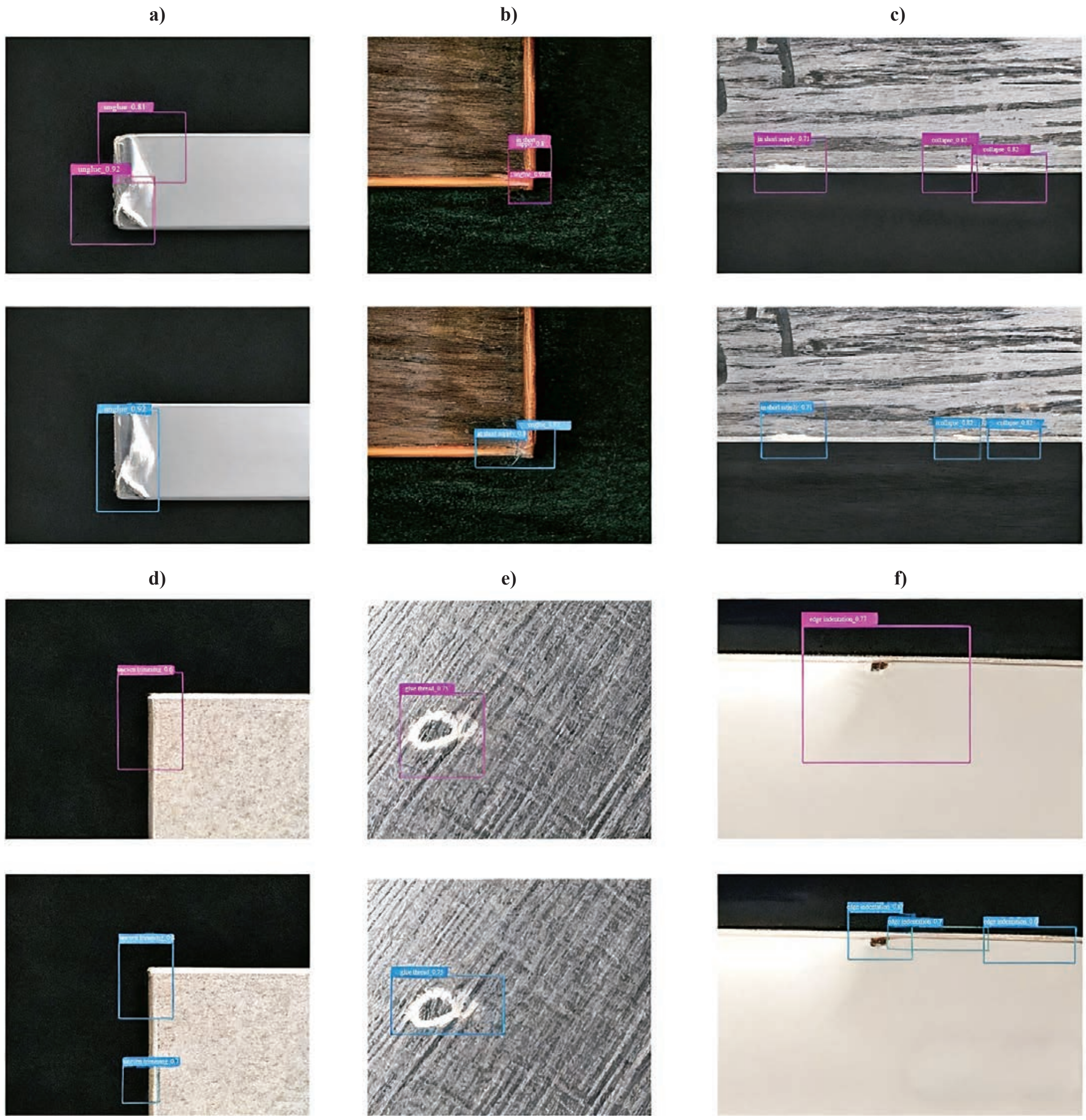

Figure 6 Comparison of the actual detection effect of edge banding defects: a) unglue, b) in short supply, c) collapse, d) uneven trimming, e) glue thread, f) edge indentation
Slika 6. Usporedba stvarnog učinka detekcije grešaka rubne trake: a) odljepljivanje, b) manjak nanosa ljepila, c) kolaps, d) neravnomjerno obrezivanje, e) probijanje ljepila, f) uvlačenje ruba

trimming, glue lines, and indentation. Notably, the final accuracy rate of the model was maintained above 82 %, which indicates a strong ability to detect defects in edge banding panels with high precision.

3.3 Performance evaluation
3.3. Evaluacija performansi

As can be seen from Figure 6, the trained YOLOv7 model was subjected to a series of comprehensive performance evaluations to assess its effectiveness in defect detection for edge banding panels. The key performance metrics used for this evaluation included mean average precision (mAP), recall rate, precision rate, and detection speed (FPS).

The mean average precision (mAP), a crucial indicator of overall model performance, was calculated to be 74.8 %. This metric reflects the model's ability to correctly classify and localize defects across multiple categories. When compared with other state-of-the-art models, such as YOLOv4 (68.2 % mAP) and Faster R-CNN (71.5 % mAP), the YOLOv7 model demonstrated superior performance in both accuracy and precision. This higher mAP indicates that YOLOv7 can detect defects more reliably, even in complex and variable conditions, offering a significant improvement over previous model.

The recall rate, which measures the model's ability to correctly identify all relevant defects, was found to be 75.4 %. A recall rate of this magnitude suggests that the model is highly effective in reducing false negatives, i.e., defects that are not identified by the system. This is particularly important for ensuring that the inspection process does not overlook critical defects, which could compromise the overall quality of the product.

The precision rate, a metric that assesses the model's ability to minimize false positives (incorrectly identified defects), was also high, indicating that the YOLOv7 model only flagged defects that were truly present in the images. This balance between high recall and precision ensures that the model not only identifies defects accurately but also avoids excessive misclassification of non-defective areas as defects.

Finally, the model's real-time processing speed, evaluated at 57.63 frames per second (FPS), was more than adequate for high-speed production lines. This speed ensures that the system can analyze images in real time without introducing significant delays in the production process. It confirms that the YOLOv7 model meets the requirements of industrial settings, where timely defect detection is crucial to maintaining production efficiency and quality control.

In summary, the YOLOv7 model achieved high accuracy (74.8 % mAP), robust defect detection capabilities (75.4 % recall rate), and fast processing speed (57.63 FPS), making it a highly effective solution for real-time defect detection in edge banding panels.

3.4 Real-world application
3.4. Stvarna primjena

To validate the practical applicability of the YOLOv7 model beyond the controlled test environment, it was deployed in a real-time industrial setting on a production line producing edge banding panels. The flow of using the tool is shown in Figure 7. The integration of the model into the production line was conducted to assess its performance under actual operating conditions, where variables such as lighting changes, product variability, and production speed could impact detection accuracy. During the deployment, the model was tasked with detecting defects such as glue leakage, chipping, uneven trimming, and edge indentation in real-time as edge banding panels were processed. The real-time detection capability of the YOLOv7 model allowed for immediate feedback on the quality of the panels, enabling quick identification and rectification of defects before the panels moved further along the production line. One of the most notable outcomes of this real-world application was a reduction in defect escape rates, which dropped to below 5 % following the deployment of the model. This significant improvement suggests that the YOLOv7 model can effectively prevent defective panels from passing through the production process, ensuring that only high-quality products reach the final stages of manufacturing.

In contrast, previous manual inspection methods and traditional machine vision systems had higher defect escape rates due to operator fatigue and the inherent subjectivity of visual inspection. Additionally, the integration of the YOLOv7 model into the existing production line allowed for more efficient quality control, as it reduced the need for extensive manual inspections. The automated nature of the defect detection process not only reduced labor costs but also minimized human error, further ensuring the consistency and reliability of quality checks.

Nevertheless, it is important to note that the current experiments were conducted under relatively controlled lighting and production conditions. In real-world industrial environments, several external factors – such as lighting fluctuations, dust particles, or machine vibrations, can potentially influence the imaging quality and, consequently, the accuracy of defect detection. However, in the specific context of panel furniture manufacturing, these issues are generally less severe during the edge banding stage, which occurs in the later stages of processing. Unlike cutting or drilling operations, where significant dust may be generated, the edge banding process is part of the finishing phase, where dust and environmental disturbances are minimal. This characteristic of the manufacturing workflow helps mitigate some of the challenges associated with imaging system reliability.

To further improve robustness in less predictable industrial environments, several strategies can be con-

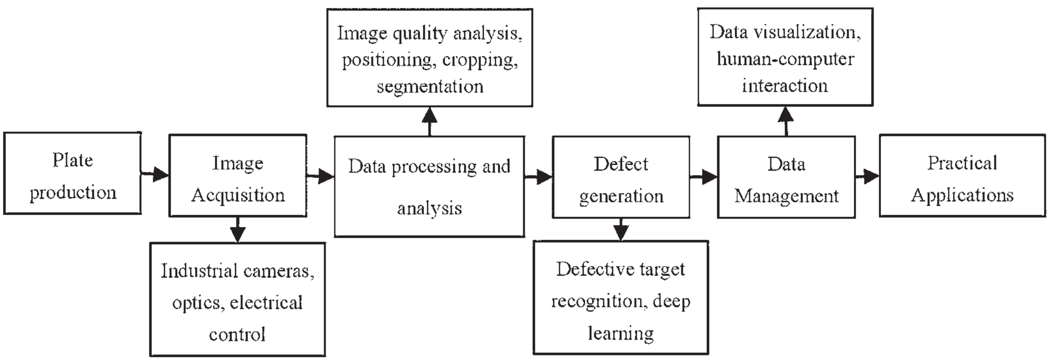

Figure 7 Appearance quality inspection process of edge-banding plate based on machine vision
Slika 7. Proces kontrole kvalitete izgleda rubnih traka na pločama uz pomoć strojnog vida

sidered. For example, introducing multi-light-source compensation could stabilize illumination, while infrared or 3D cameras might provide additional modalities to overcome visual limitations. Enhanced image preprocessing techniques could also be integrated to reduce the sensitivity of the system to noise, shadows, and reflections. These approaches represent promising directions for future research and align with the limitations discussed in the conclusion, particularly regarding the influence of lighting conditions on system performance.

Overall, the deployment of YOLOv7 demonstrated its potential to enhance quality control in the furniture manufacturing industry. The model's ability to process images in real time, coupled with its high accuracy, made it an invaluable tool in minimizing defects, reducing production costs, and ensuring product quality. This application not only verifies the model's efficacy in an industrial setting but also highlights its scalability and potential for widespread use in similar production environments.

4 CONCLUSIONS
4. ZAKLJUČAK

The results of this study have important theoretical and practical implications. From a theoretical perspective, this research explores the potential of YOLOv7-Tiny, a lightweight version of the YOLOv7 architecture, in the context of edge computing. YOLOv7-Tiny is designed to be computationally efficient while maintaining high performance, making it an ideal candidate for deployment in industrial embedded systems with limited processing power. Compact model architecture allows for real-time defect detection on edge devices, such as industrial cameras and embedded processors, without the need for cloud-based infrastructure. This capability is especially valuable in settings where low latency is critical, such as in high-speed production lines. By demonstrating the feasibility of deploying YOLOv7-Tiny on edge devices, this study contributes to the growing body of work on embedded vision systems, highlighting the potential for such lightweight models to address the computational constraints of industrial applications. Moreover, compared with existing studies, this work further contributes by exploring the integration pathway between deep learning and furniture manufacturing processes, thereby offering not only an engineering application but also an academic case for defect detection in noisy industrial environments.

From a practical standpoint, the deployment of YOLOv7-Tiny for defect detection in edge banding panels offers substantial cost-saving potential for manufacturers. Traditional defect inspection processes, often relying on manual labor or older automated systems, incur significant operational costs. The YOLOv7-Tiny-based system, by contrast, can automate defect detection with greater accuracy and speed, reducing the reliance on human inspectors, including a decrease in the need for manual labor, faster defect detection, and improved overall product quality that reduces the need for costly rework and customer returns. Furthermore, the real-time detection capabilities of the system enable timely interventions, ensuring that defective products are identified and addressed immediately, thereby enhancing overall production efficiency.

However, there are several limitations that must be addressed. One of the primary limitations of this study is the lack of data diversity. The model was trained using data from only four production lines, which may not fully capture the variability present in different production environments or across diverse types of edge banding panels. As such, the model's performance might be limited when applied to other production settings with different materials, defect types, or manufacturing conditions. Expanding the dataset to include a wider variety of production lines and defect categories would help to improve the generalizability of the model. Additionally, this study did not account for the effects of lighting variations, a factor that can significantly influence the performance of machine vision systems. In real-world industrial settings, lighting conditions are often dynamic, and changes in light intensity, shadows, or reflections can affect the accuracy of defect detection. Future research should explore the impact of lighting changes on model performance and develop strategies to mitigate these challenges, such as incorporating dynamic lighting compensation algorithms or enhancing image preprocessing techniques.

Looking ahead, there are several promising directions for future work. One potential avenue for improving defect detection is the integration of multimodal data, such as combining 3D point clouds with traditional RGB images. The addition of depth information could enhance the model's ability to detect subtle surface defects that may not be apparent in 2D images, such as slight indentations or surface deformations. By incorporating 3D imaging technologies, the model could be made more robust to variations in the geometry and surface textures of the panels. Another area of future development is the creation of an adaptive threshold adjustment algorithm to optimize detection performance in real-time. In many defect detection applications, it is essential to balance the detection of false positives (incorrectly flagged defects) and false negatives (missed defects). By dynamically adjusting the detection threshold based on contextual factors, such as defect type, environmental conditions, or production speed, it would be possible to reduce misdetections while maintaining high detection accuracy. These improvements could significantly enhance the robustness and reliability of the system, making it even more suitable for industrial deployment.

In conclusion, this study demonstrates the effectiveness of YOLOv7-Tiny as a lightweight and efficient solution for defect detection in edge banding panels. Despite limitations related to data diversity and the impact of lighting changes, the findings indicate that the model is a viable option for real-time defect detection in industrial settings. Importantly, the research extends beyond engineering practice by providing a transferable methodological framework for defect detection in high-texture-complexity materials such as wood, offering valuable theoretical insights for academic research while also serving as a practical tool for automated quality control in the furniture manufacturing industry.

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Withdrawal Capacity of Double-Threaded Nuts Mounted in 3D-Printed Wood-Plastic Composites

Izvlačni kapacitet dvonavojnih matica montiranih u 3D printane drvno-plastične kompozite

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ABSTRACT • *This paper investigated the withdrawal capacity of the double-threaded nuts mounted in 3D-printed materials. The basic technical properties and the withdrawal force of the double-threaded nuts for the specimens made of PLA, WPLA, and layered WPLA+PLA configuration (with and without STP adhesive) were investigated. The results are compared with the literature data of withdrawal force for beech wood, MDF, and particleboard with and without the adhesive. The research has determined the effects of the properties of 3D printed materials (density, compressive and tensile strength), the infill and printing patterns, and adhesive on withdrawal capacity of double-threaded nuts. Double-threaded nuts mounted with adhesive had higher withdrawal forces (about 25 % for PLA and WPLA specimens, and 15 % for layered WPLA+PLA specimens) than those mounted without adhesive. The highest values of withdrawal forces, regardless of the adhesive, were obtained for layered WPLA+PLA configuration, followed by WPLA, and the lowest for PLA. No significant difference was found between the withdrawal forces for WPLA and layered WPLA+PLA specimens for both cases – with and without an adhesive. The withdrawal forces of double-threaded nuts for the PLA specimens were higher than the withdrawal forces for the beech (16.7 % mounted without adhesive and 11.6 % mounted with an adhesive), and other combinations showed a difference higher than 35 % in favor of 3D printed materials. The present analysis, which determines and compares used traditional dismountable connectors in 3D-printed furniture elements, is applicable for research and practice.*

KEYWORDS: *3D printing; wood; wood-plastic composites (WPC); double-threaded nut; withdrawal force*

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SAŽETAK • *U ovom je radu istraživan izvlačni kapacitet dvonavojnih matica montiranih u 3D printane materijale. Ispitivana su osnovna tehnička svojstva i izvlačna sila dvonavojnih matica za uzorke izrađene od PLA, WPLA i slojevite WPLA + PLA konfiguracije (bez STP ljepila i s njim). Rezultati su uspoređeni s podatcima iz literature o izvlačnoj sili za bukovinu, MDF i ivericu bez ljepila i s njim. Istraživanjem je utvrđen utjecaj svojstava 3D printanih materijala (gustoće, tlačne i vlačne čvrstoće), ispune i šablone printanja te ljepila na izvlačni kapacitet dvonavojnih matica. Dvonavojne matice montirane uz upotrebu ljepila imale su veće izvlačne sile (oko 25 % za PLA i WPLA uzorke i 15 % za slojevite WPLA + PLA uzorke) od onih montiranih bez ljepila. Najveće vrijednosti izvlačne sile, neovisno o ljepilu, dobivene su za slojevitu WPLA + PLA konfiguraciju, zatim slijedi WPLA, a najniže su za PLA. Nije pronađena značajna razlika između izvlačne sile WPLA i slojevitih WPLA + PLA uzoraka pripremljenih bez ljepila i s njim. Izvlačne sile dvonavojnih matica za PLA uzorke bile su veće od izvlačnih sila za bukovinu (16,7 % uzoraka montiranih bez ljepila i 11,6 % montiranih s ljepilom), a ostale kombinacije pokazale su razliku veću od 35 % u korist 3D printanih materijala. Prikazana analiza, koja određuje i uspoređuje korištene tradicionalne rastavljive spojnice u 3D printanim elementima namještaja, primjenjiva je za istraživanje i praksu.*

KLJUČNE RIJEČI: *3D printanje; drvo; drvno-plastični kompoziti (WPC); dvonavojna matica*

1 INTRODUCTION
1. UVOD

Global awareness of environmental protection and sustainable resource management is rising, therefore the development and adoption of new technologies to enhance production efficiency and environmental responsibility in furniture industry is becoming essential. Consumers are demanding products made from sustainable resources that are biodegradable, have low environmental impact and pose no health risk for humans (Krapez Tomec and Kariz, 2022). In this context, traditional wood industry is facing several challenges, such as high wood resource consumption, waste generation and environmental pollution. 3D printing technology has revolutionized both innovation and environmental sustainability in traditional woodworking. Compared to subtractive manufacturing technologies, such as CNC milling and turning, which are characterized by the removal of excess material to obtain the desired shape, 3D printing, as an additive manufacturing process, only adds material where it is needed, fusing the material layer-by-layer, which contributes to significantly reducing waste generation. Also, recycled wood and plastic can be extruded into wood-plastic filaments, that are suitable for 3D printing, therefore promoting circular economy and leading to low or zero waste (Wimmer *et al*., 2015). Case studies show that 3D printing technology demonstrates up to 40 % reduction of manufacturing related material waste compared to traditional woodworking furniture production. Also, 95-98 % of non-melted raw material can be reused (Krapez Tomec *et al*., 2024). Despite the potential in increasing plastic recycling rates, consumers are demanding more environmentally friendly products that are not petroleum based. Recycled wood and wood residues generated from primary and secondary wood processing can be combined with biopolymer polylactic acid (PLA), a compostable synthetic polymer made from a monomer feedstock derived from corn starch, into additive manufacturing. Use of wood-PLA composites (WPLA) in additive manufacturing has garnered considerable attention, primarily due to the favorable ecological footprint and enhanced material attributes (Krapez Tomec *et al*., 2024). According to Jarza *et al*. (2023), small-and medium-sized companies can benefit the most from adopting the additive manufacturing. Machines can do jobs instead of workers, the use of resources is reduced and anybody with lower manual skills can produce demanding, complicated and unique products. For large companies, the major benefit from adopting the additive manufacturing is fast development of prototypes, testing, finishing and market presentation, which makes them more competitive, because they can launch a new product on the market faster than the competition.

Traditionally, mass produced furniture, based on its function, can have panel or frame structure, or a combination of both. Integrity and durability of these structures depend on the quality of the connections between the constituent elements. Various factors influence strength and durability of these connections, such as materials used, the quality of the assembly process, the type of connection between the structural elements, and the type of forces the furniture is expected to be exposed to during exploitation (Bas *et al*., 2024).

Constructive connections in furniture can be dismountable and glued. If glued connection between structural elements is used, then disassembly is not possible without breaking or damaging the connection. Dismountable connections, on the other hand, enable construction disassembly, which can be beneficial for reducing the costs of transportation, assembly and storage. Lower costs of production increase the competitiveness of the product on the market. The most widespread dismountable connections are the cam fittings and the bolt and barrel nut connectors (Bas *et al*., 2024).

The strength and stiffness of furniture constructions primarily depend on the physical and mechanical properties of the necessary connections between the structural elements. Bolt fasteners cannot endure cyclic stress without loosening, which can lead to serious accidents, even if anti-loosening bolts are used (Shinbutsu *et al*., 2017). In contrast, the double-threaded nuts and thread bolts connectors, quite common in the production of tables and beds, have an excellent anti-loosening ability. The production of this type of connection elements is very cheap, from the point of production technology, and also, such elements do not impose great requirements during assembly (Mihulja *et al*., 2012).

During exploitation, furniture is exposed to different forces that cause tension or pressure in the joints, which has an influence on their strength and durability. It has been proven that the connections with double-threaded nuts, exposed to withdrawal forces, tend to extract from the material, thus considerably weakening the structures (Ibrisevic *et al*., 2023). Mihulja *et al*. (2012) established that the proper drilling and the diameter of the hole have a large effect on the extraction of nuts. Considering different types of material that can be used in furniture production, an additional strengthening factor might be needed in order to increase the strength of the joint. The only possible solution for strengthening constructive connections with double-threaded nuts and thread bolts is to impose adhesive. The type of adhesive, distribution, adhesive line thickness and moisture content have a significant influence on the strength of the connection (Bas *et al*., 2024). Ibrisevic *et al*. (2023) examined the influence of the adhesive type and different types of wooden materials (beech, medium-density fiberboard, and particleboard) on the withdrawal capacity of double-threaded nuts. They concluded that the best withdrawal capacity was obtained for samples with beech wood glued with Silan terminated polymers (STP), while the lowest withdrawal capacity was obtained for samples with particleboard glued with polyvinyl acetate mounting D2 adhesive.

In recent years, there has been increased interest in the use of 3D printing technology for prototyping and manufacturing furniture joints, chair connectors and threaded fasteners. Smardzewski *et al*. (2016) investigated mechanical properties of externally invisible 3D printed cabinet furniture joints made of wood-based composites. The results showed that the designed joints were characterized by high stiffness and strength. Nikolau *et al*. (2022) used reinforced polylactic acid (PLA) with fiberglass (20 wt. %) to design a 3D printed connector for joining the leg and two stretchers of a chair made from larch. The authors concluded that the direction of filament layer deposition correlates with the joint's strength. Petrova and Jivkov (2024) investigated bending moments and stiffness of joints of thin structural elements connected by 3D printed connectors made of polylactic acid (PLA). The results showed high strength under arm compression bending load. The stiffness coefficients of 3D-printed joints were higher than of conventional detachable mitre joints, but lower than the glued ones. Hajdarevic *et al*. (2018) investigated stress and strain in frontal parallel joints connected with two different 3D printed connectors made of PLA and bonded to spruce wooden parts with one component polyurethane adhesive. The results showed that the values of normal stress at the point of failure of the joints and at the proportional limit of frontal parallel joints with PLA connectors were significantly lower compared to clear spruce wood beam. Also, the values of the effective modulus of elasticity of the joint with PLA connectors were lower than the modulus of elasticity of spruce wood. Krzyżaniak and Smardzewski (2019) analyzed the effect of assembly forces on stiffness and strength of 3D printed, externally invisible and demountable, furniture joints made of polyamide. They concluded that designed 3D printed joints can be used as an alternative to replace metal joints to assemble furniture, while providing external invisibility and the possibility not to use tools during assembly. Hajdarevic *at al*. (2023) investigated if 3D-printed connectors could replace the typical L-shaped joints in the construction of a chair. Different connectors were designed and manufactured using acrylonitrile butadiene styrene (ABS). The results showed that joints with 3D-printed connectors had 42–51 % lower strength than traditional wooden mortise-and-tenon joints. The authors concluded that with the proper design, optimization and materials selection, 3D-printed connectors could have similar mechanical characteristics as connectors made from plywood or aluminum. Eraliev *et al*. (2022) investigated if 3D printed threaded fasteners could lower their self-loosening. They used three types of 3D printing materials: acrylonitrile butadiene styrene (ABS-2), poly lactic acid (PLA), and glass. The results showed that ABS-2 bolt has good anti-loosening performance under cyclical temperature changes. The PLA bolt did not show good performance in low temperature changes, and the glass bolt showed the lowest performance in high temperature changes. Krapez Tomec *et al*. (2024) evaluated the environmental aspect of PLA and wood – PLA products and compared them to traditional metal parts used as connectors in traditional wood furniture industry. They concluded that metal parts manufactured using conventional subtractive processes have higher environmental impact compared to 3D-printed parts obtained from PLA and wood-PLA. They also concluded that the mechanical and physical properties of the printed parts are not significantly lower, compared to conventional wood composites (particleboard and fiberboard). In order to improve the mechanical and physical properties of 3D-printed alternatives from renewable materials, wood fibers and nanocellulose can be added.

This paper aims to determine how different types of 3D printed materials affect the withdrawal force of double-threaded nuts in constructions made of PLA and wood-PLA composites. Withdrawing force of double threaded nuts mounted with and without adhesive will be tested. The obtained results will be compared with the results of withdrawal force of double-threaded nuts in different types of wooden materials in order to determine if double-threaded nuts can be used in dismountable connections in 3D printed furniture made of polylactic acid (PLA) and wood-PLA.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The idea for this research was to examine whether traditional dismountable connectors, mostly used in wooden furniture, could also be used in 3D-printed furniture. Two different kinds of materials: Creality Hyper PLA (CR-Hyper PLA) and Creality Wood (CR-Wood) in three different configurations were used to determine their technical properties and withdrawal capacity of double-threaded nuts. One set of samples was made of CR-Hyper PLA, another set of samples was made of CR-Wood, and a third set of samples was made of layered CR-Hyper PLA and CR-Wood (samples with CR-Wood faces and CR-Hyper PLA core). Hyper fast white PLA (CR-Hyper PLA) was used because of its good adhesion properties. WPLA (CR-Wood) was made of white pine wood flour and biodegradable PLA.

2.1 3D printing sample setup
2.1. Izrada 3D printanih uzoraka

Bambu Lab X1 carbon with AMS was used for printing testing specimens. Bambu Lab X1C was calibrated out of the box. For dimensional accuracy test specimens were printed and measured with Holex digital caliper. They passed dimensional accuracy of ±2 %. Filament was stored in AMS (Automatic Material System) enclosure during printing, conditions of environment were consistent (enclosed). The AMS enclosure helped maintaining a dry environment during printing, which prevents moisture absorption and filament degradation. Filament settings used were configured according to manufacturers' (Creality) recommendations for speed and temperature. The 3D printer had a nozzle diameter of 0.4 mm. The infill density was set to 100 %, the layer height was 0.2 mm, the print speed was 50 mm/s. The printing temperature was set to 220 °C. The printing bed temperature was 60 °C. All samples were printed in the 0° orientation to the build plate. Brim was used for better adhesion to build-plate in all printed specimens. Hot adhesive has been used periodically only on 15 printed specimens for tensile strength testing (Figure 2a), since printing orientation caused adhesion problems and tool head had collision with the last layers of printed specimens and moved them from a build-plate.

2.2 Methods for examining properties of PLA and WPLA materials and WPLA+PLA layered configuration
2.2. Metode ispitivanja svojstava PLA i WPLA materijala te WPLA + PLA uslojene konfiguracije

Density, tensile strength and compressive strength of the 3D printed materials were tested. Determination of selected mechanical properties was done according to the ISO 527-2 and ASTM D695 standards for tensile strength and compressive strength, respectively. Test specimen geometry and dimensions are shown in Figure 1.

For tensile strength testing, five specimens were 100 % infill PLA, five specimens were 100 % infill WPLA and five specimens were 100 % infill with PLA, in combination with WPLA. The testing area of 80 mm length for WPLA / PLA / WPLA testing specimens was divided into three parts. The length of PLA in the middle was 26.5 mm. The rest of the length was WPLA (Figure 2.a.). For compressive strength testing, a total of 15 test specimens were printed. Five specimens were 100

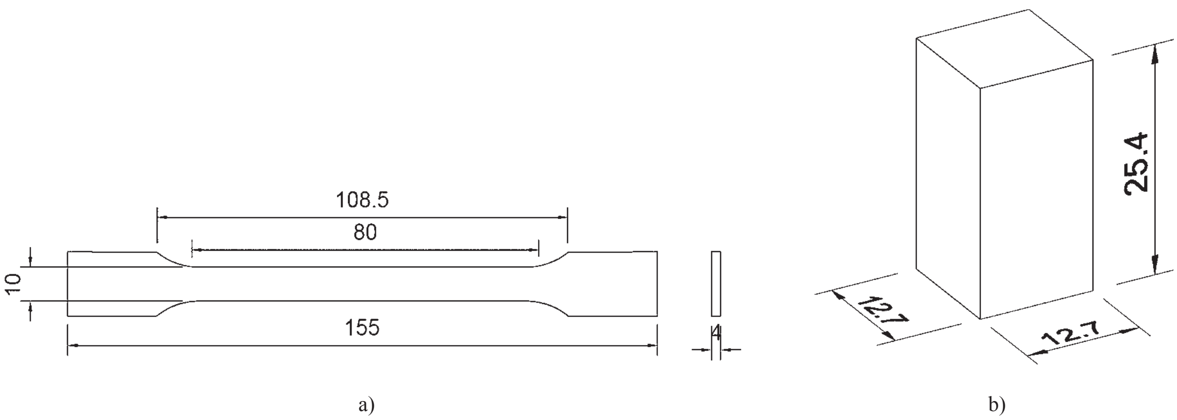
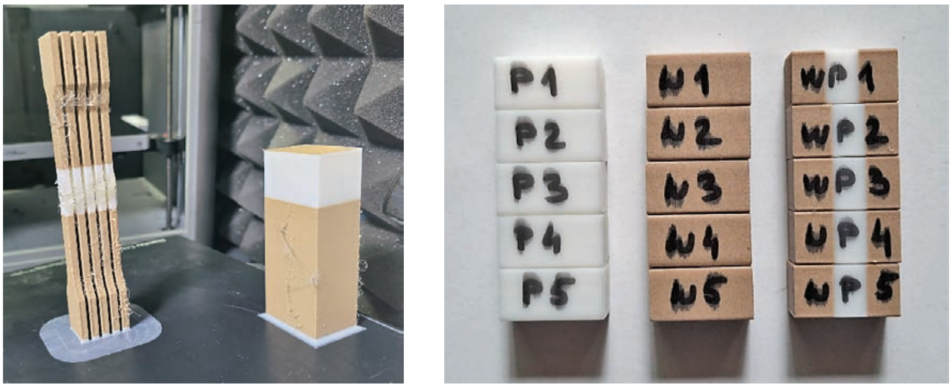
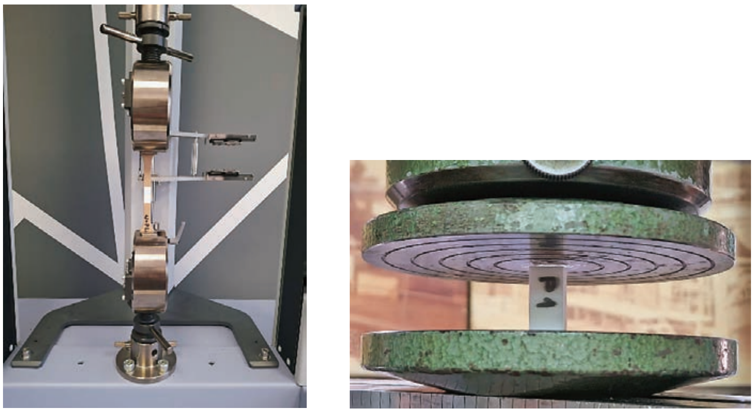


Figure 1 Test specimens: a) tensile strength testing, b) compressive strength testing
Slika 1. Ispitni uzorci: a) za ispitivanje čvrstoće na vlak, b) za ispitivanje čvrstoće na tlak



a) b)

Figure 2 Test specimens for testing mechanical properties of material: a) tensile strength testing, b) compression strength testing
Slika 2. Uzorci za ispitivanje mehaničkih svojstava materijala: a) za ispitivanje čvrstoće na vlak, b) za ispitivanje čvrstoće na tlak



a) b)

Figure 3 Strength testing: a) tensile strength, b) compressive strength
Slika 3. Ispitivanje: a) čvrstoće na vlak, b) čvrstoće na tlak

% infill PLA, five specimens were 100 % infill WPLA and five specimens were 100 % infill with 8.46 mm, or 1/3 of specimen thickness in the middle (core), with PLA, in combination with WPLA (faces) (Figure 2b).

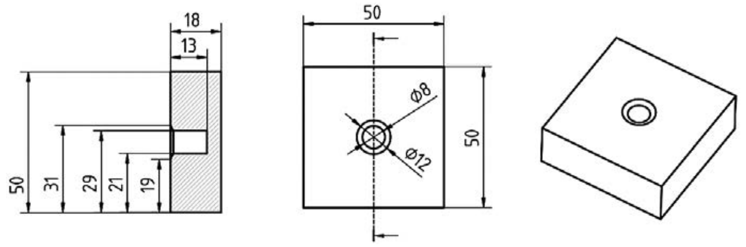
The tensile strength tests were carried out on a universal testing machine, Shimadzu, 10kN (Figure 3a.). The displacement velocity during tests was maintained at 5 mm/min. The compressive strength tests were carried out on a universal testing machine, ZWICK, 50kN (Figure 3b.). The tensile/compressive strength (σ_t; σ_c) of the tested material was determined using the following equation: $\sigma=F_{max}/A_0$ MPa, where F_{max} is maximal force (N) and A_0 cross-sectional area (mm^2).

2.3 Method of examining the withdrawal capacity of double-threaded nuts for PLA and WPLA materials and WPLA+PLA layered configuration

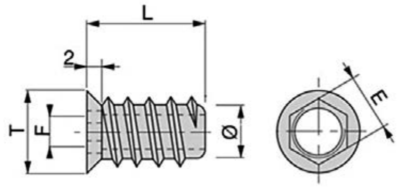
2.3. Metoda ispitivanja izvlačnog kapaciteta dvonavojnih matica za PLA i WPLA materijale te WPLA + PLA uslojene konfiguracije

The geometry and dimensions of the samples for examining the withdrawal capacity of double-threaded nuts were 50 × 50 × 18 mm (Figure 4a). These dimensions were chosen because of the better positioning of the work piece in the process of fastening the nuts. The diameter and depth of the hole in the middle of each sample was 8 mm and 13 mm, respectively. Dimensions of double-threaded nuts used to test the withdrawal capacity are shown in Figure 4b.

Three types of 3D printed materials were used to test the withdrawal capacity of double-threaded nuts. A total of 30 test specimens were printed. Ten specimens were 100 % infill PLA, ten specimens were 100 % infill WPLA, and ten layered specimens were 100 % infill with WPLA faces and PLA core with identical thickness of each layer (6 mm, or 1/3 of specimen thickness), as shown in Figure 5a. Before testing, specimens were divided into two groups. In the first group, there were 15 specimens with double threaded nuts mounted without adhesive. In the second group, there were 15 specimens with double threaded nuts mounted with adhesive. Before mounting the double-threaded nuts, the adhesive (cca 0.35 cm^3) was put in the holes to further strengthen the nuts, using a syringe. Silane terminated polymers – STP adhesive (Kleiberit STP 605.1) was used. Double-threaded nuts were mounted into the specimens with an electric screwdriver. The



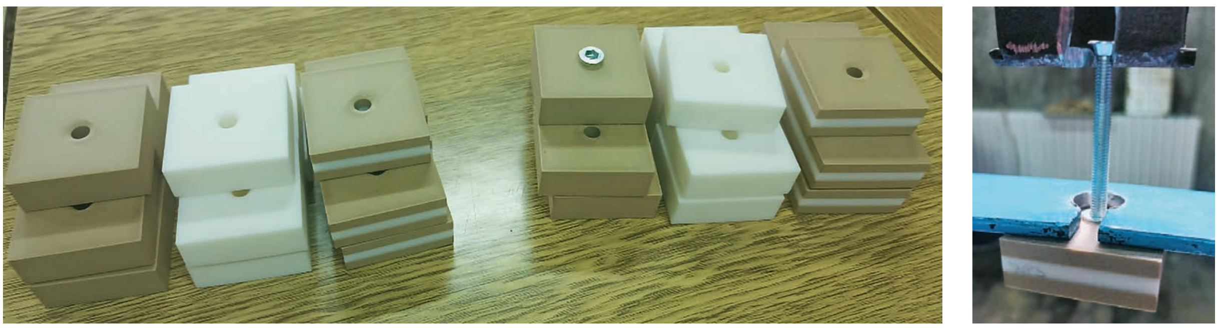
a)



L	13 mm
F	M6
T	11 mm
E	6 mm
Ø	7 mm

b)

Figure 4 Geometry and dimensions: a) specimens for withdrawal capacity of double-threaded nuts testing, b) double-threaded nuts M6×13 (https://www.lccshop.hr; SKU: 008005)
Slika 4. Geometrija i dimenzije: a) uzorci za ispitivanje izvlačne sile dvonavojnih matica, b) dvonavojne matice M6 × 13 (https://www.lccshop.hr; SKU: 008005)



a) b)

Figure 5 Withdrawal capacity testing: a) 3D printed specimens, b) testing device
Slika 5. Ispitivanje izvlačne sile: a) 3D printani uzorci, b) pristroj za ispitivanje

tests were carried out on a universal testing machine (ZWICK, 50 kN), as shown in Figure 5b. The withdrawal force of the double-threaded nuts was read on the force indicator.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Properties of PLA and WPLA materials and WPLA+PLA layered configuration
3.1. Svojstva PLA i WPLA materijala i WPLA + PLA uslojene konfiguracije

Table 1 gives the results of density, compression strength, and tensile strength of the specimens made of PLA, WPLA, and layered WPLA + PLA filament. The mean density of the WPLA specimens was 6 % lower than those of the PLA specimens, and 5 % lower than the layered composite WPLA + PLA specimens. All groups of specimens had a low and similar coefficient of density variations. Additionally, the t-test was used to determine if the means of two sets of experimental results were significantly different from each other. No significant difference (p = 0.135) was observed with a 95 % confidence level (α=0.05) between density of the PLA samples and layered WPLA + PLA samples.

Compressive strength was higher than tension strength for all three groups of printed specimens. The mean compression strength of the PLA specimens was 79.3 %, and of the layered WPLA+PLA 10.9 % higher than that of the WPLA specimens. A significant difference was observed between compression strength for all three groups of samples. The differences are dominantly the result of different responses of the material to the compression load shown in the force-displacement diagrams of the tested specimens (Figure 6a). The PLA specimens had a wide defined elastic region, i.e. proportional zones with high failure points as brittle material. The diagram and deformed WPLA and layered WPLA+PLA specimens show the ductile characteristics (Figure 6b). Forces at the yield points are taken to calculate compression strength.

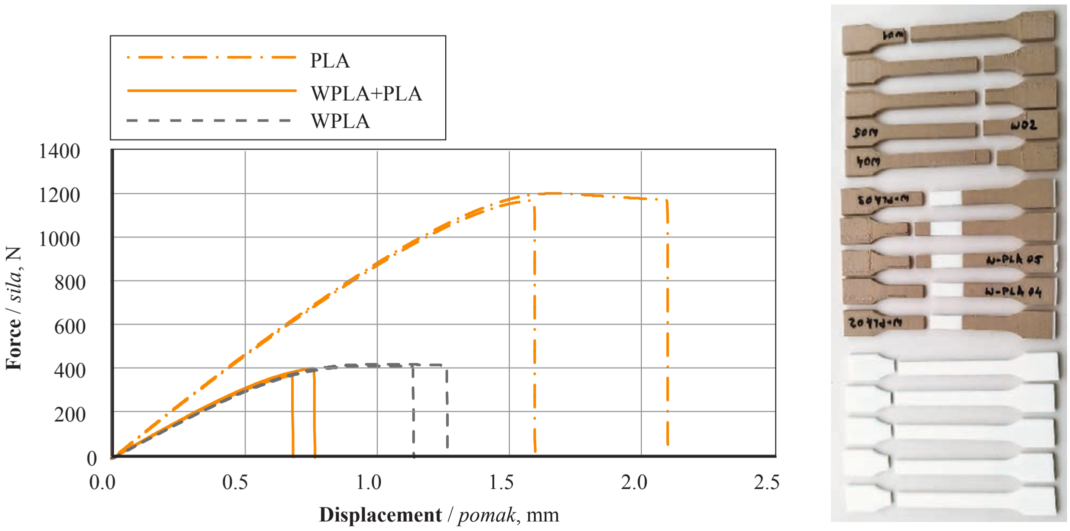
Table 1 Density, compression strength, and tensile strength of printed material
Tablica 1. Gustoća, čvrstoća na tlak i čvrstoća na vlak printanog materijala

Properties *Svojstvo*	**PLA**			**WPLA+PLA**			**WPLA**		
	Mean	Std. Dev.	Coef.of var. %	Mean	Std. Dev.	Coef.of var. %	Mean	Std. Dev.	Coef.of var. %
ρ, g/cm^3	1.17	0.01	0.85	1.16	0.01	0.86	1.10	0.01	0.91
σ_c, MPa	73.49	2.35	3.19	45.47	0.28	0.61	40.99	1.27	3.09
σ_t, MPa	28.82	0.54	1.86	10.12	0.51	5.01	10.10	0.47	4.64

ρ – density, σ_c – compression strength, σ_t – tensile strength / *ρ – gustoća, σ_c – čvrstoća na tlak, σ_t – čvrstoća na vlak*

a) b)

Figure 6 Compression strength: a) sketch of deformation – force diagram, b) characteristic failures (specimens from left to right: PLA, WPLA+PLA, and WPLA)
Slika 6. Čvrstoća na tlak: a) skica dijagrama deformacija – sila, b) karakteristični lomovi (uzorci slijeva nadesno: PLA, WPLA + PLA i WPLA)



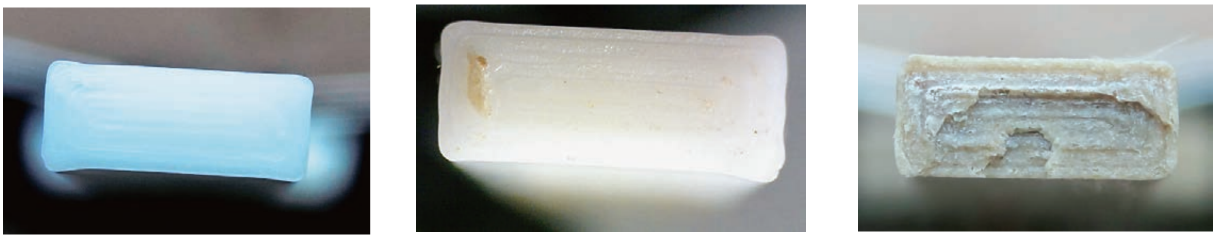
a) b)

Figure 7 Tensile strength: a) deformation – force diagram of randomly selected samples, b) characteristic failures (specimens from top to bottom: WPLA, WPLA+PLA, and PLA)
Slika 7. Čvrstoća na vlak: a) dijagram deformacija silâ za slučajno izabrane uzorke, b) karakteristični lomovi (uzorci od vrha prema dnu: WPLA, WPLA + PLA i PLA)

The deformation – force diagrams obtained by testing the tensile strength of six randomly selected samples are shown in Figure 7a. The mean tensile strength of the PLA specimens was 2.85x, and a layered WPLA+PLA 0.2 % higher than the WPLA specimens. No significant difference was observed between tensile strength for the layered WPLA+PLA and WPLA (p = 0.9606). The angle between printed orientation and the tensile force line (90°), and the adhesion properties of printed materials had a dominant influence on tensile strength value. The results showed no differences in adhesion between the WPLA layers and adhesion in the contact surface of the WPLA and PLA layers (Figure 7b).

Figure 8 shows a 20x magnified view of the characteristic deformations and fracture zones of PLA, layered WPLA+PLA, and WPLA materials after strength testing. After the compression strength test, the PLA material showed no significant deformation and noticeable failure, in contrast to the WPLA material, which

a)



b)

Figure 8 Specimens failures (from left to right: PLA, WPLA+PLA, and WPLA): a) compression strength, b) tensile strength
Slika 8. Lomovi uzoraka (slijeva nadesno: PLA, WPLA + PLA i WPLA): a) čvrstoća na tlak, b) čvrstoća na vlak

Table 2 Withdrawal force of double-threaded nuts (F_{max})
Tablica 2. Izvlačna sila dvonavojnih matica (F_{max})

Specimens *Uzorci*	**PLA**		**WPLA+PLA**		**WPLA**	
	No adhesive *Bez ljepila*	Adhesive *S ljepilom*	No adhesive *Bez ljepila*	Adhesive *S ljepilom*	No adhesive *Bez ljepila*	Adhesive *S ljepilom*
1.	3433.50	3963.24	4689.18	5248.35	3659.13	4836.33
2.	3109.77	3953.43	4542.03	4924.62	4208.49	5052.15
3.	2962.62	4208.49	4973.67	5356.26	3796.47	5248.35
4.	3149.01	4355.64	4179.06	5317.02	4394.88	4767.66
5.	3796.47	4071.15	4247.73	5297.40	3865.14	5071.77
Mean, N	3290.27	4110.39	4526.33	5228.73	3984.82	4995.25
Std.Dev., N	330.39	171.46	326.00	174.39	305.80	193.78
Coef.of var., %	10.04	4.17	7.20	3.34	7.67	3.88

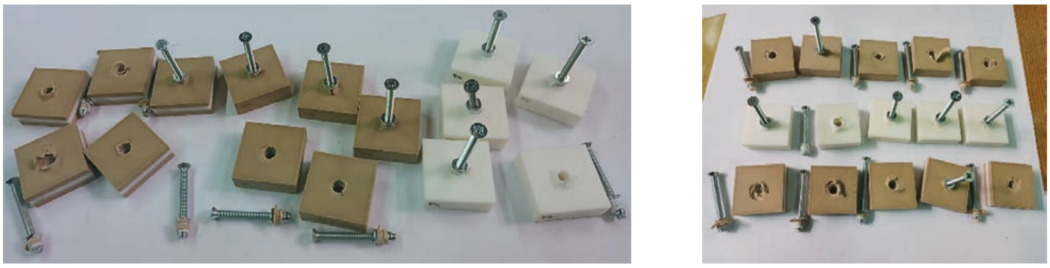
exhibited yielding and large plastic deformation with a rough surface. Delamination of the layer was a typical fracture of PLA and WPLA material under tension.

3.2 Withdrawal capacity of double-threaded nuts mounted into PLA and WPLA materials and WPLA+PLA layered configuration
3.2. Izvlačni kapacitet dvonavojnih matica montiranih u PLA i WPLA materijale te u WPLA + PLA uslojenu konfiguraciju

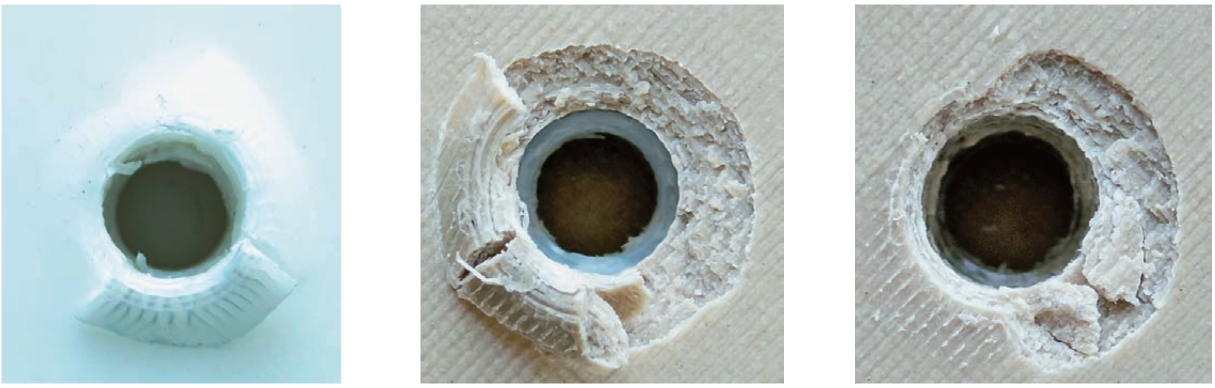
The results of the maximum withdrawal forces (F_{max}) of the double-threaded nuts (mounted with and without STP adhesive) are given in Table 2. Mean values of withdrawal forces of the double-threaded nuts mounted with adhesive were higher than those mounted without adhesive for all three groups of printed specimens. The withdrawal forces of specimens without adhesive exhibit approximately twice as high variability as those with the adhesive.

The PLA specimens with adhesive had 24.9 %, the layered WPLA+PLA specimens with adhesive 15.5 %, and the WPLA specimens with adhesive 25.4 % higher mean withdrawal forces of the double-threaded nuts for the same group of specimens without adhesive. Withdrawal forces of double-threaded nuts for the layered WPLA+PLA specimens were 13.6 % and 37.6 % higher for specimens without adhesive, and 4.7 % and 27.2 % higher for the specimens with adhesive, than the withdrawal forces of the WPLA and PLA specimens, respectively. For WPLA specimens, the withdrawal force was approximately 21 % higher than for the PLA specimens, regardless of the adhesive application. The minimal percentage difference in withdrawal force was 3.1 %, between WPLA without adhesive and PLA with adhesive, and the maximal percentage difference in withdrawal force was 45.5 %, between PLA without adhesive and WPLA+PLA with adhesive.

The characteristic patterns of the fractures of the double-threaded nuts caused by the withdrawal forces are shown in Figure 9. The fracture modes of the double-threaded nuts are similar to common fractures in wood, or other fiber materials. The nut started to pull out after the material around the thread failed. The material remains partially attached to the thread while the



a)



b)

Figure 9 Failures caused by withdrawal force of double-threaded nuts: a) specimens without adhesive (left), specimens with adhesive (right), b) failures of PLA, WPLA+PLA, and WPLA material
Slika 9. Lomovi uzrokovani izvlačenjem dvonavojnih matica: a) uzorci bez ljepila (lijevo) i uzorci s ljepilom (desno), b) lomovi PLA, WPLA + PLA i WPLA materijala

outer layers delaminate and/or the fibers break. The amount of the pulled-out material and size of the degraded zone of material in the outer layers and/or the amount of the material that remains attached to the double-threaded nuts after fractures are generally higher for double-threaded nut samples mounted with adhesive, particularly so for WPLA and WPLA+PLA samples.

Comparative distributions of results of maximum withdrawal forces (F_{max}) of the double-threaded nuts of the three groups of samples mounted with and without adhesive are shown in Figure 10. The samples with adhesives from the same group of materials, e.g. PLA group, have higher withdrawal forces (F_{max}) of the double-threaded nuts than those without adhesive. Results of the T-test showed a significant difference between the withdrawal forces of the double-threaded nuts between samples without adhesive and the samples with adhesive for the same group of printed materials used.

No significant difference was found between the withdrawal forces (F_{max}) of the double-threaded nuts

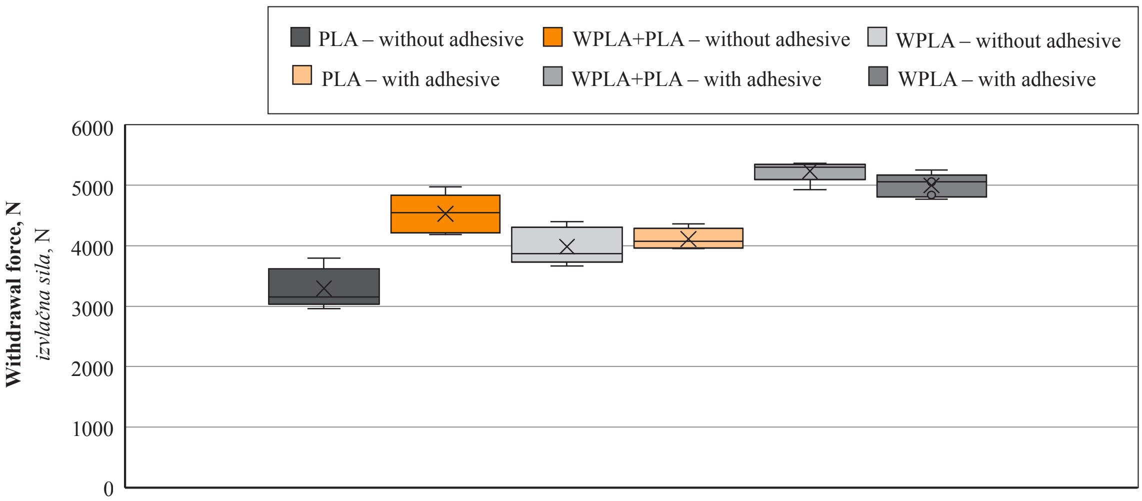


Figure 10 Distribution of results of withdrawal forces of double-thread nuts mounted into PLA, WPLA+PLA, and WPLA printed material
Slika 10. Distribucija rezultata izvlačne sile dvonavojnih matica montiranih u PLA, WPLA + PLA i WPLA printani materijal

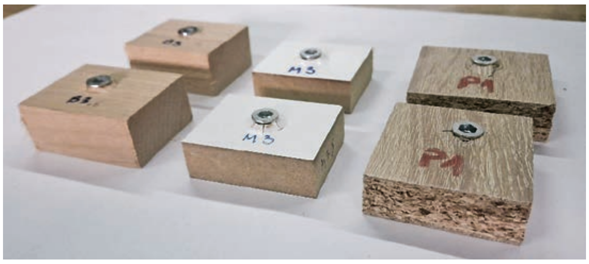


Figure 11 Failures caused by withdrawal force of double-threaded nuts mounted into beech wood, MDF, and particleboard
Slika 11. Lomovi uzrokovani izvlačenjem dvonavojnih matica montiranih u bukovo drvo, MDF i ivericu

for WPLA specimens and layered WPLA+PLA specimens without adhesive (p = 0.0998), or for the same groups of specimens with adhesive (p = 0.1186). Also, no significant difference was found between the withdrawal forces (F_{max}) of the double-threaded nuts for PLA specimens with adhesive and WPLA specimens without adhesive (p = 0.3577), or for PLA specimens with adhesive and layered WPLA+PLA specimens without adhesive (p = 0.0832).

3.3 Comparison of withdrawal capacity of double-threaded nuts mounted into PLA and WPLA materials and wooden materials
3.3. Usporedba izvlačnog kapaciteta dvonavojne matice montirane u PLA i WPLA materijale i drvne materijale

The withdrawal forces (F_{max}) of the double-threaded nuts mounted into PLA, layered WPLA+PLA, and WPLA specimens were compared with the results of withdrawal forces for wood (beech) and coated wood composites (medium-density fiberboard (MDF) and particleboard), as shown in Figure 11. The data used is from the paper that analyzed the effect of wooden material types and adhesive types on the withdrawal capacity of double-threaded nuts (Ibrisevic *et al*., 2023).

The results of the withdrawal force (F_{max}) of double-threaded nuts (without adhesive and with STP adhesive; 15 specimens for each combination) given in Table 3 are comparable because they were obtained using the same type of double-threaded nuts, the same amount of STP adhesive and the same methodology described in this paper.

Withdrawal forces of the double-threaded nuts mounted with adhesive were higher than those mounted

Table 3 Descriptive statistics of withdrawal force (F_{max}) of double-threaded nuts for beech wood, MDF, and particleboard (Ibrisevic *et al*., 2023)
Tablica 3. Deskriptivna statistika izvlačne sile (F_{max}) dvonavojnih matica za bukovo drvo, MDF i ivericu (Ibrisevic *et al*., 2023.)

Withdrawal force F_{max}, N / *Izvlačna sila F_{max}, N*	Beech / *Bukovina*			MDF			Particleboard / *Iverica*		
	Mean	Std. dev.	Coef. of var.	Mean	Std. dev.	Coef. of var.	Mean	Std. dev.	Coef. of var.
No adhesive / *Bez ljepila*	2820.2	384.8	0.1	1296.2	182.3	0.1	977.0	188.7	0.2
STP adhesive / *Sa STP ljepilom*	3684.0	399.5	0.1	1881.0	194.0	0.1	1337.3	140.8	0.1

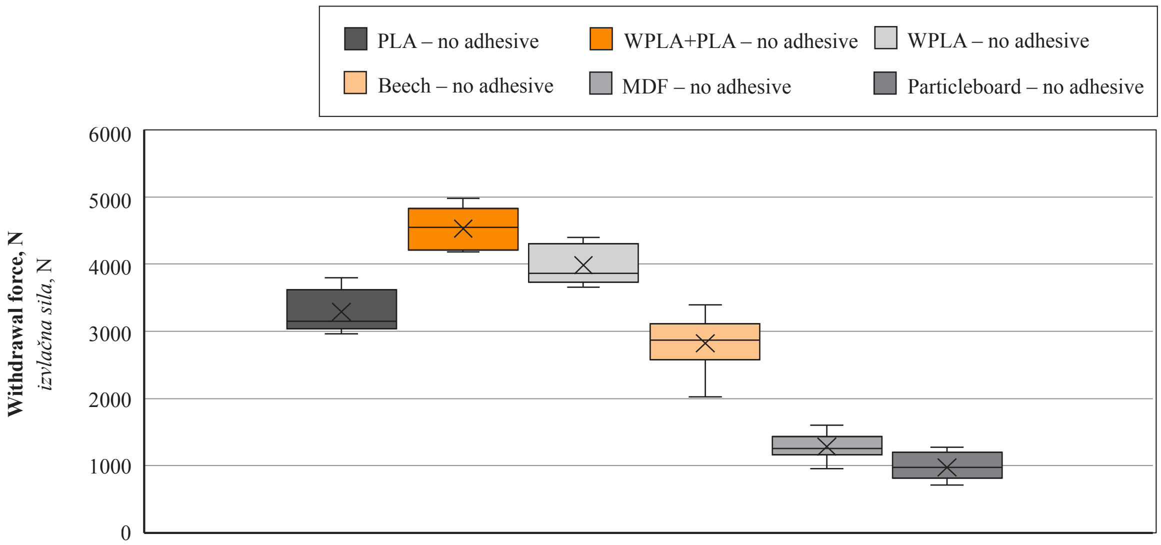


Figure 12 Distribution of withdrawal force results of double-threaded nuts mounted without adhesive into PLA, WPLA+PLA, WPLA, beech wood, MDF, and particleboard
Slika 12. Distribucija rezultata izvlačne sile dvonavojnih matica montiranih bez ljepila u PLA, WPLA + PLA, WPLA, bukovo drvo, MDF i ivericu

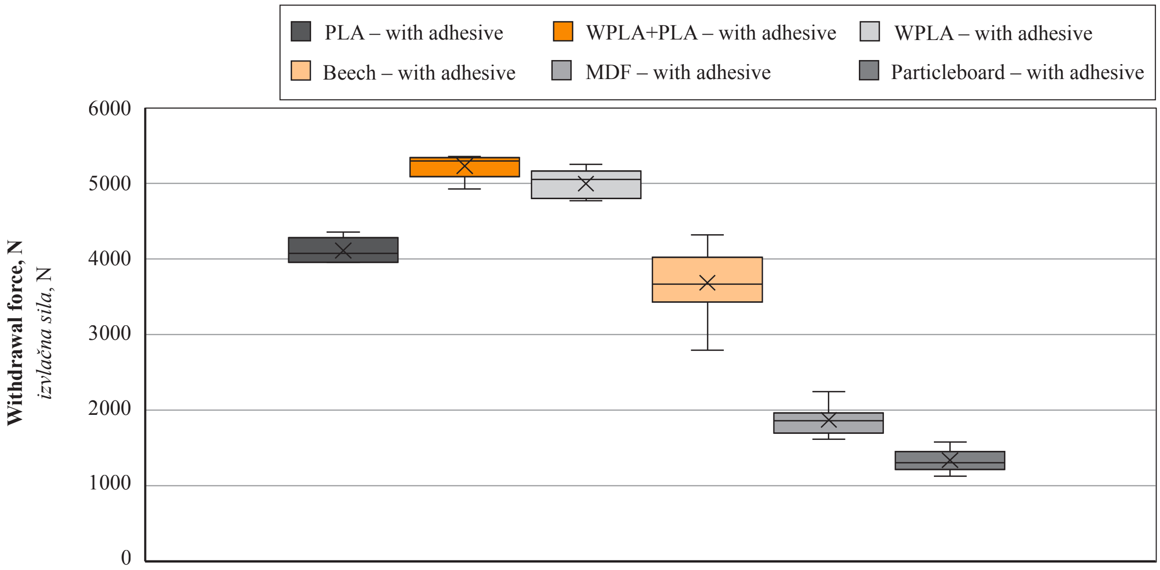


Figure 13 Distribution of withdrawal force results of double-threaded nuts mounted with adhesive into PLA, WPLA+PLA, WPLA, beech wood, MDF, and particleboard
Slika 13. Distribucija rezultata izvlačne sile dvonavojnih matica montiranih uz pomoć ljepila u PLA, WPLA + PLA, WPLA, bukovo drvo, MDF i ivericu

without adhesive for all wooden materials. The beech specimens with adhesive had 30.6 %, the MDF specimens with adhesive 45.1 %, and particleboard specimens with adhesive 36.9 % higher withdrawal forces of the double-threaded nuts for the same group of specimens without adhesive. Namely, gluing creates a solid bond between the surfaces of two different materials (metal and wood, or wood-based materials), and a different distribution of internal forces occurs in the loaded joint, i.e., a stress distribution, which ultimately affects the value of the withdrawal force. Furthermore, the withdrawal force for beech specimens was approximately 2x higher than the mean withdrawal force for MDF specimens, and approximately 3x higher than for particleboard specimens, regardless of whether adhesive was used. The withdrawal forces of the MDF specimens were 32.7 % without adhesive and 40.6 % with adhesive higher than the mean withdrawal force of the particleboard specimens.

Comparative distributions of the maximum withdrawal forces (F_{max}) results of the double-threaded nuts for the 3D printed materials and wooden materials mounted with and without adhesive are shown in Figure 12 and Figure 13. A comparison of the withdrawal forces results between 3D printed materials and wooden materials showed that withdrawal forces of double-threaded nuts for the PLA specimens without adhesive were 16.7 % higher and for specimens with adhesive 11.6 % higher than the withdrawal forces of the beech with and without adhesive, respectively. All other combinations showed a difference higher than 35 % in favor of 3D printed materials.

No significant difference was found between the withdrawal forces (F_{max}) of the double-threaded nuts for the beech specimens with adhesive and PLA specimens without adhesive (p = 0.0604), for the beech specimens with adhesive and WPLA specimens without adhesive (p = 0.1129), and for the particleboard specimens with adhesive and MDF specimens without adhesive (p = 0.3849). In general, the withdrawal capacity of double-threaded nuts mounted in materials with adhesive can reach the value of the withdrawal capacity for materials that have better physical and mechanical properties, i.e. density and strength.

4 CONCLUSIONS
4. ZAKLJUČAK

This paper analyzed the withdrawal capacity of the double-threaded nuts mounted in 3D-printed materials with and without STP adhesive. The basic technical properties and the withdrawal force of the double-threaded nuts for the specimens made of PLA, WPLA, and layered WPLA+PLA configuration, with 100 % infill, were investigated. The values of the withdrawal force of six specimen groups are compared with the literature data of withdrawal force for beech wood, MDF, and particleboard with and without the same adhesive.

The results showed that the specimens, made with 100 % infill, had a higher density than 1.1 g/cm^3. Compressive strength was higher than tension strength, and, for both strengths, PLA had higher values than WPLA and layered WPLA+PLA. Their values and failure modes resulted from the material used, the combination of materials, and dominantly the printing pattern. No significant difference was observed between tensile strength for the layered WPLA+PLA and WPLA, which is a consequence of adhesion in the contact surface of the layers.

Withdrawal forces of the double-threaded nuts mounted with adhesive were higher (about 25 % for PLA and WPLA specimens, and 15 % for layered WPLA+PLA specimens) and they showed approximately less variability than those mounted without adhesive for all three groups of printed specimens. The highest values of withdrawal forces (for both with and without an adhesive) were obtained for layered WPLA+PLA configuration, followed by WPLA and the lowest for PLA. No significant difference was found between the withdrawal forces for WPLA and layered WPLA+PLA specimen for both cases, with and without an adhesive. Also, no significant difference was found between the withdrawal forces for PLA specimens with adhesive and WPLA or layered WPLA+PLA specimens without adhesive. The test results showed a significant influence of the properties of 3D printed materials (density, brittle, and ductile characteristics), the infill and printing pattern, and adhesive used on the withdrawal capacity of the double-threaded nuts.

Withdrawal forces of double-threaded nuts for the PLA specimens were higher than the withdrawal forces of the beech specimens (16.7 % for specimens mounted without adhesive and 11.6 % for specimens mounted with adhesive), and other combinations showed a difference higher than 35 % in favor of 3D printed materials. No significant difference was found between the withdrawal forces for the beech specimens with adhesive and for PLA or WPLA specimens without adhesive. The results showed that the analyzed configurations of 3D printed materials have a higher withdrawal capacity of the double-threaded nuts than hardwood and wood-based materials.

The results of the present analysis show that common double-threaded nuts can be used in dismountable connections in 3D printed furniture, or furniture parts made of PLA and wood-PLA. It enables manufacturers to create and produce dismountable furniture construction, furniture parts on demand, and repair more easily damaged construction parts made of 3D-printed wood-plastic composites.

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Identification of Charred Wood from an Ancient Charcoal Production Site in the Black Forest of Germany

Identifikacija pougljenjenog drva s drevnog mjesta proizvodnje drvenog ugljena u Schwarzwaldu, u Njemačkoj

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ABSTRACT • *Charcoal production sites serve as palaeoarchives and contain wood charcoal, which can be identified taxonomically and be utilized to obtain information and reconstruct the past vegetation, based on the occurrence of woody taxa. In the present research, the study material was collected from the Black Forest south of Freiburg (Germany), in the Schauinsland region. Charcoal samples were gathered from the surface as well as from various depths in the soil (30 cm, 60 cm and 90 cm). The main identified taxa were Abies and Fagus, almost at the same percentage of constitution, providing evidence for their growth in the area and their selection for charcoal production. The number of growth rings and samples dimensions were measured, in order to gather information of the climatic conditions and the productivity of those past time periods.*

KEYWORDS: *archaeological wood; charred wood; charcoal assemblages; growth rings*

SAŽETAK • *Lokacije za proizvodnju drvenog ugljena služe kao paleoarhivi i sadržavaju drveni ugljen koji se može taksonomski identificirati te na temelju pojave drvenastih taksona iskoristiti za dobivanje informacija i rekonstrukciju nekadašnje vegetacije. Materijal za istraživanje prikupljen je iz Crne šume južno od Freiburga (Njemačka), u regiji Schauinsland. Uzorci drvenog ugljena prikupljeni su s površine i s različitih dubina u tlu (30, 60 i 90 cm). Glavni identificirani taksoni bili su Abies i Fagus, gotovo jednakog postotka konstitucije, što potvrđuje njihov rast na tom području i objašnjava njihov odabir za proizvodnju drvenog ugljena. Izmjereni su broj godova i dimenzije uzoraka kako bi se prikupile informacije o klimatskim uvjetima i produktivnosti u tim prošlim vremenskim razdobljima.*

KLJUČNE RIJEČI: *drvo s arheološkog nalazišta; pougljenjeno drvo; nalazišta drvenog ugljena, godovi*

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1 INTRODUCTION
1. UVOD

Wood as a raw material has been exploited by mankind since its appearance on earth and contributed not only to its survival but to the establishment of civilization as well (Tsoumis, 1983). During industrial revolution, wood was massively used in the form of charcoal for the production of energy. As a result, many charcoal production sites were established all over the forests of Europe. The locations and studies of these sites provide valuable information about the composition of the vegetation in the past, in terms of wood species and timber production taxa (Braadbaart and Poole, 2008; Figueiral and Mosbrugger, 2000; Gocel-Chalté *et al.,* 2020). In the Mediterranean region, wood exploitation for charcoal began over two thousand years ago and had almost completely ceased by the late 19th century. Many kiln sites are located in forests dominated mainly by oak, due to their large size, as well as by beech and other types of forests (Carrari *et al.*, 2017).

Archaeological charred wood can be described as a non-active, black material that has been exposed to temperatures that exceeded 350 °C for a duration of 15 minutes and was turned into charcoal due to either carbonization without oxygen or incomplete charring with a very low presence of oxygen (Braadbaart and Poole, 2008). Analysis of charcoal includes the examination and identification of wood remains based on the observation of the anatomical characteristics of wood in three-dimensional form (Kabukcu *et al.,* 2018).

Charcoal assemblages can be studied and identified based on their structure, which remains largely intact in quality when wood is incompletely combusted, as the anatomical features are not significantly altered (Koeppen, 1972; Beall *et al.,* 1974). Furthermore, in the case of large samples, the width of the growth rings can be measured as well. The data obtained can reveal the selection of wood species used for energy production in the past (Marguerie and Hunot, 2007). The identification can be implemented with various techniques depending on the study material and available equipment such as reflected light microscopy or 3D-reflected light microscopy (3DRLM) and field emission scanning electron microscopy. However, 3DRLM has proved to be more effective for charcoal identification (Zemke *et al*., 2020). The surface quality is critical, since in most cases charcoal findings are handled as they are with no previous preparation, giving only partial areas that are in focus. Although significant differences in surface roughness have been recorded among different trees, not significant differences have been detected between heartwood and sapwood or in different heights of a tree (Chavenetidou and Kamperidou, 2024).

Fragments of charcoal are buried in the soil or even lay on its surface and are found easily all over the world. Charred wood is not so sensitive to microbial attack and can preserve its natural wood anatomy. Thus, its analysis is a cornerstone for paleoenvironmental science (Nelle *et al.,* 2013). The analysis of charcoal in the aspect of taxonomic classification was applied during the 19th century, though it was mostly developed in the 1970's (Thinon, 1978). Charcoal identification can provide knowledge about climatic changes of the past. The identification is based on the knowledge of the macroscopic and microscopic features of wood, which constitute its structure and anatomy (Koeppen, 1972; Wheeler and Baas, 1998).

In most cases, charcoal findings are of small dimensions, reaching a size of several centimeters. However, there are cases where larger parts of buildings and constructions have been found, giving the opportunity to obtain additional information. For instance, the findings of excavations around Naples (southern Italy) suggest that mainly conifers were selected as a building material, such as *Abies alba* and *Cupressus sempervirens*, species that nowadays are rarely found or, in the case of cypress, almost extinct from Naples and Italy. Moreover, the collected samples of *Larix* and *Picea abies* indicate the import of wood from foreign countries (Moser *et al.,* 2018).

Anthracological studies may reveal the existence of woody plants in the past but also provide information about the evolution and the changes of the environment, as well as the way people interacted with it. In France, the studies suggest that the species chosen for fuel production were selected according to their technical features, such as oak, as well as their availability (Marguerie and Hunot, 2007). In Germany, charcoal findings dated to High and Late Medieval Times as well as Roman Iron Age indicate that the dominant species was *Quercus*, followed by significant percentage of *Ericaceae*. At the top layers, which are regarded to be younger, various species were found, including *Quercus, Fagus, Betula, Alnus, Fraxinus, Corylus, Salix, Acer*, *Pinus* and others in smaller proportions (Jansen *et al.,* 2013). Moreover, the analysis of charred wood can lead to findings related to the interaction of natural and anthropogenic environment. In the case of research in Harz Mountains (Germany) kiln sites, the findings suggest that the species used for energy production were determined by the topography of the area and the available wood species, rather than by selection (Knapp *et al.,* 2015). Even today, a large portion of wood production is still used for charcoal manufacturing, according to FAO (2017). Research by Haag *et al.* (2020) examined 150 charcoal samples from 11 countries in Europe and found that a significant share of timber originated from tropical and subtropical species (approximately 46 %), while the remainder came from Europe timber species. The study highlights the necessity to include charcoal into the scope of European Timber Regulations (EUTR).

There are cases where the disappearance of forests is attributed to humans. In Tibet (China), anthracological analyses revealed the existence of tree and shrub vegetation, which consisted mostly of *Juniperus, Salix, Betula* and *Hippofae*. At present, this area is similar to the desert with grasses and small herbs (Kaiser *et al.,* 2009).

Since the analysis of charcoal is influenced by various factors, the connection with data from other sectors of science combining geomorphological, archaeological and palaeobotanical data is necessary for more accurate conclusions (Jansen *et al.,* 2013; Knapp *et al.*, 2015). Moreover, the preservation of charred wood is a result of climatic as well as anthropogenic factors that affect its mechanical, physical and chemical properties. Decayed wood charcoal has less mechanical resistance than undecayed wood charcoal. However, most species exhibit similar properties, when transformed to charcoal, with only minor differences observed between conifers and broadleaved trees (Braadbaart and Poole, 2008; Théry-Parisot *et al.,* 2010).

The combination of charcoal analysis and dendrochronological estimations provide more detailed assessment of former conditions and vegetation, as well as the evolution of the landscape. Thus, the presence or absence of specific species can be identified in areas where kiln sites were established. In northern Belgium, where such sites were located and dated at 1300-1900 AD, the main species used for charcoal production was alder probably from coppice stands, when the dominant vegetation consisted of oak trees, probably due to conversion of woodland to grassland (Deforce *et al.,* 2013). Charred wood from the late Holocene was investigated in Bosnia- Herzegovina to reveal various genera with the most dominant those of *Quercus, Ostrya, Carpinus, Acer, Fagus* and *Pinus* (Schroedter *et al.,* 2013). In Alpine and Subalpine areas of Trentino (Italy), during the Holocene a forest expansion was detected, according to studies, at the Lateglacial around 10 500 cal. BP with *Pinus sylvestris, Pinus mugo* and *Larix decidua*, whereas sites used for grazing during the Bronze Age were naturally reforested after abandonment (Favilli *et al.,* 2010).

Dendrochronology is related to tree ring measurements for the estimation of wood age. In temperate zone, the growth rings of a tree show a periodicity in their formation, which in most cases reflects the annual cycle of growth, thus enabling the estimation of wood age. The rings are not of the same width, reflecting the environmental conditions (mainly rainfall and temperature) of each growth period. Species grown in specific geographic area are exposed to similar environments, so their tree-ring series can be cross dated and provide chronologies for dating and for calibration of the radiocarbon dating method (Creber, 1977; Schweingruber, 2012). Radiocarbon dating is a technique based on the analysis of carbon ^{14}C in biological matter and provides more accurate results when it comes to charcoal remains, which usually have small dimensions and not many obvious growth rings. However, in some cases (Rybníček *et al.,* 2022) charcoal dating with radiocarbon technique can be insufficient. Wood is suitable for the application of this method, especially because it enables the use of wiggle-matching method.

The aim of this research was a detailed analysis and identification of charred samples from charcoal production site K600 in Black Forest, Schauinsland region, from the period of late medieval to early modern times, as an effort to enrich the archaeological archives of charcoal in Germany and contribute to the botanical mapping of the past. Furthermore, a study of the anatomical characteristics and the growth rings of the samples was implemented.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The research material was collected from the Black Forest south of Freiburg (Germany), in the Schauinsland region (Figure1), during a field trip to the area. The charcoal findings were attributed to the late medieval/early modern times charcoal production sites in Baden-Württemberg.

After digging the soil, sampling material was collected at different depth profiles (0-30cm, 30-60 cm, 60-90 cm) including surface samples (Figure 2) in order to identify the species and see the evolution of their exploitation through different periods of time.

Then, they were stored in plastic bags and in a next step they were left to dry in open boxes, until their moisture content reached the equilibrium moisture content levels related to the stable relative humidity and were easy to handle without collapsing (Figure 3).

The charred wood was broken with a sharp knife, so as to have freshly broken surfaces (transversal, radial and tangential) and be easily observed in reflectance light microscope equipment with a stereo lens and a microscope (Figure 4). After identification, the samples were preserved in paper envelopes.

The estimation of the age of the trees used to produce charcoal was conducted based on the circle tool for the estimation of wood diameter size (Ludemann, 2006; Pişkin *et al.,* 2018). At the same time, growth rings number estimation was conducted during microscopic observation of the largest samples.

An estimation of the age of charred wood is also possible with the use of a circle tool that represents a cross section of the tree (Figure 5). Depending on the

Figure 1 Research area of Black Forest in Germany (https://www.worldatlas.com/maps/germany, https://www.schauinsland.de/museums-bergwerk/wp-content/uploads/2019/09/anfahrtsskizze.jpg)
Slika 1. Područje istraživanja Crne šume u Njemačkoj (https://www.worldatlas.com/maps/germany, https://www.schauinsland.de/museums-bergwerk/wp-content/uploads/2019/09/anfahrtsskizze.jpg)

a)

b)

c)

Figure 2 Fieldwork: a) digging, b) pit depth, c) collection of samples
Slika 2. Terenski rad: a) kopanje, b) određivanje dubine jame, c) prikupljanje uzoraka

a) b)

Figure 3 a) storage of samples, b) placement in open boxes for drying out
Slika 3. a) Skladištenje uzoraka, b) stavljanje uzoraka u otvorene kutije za sušenje

a) b)

Figure 4 Observation with the use of a) sterescope Nikon SMZ1270, b) microscope with an attached camera Nikon DS-Ri2 (Nikon Eclipse LV100ND)
Slika 4. Promatranje uzoraka: a) stereoskopom Nikon SMZ1270, b) mikroskopom s kamerom Nikon DS-Ri2 (Nikon Eclipse LV100ND)

curves of the growth rings, the dating of the charcoal sample is possible, atlthough not so accurate (Pişkin *et al.,* 2018).

The statistical analysis of the results was performed by using IBM SPSS software, version 23 (IBM, 2015) and an analysis of Variance (Anova) was implemented as well as a Kolmogorov-Smirnoff test, so as to identify whether any differences were stastitically important.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In total, 113 charcoal assemplages were examined from different soil depths of the study area (Table 1). The main identified genera were *Abies* and *Fagus* (Figure 6).

Figure 6 a, b shows a charcoal sample of conifer tree, with no resin canals, uniserate rays with absence of radial tracheids. Based on the distribution of the species in the past area, the dominant conifer tree with such wood anatomy is *Abies alba* (Schweingruber, 1990). Figure 6b depicts a diffuse porous hardwood with small vessels, which are slightly larger in

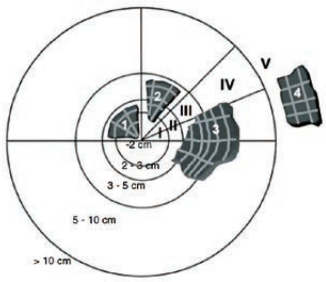

Figure 5 Circle tool for the estimation of wood diameter size applied in an anthracological sample (Ludemann, 2006; Pişkin *et al*., 2018)
Slika 5. Kružni alat za procjenu promjera drva antrakološkog uzorka (Ludemann, 2006.; Pişkin i dr., 2018.)

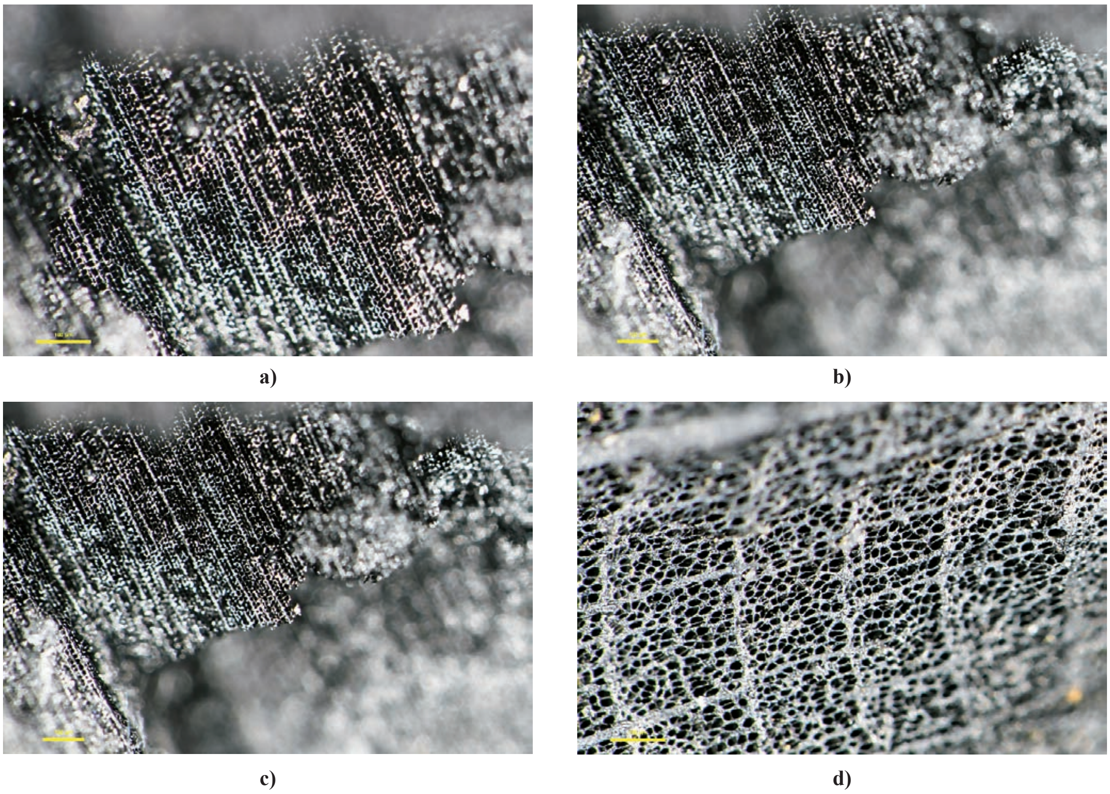

Figure 6 Stereoscopic pictures of transverse sections of: a), b) *Abies*; c), d) *Fagus* (bar = 100µm)
Slika 6. Stereoskopske slike poprečnih presjeka: a) i b) *Abies*; c) i d) *Fagus* (oznaka = 100µm)

Table 1 Total number of charcoal samples
Tablica 1. Ukupan broj uzoraka drvenog ugljena

K600 samples / *K600 uzorci*	**Sample descriptipn** / *Opis uzoraka*	***N***	***Abies***	***Fagus***
K600a	Samples collected from the surface before digging were seperated in two categories based on their size. *Uzorci prikupljeni s površine prije kopanja podijeljeni su u dvije kategorije na temelju njihove veličine.*	20	11	9
K600b		19	12	7
K600 – surface	Samples collected from the surface after digging. *Uzorci prikupljeni s površine nakon kopanja.*	16	5	11
K600_profile_0 – 30 cm	Samples from the material collected at different depths and after drying in the lab. *Uzorci prikupljenog materijala s različitih dubina i nakon sušenja u laboratoriju.*	20	5	15
K600_profile_30 – 60 cm		20	13	7
K600_ profile_60 – 90 cm		17	7	10
N_Total / *ukupno*		112	53	59

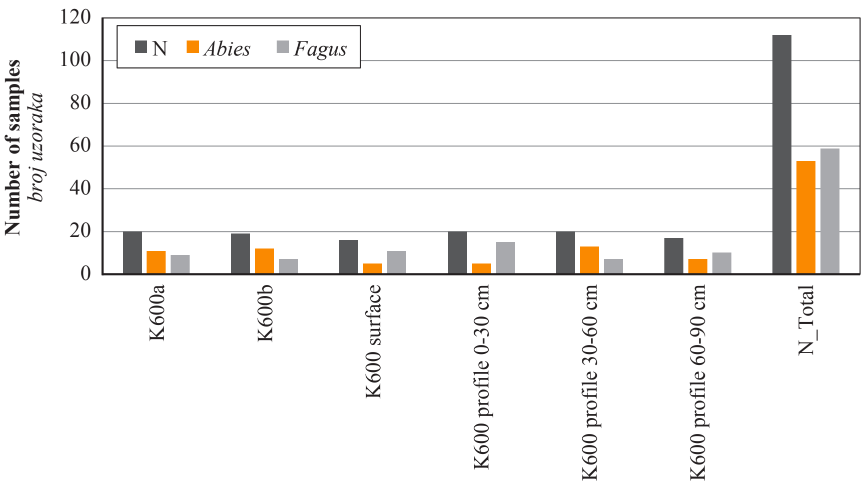

Figure 7 Distribution of species among charred wood samples
Slika 7. Raspodjela vrsta drva pougljenih uzoraka

Table 2 Analysis of variance for data collected
Tablica 2. Analiza varijance prikupljenih podataka

Analysis of variance / *Analiza varijance* (ANOVA)						
		Sum of squares *Zbroj kvadrata*	*df*	Mean square *Srednji kvadrat*	*F*	Sig.
Abies	Between groups / *među grupama*	1702.190	4	425.548	24.551	.040
	Within groups / *unutar grupa*	34.667	2	17.333		
	Total / *ukupno*	1736.857	6			
Fagus	Between groups / *među grupama*	2082.190	4	520.548	30.032	.032
	Within groups / *unutar grupa*	34.667	2	17.333		
	Total / *ukupno*	2116.857	6			

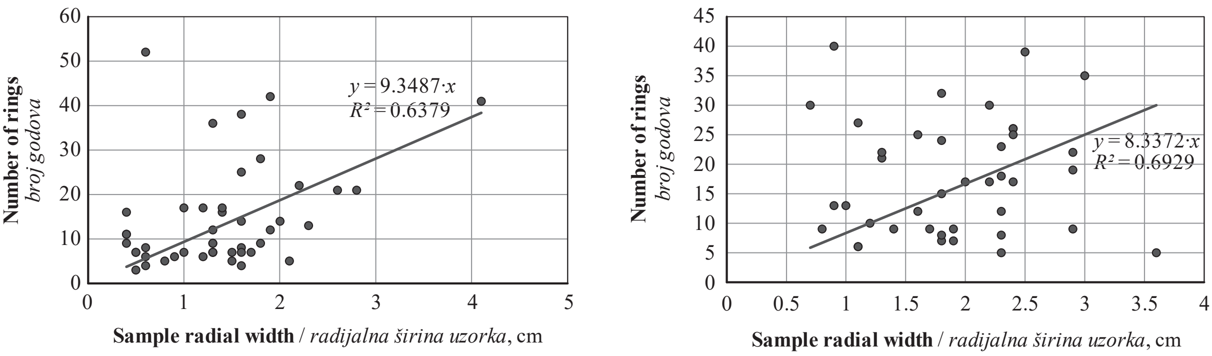

Figure 8 Graphical distribution of the number of rings per sample, in relation to radial width of the sample: a) *Abies*, b) *Fagus*
Slika 8. Grafička raspodjela godova po uzorku s obzirom na radijalnu širinu uzorka: a) *Abies*, b) *Fagus*

the earlywood, either solitary or in clusters, and often with tyloses, multiseriate rays of two sizes, i.e. 3-5 cells wide or more than 10 cells, and distinct growth ring boundaries. Based on wood anatomy features, the sample corresponds to *Fagus* sp. in the sampling area represented by *Fagus sylvatica* (Schweingruber, 1990).

According to the following table, 112 samples were studied in total. *Abies alba* (European silver fir) was detected in 53 of them, whereas the rest 59 were *Fagus sylvatica* (European beech) (Figure1).

The findings are in line with previous studies, since *Fagus sylvatica* and *Abies alba* were two of the dominant species in the area of Black Forest in the postmedieval times. (Ludemann, 2010).

According to Figure 7, the depth was not a factor of influence on the selection of wood species, since no certain tendency of the species appearance was observed.

Analysis of variance (ANOVA) showed that there are statistically significant differences between groups in the values of the variable for the species *Abies* (F = 24.551, p = 0.040) and *Fagus* (F = 30.032, p = 0.032). The F values (24.551 and 30.032) are quite high, meaning that the variation between groups is much greater than the variation within groups.

When small samples, meaning those with a small radial width, contain many growth rings, this may indicate a period of slow growth in the past, or that the samples originated from branches, which typically have a different structure compared to the trunk. In the case of *Abies*, the tendency noticed is that small samples include lower number of growth rings. On the other hand, in *Fagus* a greater distribution is observed. In case small charcoal samples include a great number of growth rings, this might indicate that charcoal was made from branches. However, R^2 is very low in both cases, and they do not demonstrate any clear trend.

4 CONCLUSIONS
4. ZAKLJUČAK

Charcoal production sites function as palaeoarchives and contain wood charcoal that can be taxonomically identified to provide information about past vegetation. In a case study conducted in the Black Forest, south of Freiburg (Germany), charcoal remains dated to the late medieval and early modern periods indicate that the dominant species used for charcoal production were *Abies alba* and *Fagus sylvatica*, as identified in the charcoal assemblages. Depth of sampling did not significantly affect species proportions. Tree ring width varied considerably but showed no correlation with sample size. Precise measurements of tree ring width and number, along with their absolute dating, other proxies (e.g. pollen analyses) and broader sampling could provide more comprehensive insights into vegetation in the area during the specific time period.

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A Model-Based Approach for Optimal Price Calculation of Primary Wood Products

Primjena pristupa zasnovanoga na modelu za izračun optimalne cijene proizvoda u primarnoj preradi drva

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ABSTRACT • *During a period of intensive changes in the market, when profits cannot be increased by raising sales prices, companies focus on improving production processes and reducing costs. Intensified competition and business development demand improved cost tracking within companies and by individual products. Accurate calculation of product costs is crucial because the final product generates revenue and impacts its growth or decline. Introducing a new model for calculating and allocating costs per product unit aims to review the concept of fixed cost distribution in the company and the calculation of product costs to assess the profitability of This model shows that most selected products are profitable to produce. Observing overall profits for selected products, Model E is the only one that ultimately shows a gain. It provides information on the actual cost of each product, enabling the company to decide whether to produce, wait for a price change, or discontinue a product. Model E suggests dividing costs into fixed and variable, then allocating variable costs to each product's cost. The difference between each product's revenue and its variable costs represents the contribution margin used to cover fixed costs. Applying Model E is expected to yield better business results over time by clearly indicating which products should be supported and which should be terminated.*

KEYWORDS: *wood industry; cost price; contribution margin; cost price calculation models*

SAŽETAK • *Tijekom razdoblja intenzivnih promjena na tržištu, kada se profit ne može povećati podizanjem prodajnih cijena, tvrtke se usredotočuju na poboljšanje proizvodnih procesa i smanjenje troškova proizvodnje. Intenzivnija konkurencija i razvoj poslovanja zahtijevaju pažljivije praćenje troškova unutar tvrtki, kao i za pojedinačne proizvode. Točan izračun troškova proizvoda ključan je korak u tom procesu jer konačni proizvod generira prihod i utječe na njegov rast ili pad. Cilj uvođenja novog modela za izračun i raspodjelu troškova po jedinici proizvoda jest preispitivanje koncepta raspodjele fiksnih troškova u tvrtki i izračun troškova proizvoda kako bi se procijenila profitabilnost svakog proizvoda. Testirani su različiti modeli obračuna troškova (od A do E), a model E pokazao*

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se optimalnim. Njime je potvrđeno da je proizvodnja većine ispitivanih proizvoda isplativa. Promatrajući ukupnu dobit za odabrane proizvode, model E je jedini koji je u konačnici potvrdio dobit. Njime se dobivaju informacije o stvarnom trošku svakog proizvoda, što omogućuje tvrtki da odluči hoće li konkretni proizvod i dalje proizvoditi, čekati promjenu cijene ili ga sasvim prestati proizvoditi. Prema modelu E, predlaže se podjela troškova na fiksne i varijabilne, a zatim dodjeljivanje varijabilnih troškova trošku svakog proizvoda. Razlika između prihoda svakog proizvoda i njegovih varijabilnih troškova čini doprinosnu maržu koja je namijenjena pokrivanju fiksnih troškova. Očekuje se da će primjena modela E s vremenom donijeti bolje poslovne rezultate jasnim naznačivanjem proizvoda koje treba podržati, kao i onih koje treba prestati proizvoditi.

KLJUČNE RIJEČI: *drvna industrija; cijena koštanja; kontribucijska marža; modeli izračuna cijene koštanja*

1 INTRODUCTION
1. UVOD

The demand for wood continues to grow steadily, yet the availability and production of wood raw materials remain limited. This situation lowers the prospects for the timber business, as the wood industry struggles to meet market demand, leading to higher prices for wood products.

Costs are the basis for many business decisions. Wood processing companies must constantly strive to improve or at least maintain their market share (Oblak and Glavonjić, 2014). There are several ways to achieve this. Increased costs reduce company profits, i.e. a company that cares about its profits will strictly monitor its costs in order to maintain profitability (Motik, 2004; Muhdi and Hanafiah, 2022). For any business situation, the rule is that the company must be the lowest cost provider in the long term, that its costs must tend to fall and that it must have a complete picture of costs and profits for each product at all times. It is not sufficient to analyse the costs for a single or limited business area, but the entire business process chain, i.e. from the supplier to the customer of products or services (Posavec *et al.*, 2022). In this way, costs are managed throughout the entire business process (Figurić, 2003). In times of difficult economic conditions, managers have to make numerous decisions and take various measures on a daily basis to ensure the long-term profitability of the company and maximise profits at the lowest possible cost. Accordingly, cost management is of central importance, which, according to Belak *et al.* (2009) pursues two fundamental objectives, cost reduction and cost control. It is possible to manage costs in different ways and with different models, but in order to achieve a positive outcome of the cost management process, it is important to know the existing structure of the organisation's total costs. This should be the first step towards cost management and towards achieving the company's goals. The most effective cost management is reflected in the management of business processes. Therefore, improving the methods of collecting and reporting financial cost data is critical to support management decision-making (Zimmerman, 2011). In today's fast-paced and dynamic market, knowing how to manage costs appropriately and to a high standard is a complex process that requires the application of modern methods. For a long time, cost management was carried out using traditional methods and the resulting allocation key. However, due to major market changes in the forestry and wood processing industries, there was a need to develop new methods and business models whose cost allocation keys are more appropriate and precise than those of traditional methods (Kajanus *et al.*, 2019).

The wood-based sector development strategies include modernising production and increasing the proportion of end products with higher added value (Posavec and Vuletić, 2004). The industry in Europe has called for better recognition of its potential as a driver for sustainability in key EU policies, including the EU Industrial Strategy, the EU Green Deal, and the EU Bioeconomy Strategy (European Economic and Social Committee, 2024). In 2020, the share of wood processing and furniture manufacturing in the GDP of the Republic of Croatia was around 1 %. Wood processing (C 16) (according to the National Classification of Activities – NKD2007) accounted for 0.7 %, and furniture production (according to NKD C 31) for 0.3 %. In total, there were around 2,000 business entities that, together with forestry, employ around 53,000 people. Additionally, wood processing accounted for 66.40 % of the total annual revenue of both activities and 73.88 % of total foreign trade, while furniture production accounted for 33.60 % and foreign trade for 26.12 %. The average monthly net wage per employee in wood processing was EUR 662.15. The activities provided the supply of goods to the European Union market and exports to third countries to the value of 957 million euros, and at the same time the value of the acquisition and import of goods amounted to 672 million euros, resulting in a surplus in foreign trade of 285 million euros (GoC, 2023). However, in 2022 there were more than 1340 companies operating in the Republic of Croatia, registered according to their main economic activity (NKD 2007) in the sector Processing of wood and wood products (C 16). According to the Croatian Bureau of Statistics and Croatian Financial Agency, in 2022 wood processing generated an income of 2.1 billion euros employing around 18,000 people. The average monthly net wage per employee in wood processing was 770 euros. The activities provided the supply of goods to the European Union market and exports to third countries to the value of 981 million euros.

Although new wood-based materials have entered the market, coniferous sawn wood remains the most significant solid wood product in terms of both production volume and economic importance (Andersch *et al.*, 2013).

A similar situation is observed in the Croatian market, where the competitiveness of primary wood processing is a key challenge. In line with this, the main aim of this paper is to explore possibilities for reducing the cost price in the manufacturing process of primary wood products, as a means to increase competitiveness. Using a selected medium sized wood processing company as a case study, the research has two specific objectives:

i. to analyse the current system of cost calculation and overhead allocation, and
ii. to present and compare alternative costing models — full costing, partial costing, and direct costing — in order to identify which model best supports business success.

The development of models and the proposal for the application of an appropriate method for calculating the cost price will contribute to the improvement of the business activities of companies in the field of primary wood processing. On the example of the selected wood processing company, the cost price will be determined and calculated using different cost calculating methods (division calculation, additional calculations, and calculations of by-products).

2 THEORETICAL BACKGROUND
2. TEORIJSKA PODLOGA

The accounting system is one of the most important foundations for the success of any company, as the correct and efficient application of the accounting system contributes to enhancing the economic efficiency of the company, reduces the excess costs, and reduces the risks that the company may encounter (Kamal, 2015).

Costs are an integral part of any business, including manufacturing companies. In the context of manufacturing, costs are incurred in order to achieve useful effects, i.e. the production of finished products. Many costs are incurred in the production process (product costs, direct labour costs, general production costs, material costs, depreciation costs, etc.). It is necessary for the management of a production company to know how to recognise costs, in which phases costs arise and which products cause these costs. We need to know the costs in order to determine the cost price and thus the selling price of the product and to see how it behaves in relation to competitive prices on the domestic and foreign market (Škrtić, 2015).

The goal of every company is to produce as much as possible with as few costs as possible, i.e. to generate as much profit as possible (Škrtić, 2015).

Prices are exogenous factors when viewed from the perspective of a company's business policy. Price is a consequence of the relationship between supply and demand, but it is also the cause of supply and demand and has its own constituent elements. The relationship among the elements within the price represents the structure of the price.

Although the specific costs estimated vary among fields, the generic categories of costs are often similar (e.g. equipment, human resources, and consumables (Brunetti *et al.*, 2013). Other disciplines also provide lessons on how to report costs in a transparent manner, such as capturing generic units (e.g. person hours or days) rather than monetary estimates due to context dependence (e.g. geographic and temporal variation) of costs (Baltussen *et al.*, 2003).

Some elements of the cost price structure of a manufacturing company are production materials, depreciation, unit labour costs, external services, general management and distribution costs, i.e. production costs. Cost calculation starts with calculating the direct material cost (Andersch *et al.*, 2013).

Similarly, the structure of the selling price is influenced by the utility of a product, the costs of transportation, trade, capital and distribution, and the influence of the state through taxes, customs duties, surcharges and various fees may also be present.

As it is not possible to avoid costs in the production process, it is necessary to plan, identify, manage and correctly allocate them to the products and services in which the costs were incurred. In order for the company to better manage costs in the future and achieve higher profits, management must plan costs well. For successful cost planning, it is important that the same conditions prevail in the future business as in the past, and management also needs to know how the increase (decrease) in production will affect the change in cost levels. Management often requests cost reports that are classified in such a way that they serve the purpose most effectively, i.e. that they are most suitable for management when making important decisions for the company as a whole.

The weighting coefficient for analysing the contribution of jobs in the creation of added value makes it possible to control the cost price of products. Activities related to labour costs are important signals for the competitiveness of traded goods, as labour costs account for a significant proportion of the cost price of products (Stutely, 2011). Products inevitably have a significant impact on competitiveness, and this means that the correct calculation of cost price is crucial (Kourdi, 2011). Managers often overlook rising indirect costs and tend to focus almost exclusively on direct costs. The introduction of sophisticated information technology (IT) systems and automated processes lowers direct costs but increases indirect costs as extensive maintenance and computer programmers are required to prepare the production lines on the machines (Porter, 2008). Profitable companies are aware of the simple fact that there are costs wherever production takes place and that every unit of money in unnecessary costs reduces the company's profit by exactly that amount (Samuelson *et al.*, 2021).

Cost management is defined as the achievement of business goals on the basis of optimised costs under certain corporate conditions. This definition is based on the observation of the relationship between costs and benefits, i.e. on the so-called COST – BENEFIT philosophy, which is the fundamental approach in the field of cost management (De Rus, 2021).

3 MATERIALS AND METHODS
3. MATERIJALI I METODE

3.1 Research polygon
3.1. Istraživački poligon

The research polygon represents a medium sized company in which the following products are manufactured as part of its production programme: fir and beech sawn timber, fir elements for pallets, pallets, interlayers for parquet and panels for building formwork, various wall panelling and flooring (panelling, mouldings, decking, and farmhouse floorings), and pellets. The production facility of the polygon is divided into six departments (work units): Raw Material Preparation, Sawmill, Cutting (Decimating), Refining, Finishing, and Pellet Mill, in which 86 people are employed. The data collection for the selected business year company report was 2021 and data were processed in 2022.

In the production process, 90 % of fir and 10 % of beech raw material is processed. The raw material is classified into three classes of technical roundwood and three thickness classes. The production programme is based on fir raw materials of the second and third class of technical roundwood, while wall panelling and flooring are made from the first class, and joinery work is carried out separately. The beech raw material is mainly supplied in the third class of technical roundwood and is used for the production of blocks for pallets. The production plant is an integral part of the polygon, as well as the maintenance department and management. Eight people are employed in the management. The maintenance department is composed of electrical maintenance (with three employees), mechanical maintenance (three employees), the grindery (two employees), and the boiler room (five employees). In the department for the preparation of raw materials, a raw material warehouse and a debarking unit are located. Six workers are employed in this department. The debarked logs are transported to the sawmill, where they are sawn into timber of different thicknesses depending on the work order. For special orders related to roof construction, prisms are produced directly during sawing on a band saw. The sawn timber is transported by side forklifts to either the material warehouse or for further processing to the cutting department, where two prism production lines are installed, consisting of a multi-blade circular saw and a double-sided profiler. Eighteen workers are employed in this department across two shifts.

The waste generated during timber sawing is transported, along with low-grade timber, to the Refining and Finishing Department by a side loader. First-class raw materials are used for the production of joinery, wall panelling, and flooring, depending on market demand. The joinery production process is initiated in the sawmill, where timber with a thickness of 25 mm and 50 mm is sawn from first-class raw material. After drying, the material is transported to the Cutting Room, where it is processed into cants, packaged, and dispatched to the end customer. The production process for wall panelling and flooring is also initiated in the sawmill with timber sawing. Timber of 175 mm, 150 mm, and 120 mm thickness is sawn. The prisms are arranged into packages, which are then transported to the dryers by loader. Once dried, the packages are transported by forklift to the four-sided milling machine, where wall panelling and flooring are produced in accordance with market requirements. In the Pellet Mill, the process is started with the loading of sawdust into the dosing bunker. From the dosing bunker, the sawdust is conveyed via a screw conveyor to the inclined rubber conveyor, which is used to dose the large mill. Woodchips and sawdust are fed into the mill through a sieve with 7 mm diameter holes and are transported by ventilation into the large sawmill silo. The material from the silo is dosed into the dryer. The dried material is separated and fed into the pellet-making machine. The final product is packed into 15 kg bags. The Pellet Production Department is staffed by eight workers who work in shifts.

3.2 Data collection
3.2. Prikupljanje podataka

Primary and secondary data sources were used for the research. Secondary data was collected within the research polygon from business, financial and accounting reports. Primary data was collected in the research area by observing the production process in order to obtain information on the quantity produced, capacity utilisation, price of raw materials with transport, material costs of production, production time and all unit costs, so that the cost price of a single product could be determined as a result. The monetary values expressed in the national currency, the Croatian kuna (KN), were converted into euros (1 EUR = 7.53450 KN).

In the first phase of the research, the following basic factors influencing production and the cost price were defined: the cost of raw materials with transport, percentage utilisation of raw materials, production time, hourly labour rate, total wage costs for the product, labour cost per m^3 and proportion of fixed costs per work unit in relation to the total cost.

The prices of sawn logs and the prices of their transport are given for the types of wood (raw materials) processed in the research polygon (beech and fir with spruce). For each type of sawn log, the number of sawing days and the total number of working days in the current year are given, the monthly data are summarised, and the monthly and daily average of sawing work and the corresponding monthly and daily costs of raw materials and transport costs are calculated. Utilisation is calculated by daily monitoring of the amount of input and output of raw materials in production by the individual work unit. Utilisation is monitored from the log to the finished product. When a new dimension is introduced in production, the recordings of the working day are made and the production time for each product is calculated. As not all products place the same burden on each work unit, a table was created in which the production time of an individual product was recorded by each work unit, as well as the total time required to manufacture the product. For each product, the time required to produce 1 m3 of the final product is calculated for all production stages, i.e. for all work units. In the accounting programme, the workers of the research polygon are deployed across the production departments. Employees in the maintenance and management departments are categorised according to a specific key. Monthly data on salary payments were collected and a table of total salaries per month was created, in which the gross hourly value was calculated for the entire research polygon. In another table, the total salary and the hourly value were calculated by production department.

In the course of consumption, non-current assets (fixed assets) transfer part of their value to the products, which is why depreciation is calculated as the cost of the obtained product and is included in its cost price. The research polygon is divided into four work units, and the work machines with their monetary values are also grouped in this way. Depreciation was calculated separately for each work unit, while the depreciation costs of the other parts of the research polygon were allocated to the work units according to a specific key. This is based on the distribution of workers in each unit.

The share of fixed costs in total costs was calculated on the basis of accounting data. For the sawmill, cutting, refining and finishing work units, it is 25 %, while in the pellet mill it is 30 %.

3.3 Product selection
3.3. Odabir proizvoda

When a new dimension is introduced in production, the footage of the working day is recorded, and the production time is calculated for each product. As not all products place the same burden on each work unit, a table was created in which the production time of an individual product was recorded for each work unit and the total time required to manufacture the product. For each product, the time required to produce 1 m^3 of the final product is calculated for all production stages, i.e. for all work units. Due to the large number of different products in the production process, fourteen different products were selected for the purpose of this work, which best represent the production process in the sawmill and cutting work unit. At the same time, most of the finished products in the research area are manufactured in these work units. The selected products account for 40 % of the total number of products manufactured in these work units.

Table 1 shows the selected products (pure dimension – length × width × thickness):

- unedged board/sawmill 4000 × 98 × 23 mm (P1),
- scantling/sawmill 5000 × 120 × 120 mm (P2),
- edged board/cutting unit 5000 × 150 × 25 mm (K1),
- scantling/cutting unit 5000 × 80 × 80 mm (K2),
- fixed board/cutting unit 3985 × 74 × 25 mm (K3),
- scantling/cutting unit 3985 × 59 × 59 mm (K4),
- scantling/cutting unit 3985 × 60 × 36 mm (K5),
- scantling/cutting unit 3980 × 73 × 73 mm (K6),
- scantling/cutting unit 4000 × 74 × 7 mm (K7),
- scantling/cutting unit 3980 × 76 × 76 mm (K8),
- scantling/cutting unit 3980 × 78 × 36 mm (K9),
- scantling/cutting unit 3980 × 86 × 43 mm (K10),
- edged prism/cutting unit 3980 × 100 × 24 mm (K11),
- and edged prism/cutting unit 3980 × 150 × 48 mm (K12)

with details of the volume, number of pieces per cubic metre, number of pieces in the finished package, quality, construction price and production quantity.

The production time and utilisation of logs for the production of individual (selected) products was determined by monitoring production and recording the working day, as shown in Table 2. Prisms with a thickness of 19 to 25 mm (K3, K11 and K12) have the longest production time in the cutting unit, which is due to both the number of pieces processed and the production time,

Table 1 Products selected for analysis
Tablica 1. Proizvodi odabrani za analizu

	V_1, m³/piece	Q_1, piece/m³	V_2, m³/piece	GQ	Pc_1, EUR/piece	Pc_2, EUR/m	Q_{pc}, piece	Q_m, m³	Pc, EUR
P1	0.00902	111	1.3000	III	1.05	116.45	35001	315.567	36746.45
P2	0.07200	14	1.0000	II	12.04	167.23	332	23.934	4002.50
K1	0.01875	53	2.5000	II	2.85	151.97	6167	115.625	17571.26
K2	0.03200	31	4.1600	II	5.39	168.56	4728	151.296	25502.15
K3	0.00737	136	2.3000	II/III	1.84	249.56	9359	69.000	17219.41
K4	0.01387	72	1.8778	II/III	2.45	176.57	31416	435.792	76947.99
K5	0.00861	116	2.2010	II/III	2.32	269.46	4091	35.216	9489.42
K6	0.02121	47	2.2060	II/III	5.01	236.09	36612	776.512	183329.13
K7	0.02190	46	2.2670	II/III	5.23	238.71	21527	471.536	112560.21
K8	0.02299	44	2.2070	II/III	6.00	261.21	29185	670.928	175251.88
K9	0.01118	89	2.2800	II/III	3.17	283.25	22849	255.360	72331.90
K10	0.01472	68	2.2670	II/III	3.97	269.46	2464	36.272	9773.98
K11	0.00955	105	2.8217	čpč – II	2.38	248.86	4333	41.392	10300.62
K12	0.02866	35	2.7269	čpč – II	7.42	258.81	10802	309.534	80110.33

Legend: V_1 – volume; Q_1 – quantity, V_2 – volume; GQ – group quality; Pc_1 – price; Pc_2 –price; Q_{pc} – produced quantity; Q_m – producted quanitity; P_c – total price
Legenda: V_1 – volumen; Q_1 – količina; V_2 – volumen; GQ – grupna kvaliteta; Pc_1 – cijena; Pc_2 – cijena; Q_{pc} – proizvedena količina; Q_m – proizvedena količina; Pc – ukupna cijena

Table 2 Production time and percentage utilisation of the selected products by work unit and in total
Tablica 2. Vrijeme proizvodnje i postotna iskorištenost odabranih proizvoda prema radnim jedinicama i ukupno

	I_p, %	I_k, %	I_{uk}, %	H_p, min/m³	H_k, min/m³	H_{uk}, min/m³	H, h/m³
P1	75.0 %	-	75.0 %	37.00	0.00	37.00	0.617
P2	40.0 %	-	40.0 %	50.00	0.00	50.00	0.833
K1	75.0 %	47.0 %	35.3 %	32.00	0.00	32.00	0.533
K2	70.0 %	61.0 %	42.7 %	20.00	17.84	37.84	0.631
K3	75.0 %	50.0 %	37.5 %	20.00	37.67	57.67	0.961
K4	66.0 %	63.0 %	41.6 %	22.00	21.30	43.30	0.722
K5	66.0 %	58.0 %	38.3 %	21.00	25.40	46.40	0.773
K6	66.0 %	65.0 %	42.9 %	20.00	17.29	37.29	0.622
K7	66.0 %	66.0 %	43.6 %	20.00	17.40	37.40	0.623
K8	66.0 %	63.0 %	41.6 %	21.00	18.30	39.30	0.655
K9	66.0 %	58.0 %	38.3 %	20.00	23.76	43.76	0.729
K10	66.0 %	66.0 %	43.6 %	20.00	20.64	40.64	0.677
K11	75.0 %	47.0 %	35.3 %	37.00	59.13	96.13	1.602
K12	75.0 %	55.0 %	41.3 %	30.00	27.33	57.33	0.956

Legend: I_p – sawmill capacity utilisation; I_k – cutting capacity utilisation; I_{uk} – total capacity utilisation; h_p – manufacturing time, sawmill; h_k – manufacturing time, cutting; h_{uk} – total manufacturing time; H – manufacturing time.
Legenda: I_p – iskorištenost kapaciteta pilane; I_k – iskorištenost kapaciteta krojačnice; I_{uk} – ukupna iskorištenost kapaciteta; h_p – vrijeme proizvodnje, pilana; h_k – vrijeme proizvodnje, krojačnica; h_{uk} – ukupno vrijeme proizvodnje; H – vrijeme proizvodnje

as the time for passing through the machine must be reduced because of the load on the machine.

3.4 Choice of methods for calculating the cost price of the product
3.4. Odabir metoda za kalkulaciju troškova proizvodnje

In the research polygon, there is no standardised end product. The end products are similar but differ in terms of type, dimensions, shape and quality, and they also differ in the production stages, i.e. not all products place the same burden on the production departments. In this paper, the cost price is calculated using the full cost price, i.e. using the division, the additional calculation and the calculation of the related products. Since it is not possible to track how much each product contributes to covering fixed costs with the existing methods, the cost price is also calculated using the direct cost method.

3.4.1 Division calculation with equivalent numbers
3.4.1. Djelidbena kalkulacija s ekvivalentnim brojevima

For this type of calculation, it was necessary to determine the production stages for each product and group them in such a way that equal equivalent numbers could be used for equal stages. The production time was measured for each product per production stage, as were the associated costs. Production wages are used as an equivalent number as they can be calculated for all products. It was also necessary to determine the product on the basis of which the equivalent figures are calculated separately for each production stage (Figurić, 2003). In order to determine the cost price, it was necessary to calculate the amount of production by types and production stage, then to multiply the amount of production by the corresponding equivalent numbers, and the equivalent amounts thus obtained had to be added up separately for each production stage (Blaško, 1980). By multiplying the cost price of a product unit by its equivalent number, the amount of costs incurred separately for each product unit at each stage of production is obtained. By adding the amounts received per product unit for each product separately, the total cost price of each product unit by production stage is calculated.

3.4.2 Additional calculation
3.4.2. Dodatna kalkulacija

In the research polygon, the costs per work unit are monitored daily. For each work unit, depreciation costs, labour costs, energy costs and overhead costs were monitored and added to the direct production costs according to a specific key. This is exactly what is required with this method – to group overhead costs by work units. The key for calculating overheads is calculated separately for each work unit and the individual products are charged proportionally with the overheads of the labour unit in which the product was processed. First, the direct costs are incorporated in the products pricing, then the overhead costs are added to the price of the product according to the appropriate key. When using this method, the cost calculation is carried out in several steps: 1. determination of costs relating to all work units and all products; 2. determination of costs relating to only some cost centres of the basic activity, which are unevenly represented; 3. determination of costs of the basic activities successively in the order of production phases by work units up to the last cost centre. In this procedure, the costs of the first and second step only represent overheads that are allocated according to a specific key. The costs of subsequent steps are made up of direct costs and overheads. The overheads of these steps are transferred to the following cost centres on the basis of the same key, up to the last one, where the final price of all products is formed.

3.4.3 Calculation of by-products
3.4.3. Kalkulacija vezanih proizvoda

In the research polygon, by-products are created in addition to the main products, so that the cost price is calculated using this method. In the first phase, the products are divided by work units into the main and by-products. There are several main products and several by-products, and the main products are even produced from some by-products through further processing. In the second phase, a calculation is carried out using the subtraction method for individual work units. Woodchips and sawdust are by-products that are common to all work units. In the work units of the sawmill, refining and finishing, it is a by-product, while in the work unit of the pellet mill it is the raw material from which the main product, pellets, is made. The by-product in the cutting unit is, apart from sawdust, useful waste. During further processing in the refining unit, the useful waste from the cutting unit is used to produce elements for pallets, which are the main product in this work unit, the finished pallets. In the pellet mill unit, in addition to the main product, pellets, a by-product in the form of briquettes is produced, which is used as fuel for the boiler room in the research polygon. The by- products are not sold in the research polygon but are used in further production. The market prices for the individual by-products are therefore used to determine the cost price using this method.

3.4.4 Direct costing method
3.4.4. Metoda direktnih troškova

When applying this method, it was necessary to distinguish between fixed and variable costs. Financial cost data are valuable on their own and can contribute to a full economic costing of an intervention when paired with nonmonetary costs, such as opportunity costs (Drummond *et al.*, 2005). In order to apply this method, the costs are first divided into direct and overhead, i.e. fixed costs. Since only the direct costs are included in the cost price, the following is calculated for each product: production materials, salaries of employees in production, direct external services and the variable part of overhead costs. In the direct cost method, the difference between the selling price of the product and the variable costs is called the contribution margin and is the basic indicator of how much a product contributes to covering the fixed costs in the research polygon. When calculating the cost price, the main and by-products are defined by work units, as material costs, production wages and other variable costs are not included in the by-products.

4 RESULTS AND DISCUSSION
4. REZULTATI I RASPRAVA

4.1 Choice of model for the cost price calculation
4.1. Izbor modela izračuna cijene koštanja

Due to the large number of different products in the production process, fourteen different products were selected for the purpose of this work, which best represent the production process in the sawmill and cutting work units. At the same time, most of the finished products are also manufactured in these work units.

The depreciation values were determined from the accounting data of the fixed assets for the research year. Data on total depreciation costs per work unit and data on the total number of hours per work unit were used to calculate depreciation costs per hour. Machinery, buildings and vehicles are divided into work units, and the depreciation costs can be accurately calculated separately for each work unit. For buildings and machines that are not located within the production units, the depreciation costs are allocated to the production units according to a specific key. The key is determined according to the needs of the individual work units or their utilisation. Production operations are conducted on all machines.

The values of the total salaries of the workers amounting to 931.107.45 EUR were taken from accounting data. The hourly value for the selected products was calculated by dividing the sum of the total gross hours of the sawmill department and the total gross hours of the cutting department divided by the sum of the total hours of the sawmill department and the total hours of the cutting department. It amounts to 5.57 EUR/h (594618.52 EUR / 106760.66 h = 5.57 EUR/h).

Furthermore, the average raw material price including transport for the selected products P1 to K10 is 56.94 euros, while the average price per m3 for products K11 and K12 is 84.94 euros.

Table 3 shows the products selected from the sawmill and cutting work units. Table 3 will be the base table for most models, and additional columns will be added depending on the type of calculation.

4.2 Model A and Model B
4.2. *Model A* i *model B*

Cost monitoring in the polygon is based on the Traditional Product Costing (TPC) Model. This means that the costs for direct materials and direct labour are included in the accounting – direct costs, while the overheads – indirect costs – are added to the direct production costs according to a specific key. The profit and loss account is prepared monthly. In terms of accounting, the polygon is divided into two production units: Sawmill (in which there are departments for raw material preparation, sawmilling, cutting, refining and finishing) and Pellet Mill. Such a division is acceptable for accounting purposes, but in this way, it is not possible to track costs per product. At the end of each month, the average cost price for each unit is calculated using the full cost price. For the Pellet Mill production unit, which has only one product, the calculated price represents the actual cost price of this product, while for the Sawmill production unit this price represents only the break-even point of all products manufactured in this production unit. Such a cost tracking model for calculating the cost price has not proven to be effective as it is of limited use in production decisions. A major problem is that the cost price is not calculated per product, so it is not possible to determine which product is profitable for further production and which should be removed from the production process. The sales price in the research polygon is determined by the market and cannot be influenced, but it is also not possible to react quickly to its change, as a certain amount of time must pass before all production costs are calculated. Average production costs are monitored by each department. The average daily costs per department are calculated on the basis of previous years. Production is entered daily in the tables, and the results can be compared with the sales price on the basis of the daily

Table 3 Products selected from sawmill and cutting work units
Tablica 3. Odabrani proizvodi iz pilane i pogona za rezanje

	$Q_{I/P}$ m³	I_{UK} %	Q_m m³	$Pc_{I/}P$+tran EUR	*MC* EUR/m³	*H* h/m³	H_{price} EUR/h	*SC* EUR	*Sc* EUR/m³
P1	420.76	75.00 %	315.57	23957.04	75.92	0.62	5.57	1083.73	3.43
P2	59.84	40.00 %	23.93	3406.89	142.35	0.83	5.57	111.07	4.64
K1	328.01	35.25 %	115.63	18676.50	161.53	0.53	5.57	343.42	2.97
K2	354.32	42.70 %	151.30	20174.48	133.34	0.63	5.57	531.38	3.51
K3	184.00	37.50 %	69.00	10476.61	151.83	0.96	5.57	369.34	5.35
K4	1048.08	41.58 %	435.79	59675.71	136.94	0.72	5.57	1751.45	4.02
K5	92.00	38.28 %	35.22	5238.07	148.74	0.77	5.57	151.67	4.31
K6	1810.05	42.90 %	776.51	103060.85	132.72	0.62	5.57	2687.64	3.46
K7	1082.50	43.56 %	471.54	61635.35	130.71	0.62	5.57	1636.88	3.47
K8	1613.58	41.58 %	670.93	91874.35	136.94	0.66	5.57	2447.36	3.65
K9	667.08	38.28 %	255.36	37982.52	148.74	0.73	5.57	1037.19	4.06
K10	83.27	43.56 %	36.27	4741.18	130.71	0.68	5.57	136.82	3.77
K11	117.42	35.25 %	41.39	9974.31	240.97	1.60	5.57	369.32	8.92
K12	750.39	41.25 %	309.53	63739.69	205.92	0.96	5.57	1647.10	5.32
Total	8611.30		3707.964	514613.55	2077.36			14304.39	60.89

Legend: $Q_{I/P}$ – quantity input; Q_m – produced quantity; I_{UK} – total capacity utilisation; P_{cI}/P+tran – input raw material price including transport; *MC* – material costs; *H* – production time; H_{price} – the value of working hours; *SC* – total salary costs; *Sc* – salary cost per product
Legenda: $Q_{I/P}$ *– količina ulazne sirovine; Qm – proizvedena količina;* I_{UK} *– ukupna iskorištenost kapaciteta;* P_{cI}/P *+ tran – cijena ulazne sirovine uključujući transport; MC – trošak materijala; H – vrijeme proizvodnje;* H_{price} *– vrijednost radnog sata; SC – ukupni trošak plaća; Sc – trošak plaće po proizvodu*

Table 4 Model A – Existing and Model B – Divisive calculation
Tablica 4. *Model A* – postojeći model i *model B* – djelidbena kalkulacija

	Model A				Model B					
	Ck EUR/m³	*p* EUR/m³	*Pf* EUR	*e*	*Qe* m³	*Tm* EUR	*tm* EUR/m³	*Ck* EUR/m³	*p* EUR/m³	*Pf* EUR
P1	224.53	-108.08	-34107.76	0.94	297.10	27878.63	88.34	167.70	-51.25	-16172.96
P2	224.53	-57.30	-1371.40	1.27	30.45	2857.35	119.38	266.37	-99.14	-2372.81
K1	224.53	-72.56	-8390.01	0.81	94.15	8834.46	76.41	240.90	-88.94	-10283.13
K2	224.53	-55.97	-8468.32	0.96	145.68	13669.63	90.35	227.21	-58.65	-8873.35
K3	224.53	25.03	1726.85	1.47	101.25	9501.17	137.70	294.89	-45.33	-3127.71
K4	224.53	-47.96	-20900.32	1.10	480.15	45055.24	103.39	244.34	-67.77	-29534.42
K5	224.53	44.93	1582.38	1.18	41.58	3901.54	110.79	263.84	5.63	198.15
K6	224.53	11.56	8979.02	0.95	736.80	69138.31	89.04	225.22	10.87	8442.33
K7	224.53	14.18	6686.31	0.95	448.74	42108.00	89.30	223.48	15.23	7179.98
K8	224.53	36.68	24608.53	1.00	670.93	62957.38	93.84	234.42	26.79	17972.78
K9	224.53	58.72	14995.96	1.11	284.34	26681.39	104.49	257.29	25.97	6630.80
K10	224.53	44.93	1629.83	1.03	37.51	3519.68	97.04	231.52	37.94	1376.29
K11	224.53	24.33	1006.88	2.45	101.25	9500.65	229.53	479.42	-230.57	-9543.67
K12	224.53	34.28	10610.72	1.46	451.54	42370.98	136.89	348.13	-89.32	-27647.44
total			-1411.31		3921.45	367974.42				-65755.14

Legend: *Ck* – cost price; *p* – profit; *Pr* – profit; *e* – equivalent number; *Qe* – equivalent quantity; *Tm* – total other costs of selected products; *tm* – average other costs of selected products
Legenda: Ck – cijena koštanja; p – dobit; Pr – profit; e – ekvivalentni broj; Qe – ekvivalentna količina; Tm – ukupni ostali troškovi odabranih proizvoda; tm – prosječni ostali troškovi odabranih proizvoda

costs. This method of cost monitoring helps to manage production by department as it shows when production is positive and when it is not, but it still does not show the profitability of the product itself and the cost price of an individual product.

In Model A, the cost price is presented according to the existing method for calculating the cost price in the research polygon. According to the existing method, the average cost price for all products produced in the research polygon, with the exception of the pellet mill unit, is calculated using the full cost price and amounts to 224.53 EUR/m³ in 2021.

Table 4 was created by adding to Table 3 a column with the cost price according to the existing model, which is the same for all selected products and amounts to 224.53 EUR/m³ regardless of the actual material cost per product, recognising that for a single product the material costs are higher than the cost price for this product. It is evident from the table that products P1, P2, K1, K2 and K4 do not generate a profit but a loss and that the profitability of their production is questionable, while products K3, K5, K6, K7, K8, K9, K10, K11 and K12 generate a profit. The table also shows that the products that generate a profit do not compensate for the loss of the other products, so the overall result is negative.

In Model B, the cost price for the selected products was calculated using a divisive calculation with equivalent numbers. The production wages were used to allocate the other costs to the products. The basis for the calculation of the equivalent numbers is the production wages, and the product K8 was selected as the reference product for the calculation of the equivalent numbers as it is produced most frequently in the research polygon. The price of one equivalent unit is 102.11 EUR (Tm = 367974.42 EUR; Qe = 3603.82 m³). The table also shows that products P1, P2, K1, K2, K4, K11 and K12 do not generate a profit but a loss and that the profitability of their production is questionable, while products K5 to K10 generate a profit. It is evident from the table that products that generate a profit do not compensate for the loss of the other products, so the overall result is negative.

4.3 Model C
4.3. Model C

Model C shows the cost price for selected products calculated with the help of additional calculation (Table 5). The basis for the distribution of overheads are the production wages. For the first two selected products, the depreciation value was taken only for the Sawmill, while for the other products the depreciation values of the Sawmill and the Cutting unit were added together (*Am* = *QI*/*P* – quantity used (m³) × *H* – production time (h/m³) × value of the depreciation hour (EUR/h)). The distribution coefficient for the production costs is calculated by dividing the total production costs by the total production wages (production wages – see Table 3; column SC (in ERU) = 14304.39 EUR), and it amounts to 10.110. Table 5 shows that products P1, P2, K1, K2, K3, K4, K11 and K12 do not make a profit but a loss and that the profitability of their production is questionable, while products K5, K6, K7, K8, K9 and K10 make a profit. On the other hand, the

Table 5 Model C – Additional calculation
Tablica 5. *Model C* – dodatna kalkulacija

	t_{am} EUR/h	*Am* EUR	*am* EUR/m³	T_I EUR	t_i EUR/m³	T_{up} EUR	t_{up} EUR/m³	*Ck* EUR/m³	*p* EUR/m³	*Pf* EUR
P1	0.57	110.88	0.35	11009.25	34.89	15255.39	48.34	162.95	-46.51	-14675.74
P2	0.57	11.26	0.47	1117.62	46.70	1548.68	64.72	258.86	-91.63	-2192.66
K1	1.13	69.54	0.60	3448.42	29.82	4778.44	41.33	236.23	-84.26	-9743.00
K2	1.13	108.17	0.71	5363.57	35.45	7432.24	49.12	222.14	-53.58	-8107.01
K3	1.13	75.17	1.09	3727.30	54.02	5164.88	74.85	287.14	-37.59	-2593.40
K4	1.13	356.06	0.82	17655.67	40.51	24465.26	56.14	238.42	-61.85	-26952.19
K5	1.13	30.77	0.87	1526.00	43.33	2114.56	60.04	257.27	12.19	429.47
K6	1.13	546.32	0.70	27090.26	34.89	37538.67	48.34	220.11	15.98	12411.32
K7	1.13	331.76	0.70	16450.71	34.89	22795.56	48.34	218.10	20.61	9719.25
K8	1.13	502.50	0.75	24916.99	37.14	34527.19	51.46	229.96	31.25	20964.78
K9	1.13	211.54	0.83	10489.39	41.08	14535.03	56.92	251.63	31.62	8075.22
K10	1.13	27.99	0.77	1387.81	38.26	1923.08	53.02	226.55	42.91	1556.28
K11	1.13	75.15	1.82	3726.40	90.03	5163.63	124.76	466.49	-217.63	-9007.70
K12	1.13	337.20	1.09	16720.47	54.02	23169.36	74.85	341.23	-82.42	-25511.43
total		2794.30		144629.85		200411.97				-45626.80

Legend: t_{am} – value of depreciation hour; cost of depreciation; *Am* – total cost of depreciation; *am* – cost of depreciation; T_I – production cost; t_i – production cost (EUR/m³); T_{up} – management and distribution cost; t_{up} – management and distribution cost; *Ck* – cost price; *p* – profit; P_r – profit
Legenda: t_{am} – vrijednost sata amortizacije; trošak amortizacije; Am – ukupni trošak amortizacije; am – trošak amortizacije; T_I – trošak proizvodnje; t_i – trošak proizvodnje (EUR/m³); T_{up} – trošak upravljanja i distribucije; t_{up} – trošak upravljanja i distribucije (EUR/m³); C_k – cijena koštanja; p – dobit; P_r – profit

products that make a profit do not cover the loss of the other products and the overall result is negative.

4.4 Model D – additional calculation
4.4. *Model D* – dodatna kalkulacija

Model D shows the cost price for the selected products, which is calculated based on the related products. This calculation method assumes the production of a by-product alongside the main product, i.e. a by-product is also manufactured, which cannot be influenced. In this model, the subtraction method is used, in which the value of the by-products is subtracted from the costs incurred in the production process that resulted in the related products, and which cannot be directly allocated to each product individually, so that the remainder is the costs attributable to the selected products. By-products generated in the production process in the Sawmill work unit are woodchips with sawdust and residues, and in the Cutting department, these are wood chips with sawdust, and useful waste is defined as residues in this paper. The basis for calculating the equivalent numbers is the production wages, and the product K8 was chosen as the base product for calculating the equivalent numbers because it is most often produced in the research polygon. The total revenue from by-products (UPs) amounts to 41122.84 euros. The distribution coefficient is obtained by deducting the revenue from by-products (UPs) from the other costs of the selected products (they amount to 40 % of the total other costs of the Sawmill and Cutting department) (see Table 4; column Tm) and dividing it by the total equivalent production. The distribution coefficient is 83.35.

Table 6 shows that products P1, P2, K1, K2, K4, K11 and K12 do not make a profit but a loss and that the profitability of their production is questionable, while products K3, K5, K6, K7, K8, K9 and K10 make a profit. It is evident from the table that the products that make a profit do not compensate for the loss of the other products, so the overall result is negative.

4.5 Model E – calculation of the cost price using the direct costing method
4.5. *Model E* – izračun cijene koštanja metodom izravnih troškova

The main advantage of the direct cost method is that only the variable costs is considered when calculating the cost price of the individual products, i.e. the costs that are incurred as production increases. The product with the highest contribution margin (the difference between the revenue and the variable costs) is the most useful, not the one whose sales price is higher than the full cost price, because the product with the highest contribution margin largely compensates for the fixed costs and thus contributes to a more successful business. When calculating the cost price, the main and by-products are defined, as material costs, production wages and other variable costs are not included in by-products. By-products (woodchips with sawdust, residues and useful waste) are created as a product of the main products, but they generate revenue on the market, therefore their market value is added to the contribution margin of the main products and the total contribution margin for this group of products is obtained. The total revenue of the by-products in the sawmills and cutters department (UPs) is 41.122,84 euros. The fixed costs amount to 30 % of the total costs. The

Table 6 Model D – Application of the related calculation with equivalent numbers
Tablica 6. *Model D* – primjena vezane kalkulacije s ekvivalentnim brojevima

	e	***Q*** m^3	***T***$_{m-s}$ EUR	***t***$_{m-s}$ EUR/m^3	***C***$_k$ EUR/m^3	***p*** EUR/m^3	***P***$_f$ EUR
P1	0.94	297.10	26945.62	85.39	164.74	-48.29	-15239.95
P2	1.27	30.45	2761.72	115.39	262.38	-95.14	-2277.19
K1	0.81	94.15	8538.80	73.85	238.35	-86.38	-9987.47
K2	0.96	145.68	13212.15	87.33	224.18	-55.63	-8415.87
K3	1.47	101.25	9183.20	133.09	290.28	-40.72	-2809.74
K4	1.10	480.15	43547.39	99.93	240.88	-64.31	-28026.56
K5	1.18	41.58	3770.97	107.08	260.13	9.33	328.72
K6	0.95	736.80	66824.47	86.06	222.24	13.85	10756.17
K7	0.95	448.74	40698.78	86.31	220.49	18.22	8589.20
K8	1.00	670.93	60850.40	90.70	231.28	29.93	20079.77
K9	1.11	284.34	25788.44	100.99	253.79	29.46	7523.74
K10	1.03	37.51	3401.89	93.79	228.27	41.19	1494.09
K11	2.45	101.25	9182.70	221.85	471.74	-222.89	-9225.71
K12	1.46	451.54	40952.95	132.31	343.55	-84.74	-26229.41
		3921.45	326851.46				-53440.20

Legend: C_k – cost price; p – average profit; P_r – profit; e – equivalent number; Q_e – equivalent quantity; T_{m-s} – other costs of the selected products minus the revenues of the by- products; t_{m-s} – average other costs of the selected products minus the revenues of the by- products (eur/m^3)
Legenda: C_k – cijena koštanja; p – prosječan profit; P_r – profit; e – ekvivalentni broj; Q_e – ekvivalentna količina; T_{m-s} – ostali troškovi odabranih proizvoda umanjeni za prihod sporednih proizvoda; t_{m-s} – prosječni ostali troškovi odabranih proizvoda umanjeni za prihod sporednih proizvoda (EUR/m^3)

data used to calculate the other variable costs are the depreciation costs, energy costs and other costs (maintenance and management costs and distribution costs). They were calculated by multiplying the quantity produced (Qm) by the production time (H) and the value per hour (Hprice). In addition, the total variable costs per unit were calculated by adding the raw material price per product unit (Pc2), the labour costs per product unit (sc) and the other variable costs per product unit. The contribution margin (Cm) was calculated by subtracting the total variable costs (V) from the total value produced (see Table 1; column Pc), while the contribution margin per unit of product (km) was calculated by dividing the contribution margin for the product (Cm) by the quantity produced (Qm). The profit gained for each selected group of products was calculated by de-ducting the fixed costs for this product (F) from the contribution margin of the selected product (Km).

Table 7 shows that products K1 and K11 do not generate a profit but a loss and that the profitability of their production is questionable, while products P1, P2, K2, K3, K4, K5, K6, K7, K8, K9, K10 and K12 generate a profit. The table shows that the products that make a profit cover for the loss of the other products and that the overall result is positive, amounting to 259.666,02 euros.

However, the total contribution margin for all selected items (Σ *Cm = Cm P1 + Cm P2 + Cm K1 + Cm K2 + Cm K3 + Cm K4 + Cm K5 + Cm K6 + Cm K17+ Cm K8 + Cm K9 + Cm K10 + Cm K11 + Cm K12*) is increased by the realised revenue of by- products (*UPs*). The total contribution margin increased by the realised revenue of by- products (Σ *Cm + UPs*) amounts to 313554,87 euros, and the total profit of the selected products ((Σ *Cm + UPs*) – *F*) in this case amounts to 300788,87 euros.

4.6 Comparison of cost prices in selected models
4.6. Usporedba cijena koštanja u odabranim modelima

As depicted in Figure 1, Model A illustrates the cost price according to the existing method for its calculation in the research polygon. According to the existing method, the average cost price is calculated using the full cost price for all products manufactured in the research polygon, except for the pellet mill department, and it amounts to 224,53 EUR/m^3 in 2021. In the existing model, the cost price is the same for all products and shows that it is worthwhile to produce only the products whose selling price is equal to or higher than the average cost price. It is evident from the table that products P1, P2, K1, K2 and K4 do not make a profit but a loss and that the profitability of their production is questionable, while products K3, K5, K6, K7, K8, K9, K10, K11 and K12 make a profit. In addition, according to Table 3 (MC column) and Table 4 (*Ck* for Model A), 9 of 14 selected products have a higher selling price, but if the Material cost column is considered, it can be seen that the material cost of some products is higher than the cost price, while according to the existing model, they make a profit, thus giving a false picture of the profitability of that product. Looking at the total profit for the selected products, Model A shows a loss of 1411,31 euros.

In Model B, a division formula with equivalent numbers was used to calculate the cost price. Of 14

Table 7 Model E – Calculation of the cost price using the direct costing method
Tablica 7. *Model E* – izračun cijene koštanja metodom izravnih troškova

	V_o EUR	v_o EUR/m³	*V* EUR	*Ck* EUR/m³	*Cm* EUR	*cm* EUR/m³	*F* EUR	*Pf* EUR
P1	1269.70	4.02	26310.47	83.38	10435.98	33.07	544.19	9891.79
P2	130.13	5.44	3648.10	152.42	354.40	14.81	55.78	298.63
K1	743.65	6.43	19763.57	170.93	-2192.32	-18.96	318.71	-2511.03
K2	1150.66	7.61	21856.52	144.46	3645.62	24.10	493.14	3152.48
K3	799.77	11.59	11645.72	168.78	5573.69	80.78	342.76	5230.93
K4	3792.58	8.70	65219.74	149.66	11728.25	26.91	1625.39	10102.86
K5	328.42	9.33	5718.15	162.37	3771.27	107.09	140.75	3630.52
K6	5819.79	7.49	111568.28	143.68	71760.85	92.41	2494.20	69266.65
K7	3544.49	7.52	66816.71	141.70	45743.50	97.01	1519.07	44224.43
K8	5299.51	7.90	99621.22	148.48	75630.66	112.73	2271.22	73359.44
K9	2245.94	8.80	41265.65	161.60	31066.25	121.66	962.54	30103.71
K10	296.27	8.17	5174.28	142.65	4599.70	126.81	126.97	4472.73
K11	799.73	19.32	11143.36	269.22	-842.74	-20.36	342.74	-1185.48
K12	3566.62	11.52	68953.41	222.77	11156.92	36.04	1528.55	9628.37
			558705.19		272432.03		12766.00	259666.02

Legend: V_o – other variable costs of a specific production stage; v_o – other variable costs of a specific production stage; *V* – total variable costs; *Cm* – total contribution margin; *cm* – contribution margin; *F* – fixed costs; *Pr* – profit
Legenda: V_o – ostali varijabilni troškovi određene faze proizvodnje; v_o – ostali varijabilni troškovi određene faze proizvodnje; V – ukupni varijabilni troškovi; Cm – ukupna kontribucijska marža; cm – kontribucijska marža; F – fiksni troškovi; Pr – profit

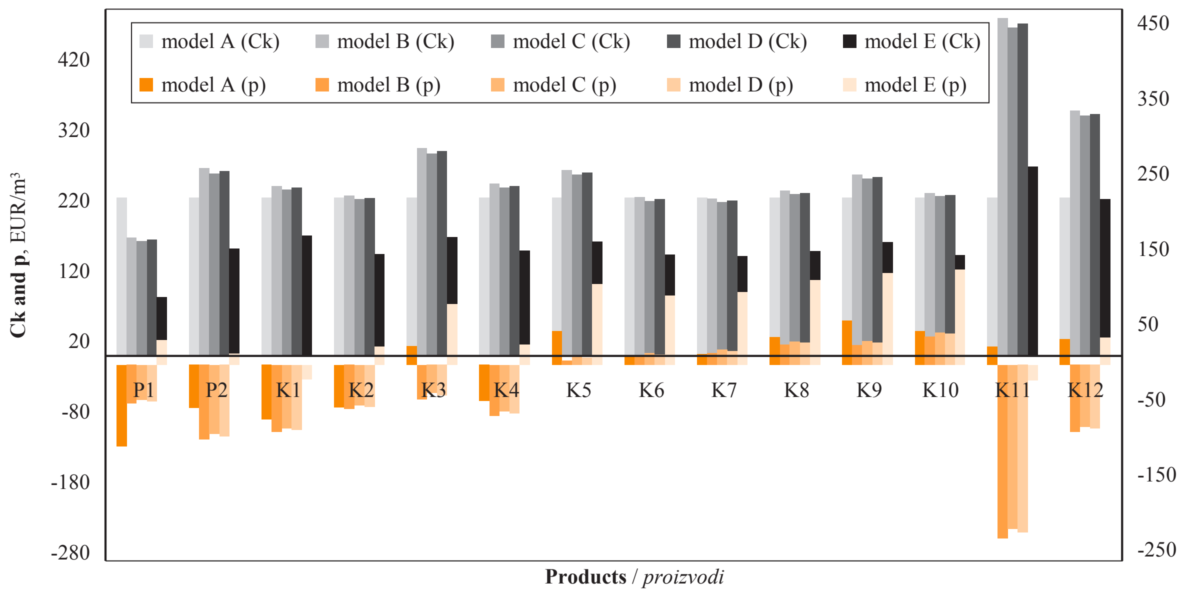

Figure 1 Cost prices and realised profit/loss of products P1, P2, and K1 – K12
Slika 1. Cijene koštanja i ostvarena dobit/gubitak proizvoda P1, P2 i K1 – K12

selected products, only 5 generate a profit. According to this model, it turns out that most of the selected products are not worth producing, and when looking at the total profit for the selected products, Model B results in a loss of 65.755,14 euros.

In Model C, the cost price for selected products is calculated with the help of an additional calculation. The production wages are the basis for the distribution of general costs. The total profit for the selected products according to Model C is negative, i.e. a loss is realised as 9 products out of 14 selected products make a loss, and the cost price is higher than the sales prices. According to this model, it turns out that the seven selected products are not worth producing. Looking at the total profit for the selected products, Model C results in a loss of 45.626,80 euros.

In Model D, the cost price for the selected products was calculated using the calculation of related products. It is based on the fact that in addition to the main product, by-products whose manufacture cannot be influenced, are also produced. The subtraction method is used here. This means that the value of the by-products is subtracted from the costs incurred in the manufacturing process that generated the by-products, and which cannot be directly allocated to each product individually, so that the remainder is the costs attributable to the selected products. The total profit for the selected products according to Model C is negative;

out of 14 selected products, 8 products make a loss, i.e. the cost price is higher than the selling price. According to this model, it turns out that most of the selected products are not worth producing. Looking at the total profit for the selected products, Model D results in a loss of 53.440,20 euros.

In Model E, the cost price of the selected products was calculated using the direct co-sting method. When calculating the cost price of the individual products, only the variable costs are considered, i.e. the costs that are generated when production increases. The most profitable product is the one with the highest contribution margin, not the one whose sales price is higher than the cost price, because the product with the highest contribution margin mostly covers the fixed costs and therefore contributes to a more successful business.

Figure 1 shows that out of 14 products, only 2 do not achieve a positive result. In addition, the total revenue for products selected according to Model E is positive. According to this Model, products K1 and K11 are not profitable, while products K6, K7, K8 and K9 achieve the highest contribution margin, showing that they are most profitable and contribute to a more successful business in the research polygon. According to this model, it turns out that most of the selected products are worth producing, and when looking at the total profit for the selected products, Model E is the only one that shows a profit of 259,666.02 euros. Model E provides the company with information on the actual cost price of an individual product and, in view of the change in the sales price over the course of the year, it helps determine which product is worth producing, which is better suited to waiting for a change in the sales price and which is not worth producing at all.

4 CONCLUSIONS
4. ZAKLJUČAK

If the company uses the full cost price when calculating the cost price in the production of primary wood products, it will probably not be able to dynamically monitor the production costs of a particular product. In addition, when using this method, all fixed and variable costs are included in the cost price of the product, with the cost of raw materials being considered a variable cost and allocated directly to the product, while all other costs are allocated to products according to specific keys. In this case, the company cannot know which product contributes most to a positive business result. In this way, completely wrong conclusions are often drawn and products that are not the most profitable are promoted, while products that contribute significantly to the company's success are removed from the production programme.

The aim of this article was to emphasise the importance of choosing the right method for calculating the cost price of products in the production of primary wood products. When considering the cost price and profit in all five selected models, it becomes clear that both the cost price and the profit change depending on the distribution of costs.

By analysing and processing the data obtained from the research polygon and using the example of five selected models, the results have shown that Model E is optimal, while the most acceptable costs are to be divided into fixed and variable costs and then the variable costs are to be included in the cost price of each product. The difference between the revenue of each individual product and the variable costs of these same products is the contribution margin, which covers the fixed costs of the research polygon.

The other selected models A, B, and C used for the calculations generate negative business result (loss) for most of the selected products in wood processing company. The reason for that could be input of different fixed and variable costs or market influence on sales prices for selected products or assortments during the analysed year.

Model E used in this work follows the cost prices of the products and is the most acceptable in the research polygon. Therefore, it can be concluded that a well-chosen cost price calculation model can determine which product makes the greatest contribution to cost recovery. It is expected that the application of Model E in the research polygon will lead to better business results in the coming period, because by applying this model the company receives clear information about which products should be developed, and which should be removed from the production programme. By investing in the modernisation of production, it is expected that product quality will increase, new products will be introduced, the cost price and the cost of manual labour will decrease, as well as the total cost of production.

Research limitations are related to the inputs, such as input costs of raw material, services and salaries, which could influence the result of different model-based calculations. The research is based on a sample of 14 products, which cover approximately 40 % of total production, and does not cover all production departments or the entire product range. All models were tested within one business year. Business seasonality and market changes over a longer period were not considered.

It is necessary to continue the research in this area, i.e. to apply Model E to the entire production process and, based on calculations, to develop computer software that monitors the production process on the basis of various purchase prices for raw materials and planned sales prices on the market determined by supply and demand. This would enable long-term planning of the product range, with greater added value or profit in the wood processing market. The innovative application of new raw materials, products and calculation models (Kropivšek et al 2021) can also improve the company's business results.

In the Republic of Croatia, there are more than 800 small or micro companies engaged in a similar production programme that monitor production and process costs as the analysed company after the past period (ex post). By applying the proposed method for calculating the cost price, these business entities can improve their work processes in the production of wood products with higher added value. Future research should be focused on implementing the calculation model in more small and medium sized wood production companies to adapt this model to different production contexts.

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Unethical Practices in Furniture Sales: Consumer Experiences and Recommendations for Responsible Business

Neetične prakse u prodaji namještaja: iskustva potrošača i preporuke za odgovorno poslovanje

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ABSTRACT • *Consumer satisfaction is closely tied to ethical business conduct, yet unethical sales practices remain prevalent in the furniture sector. This study, based on a survey conducted in Slovakia, identifies the most common unethical behaviours perceived by consumers – particularly misleading information about product quality and materials, unprofessional staff conduct, false discount claims, and refusal to accept legitimate complaints. The results indicate that these practices significantly affect consumer trust and satisfaction, especially among older or economically vulnerable groups. In response, the study recommends improving transparency in product communication, investing in staff training, and strengthening complaint resolution processes. These steps can enhance customer trust and build long-term loyalty in the furniture market. The research contributes to new empirical insights into consumer ethics, highlighting both systemic issues and actionable strategies for ethical improvement within the industry.*

KEYWORDS: *furniture industry; unethical practices; correlation analysis; cluster analysis*

SAŽETAK • *Zadovoljstvo potrošača usko je povezano s etičnim poslovnim ponašanjem poduzećâ, no u sektoru prodaje namještaja i dalje prevladavaju neetične prodajne prakse. Ova je studija utemeljena na istraživanju provedenome u Slovačkoj i identificira najčešće neetične prakse koje potrošači percipiraju. To se osobito odnosi na obmanjujuće informacije o kvaliteti proizvoda i materijalima, neprofesionalno ponašanje zaposlenika, lažne popuste i neprihvaćanje legitimnih i opravdanih pritužbi. Rezultati pokazuju da te prakse znatno utječu na povjerenje i zadovoljstvo potrošača, posebice starijih ili ekonomski ranjivih skupina potrošača. Kao odgovor na te probleme studija preporučuje povećanje transparentnosti u komunikaciji o proizvodima, veća ulaganja u obučavanje osoblja i u unapređenje procesa rješavanja pritužbi. Ti koraci mogu pridonijeti povećanju povjerenja kupaca i izgradnji dugoročne lojalnosti na tržištu namještaja. Istraživanje pridonosi novim empirijskim uvidima u etiku potrošača, ističući i sistemske probleme i praktične strategije za etična poboljšanja unutar industrije.*

KLJUČNE RIJEČI: *industrija namještaja; neetične prakse; korelacijska analiza; klasterska analiza*

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1 INTRODUCTION
1. UVOD

Ethics is a set of moral guidelines that influence the choices that individuals or groups make. Applying moral rights and wrongs, or norms of justice, to marketing decision-making, behaviour, and practice within the company is known as "practicing ethics in marketing." A company may be expected to act in what it considers to be its own best interest in a market economy. Gaining a competitive edge is the goal of marketing. Businesses that cultivate this edge can meet the needs of their clients as well as their own needs (Sihem, 2013).

Business ethics refers to the moral principles that shape corporate behaviour toward consumers, stakeholders, and the wider society. In the retail sector, this is reflected in transparency, fairness, and respect for consumer rights. These ethical responsibilities extend to multiple actors—consumers, producers, employees, and investors—though their scope and nature differ across groups (Lütge and Uhl, 2021; Vieweg, 2021). Violations of these principles undermine customer trust and jeopardise long-term brand loyalty (Vitell and Muncy, 1992; Ferrell *et al*., 2019; Tanveer *et al.*, 2021). By contrast, ethical marketing practices foster consumer confidence and loyalty while aligning business objectives with broader moral values (Kamila and Jasrotia, 2023; Kobiyh *et al.,* 2024).

In the past twenty years, firms have enhanced their competitiveness through internationalisation, more sophisticated marketing, and expanded sales operations. Nevertheless, the contemporary business environment is increasingly defined by volatility, uncertainty, complexity, and ambiguity (Ameer and Halinen, 2019; Pomirleanu *et al.,* Townsend, 2022; Anand *et al.,* 2023). Unfortunately, in an effort to quickly enter the market, secure a strong position, and maximise profits, some companies engage in unethical or even illegal practices that harm both competition and consumer rights (Chavda and Deshpande, 2022). Although these strategies may yield short-term gains, they can seriously damage consumer trust and a company's long-term reputation.

To address unethical business conduct, the European Union introduced a legal framework centred on Directive 2005/29/EC, which defines unfair commercial practices as aggressive or deceptive. Misleading marketing, including exaggerated claims, omission of key information, manipulated visuals, or fine print disclaimers is a typical example (Ahmed *et al.,* 2025). Such practices highlight the need for strong consumer protection and ethical business principles. While they may boost short-term sales, they ultimately erode consumer trust, damage brand reputation, and threaten long-term business stability. As a result, customer satisfaction has become a strategic priority, particularly in sectors where unethical conduct can severely undermine not only satisfaction but the entire consumer experience (Mbonigaba *et al.,* 2024).

Unethical behaviour is encountered in virtually all areas of the market, and the furniture sector is no exception. Various forms of misleading customers occur in the sale of furniture, whether it be false claims about quality, origin of materials, environmental friendliness of products, or hidden charges and opaque terms and conditions.

An important area of many discussions is the questionable quality of the materials used to make the furniture and its durability. Many furniture companies prefer cheap and less durable materials to high-quality, environmentally responsible alternatives for the sole reason of maximizing profits. This limited thinking of companies has a negative impact not only on the environment (excessive carbon dioxide emissions, deforestation, huge amounts of waste) but also, of course, on the consumer, who, when investing in furniture, expects it to serve its purpose for a longer period of time (Friedrich, 2022).

In an era of growing environmental awareness, many furniture manufacturers have begun to present themselves as responsible and sustainable, labelling their products with various "green" certificates and slogans promising to be ethical and environmentally friendly. In recent years, greenwashing has emerged as a widespread trend in the corporate world. Large enterprises enthusiastically promote their environmental initiatives, yet in many cases, these efforts are little more than empty slogans and vague concepts (Huang *et al.*, 2022).

In this context, greenwashing has become a common practice where companies deliberately misrepresent the environmental or social impact of their products. It misleads consumers and damages the reputation of businesses genuinely committed to sustainability. Such practices erode public trust, encourage unsustainable consumption, and create unfair competition by disadvantaging transparent companies. Moreover, greenwashing slows progress toward a truly sustainable future by giving consumers a false sense of responsibility, reducing their motivation to demand real change and accountability (Ecobalanza.com, 2024).

Growing attention to ethical conduct in business is reflected in the increasing number of studies and surveys assessing how companies implement and maintain ethical standards. Previous research has addressed ethical issues in marketing, including sales practices, promotional activities, and product safety (Hermann, 2022; Martínez *et al.,* 2021) and several studies (Vitell and Muncy, 1992; Rallapalli *et al.,* 1994) have demonstrated that unethical practices can negatively influence customer satisfaction, purchase intentions, and long-term loyalty.

Despite growing academic interest in business ethics, the furniture retail sector remains underexplored in this regard. Most existing literature addresses ethical issues at a general level, without considering the specific dynamics of high-involvement purchases such as furniture, where expectations regarding durability, quality, and after-sale service are particularly high.

To address this gap, this study presents findings from an empirical survey conducted in Slovakia, which investigates the prevalence of unethical practices in the furniture retail industry and their perceived impact on customer satisfaction. Additionally, it examines how socio-demographic characteristics shape consumer perceptions and responses to unethical business conduct.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The questionnaire was distributed primarily via social media, and participation in the survey was voluntary and anonymous. During the data collection period (February – April 2025), a total of 221 fully completed questionnaires were collected. As distribution was carried out in the manner described above, it is not possible to calculate the exact response rate for the questionnaires; instead, the study is based on the number of valid responses obtained within the specified time frame.

The questionnaire consisted of 19 questions. Four questions related to demographic data, allowing respondents to be categorised by gender, age, achieved education and economic status. The remaining 15 questions were aimed at these areas:

– Purchasing behaviour in the furniture sector (frequency and recency of furniture, purchases, place of purchase, type of furniture purchased, influence of advertising on purchase decisions).
– Product quality and conformity with customer expectations (quality and transparency of information provided before purchase, compliance with delivery deadlines, consistency between the ordered and delivered product, identification of product deficiencies after purchase (technical, visual, functional).
– Post-purchase service experience (frequency and reasons of complaints, outcome of complaint resolution (justified vs. unjustified claims), Perception and occurrence of unethical behaviour by furniture retailers, forms of unethical conduct (withholding information, deceptive practices), personal experiences with unethical sellers, consumers responses to unethical practices.

The research aimed to answer two research questions:

– To what extent is consumer education associated with the perception of unethical practices in retail?
– How does the perceived relevance of pre-purchase product information influence overall consumer satisfaction?

Regarding the research questions, the following hypotheses were formulated to test the relationships between the monitored factors and consumer experiences:

H1: There is a statistically significant relationship between consumer education and consumers' perception of unethical retail practices.

H2: There is a statistically significant relationship between the perceived relevance of pre-purchase product information and consumer satisfaction.

To explore relationships between selected variables, Pearson's correlation coefficient was used.

The Pearson correlation coefficient r is mathematically defined as follows (Salomão, 2024):

$$r = \frac{N\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{Nx_i^2 - (\sum x_i)^2}\sqrt{Ny_i^2 - (\sum y_i)^2}} \tag{1}$$

Where:
x and y denote the two variables being compared,
N is the number of data points,
$\sum xy$ represents the sum of the product of paired values,
$\sum x^2$ and $\sum y^2$ are the sums of squares for each variable.

It measures the strength and direction of the linear relationship between two variables, ranging from -1 to 1. Values close to 1 or -1 indicate a strong positive or negative correlation, respectively, while values near 0 suggest little to no linear dependence. Understanding this relationship is essential for correctly interpreting correlation results (Liao *et al.*, 2015). To clearly present and interpret these relationships across multiple variables simultaneously, a correlation matrix was constructed.

The correlation matrix displays the calculated Pearson coefficients between monitored variables, allowing for a clear overview of their relationships. Each cell indicates the strength and direction of the association between two variables. This method helps to identify relevant patterns and complements other statistical analyses used in the study (Wagavkar, 2024).

Subsequently, a hierarchical cluster analysis was chosen to analyse the data to identify groups of respondents with common features – either demographic or based on their experiences and attitudes towards unethical behaviour when buying furniture. This approach is particularly useful when examining multiple variables simultaneously, where simple pairwise comparisons are not sufficient (CodeSignal, 2025).

Cluster analysis is used to group observations into clusters according to their similarity. Similarity is measured based on responses to selected questions such as:

– the influence of advertising on the purchase,
– the presence of any shortcomings after the purchase,
– whether the respondent dealt with a complaint,

– and personal experience of unethical behaviour by the seller.

The Ward method is an agglomerative clustering approach that groups elements into a predefined number of clusters through a series of steps. Initially, each element is treated as its own separate cluster. Then, at each step, the algorithm merges the elements that are closest to one another based on a chosen distance metric. This process continues until all elements are grouped into clusters. The number of steps can range from 1, where all elements are combined into a single cluster to *n*, where each element remains in its own individual cluster. Once elements are grouped into a cluster, they cannot be split apart again. The method aims to determine the most appropriate number of clustering steps to form meaningful groupings (Aggarwal and Reddy, 2014; Eszergár-Kiss and Caesar, 2017).

This procedure helps to clearly structure respondent groups, potentially representing different types of consumers with varying perceptions and experiences of unethical behaviour in the context of furniture purchases. Such an approach provides valuable insights into which demographic groups are most exposed to unethical practices and will also help to identify typical patterns of behaviour or problem areas in the furniture sales sector.

Among several hierarchical clustering methods (e.g. single-linkage, complete-linkage, average-linkage), Ward's method was chosen because it is considered one of the most accurate. It aims to minimise the internal variability within each cluster, thus ensuring greater homogeneity of respondents within groups. According to Everitt *et al.* (2011) and Almeida *et al.* (2007), Ward's method has the advantage of forming clusters of similar size and consistency but can be sensitive to the occurrence of outliers.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

A total of 221 questionnaires were correctly completed, and the data were subsequently analysed using selected methods of one-dimensional and multi-dimensional analysis.

Table 1 presents distribution of respondents by gender, age, education, and economic status (in the absolute as well as relative values).

Most respondents were women (67 %) aged 26 – 45 with a high school education and employed. This group presents a key market segment and is highly active in furniture purchases. Based on the characteristics of this key consumer segment, several patterns in purchasing behaviour have emerged.

– Consumers prefer bricks-and-mortar stores (61.5 %), but online sales are also growing in importance (38.5 %). This trend points to the need for the same level of consumer rights protection on both retail channels.
– Practical pieces of furniture (such as wardrobes and sofas) dominate, indicating that customers more often choose furniture with a high degree of utilisation. Marketing tools (mainly promotion) have limited influence on their purchasing decisions, personal experience and recommendations are decisive.
– A significant number of customers declared that they were correctly and sufficiently informed about the products and up to 90.5 % were satisfied with their

Table 1 Sociodemographic structure of respondents
Tablica 1. Sociodemografska struktura ispitanika

Variable *Varijabla*	Category *Kategorija*	Absolute value *Apsolutna vrijednost*	Relative value *Relativna vrijednost*
Gender *spol*	Female / *ženski*	148	67.0 %
	Male / *muški*	73	33.0 %
Age *dob*	to 25 years / *godina*	92	41.6 %
	26 – 45 years / *godina*	95	43.0 %
	46 – 60 years / *godina*	28	12.7 %
	over 61 years / *godina*	6	2.7 %
Education *obrazovanje*	Secondary education with school leaving exam *srednje obrazovanje sa završnim ispitom*	110	49.8 %
	Secondary education without school leaving exam *srednje obrazovanje bez završnog ispita*	23	10.4 %
	Tertiary education (1st degree) *visoko obrazovanje (1. stupanj)*	60	27.1 %
	Tertiary education (2nd degree) *visoko obrazovanje (2. stupanj)*	28	12.7 %
Economic status *ekonomski status*	Employed / *zaposlen*	116	52.5 %
	Student / *student*	78	35.3 %
	Maternity leave / *na porodiljnom dopustu*	11	5.0 %
	Unemployed / *nezaposlen*	8	3.6 %
	Retired / *umirovljenik*	8	3.6 %

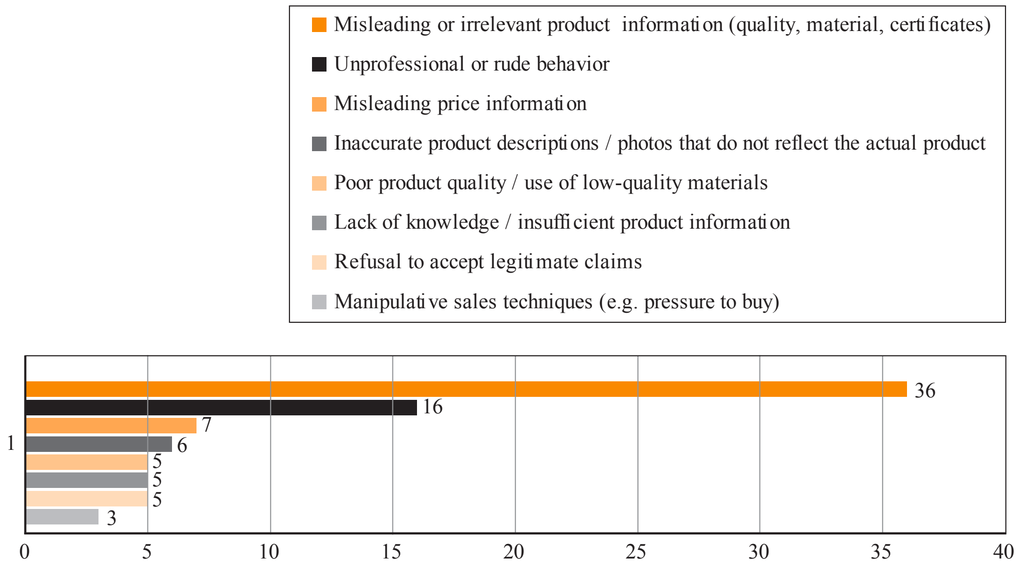

Figure 1 Most common unethical practices in furniture sales
Slika 1. Najčešće neetične prakse u prodaji namještaja

purchase, indicating a generally positive experience – but not without exceptions.

– Despite the positive aspects, the incidence of unethical practices is significant and widespread. Figure 1 presents the most common misleading practices applied in selling furniture.

Although most consumers reported satisfaction with their furniture purchases, unethical practices remain common. The most frequent issue, reported by 36 respondents, is misleading or irrelevant product information, including false claims about quality, materials, and certifications, which erodes consumer trust. Unprofessional or rude staff behaviour is the second most cited problem, underscoring the importance of respectful customer service. Other concerns include misleading pricing, inaccurate descriptions, refusal to accept valid complaints, poor product knowledge, low-quality materials, and manipulative sales tactics. Overall, dishonest practices in furniture sales often involve poor service, lack of transparency, and false information, negatively affecting consumer experience and retailer reputation.

The following suggestions reflect the most frequently identified problems and aim to eliminate them:

– Adopt a binding code of conduct for furniture retailers to ensure honest and complete product information (origin, quality, features), developed jointly by industry and consumer organisations.
– Equal rules for online and offline sales must be ensured, including mandatory access to full product details and clear visualisations to allow easy product verification.
– Standardise the complaint process, requiring written justification for rejected claims and enabling appeals to an independent body (e.g. consumer ombudsman).
– Promote consumer education through campaigns on buyer rights, complaint procedures, and recognition of manipulative tactics.
– Create a simple online consumer guide with practical tips, available on official consumer and government websites.
– Establish a public rating system for furniture sellers based on customer satisfaction and complaint handling, with an option to award a trustmark to ethical retailers.

To further understand the correlation between the observed variables in which unethical traits occur and demographic characteristics, a correlation analysis was conducted. The relationships between the variables under study are shown within the correlation matrix (see Table 1).

The correlation analysis provided a deeper insight into the relationships among the monitored variables and made it possible to verify the extent to which the individual factors are related to each other. In Table 2, the colour of the coefficients indicates their statistical significance. Values shown in red represent correlations that are statistically significant at the 5 % level ($p < 0.05$), whereas values in black denote correlations that are not statistically significant. This distinction helps to quickly identify which relationships among the variables are supported by the data and which may be due to random variation.

Weak to slightly negative relationships were observed among the demographic variables: age, gender, education, and economic situation. There is a moderate negative correlation between age and economic status (r = -0.283), which may indicate that older respondents are more likely to be in a more difficult economic situation (e.g. retired). Similarly, the weak negative correlation between age and education

(r = -0.148) may reflect differences in access to education across generations.

The quality and relevance of information play a key role in how consumers perceive marketing practices – a lack of it is associated with perceptions of unethical behaviour and lower satisfaction. Thus, ethical marketing is not only morally right, but also practically effective in terms of trust and customer satisfaction.

The most significant positive correlations emerged among the variables related to purchase experience. The moderately strong correlation observed between the relevance of information during purchase and whether the product met expectations (r = 0.445) confirms that good quality, accurate and transparent information contribute significantly to customer satisfaction. These results are further supported by the positive correlation between information relevance and the experience of unethical behaviour (r = 0.332) as well as the handling of complaints (r = 0.232). This means that inadequate or misleading information may lead to unmet expectations, which in turn creates the perception of unethical behaviour on the part of the retailer and a higher likelihood of a complaint.

Based on the correlation analysis, Hypothesis H1, which assumed a statistically significant relationship between consumers' education and the perceived likelihood of experiencing unethical retail practices, was not confirmed. The observed correlations between education and perceived unethical practices were weak and statistically insignificant, indicating that education level did not play a decisive role in shaping consumers' perception of unethical behaviour.

In contrast, Hypothesis H2 was confirmed. A moderate positive correlation (r = 0.445, $p < 0.05$) was found between the perceived relevance of pre-purchase product information and consumer satisfaction. This result highlights the crucial role of transparent and accurate information in increasing customer satisfaction and reducing the perception of unethical practices in the furniture market.

These findings are consistent with previous research (e.g., Vitell and Muncy, 1992; Rallapalli *et al.*, 1994) that highlights the negative impact of unethical behaviour on consumer attitudes, satisfaction, and loyalty (Lim *et al.,* 2023). The correlations between the variables clearly indicate that the different aspects of the buying process are closely interrelated and form a complete picture of the customer's experience. The results thus underline the need for an ethical approach, transparent communication and an effective complaint handling system. In the future, we recommend that increased attention be paid to the individualisation of marketing communications by demographic segments and that research into trust and perceptions of ethics in relation to long-term customer loyalty be deepened.

Cluster analysis using Ward's method and Euclidean distance metric was applied to analyse the relationship among a set of 10 variables related to socio-demographic characteristics of the respondents and chosen tools of marketing mix with unethical occurrence. The resulting dendrogram (see Figure 2) identifies several significant relationships among monitored variables that may indicate latent patterns in respondents' behaviour.

Cluster analysis reveals that demographic characteristics such as gender and economic situation of individuals play an important role in their furniture buying behaviour. These characteristics influence where customers buy (online vs. brick-and-mortar stores) and the extent to which they are influenced by marketing communications such as advertisements, discounts, and promotions. Women and men may have different preferences in terms of which sales outlets they prefer. Women may prefer brick-and-mortar stores more because of the ability to physically view the product, while men may prefer the convenience of online shopping. At the same time, customers with lower economic status may be more sensitive to promotions and discounts, while those with higher status may be more focused on other features related to the furniture, such as its design, quality or brand.

The grouping of these four variables therefore suggests that marketing strategies and business decisions should take these contexts into account. Advertising targeting, the choice of sales channels, or the type of communication should consider the demographic characteristics of the selected customer groups, as these factors influence their behaviour and decision-making.

The cluster analysis reveals a strong connection between the relevance of information at the point of purchase, fulfilment of product expectations, experiences of unethical behaviour, and complaint resolution. These factors together shape the overall customer experience and significantly affect satisfaction levels. When customers receive clear, accurate, and trustworthy information, the product is more likely to meet their expectations, reducing the risk of disappointment. Conversely, incomplete or misleading information can lead to dissatisfaction, complaints, and feelings of being deceived. An effective complaint resolution system plays a vital role in addressing these issues, helping to mitigate negative experiences and rebuild customer confidence.

Outside our survey, several other surveys have already been carried out. They have focused on consumer attitudes towards unethical practices, the identification of the factors that influence these attitudes, and their impact on consumer behaviour. Demographic variables

Table 2 Correlation matrix
Tablica 2. Korelacijska matrica

	Gender *Spol*	**Age** *Dob*	**Education** *Obrazovanje*	**Economic status** *Ekonomski status*	**Place of purchase** *Mjesto kupnje*	**Influence of promotion** *Utjecaj promocije*	**Relevance of information when buying furniture** *Relevantnost informacija pri kupnji namještaja*	**The product met expectations** *Proizvod je ispunio očekivanja*	**Complaint handling** *Rješavanje pritužbi*	**Experience with unethical behaviour** *Iskustvo s neetičnim ponašanjem*
Gender / *Spol*	1.000000	-0.255953	0.056041	0.100552	0.001521	0.055247	0.026542	0.034886	0.066432	0.101877
Age / *Dob*	-0.255953	1.000000	-0.148193	-0.283125	0.052032	-0.039635	0.024117	-0.013517	-0.056678	-0.015232
Education / *Obrazovanje*	0.056041	-0.148193	1.000000	0.117115	-0.018763	0.011001	0.010116	0.150092	-0.034691	-0.049065
Economic status / *Ekonomski status*	0.100552	-0.283125	0.117115	1.000000	0.066283	-0.066606	-0.004824	0.020802	0.019969	-0.017395
Place of purchase / *Mjesto kupnje*	0.001521	0.052032	-0.018763	0.066283	1.000000	-0.011514	0.041412	0.034157	0.034563	0.057735
Influence of promotion / *Utjecaj promocije*	0.055247	-0.039635	0.011001	-0.066606	-0.011514	1.000000	-0.078108	-0.024079	-0.115042	-0.045584
Relevance of information when buying furniture / *Relevantnost informacija pri kupnji namještaja*	0.026542	0.024117	0.010116	-0.004824	0.041412	-0.078108	1.000000	0.445360	0.232379	0.331540
The product met expectations / *Proizvod je ispunio očekivanja*	0.034886	-0.013517	0.150092	0.020802	0.034157	-0.024079	0.445360	1.000000	0.173611	0.169031
Complaint handling / *Rješavanje pritužbi*	0.066432	-0.056678	-0.034691	0.019969	0.034563	-0.115042	0.232379	0.173611	1.000000	0.208941
Experience with unethical behaviour / *Iskustvo s neetičnim ponašanjem*	0.101877	-0.015232	-0.049065	-0.017395	0.057735	-0.045584	0.331540	0.169031	0.208941	1.000000

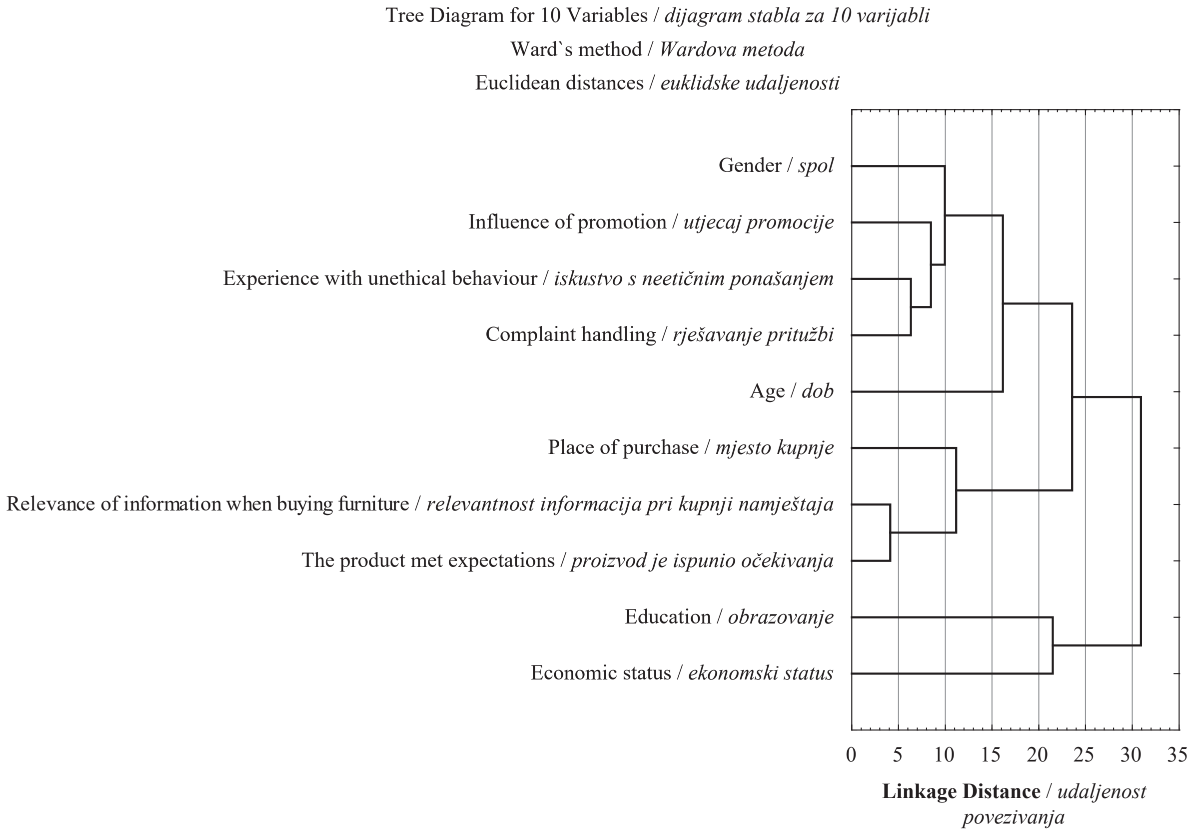

Figure 2 Cluster analysis of relationship of demographic variables and chosen tools of marketing mix with unethical occurrence
Slika 2. Klasterska analiza odnosa demografskih varijabli i odabranih alata marketinškog miksa s neetičnim pojavama

such as age, education, and income, along with personality traits, have been shown to significantly influence ethical judgments. At the same time, unethical marketing practices have been proved to have a negative impact on consumers' expectations, attitudes, satisfaction levels, and intention to continue purchasing, irrespective of whether the experience is personal or mediated (Vitell and Muncy, 1992, Rallapalli *et al*., 1994).

Ingram *et al.* (2005) found that a strong consumer-brand relationship can lessen perceptions of minor unethical behaviour. However, as the severity of the wrongdoing increases, even loyal customers become less forgiving. The study emphasises the importance of ethical conduct, as perceived unethical behaviour can drive away loyal customers—posing a significant risk for firms, since retaining customers is generally less costly than acquiring new ones.

All these findings highlight the importance of ethical communication and customer-centric approaches in retail strategy. In each marketing mix tool, it is essential to meet the requirements of fairness, transparency, and responsiveness, which are important competitive advantages that companies can build on. Moreover, given the proven sensitivity of consumers to unethical behaviour, companies should integrate ethical guidelines not only in sales but also in internal corporate culture and training.

The present study is subject to several limitations. First, the research sample focuses on consumer experiences with furniture purchases in Slovakia, which restricts the generalisability of the findings to other cultural or regulatory contexts. Second, the collected data reflect consumers' subjective perceptions of retailer behaviour and product quality rather than objective measures. Third, the method of data collection may have influenced the composition of the sample, which might not fully represent the demographic diversity of the consumer population. In particular, the online format of the survey may have excluded individuals with limited internet access or lower digital literacy, especially among older respondents. Future studies should therefore consider alternative sampling strategies to enhance representativeness and improve the robustness of the findings.

4 CONCLUSIONS
4. ZAKLJUČAK

The furniture industry is currently facing increasing criticism from both consumers and experts, primarily due to unethical business practices. Among the most frequently mentioned are the sale of low-quality products, withholding information about the materials used, deliberately shortening product lifespan, and insufficient communication regarding complaint procedures. While these practices may contribute to increased profits in the short term, they contradict the principles of sustainable business and indicate the absence of a responsible business model. A sustainable business model should not be understood solely as an environmentally friendly production process but, above all, as a comprehensive and transparent approach to customers, based on ethics, quality, trust, and efficient resource management.

In the context of the furniture industry, implementing these principles would not only emphasise product durability and promote the reuse of materials through circular design but also maintain open communication about the origin of raw materials, production conditions, and environmental impacts. Linking sustainability with the business model thus represents not only a tool for eliminating unethical practices but also a potential means to build a competitive advantage based on customer-perceived value – not only through price but also through the moral and ecological aspects of the product.

Based on the results of the cluster analysis carried out, several recommendations for improving current practices can be identified. Particularly significant is the discovered relationship between consumer gender and their responsiveness to marketing messages, suggesting that targeted, personalised marketing campaigns may be more effective. However, personalisation must be carried out in accordance with ethical standards—the communication with customers should be transparent, respectful, and inclusive, without any manipulative or discriminatory elements. Only in this way can trust be strengthened and stable, and long-term consumer relationships be established.

Among the tested hypotheses, the relevance of pre-purchase information showed the strongest statistical relationship with customer satisfaction, indicating its central role in shaping consumer experiences. This relationship highlights the need to enhance transparency and professionalism throughout the entire sales process. It is therefore recommended to consistently build an ethical approach to customers at all stages of the sale to minimise the occurrence of unethical or misleading practices.

Finally, it is essential to invest in a high-quality customer service system and efficient complaint handling. The ability to respond promptly and fairly to customer dissatisfaction plays a decisive role in maintaining trust and preventing damage to the company's reputation. From a long-term perspective, an ethical and sustainable approach to business thus represents not only a moral obligation but also a strategic advantage that can significantly influence brand perception and customer loyalty.

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Drvo poljskog jasena
Fraxinus angustifolia Vahl

MIKROSKOPSKA OBILJEŽJA

Drvo poljskog jasena prstenasto je porozno. Traheje ranog drva su ovalne do okrugle, raspoređene pojedinačno ili u parovima te u jedan do četiri reda u nizu. Vrlo su velike, tangentnog promjera do 345 µm. Traheje kasnog drva rijetko su raspoređene, pojedinačne, te u malim skupinama ili kratkim radijalnim nizovima, promjera oko 50 µm. Perforacija članaka traheja je potpuna. Drvna vlakanca su duljine 150 do 1600 µm, sa staničnom stijenkom srednje debljine. Drvni traci su homocelularni, višeredni (širine 1 – 4 stanice, visine do 500 µm) i gustoće od 5 do 9/ mm u tangentnom smjeru. Aksijalni je parenhim paratrahealno vazicentričan, konfluentan. U stanicama drvnog traka nema kristala.

RELEVANTNE SPOZNAJE O STRUKTURI, SVOJSTVIMA I VARIJACIJAMA DRVA POLJSKOG JASENA

Pregled ograničenog broja istraživanja drva poljskog jasena donosi spoznaje: a) o sličnosti svojstava drva poljskog jasena sa svojstvima običnog jasena (Tirak Hizal i Erdín, 2020.); b) o većoj gustoći drva, debljim staničnim stijenkama drvnih vlakanaca, manjoj gustoći pora ranoga drva, većoj i/ili sličnoj širini drvnih trakova, kraćim porama ranoga drva te o manjoj visini i duljini drvnih trakova u stabala iz plantažnog uzgoja (Tirak Hizal i Erdín, 2020.); c) o razlici u otpornosti drva iz plantažnog uzgoja i onoga iz prirodnih populacija prema bijelim i smeđim gljivama truležnicama koja nije značajna (Tirak Hizal i Erdín, 2016.); d) o smanjenju sadržaja celuloze s porastom visine u trupcu, dok vertikalan položaj nije utjecao na sadržaj lignina (Popović i dr., 2016.); e) o povećanju promjera lumena pora i debljine stijenki drvnih vlakanaca u radijalnom smjeru, od srčike prema kori, smanjenju promjera lumena drvnih vlakanaca u istom smjeru te o povećanju duljine drvnih vlakanaca u smjeru prema kori, pri čemu dosežu maksimalnu vrijednost na sredini radijusa (Popović i dr., 2023.).

MICROSCOPIC CHARACTERISTICS

Narrow-leaved ash wood is ring porous. Earlywood vessels are oval to round, arranged individually or in pairs, one to four in rows. They are very large, with a tangential diameter of up to 345 µm. Latewood vessels are arranged individually, in pairs and in short radial rows, and are about 50 µm in diameter. Perforation plates are simple. Wood fibers are 150 to 1600 µm in length, with medium wall thickness. Wood rays are homocellular, multiseriate (1-4 cells in width, with a length up to 500 µm) and with a density of 5 to 9 per tangential mm, paratracheal axial parenchyma vasicentric and confluent. Crystals in wood rays are not observed.

RELEVANT KNOWLEDGE ABOUT NARROW-LEAVED ASH WOOD STRUCTURE, PROPERTIES AND THEIR VARIATIONS

A review of limited research on narrow-leaved ash wood provides the following knowledge: a) wood characteristics of narrow leaved ash show similarities to common ash (Tirak Hizal and Erdín, 2020); (b) planted trees have higher density, thicker double fiber cell wall, lower earlywood vessel frequency, higher and/or similar ray width, shorter earlywood vessels and lower multiseriate ray height and length (Tirak Hizal and Erdín, 2020); (c); no significant difference is observed between plantation and natural grown narrow-leaved ash wood durability against brown and white rot fungi (Tirak Hizal and Erdín, 2016); (d) the cellulose content decreases with the increase in height of the tree trunk, while the vertical position has no significant effect on the lignin content (Popović *et al*., 2016); (e) both the lumen width of vessels and the cell wall thickness of mechanical fibers increase in the radial direction, from the core towards the bark, the lumen width of fibers decreases in the same direction and the length of mechanical fibers increases towards the bark, reaching its maximum value at the middle section of the radius (Popović *et al*., 2023).

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Upute autorima

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Primjer

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Figures should be inserted into the text. They should be of 600 dpi resolution, black and white (color photographs only on request), in jpg or tiff format, completely clear and understandable without reference to the text of the contribution.

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Discussion and conclusion may, if desired by authors, be combined into one chapter. This text should interpret the results relating to the problem outlined in the introduction and to related observations by the author(s) or other researchers. Repeating the data already presented in the "Results" chapter should be avoided. Implications for further studies or application may be discussed. A conclusion shall be expressed separately if results and discussion are combined in the same chapter. Acknowledgements are presented at the end of the paper. Relevant literature shall be cited in the text according to the Harvard system ("name – year"), e.g. (Bađun, 1965). In addition, the bibliography shall be listed at the end of the text in alphabetical order of the author's names, together with the title and full quotation of the bibliographical reference. The list of references shall be selective, and each reference shall have its DOI number (http://www.doi.org) (check at http://www.crossref.org).:

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Example:
Kärki, T., 2001: Variation of wood density and shrinkage in European aspen (*Populus tremula*). Holz als Roh- und Werkstoff, 59: 79-84. http://dx.doi.org/10.1007/s001070050479.

Books:
Author's second name, initial(s) of the first name, year: Title. (ev. Publisher/editor): edition, (ev. volume). Place of publishing, publisher (ev. pages from - to).

Examples:
Krpan, J. 1970: Tehnologija furnira i ploča. Drugo izdanje. Zagreb: Tehnička knjiga.
Wilson, J.W.; Wellwood, R.W. 1965: Intra-increment chemical properties of certain western Canadian coniferous species. U: W. A. Cote, Jr. (Ed.): Cellular Ultrastructure of Woody Plants. Syracuse, N.Y., Syracuse Univ. Press, pp. 551-559.

Other publications (brochures, studies, etc.):
Müller, D. 1977: Beitrag zur Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanslalt für Forst- und Holzwirtschaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

Websites:
***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/department/docs/punctuation/node00.html. First published 1997 (Accessed Jan. 27, 2010).

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HRVATSKA KOMORA INŽENJERA ŠUMARSTVA I DRVNE TEHNOLOGIJE

HRVATSKA KOMORA INŽENJERA ŠUMARSTVA I DRVNE TEHNOLOGIJE

Osnovana je na temelju Zakona o Hrvatskoj komori inženjera šumarstva i drvne tehnologije.

Komora je samostalna i neovisna strukovna organizacija koja obavlja povjerene joj javne ovlasti, čuva ugled, čast i prava svojih članova, skrbi da ovlašteni inženjeri obavljaju svoje poslove savjesno i u skladu sa zakonom, promiče, zastupa i usklađuje njihove interese pred državnim i drugim tijelima u zemlji i inozemstvu.

Članovi komore:

inženjeri šumarstva i drvne tehnologije koji obavljaju stručne poslove iz područja šumarstva, lovstva i drvne tehnologije.

Stručni poslovi:

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Zadaci Komore:

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- poticanje donošenja propisa kojima se utvrđuju javne ovlasti Komore,
- reagiranje struke na pripremu propisa iz područja šumarstva, lovstva i drvne tehnologije,
- suradnja s nadležnim institucijama i zastupanje struke u odnosu prema njima,
- organizacija stručnoga usavršavanja,
- zastupanje interesa svojih članova,
- izdavanje pečata i iskaznice ovlaštenim inženjerima,
- briga i nadzor poštivanja kodeksa strukovne etike,
- osiguravanje članova Komore za štetu koja bi mogla nastati investitorima i trećim osobama i sl.

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- Razred inženjera drvne tehnologije

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