# DRVNA INDUSTRIJA

SCIENTIFIC JOURNAL
OF WOOD TECHNOLOGY

ZNANSTVENI ČASOPIS
ZA PITANJA DRVNE TEHNOLOGIJE

*Populus* spp.

UDK 674.031.677.7
ISO: Drv. Ind.
CODEN: DRINAT
JCR: DRVNA IND
ISSN 0012-6772

2/23
VOLUME **74**

UDK 630*8+674 Coden: Drinat ISSN 0012-6772

# DRVNA INDUSTRIJA

## SCIENTIFIC JOURNAL OF WOOD TECHNOLOGY

Znanstveni časopis za pitanja drvne tehnologije


**PUBLISHER AND EDITORIAL OFFICE**
Izdavač i uredništvo
***University of Zagreb***
***Faculty of Forestry and Wood Technology***
*Sveučilišta u Zagrebu*
*Fakultet šumarstva i drvne tehnologije*
*www.sumfak.unizg.hr*

**CO-PUBLISHER** / Suizdavač
*Hrvatska komora inženjera šumarstva i drvne tehnologije*

**FOUNDER** / Osnivač
*Institut za drvnoindustrijska istraživanja, Zagreb*





***The journal Drvna industrija is a public scientific journal for publishing research results on structure, properties and protection of wood and wood materials, application of wood and wood materials, mechanical woodworking, hydrothermal treatment and chemical processing of wood, all aspects of wood materials and wood products production and trade in wood and wood products.***
***The journal is published quarterly and financially supported by the Ministry of Science and Education of the Republic of Croatia***

*Časopis Drvna industrija javno je znanstveno glasilo za objavu rezultata istraživanja građe, svojstava i zaštite drva i drvnih materijala, primjene drva i drvnih materijala, mehaničke i hidrotermičke obrade te kemijske prerade drva, svih aspekata proizvodnje drvnih materijala i proizvoda te trgovine drvom i drvnim proizvodima.*
*Časopis izlazi četiri puta u godini uz financijsku potporu Ministarstva znanosti i obrazovanja Republike Hrvatske.*

# Contents
# Sadržaj

**CIRCULATION:** *400 pieces*

**INDEXED IN:** *Science Citation Index Expanded, Scopus, CAB Abstracts, Compendex, Environment Index, Veterinary Science Database, Geobase, DOAJ, Hrčak*

**MANUSCRIPTS ARE TO BE SUBMITTED** *by the link http://journal.sdewes.org/drvind*

**CONTACT WITH THE EDITORIAL** *e-mail: editordi@sumfak.hr*

**SUBSCRIPTION:** *Annual subscription is 55 EUR. For pupils, students and retired persons the subscription is 15 EUR. Subscription shall be paid to the IBAN HR0923600001101340148 with the indication "Drvna industrija".*

**PRINTED BY:** *DENONA d.o.o., Getaldićeva 1, Zagreb, www.denona.hr*

**DESIGN:** *Bernardić Studio*

**THE JOURNAL IS AVAILABLE ONLINE:** *https://drvnaindustrija.com*

**COVER:** *Tangential section of Populus spp., xylotheca of Institute for Wood Science, Faculty of Forestry and Wood Technology University of Zagreb*

**DRVNA INDUSTRIJA · VOL. 74, 2 · P. 137-264 · SUMMER 2023. · ZAGREB**
**EDITORIAL COMPLETED 1. 6. 2023.**

**NAKLADA:** *400 komada*

**ČASOPIS JE REFERIRAN U**: *Science Citation Index Expanded, Scopus, CAB Abstracts, Compendex, Environment Index, Veterinary Science Database, Geobase, DOAJ, Hrčak*

**ČLANKE TREBA SLATI** *putem poveznice http://journal.sdewes.org/drvind*

**KONTAKT S UREDNIŠTVOM:** *e-mail: editordi@sumfak.hr*

**PRETPLATA:** *Godišnja pretplata za pretplatnike u Hrvatskoj i inozemstvu iznosi 55 EUR. Za đake, studente i umirovljenike 15 EUR. Pretplata se plaća na IBAN HR0923600001101340148 s naznakom "Drvna industrija".*

**TISAK:** *DENONA d.o.o., Getaldićeva 1, Zagreb, www.denona.hr*

**DESIGN**: *Bernardić Studio*

**ČASOPIS JE DOSTUPAN NA INTERNETU:** *https://drvnaindustrija.com*

**NASLOVNICA**: *Tangentni presjek Populus spp., ksiloteka Zavoda za znanost o drvu, Fakultet šumarstva i drvne tehnologije Sveučilišta u Zagrebu*

**DRVNA INDUSTRIJA · VOL. 74, 2 · STR. 137-264 · LJETO 2023. · ZAGREB**
**REDAKCIJA DOVRŠENA 1. 6. 2023.**

Umit Ergin[1], Sait Dundar Sofuoglu[2]

# Determination of Machining Characteristics of Heat-Treated Siberian Pine (*Pinus sibirica*)

# Određivanje svojstava obradivosti toplinski modificiranog drva sibirskog bora (*Pinus sibirica*)

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 20. 12. 2021.
Accepted – prihvaćeno: 10. 11. 2022.
UDK: 674.02; 674.032.475.4
https://doi.org/10.5552/drvind.2023.0003



**ABSTRACT** • *The main objective of this study is to determine the effect of heat treatment on the machining properties of solid wood material and determine the optimum cutting parameters to obtain surfaces with minimum surface roughness. In line with this goal, Siberian pine (Pinus sibirica) wood species, widely used in the woodworking and furniture industry, was chosen as the experimental material. The heat-treated (at a temperature of 190 °C for 2 hours) and untreated samples were machined using two different cutters (carbide upcut milling cutter and carbide compression milling cutter) with 5 mm diameter at 1000, 1500 and 2000 mm/min feeds, 8000, 12000, 16000 rpm spindle speed, 50, 75 and 100 % stepover on the CNC machine. Surface roughness values (Ra and Rz) were measured to evaluate the obtained surfaces according to ISO 468 (2009), ISO 3274 (2005), and ISO 4287 (1997) using a contact profilometer. When the data was evaluated in general, the lowest roughness value for Ra occurred in upcut milling cutter, with 50% stepover, 12000 rpm, 1000 mm/min feed on untreated solid wood material. The highest roughness value for Ra occurred in a compression milling cutter, with 100 % stepover, 16000 rpm, 2000 mm/min feed on heat-treated solid wood material. It has been observed that the feed is the most critical parameter affecting the surface roughness.*

**KEYWORDS:** *heat treatment, machining parameter, roughness, Siberian pine, wood material*

**SAŽETAK** • *Glavni cilj ovog istraživanja bio je utvrditi utjecaj toplinske modifikacije na svojstva obradivosti cjelovitog drva te utvrditi optimalne parametre rezanja za postizanje obrađene površine minimalne hrapavosti. U skladu s tim ciljem, za istraživanje je odabrano drvo sibirskog bora (Pinus sibirica) koje ima široku primjenu u drvoprerađivačkoj industriji i proizvodnji namještaja. Toplinski modificirani (na temperaturi 190 °C tijekom dva sata) i nemodificirani uzorci obrađeni su na CNC stroju dvama različitim glodalima (usadnim glodalom s uzlaznom zavojnicom i usadnim glodalom s uzlazno-silaznom zavojnicom) promjera 5 mm s oštricama od tvrdog metala, te uz posmičnu brzinu od 1000, 1500 i 2000 mm/min, frekvenciju vrtnje vretena od 8000, 12 000 i 16 000 okr./min te s korakom glodanja od 50, 75 i 100 %. Hrapavost površine (Ra i Rz) izmjerena je kontaktnim profilome-*

[1] Author is graduate student at Kutahya Dumlupinar University, Institute of Graduate Education, Kutahya, Turkey. https://orcid.org/0000-0002-5476-9726
[2] Author is associate professor at Kutahya Dumlupinar University, Faculty of Simav Technology, Department of Wood Works Industrial Engineering, Simav/Kutahya, Turkey. https://orcid.org/0000-0002-1847-6985

*trom kako bi se površina ocijenila prema ISO 468 (2009), ISO 3274 (2005) i ISO 4287 (1997). Dobiveni rezultati pokazuju da je najmanja vrijednost hrapavosti Ra zabilježena za površinu nemodificiranih uzoraka obrađenih usadnim glodalom s uzlazno-silaznom zavojnicom, i to uz ove parametre obrade: korak glodanja 50 %, frekvenciju vrtnje vretena 12 000 okr./min i posmičnu brzinu 1000 mm/min. Najveća vrijednost hrapavosti Ra zabilježena je za modificirane uzorke obrađene usadnim glodalom s uzlazno-silaznom zavojnicom za ove parametre obrade: korak glodanja 100 %, frekvenciju vrtnje vretena 16 000 okr./min i posmičnu brzinu 2000 mm/min. Uočeno je da je posmična brzina najkritičniji parametar koji utječe na hrapavost obrađene površine.*

**KLJUČNE RIJEČI:** *toplinska modifikacija, parametri obrade, hrapavost, drvo sibirskog bora, drvni materijal*

## 1 INTRODUCTION
## 1. UVOD

From the past to the present, different "Wood Modification Methods" have been developed due to all scientific studies and research done to eliminate some of the negativities of solid wood material. Wood modification is applied to change or improve the negative properties of wood material (Senol, 2018; Senol and Budakci, 2016).

Today, heat treatment is applied to wood material to improve its dimensional stability and increase its biological durability. This is a nature and environment friendly method.

The physical and mechanical properties of heat-treated wood materials change. This change can be positive or negative, occurring during production and post-production use. The effect of heat treatment needs to be determined for each tree species and condition. However, there are not enough studies in the literature on the subject.

Related to heat treated wood materials, there are studies in the literature on mechanical properties (Akman, 2008; Bal and Kilavuz, 2021; Doruk *et al.*, 2014; Esen and Ozcan, 2012; Icel and Beram, 2017; Korkut *et al.*, 2008; Mburu *et al.*, 2008; Percin and Ayan, 2012; Percin *et al.*, 2017; Percin and Altunok, 2019; Yildiz *et al.*, 2006), mass loss (Zaman *et al.,* 2000, Esteves *et al.,* 2007; Lunguleasa *et al.*, 2018) wettability (Hakkou *et al.*, 2005a; Kilincarslan and Simsek, 2020, Petrissans *et al.*, 2003), color changes (Atar *et al.*, 2019; Ayadi *et al.,* 2003; Ayata, 2020; Baysal *et al.*, 2018; Gurleyen *et al.*, 2018; Karamanoglu and Kaymakci, 2018; Pelit, 2017; Sahin Kol *et al.*, 2017; Yasar, 2009) hardness (Adela Salca and Hiziroglu, 2014; Efe and Bal, 2016; Gurleyen *et al.*, 2017; Karamanoglu and Kaymakci, 2018), biological durability to brown rot fungi (Duzkale Sozbir and Bektas, 2019), evaluations on microscopic images of heat treated wood (Icel and Simsek, 2017), surface roughness (Ayata *et al.*, 2018; Altun and Esmer, 2017; Çakicier, 2018; Korkut and Guller, 2008; Pelit *et al.*, 2021) dimensional stability (Sahin and Guler, 2018) bonding strength of some adhesives (Percin and Uzun, 2014; Ayata and Cakicier, 2018) surface densification (Ayrilmis *et al.*, 2019; Gong *et al.*, 2010), chemical changes (Hakkou *et al*, 2005b), evaluation of studies on heat treatment (Esteves and Pereira, 2009; Ulay *et al.*, 2014). Heat treatment changes the chemical composition of wood, leading to mass loss (Esteves and Pereira, 2009). Heat treatment reduces specific wood mechanical properties, but the dimensional stability and biological durability of wood increase through heat treatment. In addition, heat treatment results in favorable changes in the physical properties of the wood, such as reduced shrinkage and swelling, low equilibrium moisture content, enhanced weather resistance, a decorative dark color, and better decay resistance (Korkut *et al.*, 2008; Yildiz, 2002). However, there are few studies on the change in machining properties and optimum machining parameters of heat-treated wood materials. Budakci *et al.* (2011) examined the effects of different circular saws on the surface roughness of heat-treated wood. Heat treatment increased the surface roughness of the wood used (Budakci *et al.*, 2011). Heat treatment of Scots pine (*Pinus sylvestris* L.), Eastern beech (*Fagus orientalis* L.), Uludag fir (*Abies bornmülleriana* Mattf.), and sessile oak (*Quercus petraea* L.) decreases the surface roughness value of the wood material and a significant difference in surface roughness cannot be detected between planing (Budakci *et al.*, 2013). Gunduz *et al.* (2008) reported that the surface roughness of modified Camiyani Black Pine wood (*Pinus nigra* Arn. subsp. *pallasiana* var. *pallasiana*) is lower. The surface roughness of heat-treated beech machined by milling was slightly higher than that of untreated wood (Ispas *et al*., 2016). Hacibektasoglu *et al.* (2017) revealed that heat-treating beech (*Fagus sylvatica* L.) for 1 h and 2 h had a negligible effect on the processing roughness after planing, measured by *Rk*.

Industrial development and international competitiveness impose higher demands on wood industry. New technologies and cutting materials are the key to successful productivity in the manufacturing process (Dobrzynski *et al*, 2018). Before heat-treated wood materials are turned into the final product, they may need to be machined with classical machines and modern CNCs. After machining, solid wood is expected to be smooth (minimum surface roughness) and free of machining defects. In this context, machining parameters will be determined to obtain the lowest surface roughness.

Therefore, the scope of this study was as follows:

1. To choose optimum machining parameters (cutter type, stepover, spindle speed, and feed) for Siberian pine wood material,
2. To determine the effect of heat treatment on machining properties and to investigate optimum machining parameters to obtain the smoothest surface.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

Siberian pine (*Pinus sibirica*), which is one of the coniferous tree species with a wide area of use and widely grown, was chosen as the experimental material in the study. The samples (heat-treated at a temperature of 190 °C for 2 hours and untreated) were all randomly selected from Atlas Tomruk, Simav, Kutahya Turkey. They were conditioned at temperatures of (20±2) °C and (65±5) °C, with a relative humidity to the moisture content (MC) of about 12 % (Nuve, ID500). The density of the Siberian pine tree species at 12 % humidity was determined as 0.623 g/cm$^3$ for untreated samples and 0.470 g/cm$^3$ for heat-treated samples (ISO 13061-1, 2014; ISO 13061-2, 2014). The experimental process flowchart of the study is given in Figure 1.

The experiments were carried out on a Diacam 3 axis CNC milling machine (Simav Vocational and Technical Anatolian High School¸ Simav, Kutahya, Turkey) with a maximum spindle speed of 24000 rpm. New and sharp cutters were used in each cutting test. Upcut milling cutter had cutting helixes and, when looking at the router bit with the tip pointing downwards, the cutting helixes were inclined to the right. When rotating clockwise, the router bit pushed the chips upwards ensuring an excellent finish on the bottom side of the workpiece. The ability of the positive cutting edge to move the chip towards the shank is called the 'pulling feature' and allows the router bit to make single passes. Carbide positive-negative milling cutter (pulling and pushing feature) with positive and negative cutting edges can achieve an optimal finish on both sides of the wood and wood-based materials. These cutters are used in CNC for contouring, sizing, and profiling hardwood and wood composites, laminated, and plastic materials. These cutters have two positive helixes at the bottom of the cutting edge and two negative ones at the top. The cutter 2+2 mouth positive and negative structure discharges chips from both the top and bottom of the material and gives smooth results for every surface cut (Figure 2). The ex-

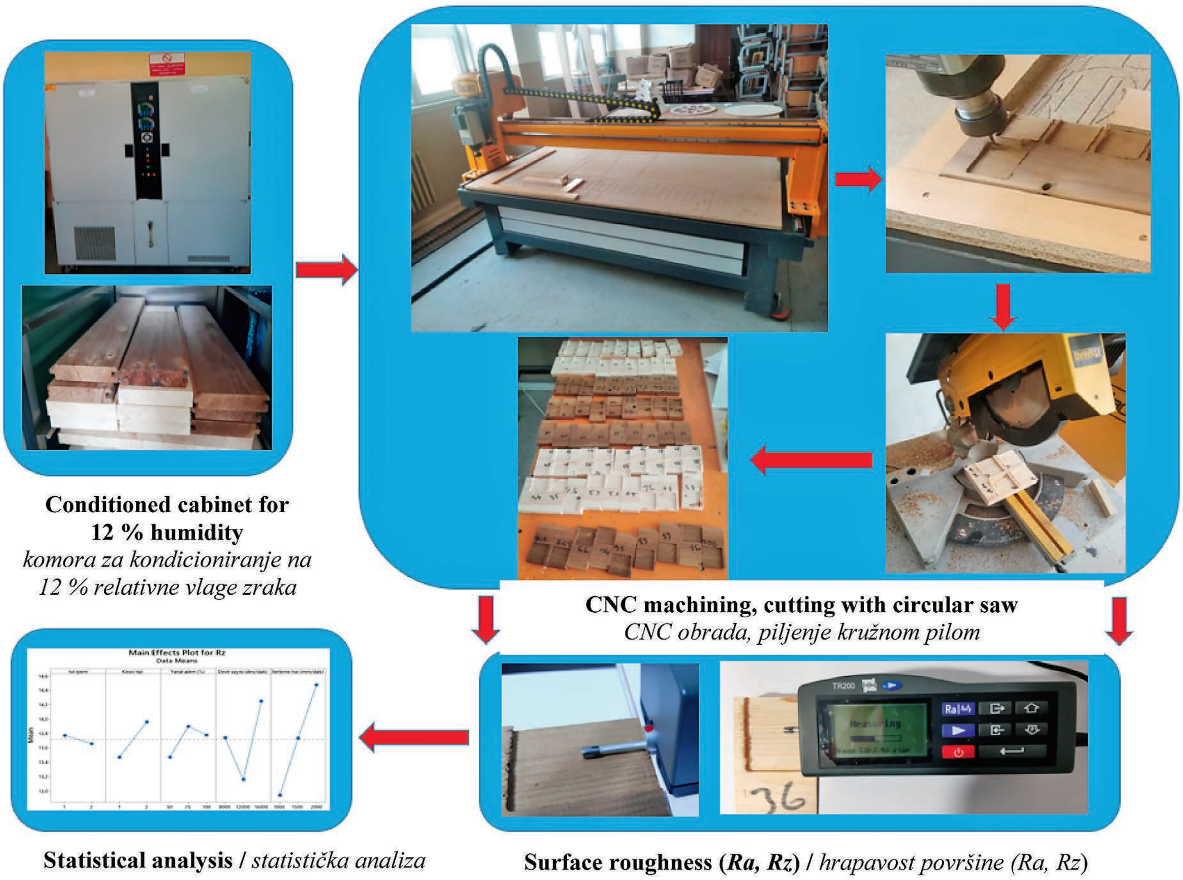
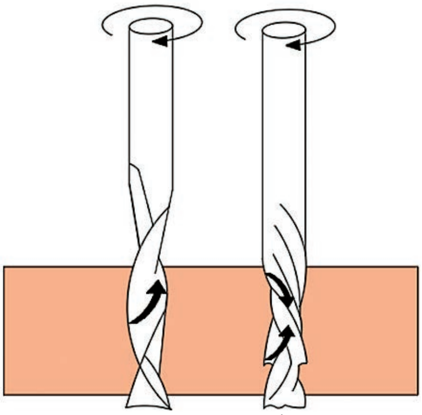
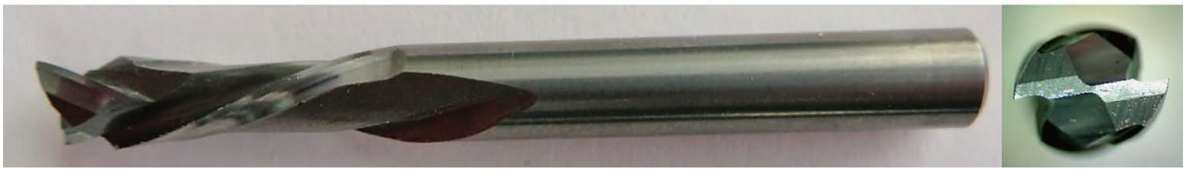



**Figure 1** Experimental process flowchart
**Slika 1.** Dijagram tijeka eksperimenta




a



b

**Figure 2** Cutter types: a) Carbide upcut milling cutter, discharges chips upwards b) Carbide compression (positive-negative) milling cutter, discharges chips from both the top and bottom
**Slika 2.** Vrste glodala: a) usadno glodalo s uzlaznom zavojnicom i oštricama od tvrdog metala; izbacuje strugotinu prema gore, b) usadno glodalo s uzlazno-silaznom zavojnicom i oštricama od tvrdog metala; izbacuje strugotinu i s gornje i s donje strane

periments were carried out with two router cutters (Toolstechnic, Tungsten carbide upcut milling cutter (helix angle: 19°) and Toolstechnic, tungsten carbide positive-negative (compression) milling cutter (helix angle:23°) with 5 mm in diameter) (Figure 3).

Stepover is a machining parameter that defines the distance between two neighboring passes over the workpiece. It is usually given as a percentage (ratio) of the tool diameter (Topal, 2009). The term stepover is illustrated in Figure 3. Various experiments were carried out in this study under stepover (50 %, 75 % and 100 of tool diameter).

A total of 108 pieces (54 treated + 54 untreated) of dimensions of 50 mm × 50 mm were grooved on wood materials by a CNC router (Figure 3). The surface roughness measurements were performed on a radial surface parallel to the grain at 3 separate lines on each specimen. The measuring parameters (average roughness (*Ra*) and ten point average roughness (*Rz*)) are described in ISO 468 (2009). The measurement of surface roughness was conducted according to the protocols in ISO 468 (2009), ISO 3274 (2005), and ISO 4287 (1997). The Surface Roughness Tester Time TR200 (Time Group Inc., China), surface roughness measurement equipment, was used for the determination of the surface roughness values via a contact stylus trace method. Gaussian filter type was used. The Robust Gaussian Regression Filter is useful for wood surfaces and can avoid the anatomical biasing effect (Gurau and Irkle, 2017). The sampling length was taken as

**Table 1** Assignment of levels to factors (parameters used in face milling of Siberian pine)
**Tablica 1.** Dodjeljivanje razina *čim*benicima glodanja (parametri koji se koriste pri *čeonom* glodanju drva sibirskog bora)

| **Parameter** / *Parametar* | **Coded levels** / *Oznake razine* | | |
|---|---|---|---|
| | Level 1 / *Razina 1.* | Level 2 / *Razina 2.* | Level 3 / *Razina 3.* |
| Heat treatment / *toplinska modifikacija* | 1 (untreated) | 2 (heat- treatment) | |
| Cutter type / *vrsta glodala* | 1 (upcut) | 2 (compression, positive- negative) | |
| Stepover / *korak glodanja,* % | 50 | 75 | 100 |
| Spindle speed, rpm<br>*frekvencija vrtnje vretena,* okr./min | 8000 | 12000 | 16000 |
| Feed, mm/min / *posmična brzina,* mm/min | 1000 | 1500 | 2000 |

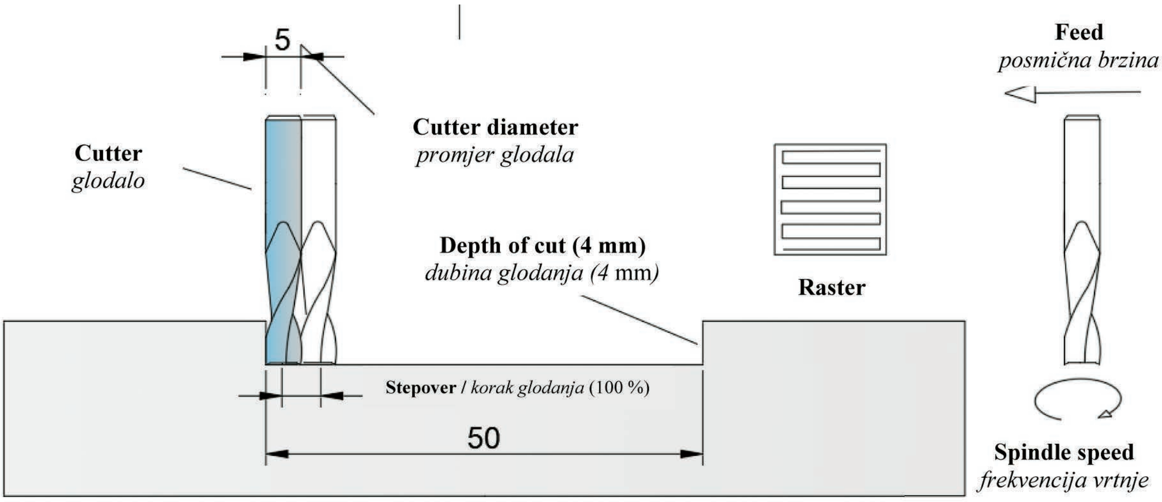



**Figure 3** Parameters of CNC process
**Slika 3.** Parametri CNC obrade

0.8 mm. With increasing scanning length, the spatial resolution (along the scanned profile) was reduced, as well as the accuracy for determining the minute surface irregularities, such as wood anatomical components (Sandak *et al*., 2020). Surface roughness values were measured with an accuracy of ±0.01 µm. The stylus probe speed was chosen as 10 mm/ min, the diameter of the measurement needle was 5 µm, and the needle tip was 90°. Care was taken to provide adequate measurement conditions - temperature around 18-22 °C with no vibrations. The tool was calibrated prior to the measurement, and the calibration was checked at established intervals.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

In the study, specimens were machined with CNC to determine the effect of heat treatment, cutter type, stepover, speed and feed on the roughness parameters (*Ra* and *Rz*). The roughness values measured on the machined surfaces are given in Table 2.

The lowest roughness value for *Ra* (*Ra* = 1.42 µm) was in the untreated specimens; it occurred in upcut milling cutter (cutter type 1), 100 % stepover, 16000 rpm and 1500 mm/min feed. The highest roughness value for *Ra* was in the untreated specimen (*Ra* =

**Table 2** Surface roughness values obtained according to machining conditions
**Tablica 2.** Vrijednosti hrapavosti površine ovisno o uvjetima obrade

| **Number** *Broj* | **Heat treatment** *Toplinska modifikacija* | **Cutter type** *Vrsta glodala* | **Stepover, %** *Korak glodanja, %* | **Spindle speed, rpm** *Brzina vretena, okr./min* | **Feed, mm/min** *Posmična brzina, mm/min* | ***Ra*, µm** | ***Rz*, µm** |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 50 | 8000 | 1000 | 2.36 | 11.20 |
| 2 | 1 | 1 | 50 | 8000 | 1500 | 2.75 | 13.63 |
| 3 | 1 | 1 | 50 | 8000 | 2000 | 1.99 | 9.95 |
| 4 | 1 | 1 | 50 | 12000 | 1000 | 2.54 | 13.19 |
| 5 | 1 | 1 | 50 | 12000 | 1500 | 2.81 | 14.09 |
| 6 | 1 | 1 | 50 | 12000 | 2000 | 1.54 | 9.70 |
| 7 | 1 | 1 | 50 | 16000 | 1000 | 2.84 | 14.48 |
| 8 | 1 | 1 | 50 | 16000 | 1500 | 2.31 | 11.42 |
| 9 | 1 | 1 | 50 | 16000 | 2000 | 2.74 | 12.81 |
| 10 | 1 | 1 | 75 | 8000 | 1000 | 1.99 | 10.87 |
| 11 | 1 | 1 | 75 | 8000 | 1500 | 2.19 | 11.73 |
| 12 | 1 | 1 | 75 | 8000 | 2000 | 2.63 | 13.24 |
| 13 | 1 | 1 | 75 | 12000 | 1000 | 2.14 | 11.04 |
| 14 | 1 | 1 | 75 | 12000 | 1500 | 2.37 | 12.19 |
| 15 | 1 | 1 | 75 | 12000 | 2000 | 3.00 | 14.98 |
| 16 | 1 | 1 | 75 | 16000 | 1000 | 3.15 | 15.45 |
| 17 | 1 | 1 | 75 | 16000 | 1500 | 2.10 | 10.03 |
| 18 | 1 | 1 | 75 | 16000 | 2000 | 3.81 | 20.67 |
| 19 | 1 | 1 | 100 | 8000 | 1000 | 3.48 | 17.21 |
| 20 | 1 | 1 | 100 | 8000 | 1500 | 2.53 | 12.63 |

| **Number** *Broj* | **Heat treatment** *Toplinska modifikacija* | **Cutter type** *Vrsta glodala* | **Stepover, %** *Korak glodanja, %* | **Spindle speed, rpm** *Brzina vretena,* okr./min | **Feed, mm/min** *Posmična brzina,* mm/min | ***Ra*, µm** | ***Rz*, µm** |
|---|---|---|---|---|---|---|---|
| 21 | 1 | 1 | 100 | 8000 | 2000 | 2.73 | 15.44 |
| 22 | 1 | 1 | 100 | 12000 | 1000 | 3.12 | 16.60 |
| 23 | 1 | 1 | 100 | 12000 | 1500 | 2.95 | 14.99 |
| 24 | 1 | 1 | 100 | 12000 | 2000 | 3.30 | 16.18 |
| 25 | 1 | 1 | 100 | 16000 | 1000 | 3.07 | 14.35 |
| 26 | 1 | 1 | 100 | 16000 | 1500 | 1.42 | 7.26 |
| 27 | 1 | 1 | 100 | 16000 | 2000 | 3.79 | 17.85 |
| 28 | 1 | 2 | 50 | 8000 | 1000 | 1.76 | 9.71 |
| 29 | 1 | 2 | 50 | 8000 | 1500 | 1.89 | 9.99 |
| 30 | 1 | 2 | 50 | 8000 | 2000 | 3.71 | 18.58 |
| 31 | 1 | 2 | 50 | 12000 | 1000 | 2.12 | 10.78 |
| 32 | 1 | 2 | 50 | 12000 | 1500 | 2.67 | 14.53 |
| 33 | 1 | 2 | 50 | 12000 | 2000 | 2.68 | 14.57 |
| 34 | 1 | 2 | 50 | 16000 | 1000 | 2.49 | 14.41 |
| 35 | 1 | 2 | 50 | 16000 | 1500 | 3.36 | 17.93 |
| 36 | 1 | 2 | 50 | 16000 | 2000 | 3.09 | 14.38 |
| 37 | 1 | 2 | 75 | 8000 | 1000 | 2.21 | 11.61 |
| 38 | 1 | 2 | 75 | 8000 | 1500 | 2.56 | 12.76 |
| 39 | 1 | 2 | 75 | 8000 | 2000 | 2.78 | 14.39 |
| 40 | 1 | 2 | 75 | 12000 | 1000 | 3.08 | 15.09 |
| 41 | 1 | 2 | 75 | 12000 | 1500 | 2.76 | 14.27 |
| 42 | 1 | 2 | 75 | 12000 | 2000 | 2.98 | 15.50 |
| 43 | 1 | 2 | 75 | 16000 | 1000 | 3.41 | 16.10 |
| 44 | 1 | 2 | 75 | 16000 | 1500 | 3.23 | 15.48 |
| 45 | 1 | 2 | 75 | 16000 | 2000 | 3.15 | 16.56 |
| 46 | 1 | 2 | 100 | 8000 | 1000 | 2.43 | 11.90 |
| 47 | 1 | 2 | 100 | 8000 | 1500 | 2.55 | 12.57 |
| 48 | 1 | 2 | 100 | 8000 | 2000 | 3.35 | 17.36 |
| 49 | 1 | 2 | 100 | 12000 | 1000 | 2.61 | 13.50 |
| 50 | 1 | 2 | 100 | 12000 | 1500 | 3.17 | 15.36 |
| 51 | 1 | 2 | 100 | 12000 | 2000 | 2.73 | 13.26 |
| 52 | 1 | 2 | 100 | 16000 | 1000 | 2.53 | 12.99 |
| 53 | 1 | 2 | 100 | 16000 | 1500 | 2.92 | 14.79 |
| 54 | 1 | 2 | 100 | 16000 | 2000 | 2.16 | 12.33 |
| 55 | 2 | 1 | 50 | 8000 | 1000 | 1.80 | 9.91 |
| 56 | 2 | 1 | 50 | 8000 | 1500 | 3.24 | 15.42 |
| 57 | 2 | 1 | 50 | 8000 | 2000 | 3.71 | 16.63 |
| 58 | 2 | 1 | 50 | 12000 | 1000 | 2.77 | 12.57 |
| 59 | 2 | 1 | 50 | 12000 | 1500 | 3.33 | 15.19 |
| 60 | 2 | 1 | 50 | 12000 | 2000 | 3.12 | 14.91 |
| 61 | 2 | 1 | 50 | 16000 | 1000 | 2.28 | 11.74 |
| 62 | 2 | 1 | 50 | 16000 | 1500 | 3.29 | 16.21 |
| 63 | 2 | 1 | 50 | 16000 | 2000 | 3.27 | 15.66 |
| 64 | 2 | 1 | 75 | 8000 | 1000 | 3.10 | 15.89 |
| 65 | 2 | 1 | 75 | 8000 | 1500 | 2.15 | 10.04 |
| 66 | 2 | 1 | 75 | 8000 | 2000 | 2.88 | 12.77 |
| 67 | 2 | 1 | 75 | 12000 | 1000 | 3.00 | 13.42 |
| 68 | 2 | 1 | 75 | 12000 | 1500 | 2.84 | 1374 |
| 69 | 2 | 1 | 75 | 12000 | 2000 | 1.89 | 9.58 |
| 70 | 2 | 1 | 75 | 16000 | 1000 | 2.39 | 13.08 |
| 71 | 2 | 1 | 75 | 16000 | 1500 | 2.87 | 14.84 |
| 72 | 2 | 1 | 75 | 16000 | 2000 | 2.81 | 14.86 |
| 73 | 2 | 1 | 100 | 8000 | 1000 | 2.49 | 13.81 |
| 74 | 2 | 1 | 100 | 8000 | 1500 | 2.75 | 14.33 |
| 75 | 2 | 1 | 100 | 8000 | 2000 | 2.47 | 11.98 |

| **Number** *Broj* | **Heat treatment** *Toplinska modifikacija* | **Cutter type** *Vrsta glodala* | **Stepover, %** *Korak glodanja, %* | **Spindle speed, rpm** *Brzina vretena, okr./min* | **Feed, mm/min** *Posmična brzina, mm/min* | ***Ra*, µm** | ***Rz*, µm** |
|---|---|---|---|---|---|---|---|
| 76 | 2 | 1 | 100 | 12000 | 1000 | 1.98 | 1023 |
| 77 | 2 | 1 | 100 | 12000 | 1500 | 2.12 | 10.20 |
| 78 | 2 | 1 | 100 | 12000 | 2000 | 2.02 | 8.95 |
| 79 | 2 | 1 | 100 | 16000 | 1000 | 2.69 | 13.61 |
| 80 | 2 | 1 | 100 | 16000 | 1500 | 3.53 | 16.33 |
| 81 | 2 | 1 | 100 | 16000 | 2000 | 3.42 | 18.34 |
| 82 | 2 | 2 | 50 | 8000 | 1000 | 2.27 | 13.44 |
| 83 | 2 | 2 | 50 | 8000 | 1500 | 2.99 | 15.34 |
| 84 | 2 | 2 | 50 | 8000 | 2000 | 3.33 | 17.19 |
| 85 | 2 | 2 | 50 | 12000 | 1000 | 2.17 | 10.85 |
| 86 | 2 | 2 | 50 | 12000 | 1500 | 3.08 | 14.77 |
| 87 | 2 | 2 | 50 | 12000 | 2000 | 2.65 | 12.57 |
| 88 | 2 | 2 | 50 | 16000 | 1000 | 2.49 | 12.19 |
| 89 | 2 | 2 | 50 | 16000 | 1500 | 2.66 | 13.40 |
| 90 | 2 | 2 | 50 | 16000 | 2000 | 2.41 | 11.67 |
| 91 | 2 | 2 | 75 | 8000 | 1000 | 3.02 | 14.73 |
| 92 | 2 | 2 | 75 | 8000 | 1500 | 2.69 | 14.51 |
| 93 | 2 | 2 | 75 | 8000 | 2000 | 3.02 | 16.99 |
| 94 | 2 | 2 | 75 | 12000 | 1000 | 2.48 | 12.91 |
| 95 | 2 | 2 | 75 | 12000 | 1500 | 2.93 | 14.64 |
| 96 | 2 | 2 | 75 | 12000 | 2000 | 2.71 | 13.22 |
| 97 | 2 | 2 | 75 | 16000 | 1000 | 2.34 | 12.48 |
| 98 | 2 | 2 | 75 | 16000 | 1500 | 3.48 | 15.20 |
| 99 | 2 | 2 | 75 | 16000 | 2000 | 3.10 | 15.58 |
| 100 | 2 | 2 | 100 | 8000 | 1000 | 2.50 | 12.26 |
| 101 | 2 | 2 | 100 | 8000 | 1500 | 3.45 | 19.15 |
| 102 | 2 | 2 | 100 | 8000 | 2000 | 3.49 | 15.48 |
| 103 | 2 | 2 | 100 | 12000 | 1000 | 1.98 | 9.33 |
| 104 | 2 | 2 | 100 | 12000 | 1500 | 2.29 | 12.07 |
| 105 | 2 | 2 | 100 | 12000 | 2000 | 3.07 | 14.81 |
| 106 | 2 | 2 | 100 | 16000 | 1000 | 2.73 | 12.88 |
| 107 | 2 | 2 | 100 | 16000 | 1500 | 2.82 | 13.49 |
| 108 | 2 | 2 | 100 | 16000 | 2000 | 2.63 | 12.29 |

3,81 µm) in upcut milling cutter, 75 % stepover, 16000 rpm spindle speed and 2000 mm/min feed. The lowest roughness value for *Rz* (*Rz* = 7.26 µm) occurred in the untreated samples, cutter type 1, 100 % stepover, 16000 rpm spindle speed and 1500 mm/min feed. Upcut milling cutters push the chips upwards and thus ensure an excellent finish on the bottom side of the wood and wood- based materials. The highest roughness value for *Rz* (*Rz* = 20.67 µm) occurred in the untreated samples, cutter type 1, 75 % stepover, 16000 rpm spindle speed and 2000 mm/min feed (Table 2).

The lowest and highest *Ra* and *Rz* values occurred at 16000 rpm. Statistical analyses were performed by using MINITAB software for a confidence level of 95 % (e.g., significance level of 0.05). The obtained data were subjected to normality test.

As seen in Figure 4, the average *Ra* and *Rz* values obtained in average roughness measurements show normal distribution at 95% confidence level, since the *P* value is higher than 0.05 (*P* = 0.923 for *Ra*; *P* = 0.680 for *Rz*).

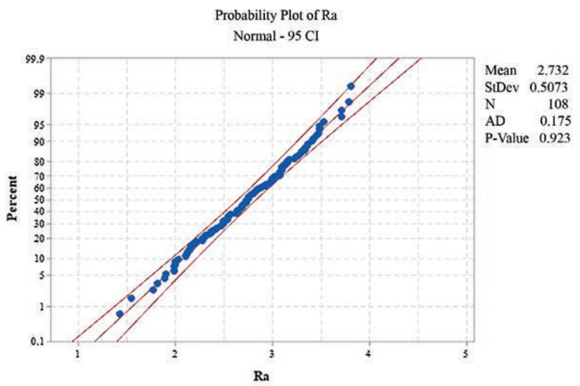
## 3.1 Surface roughness for *Ra*
## 3.1. Hrapavost površine za parametar *Ra*

Table 3 presents the results of analysis of variance for *Ra*.

According to the results of variance analysis for *Ra* at 95 % confidence level, it was seen that heat treatment (0.05 < *P* = 0.564), cutter type (0.05 < *P* = 0.520), stepover (0.05 < *P* = 0.751) and spindle speed (0.05 < *P* = 0.168) did not make a statistically significant difference, while feed (0.05 > *P* = 0.015) made a statistically significant difference (Table 3).

Figure 5 shows the interaction of heat treatment, cutter type, stepover, spindle speed and feed in terms of *Ra* in the main effect plot.

Higher *Ra* values occurred on the machined surfaces of heat-treated wood materials. Heat treatment



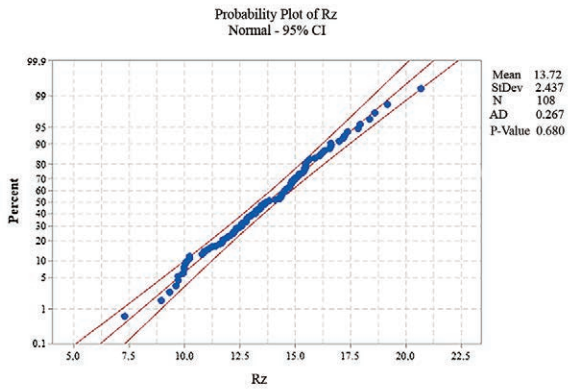




**Figure 4** Normality graphs for *Ra* and *Rz*
**Slika 4.** Normalizirani grafovi za *Ra* i *Rz*

**Table 3** Results of variance analysis (ANOVA) for *Ra*
**Tablica 3.** Rezultati analize varijance (ANOVA) za parametar *Ra*

| Source / *Izvor* | *DF* | Adj *SS* | Adj *MS* | *F* Value | *P* Value |
|---|---|---|---|---|---|
| Heat treatment / *toplinska modifikacija* | 1 | 0.0817 | 0.08173 | 0.33 | 0.564 |
| Cutter type / *vrsta glodala* | 1 | 0.1017 | 0.10171 | 0.42 | 0.520 |
| Stepover / *korak glodanja,* % | 2 | 0.1402 | 0.07009 | 0.29 | 0.751 |
| Spindle speed, rpm / *brzina vretena,* okr./min | 2 | 0.8872 | 0.44362 | 1.82 | 0.168 |
| Feed, mm/min / *posmična brzina,* mm/min | 2 | 2.1399 | 1.06995 | 4.38 | 0.015 |
| Error / *pogreška* | 99 | 24.1854 | 0.24430 | | |
| Total / *ukupno* | 107 | 27.5361 | | | |

caused the development of surface roughness (Budakci *et al*., 2011; Pelit, 2014). Heating wood causes a decrease in the volume and mass of the wood via increased stringiness, water loss from the structure of the wood because of the loss of hydroxyl groups, material losses in the cell wall, and the breakup of hemicelluloses (Budakci *et al*., 2011, Korkut and Kocaefe 2009).

With the increase in the compression ratio (from 0 % to 40 %), roughness values decreased.

Smoother surfaces (lower *Ra* values) were obtained with cutter 1. *Ra* values increased when the stepover was increased from 50 % to 75 %, and there was not much change in *Ra* values when it was increased from 75 % to 100 %. The lowest *Ra* values were observed at 50 % stepover rate. *Ra* values decrease when the spindle speed is increased from 8000 rpm to 12000 rpm. When the spindle speed was increased from 12000 rpm to 16000 rpm, a remarkable increase in *Ra*

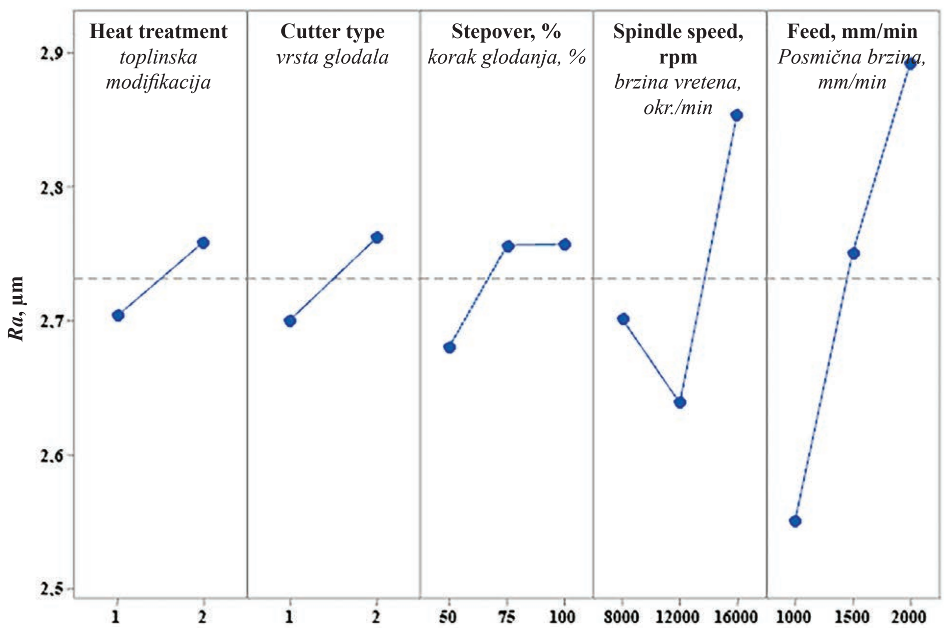



**Figure 5** Main effects plot of *Ra* in terms of heat treatment, cutter type, stepover, spindle speed and feed
**Slika 5.** Prikaz glavnih utjecaja na parametar *Ra* u smislu toplinske obrade, vrste glodala, koraka glodanja, brzine vretena i posmične brzine

values occurred. The *Ra* values increased linearly as the feed increased from 1000 mm/min to 2000 mm/min. When evaluated in general, the lowest mean *Ra* value according to main effect plot occurred in the untreated specimens, cutter type 1, 50 % stepover, 12000 rpm spindle speed and 1000 mm/min feed.

According to the literature, smoother surfaces are obtained at low feeds in wood and wood-based material experiments. Generally, as the feed increases, the roughness values increase (Bal, 2018; Ilter *et al.*, 2002; Davim vd., 2009; Sutcu and Karagoz, 2012; Karagoz, 2010; Isleyen and Karamanoglu, 2019; Hazir *et al.*, 2018; Pinkowski *et al.*, 2018; Aykac and Sofuoglu, 2021; Bal and Akcakaya, 2018; Pelit *et al.*, 2021, Sofuoglu *et al.*, 2022). The results obtained in terms of feed are similar to those found in the literature.

The increased spindle speed in the rotating cutters decreases the roughness values resulting in smoother surfaces (Aghakhani *et al.*, 2014; Aykac and Sofuoglu, 2021; Davim *et al.*, 2009; Hazir *et al.*, 2018; Isleyen ve Karamanoglu, 2019; Karagoz, 2010; Kaya *et al.*, 2017; Koc *et al.*, 2017; Patel and Patni, 2014; Rawangwong *et al.*, 2011; Sofuoglu, 2015; Sutcu and Karagoz, 2012; Sutcu and Karagoz, 2013). The larger the number of cutter marks per unit distance on the solid wood surface, the better the surfaces can be. (Malkocoglu and Ozdemir, 2006; Sofuoglu and Kurtoglu, 2014; Sofuoglu, 2008). Vibration may occur in the machine, although it varies depending on the CNC and wood type, if the spindle speed exceeds a specific value, and this may cause an increase in roughness. In addition, burning may occur on the wood surface of the material. It is assumed that the increase in *Ra* values when the speed is increased from 12000 rpm to 16000 rpm is due to vibration.

Figure 6 presents graphically the interactions of heat treatment, cutter type, stepover, spindle speed and feed in terms of *Ra*.

When the interaction graph is examined regarding heat treatment and cutter type, cutter 1 gives a lower *Ra* value than cutter 2 in the unheated specimens. In the heat-treated specimens, *Ra* values close to each other were obtained in both cutters. A smoother surface on the ground is obtained by evacuating the chips upwards of the Upcut milling cutter. The effect of the cutters was minimized with the changes in the chemical composition of wood, leading to mass loss of texture in the heat-treated wood material.

The *Ra* value increases linearly as the stepover increases in untreated specimens. The *Ra* value decreases inversely proportional to the increase in the stepover in heat-treated specimens.

In the machining of untreated specimens, the *Ra* value increases proportionally as the speed is increased from 8000 rpm to 16000 rpm. In the machining of heat-treated specimens, the *Ra* value decreases when the speed is increased from 8000 rpm to 12000 rpm, and the *Ra* value increases when the speed is increased from 12000 rpm to 16000 rpm.

### 3.1 Surface roughness for *Rz*
### 3.1. Hrapavost površine za parametar *Rz*

Table 4 presents the results of analysis of variance for *Rz*.

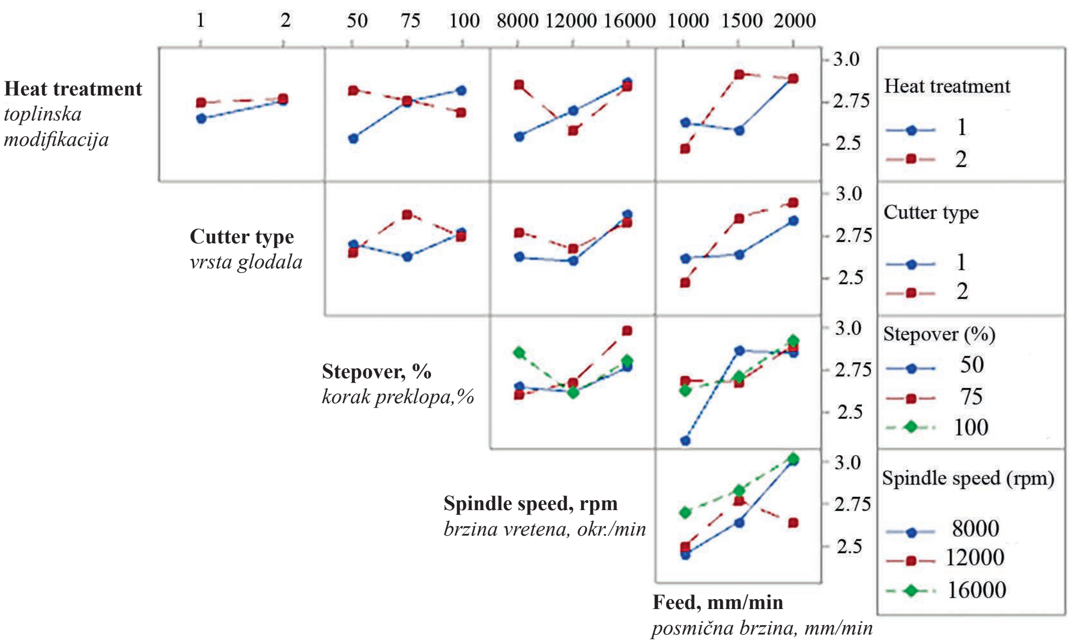



**Figure 6** Interactions of heat treatment, cutter type, stepover, spindle speed and feed in terms of *Ra*
**Slika 6.** Interakcije toplinske modifikacije, vrste glodala, koraka glodanja, brzine vretena i posmične brzine s parametrom *Ra*

**Table 4** Results of variance analysis (ANOVA) for *Rz*
**Tablica 4.** Rezultati analize varijance (ANOVA) za parametar *Rz*

| **Source** / *Izvor* | ***DF*** | **Adj *SS*** | **Adj *MS*** | ***F* Value** | ***P* Value** |
|---|---|---|---|---|---|
| Heat treatment / *toplinska modifikacija* | 1 | 0.361 | 0.3608 | 0.06 | 0.801 |
| Cutter type / *vrsta glodala* | 1 | 6.606 | 6.6064 | 1.17 | 0.283 |
| Stepover / *korak preklopa,* % | 2 | 3.524 | 1.7622 | 0.31 | 0.733 |
| Spindle speed, rpm / *brzina vretena,* okr./min | 2 | 21.557 | 10.7784 | 1.90 | 0.155 |
| Feed, mm/min / *posmična brzina,* mm/min | 2 | 42.703 | 21.3516 | 3.77 | 0.026 |
| Error / *pogreška* | 99 | 560.680 | 5.6634 | | |
| Total / *ukupno* | 107 | 635.432 | | | |

According to the results of variance analysis for *Rz* at 95 % confidence level, it was seen that heat treatment (0.05 < *P* = 0.801), cutter type (0.05 < *P* = 0.283), stepover (0.05 < *P* = 0.733) and spindle speed (0.05 < *P* = 0.155) did not make a statistically significant difference, while feed (0.05 > *P* = 0.026) made a statistically significant difference (Table 4).

Figure 7 shows the interaction of heat treatment, cutter type, stepover, spindle speed and feed in terms of *Rz* in the main effect plot.

Lower *Rz* values were obtained in the heat-treated samples and the machining with cutter 1. *Rz* values increased when the stepover was increased from 50 % to 75 % and decreased when it was increased from 75 % to 100 %. In terms of *Rz* values, a decrease occurred when the number of revolutions was increased from 8000 rpm to 12000 rpm, and an increase occurred when it was increased from 12000 rpm to 16000 rpm. *Rz* values increase proportionally as the feed is increased from 1000 mm/min to 2000 mm/min. According to the main effect graph, the lowest *Rz* value on average occurred in the heat-treated samples, cutter type 1, 50 % stepover, 12000 rpm spindle speed, and 1000 mm/min feed when evaluated in general.

Figure 8 presents graphically the interactions of heat treatment, cutter type, stepover, spindle speed and feed in terms of *Rz*.

The heat treated and untreated samples gave similar surface roughness values in both cutter types. However, cutter 1 gave lower *Rz* values in both types of samples. While the lowest *Rz* value was obtained at a 50 % stepover rate in unheated samples, it was obtained at a 100 % stepover rate in the heat-treated samples. When the stepover increased from 50 % to 100 %, the *Rz* value of the untreated samples increased, and of the heat-treated samples decreased. The *Rz* value increases linearly when the number of revolutions is increased from 8000 rpm to 16000 rpm in untreated samples. In heat-treated samples, the *Rz* value decreases when the speed increases from 8000 rpm to 12000 rpm

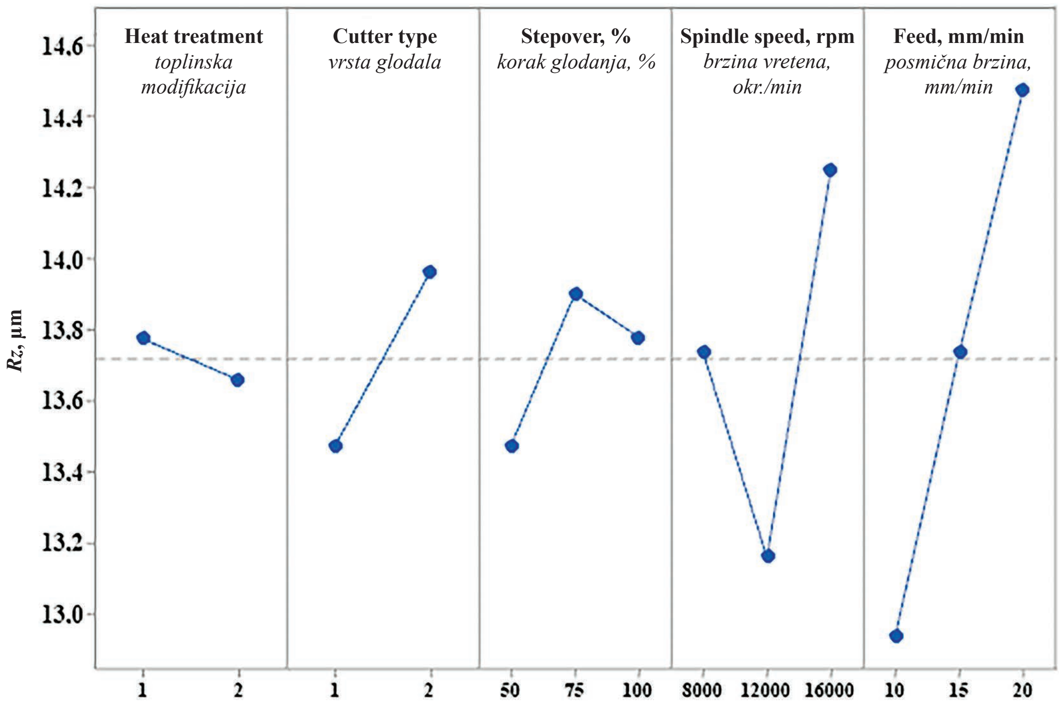



**Figure 7** Main effects plot of *Rz* in terms of heat treatment, cutter type, stepover, spindle speed and feed
**Slika 7.** Prikaz glavnih utjecaja na parametar *Rz* u smislu toplinske obrade, vrste glodala, koraka glodanja, brzine vretena i posmične brzine

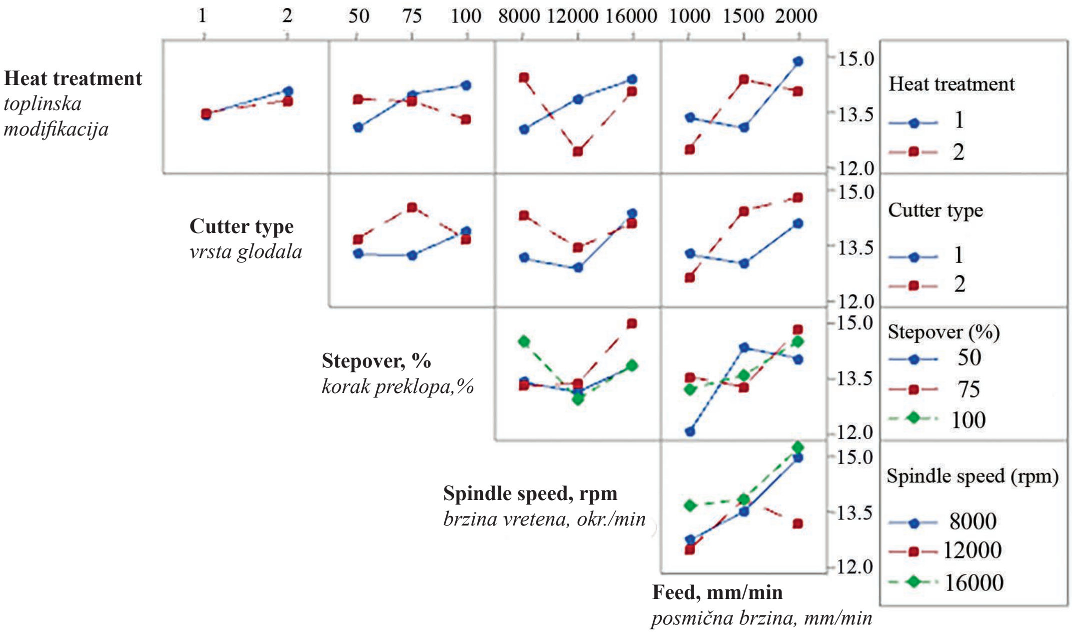



**Figure 8** Interactions of heat treatment, cutter type, stepover, spindle speed and feed in terms of *Rz*
**Slika 8.** Interakcije toplinske modifikacije, vrste glodala, koraka glodanja, brzine vretena i posmične brzine s parametrom *Rz*

and increases when the speed is increased from 12000 rpm to 16000 rpm. In general, the surface roughness increases as the feed increases in heat-treated and untreated samples. Low feed speeds (1000 mm/min) and low percentages of stepover (50 %) are recommended for a smoother surface.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

The summary of the general evaluation of roughness values obtained is given below.

In untreated wood materials, it is recommended to use low feed, upcut milling cutters due to the remachining of the same surface at low depth: low lateral step rate, low-speed parameters.

Lower Ra and Rz values were obtained on the surfaces processed with an upcut milling cutter. Upcut milling cutters push the chips upwards and thus ensure an excellent finish on the bottom side of the wood and wood-based material.

For low surface roughness values, a low stepover rate is preferred for untreated materials, and a high stepover rate is preferred for heat-treated materials.

It has been observed that the feed is the most critical parameter affecting the surface roughness.

As the feed increases, the surface roughness values increase.

Surface roughness increases as the number of revolutions increases in untreated samples.

In heat-treated samples, as the number of revolutions increases in the 8000-12000 rpm range, the surface roughness decreases, and its positive effect disappears (probably caused by vibration in the CNC due to high speed) after 12000 revolutions.


## Acknowledgements – Zahvala

This work is derived from the master's thesis titled "Effect of heat treatment on surface quality in wood machining" conducted in Kutahya Dumlupinar University, Institute of Graduate Education.


## 5 REFERENCES
## 5. LITERATURA


1. Aykac, E.; Sofuoglu, S. D., 2021: Investigation of the effect of machining parameters on surface quality in Bamboo. Tehnički vjesnik, 28 (2): 684-688. https://doi.org/10.17559/TV-20200102202928
2. Adela Salca, E. A.; Hiziroglu, S., 2014: Evaluation of hardness and surface quality of different wood species as function of heat treatment. Materials and Design, 62: 416-423. https://doi.org/10.1016/j.matdes.2014.05.029
3. Aghakhani, M.; Khazaeian, A.; Madhoushi, M., 2013: Different CNC machining condition of paulownia wood by CNC; Influence on the Abbott roughness parameters. Iranian Journal of Wood and Paper Science Research, 8 (2): 291-312.
4. Akman, M., 2018: A mechanische properties of heat treated Anatolian black pine and investigation of soil properties in growing area. Master's Thesis, Kutahya Dumlupinar University, Graduate School of Natural and Applied Sciences, Kutahya (in Turkey).
5. Altun, S.; Esmer, M., 2017: The effect of heat treatment on the surface roughness and varnish adhesion of wood. Journal of Polytechnic, 20 (1): 231-239.
6. Atar, M.; Yalinkilic, A. C.; Keskin, H., 2019: Impact of heat treatment on the exchange of color in varnished wood materials. Journal of Polytechnic, 22 (2): 407-413. https://doi.org/10.2339/politeknik.404008

7. Ayadi, N.; Lejeune, F.; Charrier, F; Charrier, B.; Merlin, A., 2003: Color stability of heat-treated wood during artificial weathering. Holz als Roh- und Werkstoff, 61: 221-226. https://doi.org/10.1007/s00107-003-0389-2
8. Ayata, U., 2020: Determination of some technological properties in Ayous wood and its color and glossiness properties after heat-treatment. Furniture and Wooden Material Research Journal, 3 (1): 22-33. https://doi.org/10.33725/mamad.724596
9. Ayata, U.; Cakicier, N., 2018: Impact of accelerated UV aging on the surface adhesion strength of water-based varnish applied and heat-treated (ThermoWood) some wood species. Journal of Polytechnic, 21 (3): 611-619. https://doi.org/10.2339/politeknik.389600
10. Ayata, U.; Gurleyen, T.; Gurleyen, L.; Cakicier, N., 2018: Determination of surface roughness parameters of heat-treated and untreated scotch pine, oak and beech woods. Furniture and Wooden Material Research Journal, 1 (1): 46-50. https://doi.org/10.33725/mamad.433945
11. Ayrilmis, N.; Kariz, M.; Kwon, J. H.; Kitek Kuzman, M., 2019: Surface roughness and wettability of surface densified heat-treated norway spruce (*Picea abies* L. Karst.). Drvna industrija, 70 (4): 377-382. https://doi.org/10.5552/drvind.2019.1852
12. Bal, B. C., 2018: The effects of some tool paths adjustments of CNC machines on surface roughness and processing time of fiberboards. Furniture and Wooden Material Research Journal, 1 (1): 21-30. https://doi.org/10.33725/mamad.427588
13. Bal, B. C.; Akcakaya, E., 2018: The effects of step over, feed rate and finish depth on the surface roughness of fiberboard processed with CNC machine. Furniture and Wooden Material Research Journal, 1 (2): 86-93. https://doi.org/10.33725/mamad.481278
14. Bal, B. C.; Kilavuz, M., 2021: Investigation of the effect of heat treatment in vacuum atmosphere on the mechanical properties of poplar wood. Kahramanmaras Sutcu Imam University Journal of Engineering Sciences, 24 (3): 146-153. https://doi.org/10.17780/ksujes.886540
15. Baysal, E.; Kart, S.; Altay, C.; Toker, H.; Turkoglu, T.; Cibo, C., 2018: Determination of color stability of heated and varnished wood after weathering. Mesleki Bilimler Dergisi (MBD), 7 (2): 142-152.
16. Budakci, M.; Ilce, A. C.; Korkut, D. S.; Gurleyen, T., 2011: Evaluating the surface roughness of heat-treated wood cut with different circular saws. BioResources, 6 (4), 4247-4258.
17. Budakci, M.; Ilce, A. C.; Gurleyen, T.; Utar, M., 2013: Determination of the surface ughness of heat-treated wood materials planed by the cutters of a horizontal milling machine. BioResource, 8 (3): 3189-3199. https://doi.org/10.15376/biores.8.3.3189-3199
18. Çakicier, N., 2018: Determination of surface roughness against the effect of accelerated UV aging on water based varnish applied and heat treated wood materials according to Thermowood method. GUSTIJ, 8 (1): 122-134. https://doi.org/10.17714/gumusfenbil.314186
19. Davim, J. P.; Clemente, V. C.; Silva, S., 2009: Surface roughness aspects in milling MDF (medium density fibreboard). International Journal of Advanced Manufacturing Technology, 40 (1-2): 49-55. https://doi.org/10.1007/s00170-007-1318-z
20. Dobrzynski, M.; Orlowski, K. A.; Biskup, M., 2019: Comparison of surface quality and tool-life of glulam window elements after planing. Drvna industrija, 70 (1), 7-18. https://doi.org/10.5552/drvind.2019.1741
21. Doruk, S.; Altınok, M.; Percin, O., 2014: The effects of heat treatment on some physical and mechanical properties of wood material. Suleyman Demirel University Journal of Natural and Applied Sciences, 14 (3): 262-270.
22. Duzkale Sozbir, G.; Bektas, I., 2019: Investigation of biological durability of heat treated and densified poplar wood against brown rot fungi. Turkish Journal of Forestry, 20: 421-426. https://doi.org/10.18182/tjf.636671
23. Efe, F. T.; Bal, B. C., 2016: Yüksek sıcaklıkta ısıl işlem görmüş kızılçam (*Pinus brutia* Ten.) odununun sertlik değerlerinde meydana gelen değişmeler (in Turkish). In: Proceedings of 1st International Conference on Engineering Technology and Applied Sciences Afyon Kocatepe University, Turkey 21-22 April 2016, pp. 79-86.
24. Ergin, U., 2021: Effect of heat treatment on surface quality in wood machining. Master's Thesis, Kutahya Dumlupinar University, Institute of Graduate Education, Turkey.
25. Esen, R.; Ozcan, C., 2012: The effects of heat treatment on shear strength of oak (*Quercus petraea* L.) wood. Turkish Journal of Forestry, 13 (2): 150-154.
26. Esteves, B.; Marques, A. V.; Domingos, I.; Pereira, H., 2007: Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood. Wood Science and Technology, 41 (3): 193-207. https://doi.org/10.1007/s00226-006-0099-0
27. Esteves, B.; Pereira, H., 2009: Wood modification by heat treatment: A review. BioResources, 4 (1): 370-404.
28. Gong, M.; Lamason, C.; Li, L., 2010: Interactive effect of surface densification and post-heat-treatment on aspen wood. Journal of Materials Processing Technology, 210 (2): 293-296. https://doi.org/10.1016/j.jmatprotec.2009.09.013
29. Gurau, L.; Irle, M., 2017: Surface roughness evaluation methods for wood products: A review. Current Forestry Reports, 3: 119-131. https://doi.org/10.1007/s40725-017-0053-4
30. Gurleyen, T.; Guler, C.; Unsal, O., 2017: Effect of heat treatment (Thermowood) on janka hardness resistance applied to some wood types. Journal of Advanced Technology Sciences, 6 (3): 876-888.
31. Gurleyen, T.; Ayata, U.; Gurleyen, L.; Esteves, B., 2018: Determination of glossiness and color values on ash, beech, red-bud maple, and red pine wood species heat-treated (Thermowood method). El-Cezeri, 5 (2): 566-575. https://doi.org/10.31202/ecjse.372941
32. Gunduz, G.; Korkut, S.; Korkut, D. S., 2008: The effects of heat treatment on physical and technological properties and surface roughness of Camiyanı black pine (*Pinus nigra* Arn. subsp. pallasiana var. pallasiana) wood. Bioresource Technology, 99: 2275-2280. https://doi.org/10.1016/j.biortech.2007.05.015.
33. Hacibektasoglu, M.; Campean, M.; Ispas, M.; Gurau, L., 2017: Influence of heat treatment duration on the machinability of beech wood (*Fagus sylvatica* L.) by planning. BioResource, 12 (2): 2780-2791. https://doi:10.15376/biores.12.2.2780-2791
34. Hakkou, M.; Pétrissans, M.; El Bakali, I.; Gerardin, P.; Zoulalian, A., 2005a: Wettability changes and mass loss during heat treatment of wood. Holzforschung, 59: 35-37. https://doi.org/10.1515/HF.2005.006
35. Hakkou, M.; Pétrissans, M.; Zoulalian, A.; Gérardin, P., 2005b: Investigation of wood wettability changes during heat treatment on the basis of chemical analysis. Polymer Degradation and Stability, 89 (1): 1-5. https://doi.org/10.1016/j.polymdegradstab.2004.10.017

36. Hazir, E.; Erdinler, E. S.; Koc, K. H., 2018: Optimization of CNC cutting parameters using design of experiment (DOE) and desirability function. Journal of Forestry Research, 29 (5): 1423-1434. https://doi.org/10.1007/s11676-017-0555-8
37. Icel, B.; Simsek, Y. 2017: Evaluations on microscopic images of heat treated spruce and ash wood. Süleyman Demirel University Journal of Natural and Applied Sciences, 21 (2), 414-420. https://doi.org/10.19113/sdufbed.17217
38. Icel, B.; Beram, A., 2017: Effects of industrial heat treatment on some physical and mechanical properties of iroko wood. Drvna industrija, 68 (3): 229-239. https://doi.org/10.5552/drind.2017.1720
39. Ispas, M.; Gurau, L.; Campean, M.; Hacibektasoglu, M.; Racasan, S., 2016: Milling of heat-treated beech wood (*Fagus sylvatica* L.) and analysis of surface quality. BioResource, 11 (4): 9095-9111. https://doi: 10.15376/biores.11.4.9095-9111
40. ***ISO 468, 1982: Surface roughness – Parameters, their values and general rules for specifying requirements, International Organization for Standardization, Geneva, Switzerland.
41. ***ISO 13061-1, 2014: Physical and mechanical properties of wood – Test methods for small clear wood specimens. Part 1: Determination of moisture content for physical and mechanical tests, International Organization for Standardization, Geneva, Switzerland.
42. ***ISO 13061-2, 2014: Physical and mechanical properties of wood – Test methods for small clear wood specimens. Part 2: Determination of density for physical and mechanical tests, International Organization for Standardization, Geneva, Switzerland.
43. ***ISO 3274, 2005: Geometrical Product Specifications (GPS) – Surface texture: Profile method – Nominal characteristics of contact (stylus) instruments, International Organization for Standardization, Geneva, Switzerland.
44. ***ISO 4287, 1997: Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters, International Organization for Standardization, Geneva, Switzerland.
45. Ilter, E.; Camliyurt, C.; Balkiz, O. D., 2002: Researches on the determination of the surface roughness values of Bornmullerian fir (*Abies bornmülleriana* Mattf.). Central Anatolia Forestry Research Institute, No. 181.
46. Isleyen, U. K.; Karamanoglu, M., 2019: The Influence of Machining Parameters on Surface Roughness of MDF in Milling Operation. BioResources, 14 (2): 3266-3277. https://doi.org/10.15376/biores.14.2.3266-3277
47. Karamanoglu, M.; Kaymakci, A., 2018: Effect of hygrothermal aging on color and hardness properties of heat treated chestnut wood. Furniture and Wooden Material Research Journal, 1 (1), 31-37. https://doi.org/10.33725/mamad.429726
48. Kaya, M.; Imirzi, H. O.; Sogutlu, C., 2017: Effect of cutter types, spindle speed and feed rate on the surface quality in CNC milling. In: Proceedings of the XXVIII$^{th}$ International Conference: Research for Furniture Industry, 21-22 September 2017, Poznan, Poland.
49. Kilincarslan, S.; Simsek, Y., 2020: The effect of heat treatment application on wettability properties of wood materials. Journal of Engineering Sciences and Design, 8 (2), 460-466. https://doi.org/10.21923/jesd.570067
50. Karagoz, U., 2010: Investigation of machining parameters on the surface quality in CNC routing wood and wood-based materials. Master's Thesis, Suleyman Demirel University, Graduate School of Natural and Applied Sciences, Isparta, Turkey.
51. Koc, K. H.; Erdinler, E. S.; Hazir, E.; Ozturk, E., 2017: Effect of CNC application parameters on wooden surface quality. Measurement, 107: 12-18. https://doi.org/10.1016/j.measurement.2017.05.001
52. Korkut, D. S.; Guller, B., 2008: The effects of heat treatment on physical properties and surface roughness of red-bud maple (Acer trautvetteri Medw.) wood. Bioresource Technology, 99 (8): 2846-2851. https://doi.org/10.1016/j.biortech.2007.06.043
53. Korkut, S., Akgul, M.; Dundar, T., 2008: The effects of heat treatment on some technological properties of Scots pine (*Pinus sylvestris* L.) wood. Bioresource Technology, 99 (6): 1861-1868. https://doi.org/10.1016/j.biortech.2007.03.038
54. Korkut, S., Kocaefe, D., 2009: Effect of heat treatment on wood properties. Duzce University Journal of Forestry, 5 (2), 11-34.
55. Korkut, S.; Alma, M. H.; Elyildirim, Y. K., 2009: The effects of heat treatment on physical and technological properties and surface roughness of European Hophornbeam (*Ostrya carpinifolia* Scop.) wood. African Journal of Biotechnology, 8 (20).
56. Kvietková, M.; Gašparík, M.; Gaff, M., 2015: Effect of thermal treatment on surface quality of beech wood after plane milling. BioResources, 10 (3), 4226-4238.
57. Lunguleasa, A.; Ayrilmis, N.; Spirchez, C.; Ozdemir, F., 2018: Investigation of the effects of heat treatment applied to beech plywood. Drvna industrija, 69 (4): 349-355. https://doi.org/10.5552/drind.2018.1768
58. Malkocoglu, A.; Ozdemir, T., 2006: The machining properties of some hardwoods and softwoods naturally grown in Eastern Black Sea Region of Turkey. Journal of Materials Processing Technology, 173 (3): 315-320. https://doi.org/10.1016/j.jmatprotec.2005.09.031
59. Mburu, F.; Dumarcay, S.; Bocquet, J. F.; Petrissans, M.; Gérardin, P., 2008: Effect of chemical modifications caused by heat treatment on mechanical properties of Grevillea robusta wood. Polymer Degradation and Stability, 93 (2): 401-405. https://doi.org/10.1016/j.polymdegradstab.2007.11.017
60. Patel, D. H.; Patni, V. N., 2014: An investigation effect of machining parameters on CNC router. International Journal of Engineering Development and Research, 2: 1583-1587.
61. Pelit, H., 2014: The effects of densification and heat treatment to finishing process with some technological properties of eastern beech and scots pine. PhD Thesis, Gazi University, Ankara, Turkey.
62. Pelit, H., 2017: The effect of different wood varnishes on surface color properties of heat treated wood materials. Journal of the Faculty of Forestry Istanbul University, 67 (2): 262-274. https://doi.org/10.17099/jffiu.300010
63. Pelit, H.; Korkmaz, M.; Budakci, M., 2021: Surface roughness of thermally treated wood cut with different parameters in CNC router machine. BioResources, 16 (3): 5133-5147. https://doi.org/10.15376/biores.16.3.5133-5147
64. Percin, O.; Ayan, S., 2012: Determination of screw withdrawal strength in heat treated wood material. Journal of Advanced Technology Sciences, 1 (1): 57-68.
65. Percin, O.; Uzun, O., 2014: Determination of bonding strength in heat treated some wood materials. Turkish Journal of Forestry, 15 (1): 72-76.
66. Percin, O.; Altunok, M., 2019: The effects of heat treatment, wood species and adhesive types on screw with-

drawal strength of laminated veneer lumbers. Kastamonu University Journal of Forestry Faculty, 19 (2): 152-163. https://doi.org/10.17475/kastorman.625819
67. Percin, O., Sadiye Yasar, S.; Altunok, M.; Uzun, O., 2017: Determination of screw withdrawal resistance of some heat-treated wood species. Drvna industrija, 68 (1): 61-68. https://doi.org/10.5552/drind.2017.1630
68. Pétrissans, M.; Gérardin, P.; Bakali, I. El.; Serraj, M., 2003: Wettability of Heat-Treated Wood. Holzforschung 57 (3): 301-307. https://doi.org/10.1515/HF.2003.045
69. Pinkowski, G.; Szymański, W.; Krauss, A.; Stefanowski, S., 2018: Effect of sharpness angle and feeding speed on the surface roughness during milling of various wood species. BioResources, 13 (3): 6952-6962. https://doi.org/10.15376/biores.13.3.6952-6962
70. Rawangwong, S.; Chatthong, J.; Rodjananugoon, J.; Boonchouytan, W., 2011: A study of proper conditions in face milling palmyra palm wood by computer numerical controlled milling machine. Silpakorn University Science and Technology Journal, 5 (2): 33-39. https://doi.org/10.14456/sustj.2011.7
71. Sahin, H. I.; Guler, C., 2018: Effect of heat treatment on the dimensional stability of ash (*Fraxinus angustifolia* Vahl.) wood/Disbudak (*Fraxinus angustifolia* Vahl.) odununun boyutsal stabilizasyonu uzerine isil islemin etkisi. Forestist, 68 (1): 42-52. https://doi.org/10.5152/forestist.2018.00
72. Sahin Kol, H.; Aysal Keskin, S.; Gunduz Vaydogan, K., 2017: Some surface characteristic of artifically weathered heat-treated wood. Journal of Advanced Technology Sciences, 6 (3): 831-838.
73. Sandak, J.; Orlowski, K. A.; Sandak, A.; Chuchala, D.; Taube, P., 2020: On-line measurement of wood surface smoothness. Drvna industrija, 71 (2): 193-200. https://doi.org/10.5552/drvind.2020.1970
74. Senol, S., 2018: Determination of physical, mechanical and technological properties of some wood materials treated with thermo-vibro-mechanical (TVM) process. PhD Thesis, Duzce University, Graduate School of Natural and Applied Sciences, Duzce, Turkey.
75. Senol, S.; Budakci, M., 2016: Mechanical wood modification methods. Mugla Journal of Science and Technology, 2 (2): 53-59. https://doi.org/10.22531/muglajsci.283619
76. Sofuoglu, S. D.; Kurtoglu, A., 2014: Some machining properties of 4 wood species grown in Turkey. Turkish Journal of Agriculture and Forestry, 38 (3): 420-427. https://doi.org/10.3906/tar-1304-124
77. Sofuoglu, S. D., 2008: Effects of wood machining properties of some native species on surface quality. PhD Thesis, Istanbul University, Institute of Graduate Studies In Sciences, Istanbul, Turkey.
78. Sofuoglu, S. D.; Tosun, M.; Atılgan, A., 2022: Determination of the machining characteristics of Uludağ fir (Abies nordmanniana Mattf.) densified by compressing, Wood Material Science & Engineering. https://doi.org/10.1080/17480272.2022.2080586
79. Sutcu, A.; Karagoz, U., 2012: Effect of machining parameters on surface quality after face milling of MDF. Wood Research, 57 (2): 231-240.
80. Topal, E. S., 2009: The role of stepover ratio in prediction of surface roughness in flat and milling, International Journal of Mechanical Sciences, 51 (11-12): 782-789. https://doi.org/10.1016/j.ijmecsci.2009.09.003.
81. Ulay, G.; Korkut, S.; Cakicier, N., 2014: Evaluation of the studies on the effect of heat treatment on wooden material in Turkey. Duzce University Journal of Forestry, 10 (1): 37-47.
82. Yasar, S., 2009: A study on color change in Brutian pine (*Pinus brutia* Ten.)) extractives exposed to heat treatment. Turkish Journal of Forestry, 10 (1): 95-100.
83. Yildiz, S., 2002: Physical, mechanical, technological and chemical properties of beech and spruce wood treated by heating. Ph. D. Thesis, Karadeniz Technical University, Trabzon, Turkey.
84. Yildiz, S.; Gezer, E. D.; Yildiz, U. C., 2006: Mechanical and chemical behavior of spruce wood modified by heat. Building and environment, 41 (12): 1762-1766. https://doi.org/10.1016/j.buildenv.2005.07.017
85. Zaman, A.; Alén, R.; Kotilainen, R. 2000: Thermal behavior of scots pine (*Pinus Sylvestris*) and silver birch (*Betula Pendula*) at 200-230. Wood and Fiber Science, 32 (2): 138-143.

**Corresponding address:**

**SAIT DUNDAR SOFUOGLU**
Kutahya Dumlupinar University, Faculty of Simav Technology, Department of Wood Works Industrial Engineering, 43500 Simav – Kutahya, TURKEY, e-mail: sdundar.sofuoglu@dpu.edu.tr

İbrahim Karaman[1], Kenan Kılıç[2,3], Cevdet Söğütlü[4]

# Prediction of Adhesion Strength of Some Varnishes Using Soft Computing Models

# Predviđanje adhezivne čvrstoće nekih lakova uz pomoć modela mekog računalstva

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 22. 3. 2022.
Accepted – prihvaćeno: 29. 11. 2022.
UDK: 004.032.26; 674.07
https://doi.org/10.5552/drvind.2023.0029



**ABSTRACT** • *The purpose of this study was to predict the adhesion strength of the varnish, which is applied as a protective coating/finish on the surface of wooden material using soft computing models. In this study, the soft computing approaches were applied to oak (Quercus Petrea L.), chestnut (Castanea sativa M.), and scotch pine (Pinus sylvestris L.) with water-based, polyurethane, and acrylic varnishes. The adhesion strength of the varnish was determined in accordance with the Turkish Standard Institute-24624 and ASTM D4541. The outcome of the experiment was used to develop artificial neural network (ANN) and fuzzy logic (FL) prediction models. The total number of 360 data points was split as 80 % of training and 20 % of test for the model development. During the application of the ANN, 6 features were used as an input, while the adhesion strength was used as an output of the model. The coefficient of determination values ($R^2$) for training and testing in the ANN models were 0.9939 and 0.9580, respectively. In the case of the ANFIS model, $R^2$ values for training and testing were 0.9917 and 0.9929, respectively. Considering the MAPE, RMSE, and $R^2$ values obtained from the results of both training and test values, it can be concluded that the ANFIS model showed a more successful performance in estimating varnish adhesion strength. Therefore, ANN and ANFIS have the potential to provide time and cost-efficient benefits in estimating wood adhesion strength.*

**KEYWORDS:** *artificial neural network, fuzzy logic, adhesion strength, wood, varnish*

**SAŽETAK** • *Cilj ovog istraživanja bio je uz pomoć modela mekog računalstva predvidjeti adhezivnu čvrstoću laka koji se nanosi kao zaštitni premaz na površinu drvnog materijala. Pristup mekog računalstva primijenjen je na uzorcima hrastovine (Quercus Petrea L.), kestenovine (Castanea sativa M.) i borovine (Pinus sylvestris L.) lakiranima vodenim poliuretanskim i vodenim akrilnim lakom. Adhezivna čvrstoća laka određena je prema normama TS EN 24624 i ASTM D4541. Rezultati istraživanja iskorišteni su za razvoj modela predviđanja umjetne neuronske mreže (ANN) i neizrazite logike (FL). Od ukupno 360 podatkovnih točaka razvoja modela 80 % njih upotrijebljeno je za trening, a 20 % za testiranje. Tijekom primjene ANN-a šest je svojstava poslužilo kao ulazna varijabla, dok je adhezivna čvrstoća primijenjena kao izlazna varijabla modela. Vrijednosti koeficijenta determinacije ($R^2$) za trening i testiranje u ANN modelima bile su 0,9939 i 0,9580. Pri primjeni ANFIS modela*

[1] Author is researcher at Yozgat Bozok University, Yozgat Vocational School, Computer Technology Department, Yozgat, Turkey. https://orcid.org/0000-0001-8396-9797
[2] Author is researcher at Gazi University, Graduate School Of Natural And Applied Sciences, Department of Wood Products Industrial Engineering, Ankara, Turkey. https://orcid.org/0000-0003-1607-9545
[3] Author is researcher at Yozgat Bozok University, Yozgat Vocational School, Design Department, Yozgat, Turkey. https://orcid.org/0000-0003-1607-9545
[4] Author is researcher at Gazi University, Faculty of Technology, Department of Wood Products Industrial Engineering, Ankara, Turkey. https://orcid.org/0000-0002-9359-1633

*$R^2$ vrijednosti za trening i testiranje iznosile su 0,9917 i 0,9929. Uzimajući u obzir vrijednosti MAPE, RMSE i $R^2$, dobivene iz rezultata treninga i testiranja, moguće je zaključiti da se ANFIS model pokazao uspješnijim u procjeni adhezivne čvrstoće laka. Stoga se može reći da modeli ANN i ANFIS mogu imati vremenske i troškovne prednosti u procjeni adhezivne čvrstoće na drvu.*

**KLJUČNE RIJEČI:** *umjetna neuronska mreža, neizrazita logika, adhezivna čvrstoća, drvo, lak*

## 1 INTRODUCTION
## 1. UVOD

The wooden material is defined as an indoor natural reinforcement engineering material as it can be processed and has high mechanical strength (Özgenç *et al*., 2022; Döngel *et al*., 2008; Hauptmann *et al*., 2013). Materials composed of wood are readily susceptible to physical and mechanical effects. Therefore, to increase the durability and aesthetics of the wooden material, synthetic and natural-based varnishes and resins are applied to the surface of the material (Kılıç, 2009). Moreover, the structure of the varnish and the heterogeneous property of the wooden material influence the adhesion strength of the varnish layers (Vitosyte *et al*., 2012; Marra, 1992). In the literature, there are several types of research about the adhesion strength of the varnish. According to the literature review, the adhesion strength of the water-based varnish is low while that of the polyurethane-based varnish is high (Vitosyte *et al*., 2012; Marra, 1992; Sönmez *et al*., 2004). Therefore, based on the previous research, the type of varnish is considered an important factor affecting the adhesion strength (Kılıç and Söğütlü, 2020; Söğütlü *et al*., 2016).

For that reason, the evaluation of the adhesion strength is important in terms of the analysis of wooden material-based product life cycle. Moreover, the adhesion strength is predicted using an artificial neural network (ANN) to decrease computation time and save energy for experimental evaluations. ANN is one of the artificial intelligence models used to solve complex and non-linear problems. The ANN consists of neurons and nodes that are activated by an activation function. Furthermore, the ANN can work with multi-input and output variables and create a relationship between non-linear parameters. The ANN is preferred rather than traditional statistical approaches because it is widely used in various engineering fields (Tiryaki *et al*., 2014b; Özşahin, 2013; Paliwal and Kumar, 2009). The ANNs and fuzzy logic (FL) have high computation ability for regression analysis and prediction compared to the traditional models (Kumar and Thakur, 2012; Londhe and Deo, 2003). Previous studies have developed the use of ANNs based on the properties of wooden materials. Budakci and Akkuş (2011) provided an ANN model to evaluate the average adhesion strength of the wooden material and laminated flooring. Tiryaki *et al*. (2014b) presented the ANN model for model surface roughness of wood in the machining process. Ceylan (2008) expressed an ANN model for the desiccation of wood, and Yang *et al*. (2015) demonstrated an ANN model to show the mechanical properties of heat-treated wooden material. Tiryaki *et al*. (2016) applied multilayered networks to predict the bonding strength of the different wooden materials. Bardak *et al*. (2016) estimated the bonding of wood materials with ANN models at four different temperatures depending on different pressing conditions. Tiryaki *et al*. (2014a) used different temperatures with various wooden materials to estimate the compression strength through the ANNs. However, Fuzzy Logic (FL) is widely used in household electrical appliances, industrial products, and manufacturing engineering (Mendel, 1995). According to the previous studies, several types of research have been implemented using FL. Yapıcı *et al*. (2009) presented an FL classification model to predict the tensile strength and elastic modulus of the flakeboard. Furthermore, Cha and Pearson, (1994) improved a model to estimate the elastic module of the laminated veneer lumber.

This study predicts the adhesion strength of different varnish types using ANN and FL models. During the experiment, different variables were used for these materials for the varnish adhesion strength test. In this study, varnish adhesion strength was estimated using ANN and ANFIS through data obtained in the experiments. By using the developed ANN model and FL methods, varnish adhesion strength was estimated, and the models were compared with the regression method.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Materials
### 2.1. Materijali

In this study, three types of wooden material were used for prediction models, namely scotch pine, chestnut and oak. According to the age period, both 100 years and new (young age) oak (*Quercus Petrea L.*), chestnut (*Castanea sativa M.*) and scotch pine (*Pinus sylvestris L.*) were selected as experimental materials. After the material selection, water-based varnish, polyurethane, and acrylic varnish were applied to the surface of the samples.

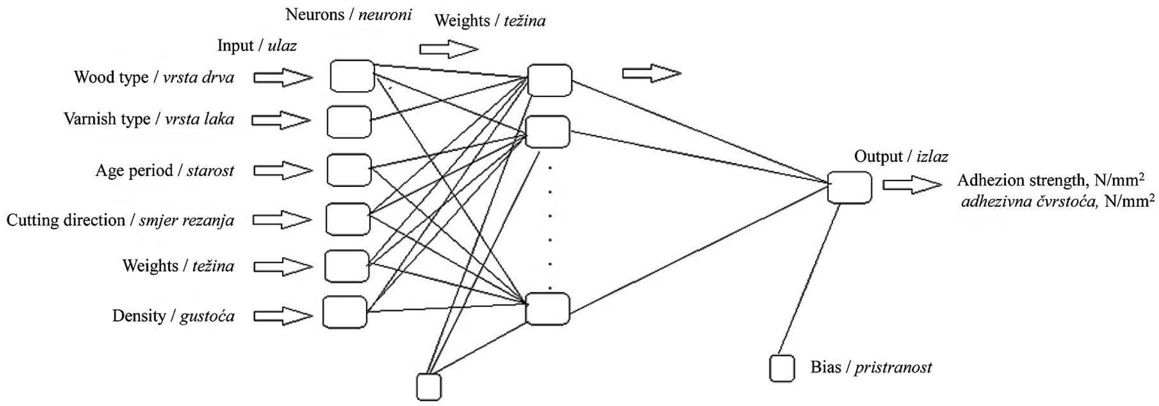



**Figure 1** Model of adhesion strength neural network
**Slika 1.** Model neuronske mreže adhezivne čvrstoće

## 2.2 Methods
## 2.2. Metode
### 2.2.1 Neural Networks
### 2.2.1. Neuronske mreže

Artificial intelligence (AI) is commonly used in different engineering disciplines with different parameters to interpret the output (dependent) parameter(s). In this study, commonly accepted artificial neural networks (ANN) and FL models were employed. Moreover, different models were implemented to predict the adhesion strength with various input features such as wood type, age period, cutting direction, varnish type, weight, and density. The models were created in Matlab R2016a software for predicting the adhesion strength. As a result of the test process, the actual (measured) values of adhesion strength and the predicted values were obtained and compared with each other. The Mean Square Error (*MSE*), Mean Squared Error (MSE) and Mean Absolute Percentage Error (*MAPE*) were calculated according to Eqs. 1–3 below.

$$RMSE=\sqrt{\frac{\sum_{t=1}^{n}(A_t-F_t)^2}{n}} \tag{1}$$

$$MSE=\frac{\sum_{t=1}^{n}(A_t-F_t)^2}{n} \tag{2}$$

$$MAPE=\frac{\sum_{t=1}^{n}\left|\frac{A_t-F_t}{A_t}\right|}{n}\cdot 100 \tag{3}$$

Where $n$ is the number of data, $A_t$ is the actual value, and $F_t$ is the predicted value.

In this study, feed-forward backprop, cascade feed-forward backprop, elman backprop, layer recurrent and NARX neural networks were applied. Feed neural networks and cascade feed-forward provided significant regression results. Besides, the models were trained as Traincgf, Trainlm and Trainrp. Using the K-fold technique, the training dataset was divided into 5 groups, 1 of which was reserved for the test and rest for the training, and the average of the performance values obtained was taken.

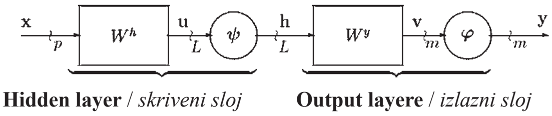



**Figure 2** Multilayered neural network with two neurons
**Slika 2.** Višeslojna neuronska mreža s dva neurona

ANNs are inspired by the human brain sensorial activities, and the sensorial neurons can be created by computers (Hedayat *et al.*, 2009). Figure 1 shows an artificial neural network consisting of nodes, neurons, and transfer functions.

Feedforward backprop neural networks include an input layer, an output layer and one or more hidden layers (Hedayat *et al.*, 2009). According to the structure of the feed-forward neural network, the first layer is the link to the entrance neuron and the forward neurons are connected to the previous layer connections, whereas the last layer is linked to the output. Figure 2 indicates the multilayered neural networks that consist of a combination of the single-layer neural networks.

The output of the hidden layers in a multilayered neural network is expressed in Eq. 1 (Hounmenou *et al.*, 2021).

$$u_j=\sum_{i=1}^{p}w_{ji}^{h}\cdot x_i \tag{4}$$

Furthermore, the output is shown in Eq. 2.

$$v_k=\sum_{j=1}^{L}w_{kj}^{y}\cdot h_j \tag{5}$$

Where $p$ is the number of input layers, $h$ is the number of hidden layers, and $L$ is the number of data.

The structure of the Cascade-Feed Forward Neural Network (CFFNN) is similar to the feed-forward neural network, and it is a type of supervised learning algorithm (Hedayat *et al.*, 2009). Moreover, the CFFNN include the weight of each neuron connection (Wadkar *et al.*, 2021).

ANN models consist of 1 hidden layer and 32 neurons. Different neuron numbers were used in the

ANN models until optimum results were obtained. The reason for the application of the different number of neurons is related to the black box of the neural networks. While creating the model in ANN, different neuron numbers were obtained by trial and error to obtain the best results. In the study, K-Folds cross validation technique was used to reduce the bias of the model, and the k value was determined as 5. This 5 different test groups were created from the data set, with 20 % of the tests. The data outside of 20 % for each group was used as the training set. 5 different training and test sets were created from the data set used for the experiments. The test rate used was determined as 20 %. The remaining 80 % was divided into two parts - with 25 % validation and 75 % training. Validation set was randomly selected from 80 % of each k cycle.

### 2.2.2 Fuzzy Logic
### 2.2.2. Neizrazita logika

The FL algorithm uses fuzzy outcomes from rules with numerical and language datasets. The FL performs a membership function for the language process. Furthermore, fuzzy logic has two different approaches - Mamdani and Sugeno (Chen and Liou, 1999). Mamdani is widely used for FL algorithm because it provides fuzzification, fuzzy rules and defuzzification. The membership function is often used to represent linguistic terms. The membership function is expressed as the closeness of the input values to the membership degree. The membership value of the input is used to determine fuzzy inference with rules. When the membership value is 0, it indicates that the fuzzy set is not a member, and when it is 1, it indicates that it is a full member of the fuzzy set. Values between 0 and 1 represent the degree of membership in the fuzzy set (Zhao and Bose, 2002). An Adaptive Neuro-Fuzzy Inference System (ANFIS) is based on a combination of the FL and an artificial neural network. The ANFIS model works with fuzzification and neural network training ability to create rules for the dataset.

In this model, 80 % data were selected for training, and the remaining 20 % data was used for testing. The data were randomly selected and used for training and testing.

### 2.2.3 Preparation of samples
### 2.2.3. Priprema uzoraka

Each wood was cut radially and tangentially with 100 mm ×100 mm ×10 mm scales and 10 pieces, and the 360 total number of the experimental samples were prepared as the type of wood (3), cutting direction (2), age period (2), and varnish type (3). According to the (TS EN-26624, 1996) and (ASTM D4541, 2009), the adhesion strength of the varnish was measured using the pneumatic adhesion equipment, as shown in Figure 3.

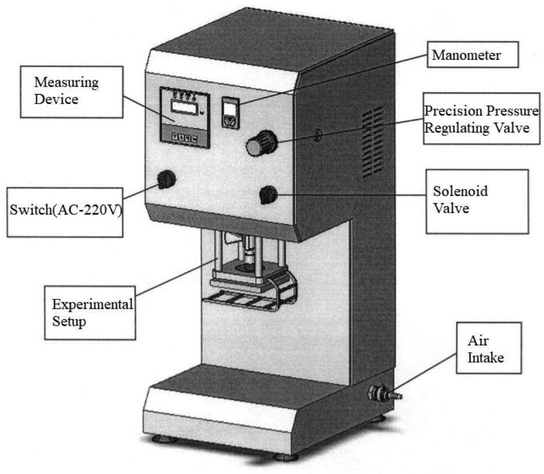



**Figure 3** Adhesion tester (Budakçi, 2006)
**Slika 3.** Uređaj za ispitivanje adhezije (Budakçi, 2006)

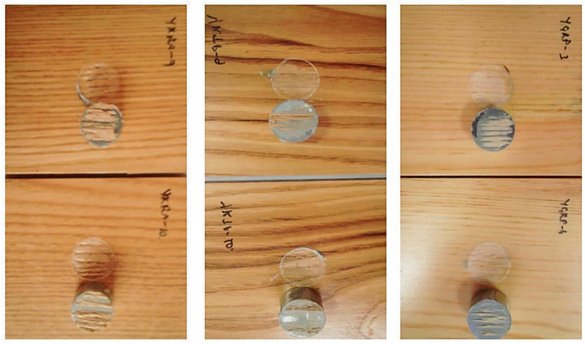


**Figure 4** Post-adhesion test of some samples
**Slika 4.** Prikaz uzoraka nakon ispitivanja adhezije

After the experiment, Figure 4 shows the results of adhesion strength of varnish layers.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

### 3.1 Adhesion Test Results
### 3.1. Rezultati ispitivanja adhezije

Table 1 presents the results of the pneumatic adhesion test equipment for the "F; Fresh and NA; Natural aged" wood type and their statistical outcomes.

According to Table 1, the adhesion strength values show different results based on the wood type, age period, cutting direction and type of varnish. The results were evaluated to check the result reliability using analysis of variance through MSTAT-C with a 95 % confidence interval. Table 2 illustrates the results of analysis of variance.

According to the results of the analysis of variance, the age period is statistically insignificant. The interaction between wood species age and period-section direction was insignificant. It can be seen that the interaction of cross-section direction and varnish type is not effective on adhesion strength ($p$=0.05).

**Table 1** Results of adhesion strength after the experiment
**Tablica 1.** Rezultati adhezivne čvrstoće

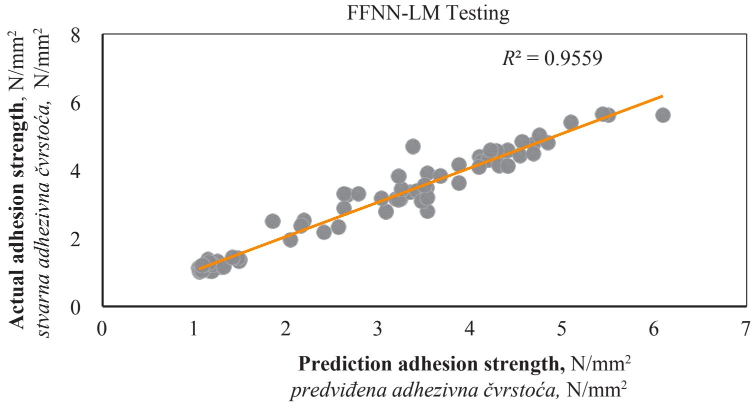
| **Wood type/ Age period** *Vrsta drva / starost* | **Water-based** / *Vodeni lak* | | | | **Polyurethane** / *Poliuretanski lak* | | | | **Acrylic** / *Akrilni lak* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Radial** | | **Tangential** | | **Radial** | | **Tangential** | | **Radial** | | **Tangential** | |
| | $\bar{X}$ | *s* | $\bar{X}$ | *s* | $\bar{X}$ | *S* | $\bar{X}$ | *S* | $\bar{X}$ | *s* | $\bar{X}$ | *s* |
| F. scotch pine *F. borovina* | 1.340 | 0.46 | 1.939 | 0.54 | 3.101 | 0.50 | 3.642 | 0.80 | 2.995 | 0.70 | 2.570 | 0.88 |
| NA. scotch pine *NA borovina* | 1.234 | 0.60 | 1.318 | 0.18 | 3.529 | 0.77 | 3.257 | 0.68 | 2.702 | 0.71 | 2.342 | 0.65 |
| F. oak *F. hrastovina* | 1.068 | 0.25 | 0.953 | 0.13 | 3.239 | 0.82 | 3.951 | 0.82 | 4.694 | 0.90 | 5.150 | 0.96 |
| NA. oak *NA. hrastovina* | 1.177 | 0.37 | 0.959 | 0.16 | 5.228 | 1.24 | 4.525 | 0.92 | 3.832 | 0.71 | 3.517 | 0.52 |
| F. chestnut *F. kestenovina* | 1.352 | 0.32 | 1.783 | 0.40 | 3.816 | 1.11 | 4.522 | 1.01 | 3.738 | 0.66 | 4.725 | 1.07 |
| NA. chestnut *NA. kestenovina* | 1.259 | 0.49 | 1.056 | 0.24 | 4.385 | 1.11 | 4.650 | 1.01 | 3.873 | 0.69 | 4.903 | 1.11 |

$\bar{X}$ – Arithmetic averages, s – Standard deviation, F – fresh, NA – Natural aged
*$\bar{X}$– aritmetičke sredine, s – standardna devijacija, F – svježe drvo, NA – prirodno ostarjelo drvo*

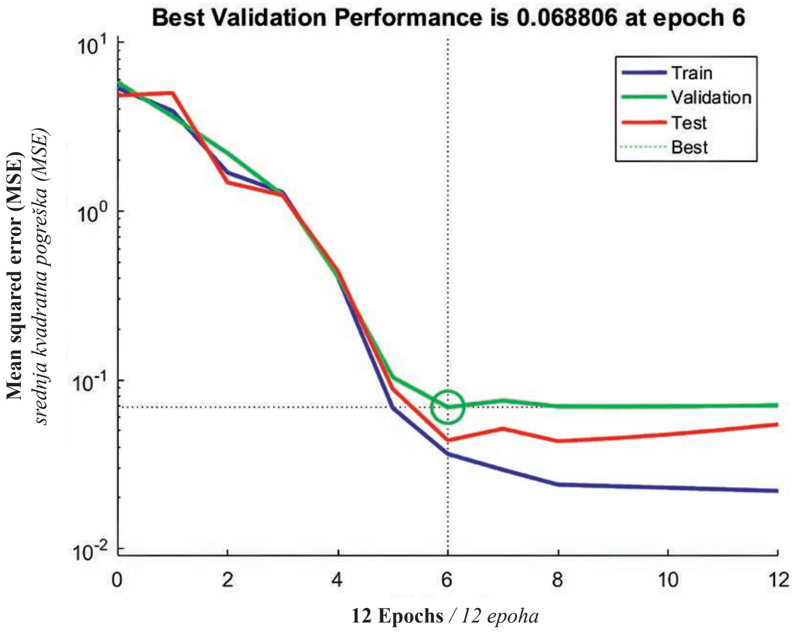
**Table 2** Variance results of adhesion strength
**Tablica 2.** Rezultati varijance za adhezivnu čvrstoću

| **Factors** / *Čimbenici* | **Degree of Independence** *Stupanj neovisnosti* | **Sum of Squares** *Zbroj kvadrata* | **Mean of Squares** *Srednja vrijednost kvadrata* | ***F* Values** *F-vrijednost* | ***P*** |
|---|---|---|---|---|---|
| Wood type (A) *vrsta drva (A)* | 2 | 50.206 | 25.103 | 45.9771 | 0.0000* |
| Age period (B) *starost drva (B)* | 1 | 0.089 | 0.089 | 0.1638 | NS |
| Interaction (AB) *interakcija (AB)* | 2 | 1.322 | 0.661 | 1.2107 | 0.2993** |
| Cross-section (C) *presjek (C)* | 1 | 2.395 | 2.395 | 4.3857 | 0.0370* |
| Interaction (AC) *interakcija (AC)* | 2 | 4.915 | 2.457 | 4.5009 | 0.0118* |
| Interaction (BC) interakcija (BC) | 1 | 6.529 | 6.529 | 11.9581 | 0.0006* |
| Interaction (ABC) *interakcija (ABC)* | 2 | 0.567 | 0.284 | 0.5197 | NS |
| Varnish type (D) *vrsta laka (D)* | 2 | 542.640 | 271.320 | 496.9330 | 0.0000* |
| Interaction (AD) *interakcija (AD)* | 4 | 50.601 | 12.650 | 23.1693 | 0.0000* |
| Interaction (BD) *interakcija (BD)* | 2 | 18.335 | 9.168 | 16.7907 | 0.0000* |
| Interaction (ABD) *interakcija (ABD)* | 4 | 18.542 | 4.635 | 8.4901 | 0.0000* |
| Interaction (CD) *interakcija (CD)* | 2 | 0.264 | 0.132 | 0.2417 | NS |
| Interaction (ACD) *interakcija (ACD)* | 4 | 7.188 | 1.797 | 3.2913 | 0.0115* |
| Interaction (BCD) *interakcija (BCD)* | 2 | 2.312 | 1.156 | 2.1173 | 0.1220** |
| Interaction (ABCD) *interakcija (ABCD)* | 4 | 1.691 | 0.423 | 0.7742 | NS |
| Error / *pogreška* | 324 | 176.901 | 0.546 | | |
| Sum / *zbroj* | 359 | 884.497 | | | |

* – Difference is significantly based on ($p$<0.05). / *razlika je značajna pri p<0,05*
** – Difference is insignificantly based on ($p$>0.05) / *razlika nije značajna pri p>0,05*
NS (Nonsignificant) – Insignificant / *nije značajno*




a)




b)

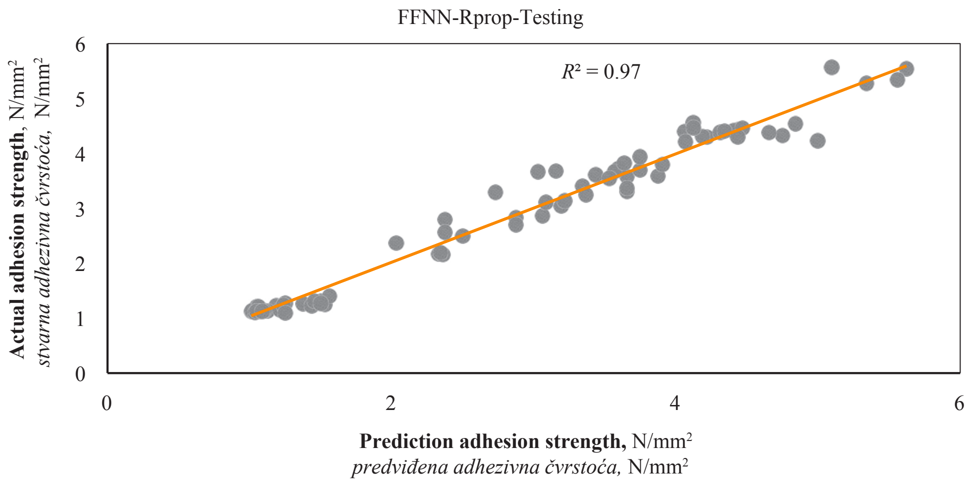
**Figure 5** Relationship between FFNN-LM model with actual and predicted adhesion strength (a) and model *MSE* performance (b)
**Slika 5.** Odnos između FFNN-LM modela sa stvarnom i s predviđenom adhezivnom čvrstoćom (a) te *MSE* svojstva modela (b)

## 3.2 Soft computing models for adhesion strength
## 3.2. Modeli mekog računalstva za adhezivnu čvrstoću

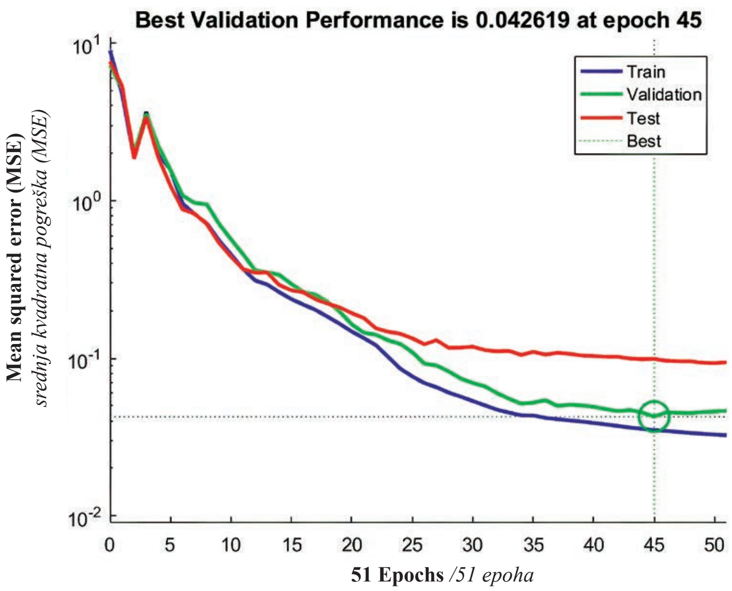
### 3.2.1 Feed forward backprop ANN (FFNN)
### 3.2.1. Aciklična umjetna neuronska mreža s propagacijom unatrag

In this model, a training algorithm was used based on a Levenberg-Marquardt (LM) optimization with updating weight and standard deviation of the values. Although the LM provides the fastest backpropagation, it needs high memory for the process. According to the outcome of the LM algorithm, the best results were obtained with 32 hidden neurons. Figure 5(a) shows the model providing $R^2$=0.9811 and $R^2$=0.9559 coefficients of determination for the training and test, respectively. In this model, the ratio of the vector was divided 0.8 for training and 0.2 for testing. Figure 5(b) shows that the model with the best performance and the lowest error rate obtained using the K-Fold technique was achieved with 6 epochs.

Moreover, two hidden layers FFNN backpropagation algorithms were applied with 10 hidden nodes in Layer 1 and 32 hidden nodes in Layer 2. Figure 6(a) demonstrates that the FFNN-Rprop had an $R^2$=0.9775 coefficient of determination for training and an $R^2$=0.9700 coefficient of determination for testing. In this model, the ratio of the vector was divided into 0.6 for training, 0.2 for validation, 0.2 for testing. Figure 6(b) shows that the model with the best performance and the lowest error rate, obtained using the K-Fold technique, was achieved with 45 epochs.




a)




b)

**Figure 6** Relationship between FFNN-Rprop model with actual and predicted adhesion strength (a) and model *MSE* performance (b)
**Slika 6.** Odnos između FFNN-Rprop modela sa stvarnom i s predviđenom adhezivnom čvrstoćom (a) te *MSE* svojstva modela (b)

### 3.2.2 Cascade-feed forward neural network (CFFNN)
### 3.2.2. Kaskadna aciklična neuronska mreža

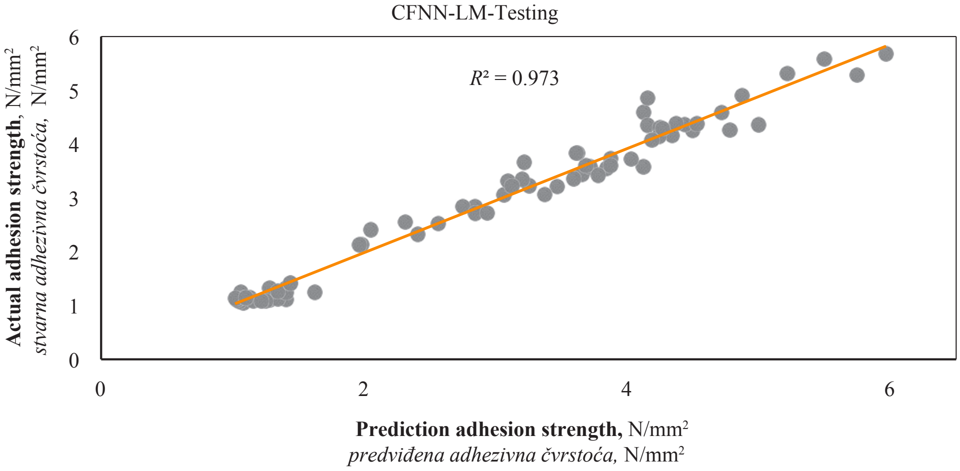
CFFNN-LM model for prediction of adhesion strength consists of 2 layers and 32 hidden neurons. The outcome of the model is shown in Figure 7(a) The CFFNN-LM provided $R^2$=0.9808 and $R^2$=0.9601 coefficients of determination for training and test, respectively. In CFFNN-LM model, the ratio of the vector was divided into 0.8 for training and 0.2 for testing. Figure 7(b) shows that the model with the best performance and the lowest error rate, obtained using the K-Fold technique, was achieved with 12 epochs.

A series of neural networks were used until the number of neurons in the hidden layer reached the minimum mean square error (*MSE*) of the output. Considering the predicted results among the proposed ANN models, *MSE* 0.046, *RMSE* 0.215 and *MAPE* 4.83 % showed the best performance in the FFNN-LM model.

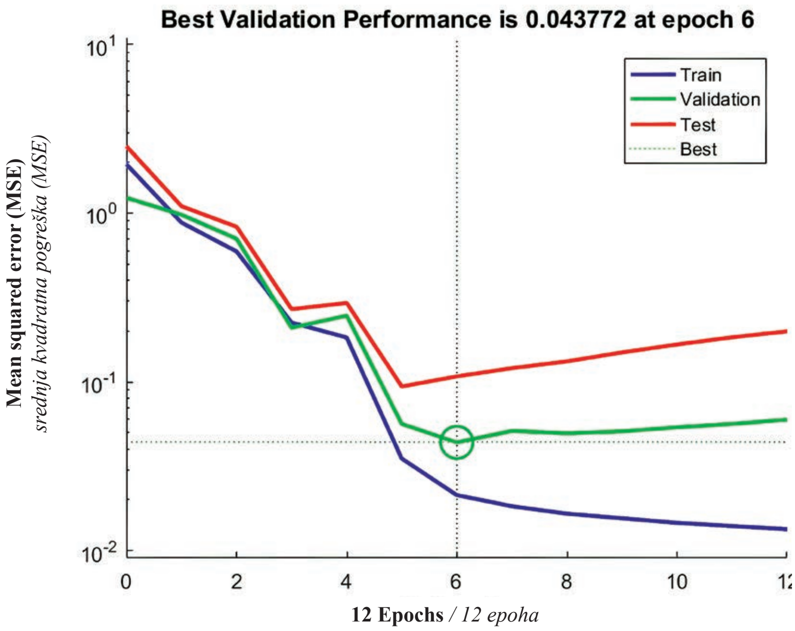
### 3.2.3 Fuzzy inference systems
### 3.2.3. Sustavi neizrazitog zaključivanja

To obtain the FL model, wood type, cutting direction and type of varnish were used as inputs. The model is illustrated in Figure 8. Fuzzification is applied to the input parameters to train the proposed model. After applying fuzzification, 18 different rules were obtained. After obtaining the table of rules, the output was acquired using defuzzification.

Figure 9 presents the adhesion strength related to the varnish and wood type.




a)




b)

**Figure 7** Relationship between CFFNN-LM model with actual and predicted adhesion strength (a) and model *MSE* performance (b)
**Slika 7.** Odnos između CFFNN-LM modela sa stvarnom i s predviđenom adhezivnom čvrstoćom (a) te *MSE* svojstva modela (b)

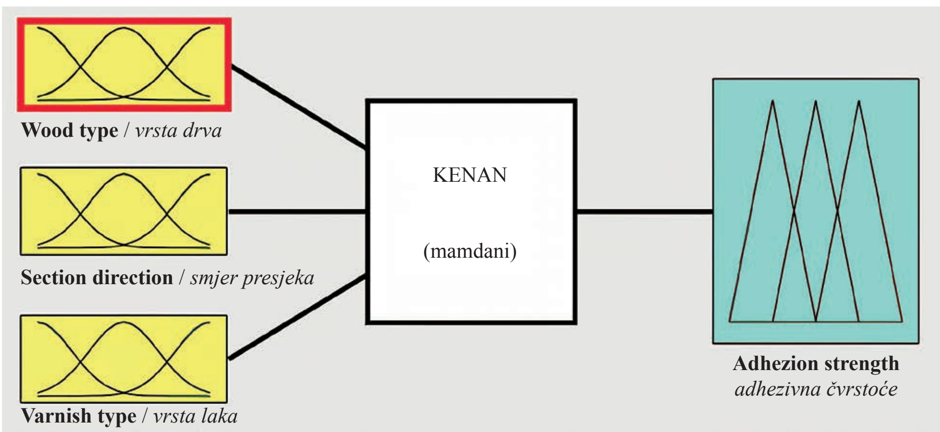



**Figure 8** FIS model for adhesion strength
**Slika 8.** FIS model za adhezivnu čvrstoću

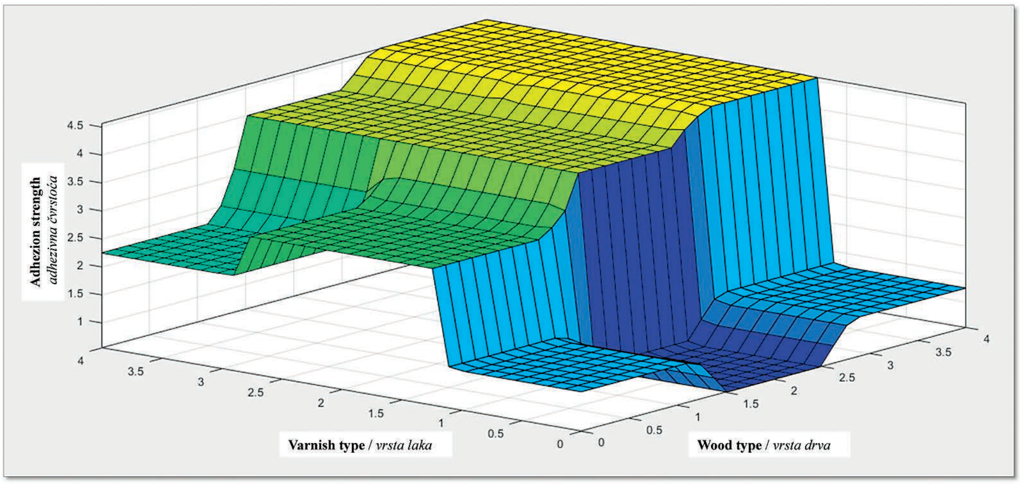



**Figure 9** FIS surface view for inputs and adhesion strength
**Slika 9.** FIS izgled površine za ulaze i adhezivnu čvrstoću

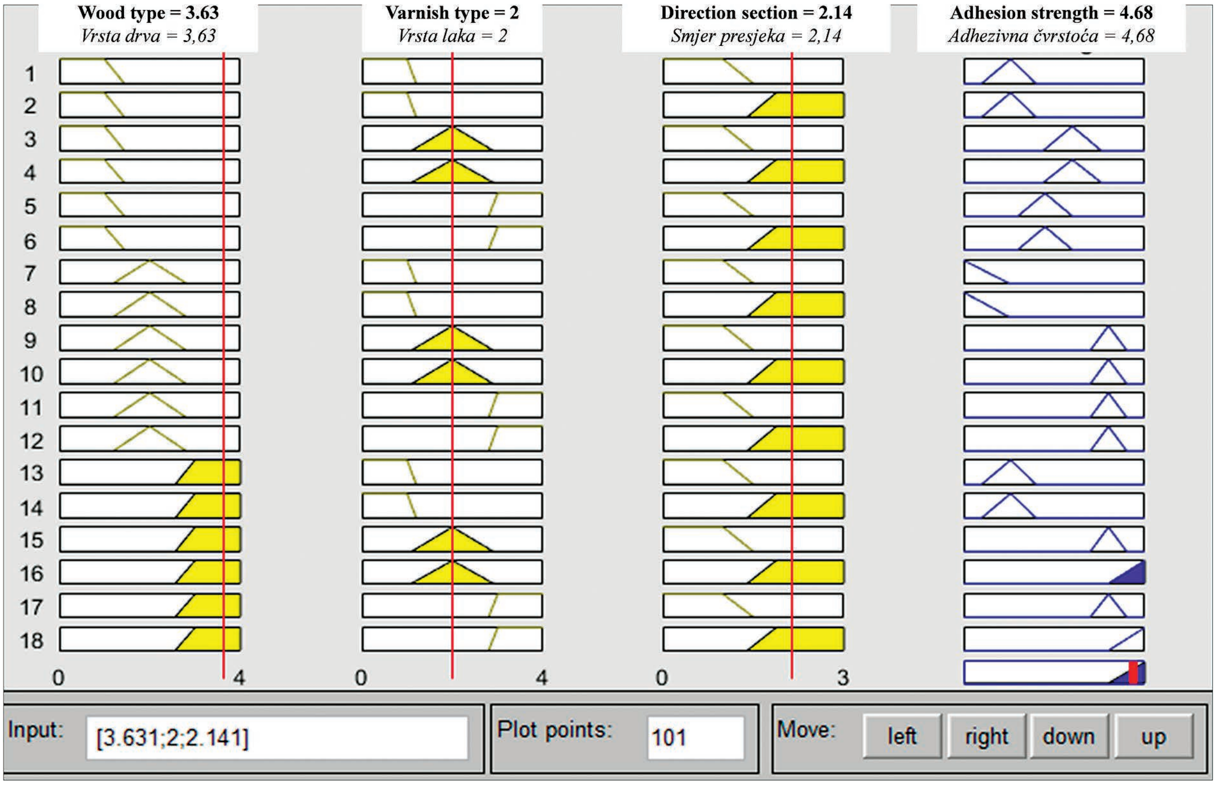



**Figure 10** FIS rules for 3 inputs and 1 output
**Slika 10.** FIS pravila za tri ulaza i jedan izlaz

Furthermore, Figure 10 illustrates the feature importance of the input parameters with the FIS surface map.

### 3.2.4 Adaptive neuro-fuzzy inference system (ANFIS)

### 3.2.4. Prilagodljivi sustav neuro-neizrazitog zaključivanja

The ANFIS consists of 6 different layers that are input, rules, normalization, member, defuzzification and output layers, respectively. The ANFIS model input values were used with wood type, age period, direction section, varnish type, density and weight of adhesion strength. Figure 11 shows the adhesion strength changing with wood type, varnish type and cutting direction through the ANFIS model.

A total of 360 data points were split as 80 % for training and 20 % for testing in the ANFIS model. Figure 12 and 13 show the results of the ANFIS model, the proposed model had $R^2$=0.9917 and $R^2$=0.9929 coefficients of determination for training and test results.

Moreover, the ANFIS can provide feature importance using an FL surface map. Figure 14 shows im-

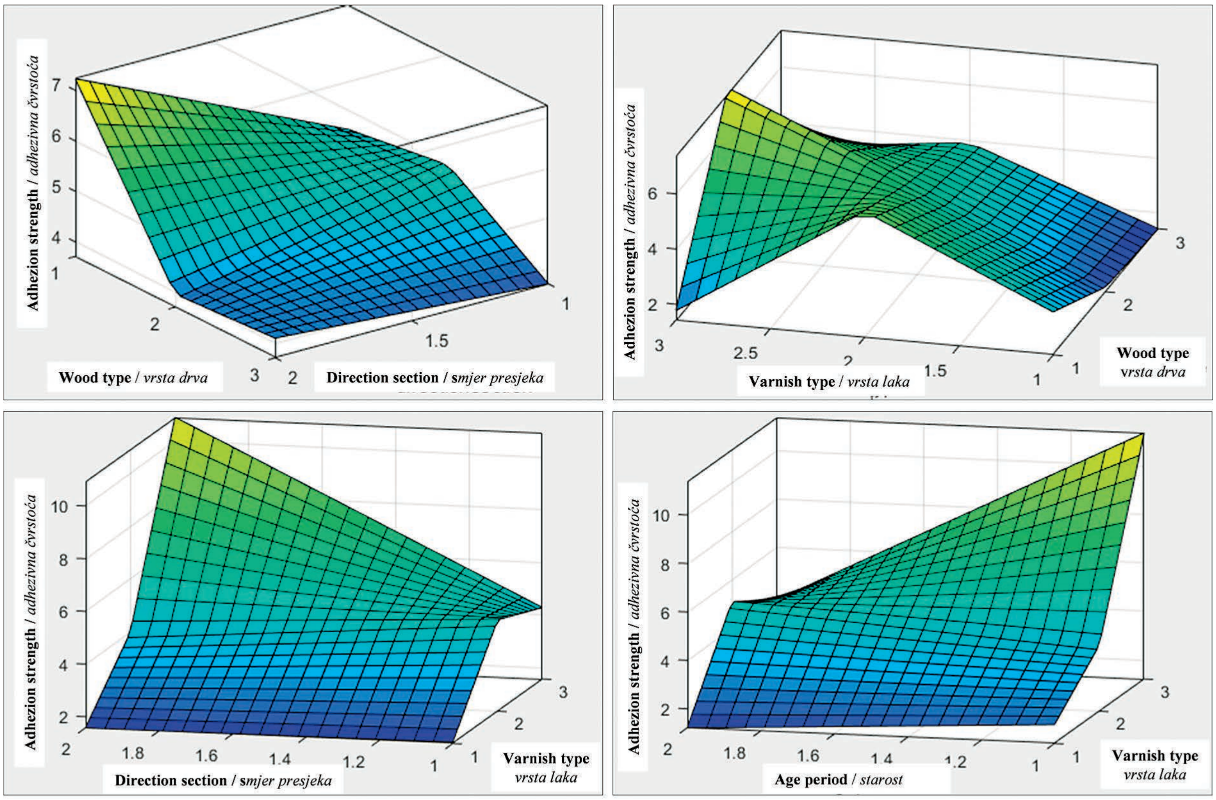



**Figure 11** ANFIS surface view for inputs and adhesion strength
**Slika 11.** ANFIS izgled površine za ulaze i adhezivnu čvrstoću

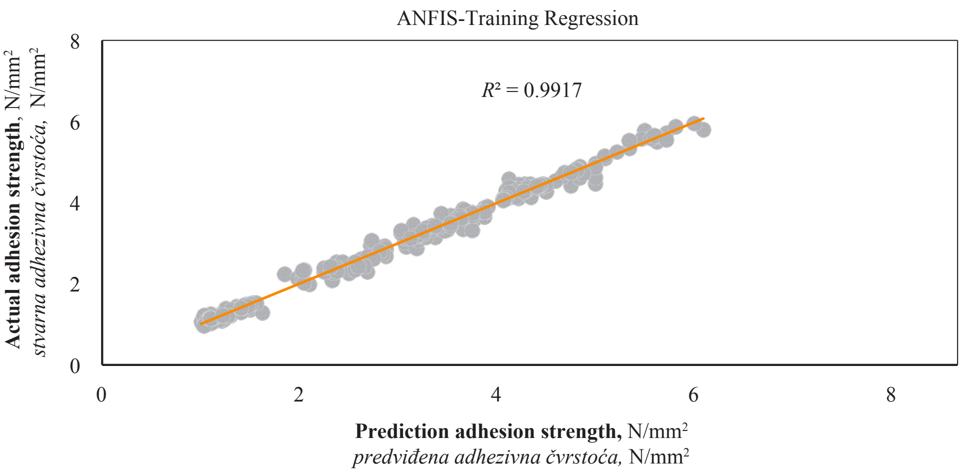



**Figure 12** Relationship between actual and predicted adhesion strength by ANFIS model for training
**Slika 12.** Odnos između stvarne i predviđene adhezivne čvrstoće u ANFIS modelu za trening

portant features for predicting adhesion strength. In this model, wood type, age period, cross-section direction, varnish type, density and weight showed high importance for the prediction of the varnish adhesion strength.

Furthermore, Figure 15 presents 324 rules for the ANFIS model with 6 inputs and 3 Gaussian values. This figure shows the consistency of the varnish adhesion strength with the actual value and the estimated FIS values.

Triangle, sigmoid, and Gaussian membership functions are generally used in fuzzy logic applications and the functions are associated with the cause and effect of the rules. These membership functions take values in the range from 0 to 1 and the corresponding number in this range represents the membership function. In this study, Gaussian was used to determine membership functions. Figure 16 and 17 demonstrate the comparison of the ANN and ANFIS models, in terms of the training and test. It has been determined that the predicted results are very close to the real values. Although the CFNN model diverges from the real values, it can be noticed that all models give optimum results.

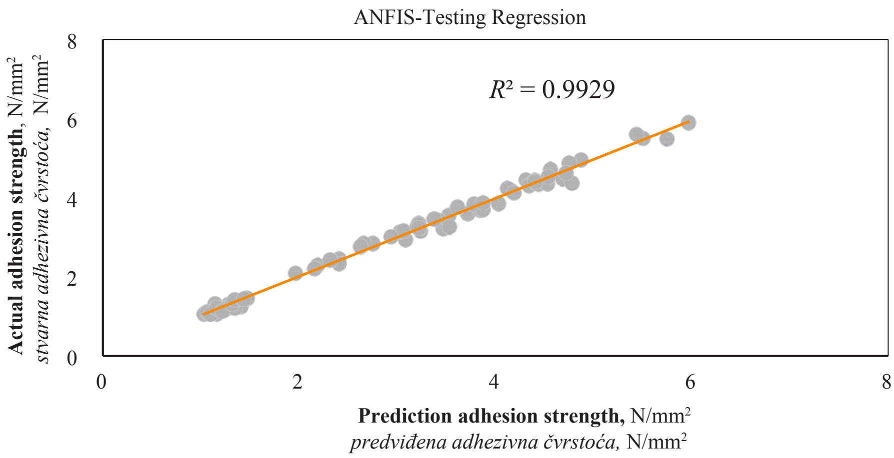



**Figure 13** Relationship between actual and predicted adhesion strength by ANFIS model for testing
**Slika 13.** Odnos između stvarne i predviđene adhezivne čvrstoće u ANFIS modelu za testiranje

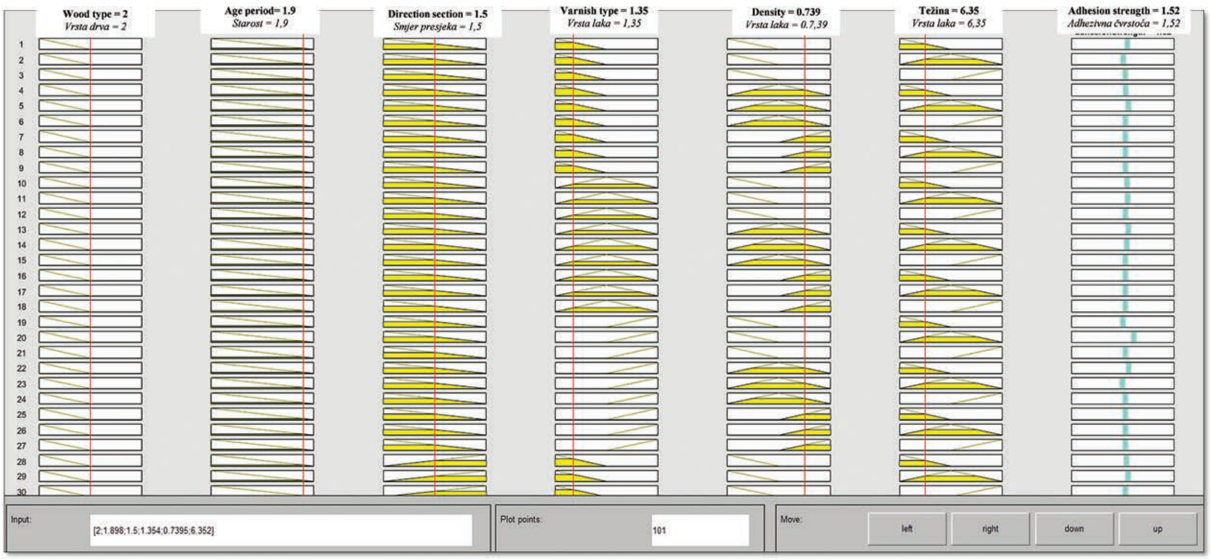



**Figure 14** ANFIS rules for 6 inputs and 1 output
**Slika 14.** ANFIS pravila za šest ulaza i jedan izlaz

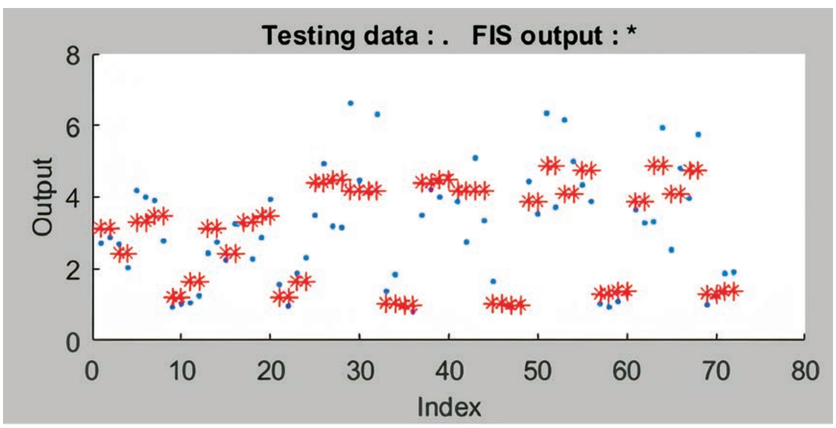



**Figure 15** ANFIS rules for 6 inputs and 1 output
**Slika 15.** ANFIS pravila za šest ulaza i jedan izlaz

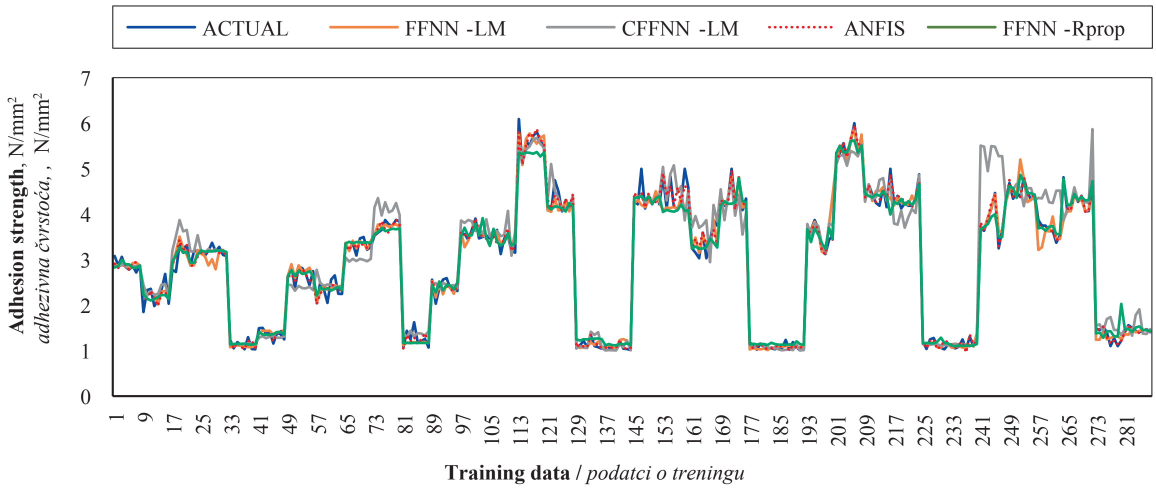



**Figure 16** Comparing ANN and ANFIS values with actual values (training)
**Slika 16.** Usporedba ANN i ANFIS vrijednosti sa stvarnim vrijednostima (treninga)

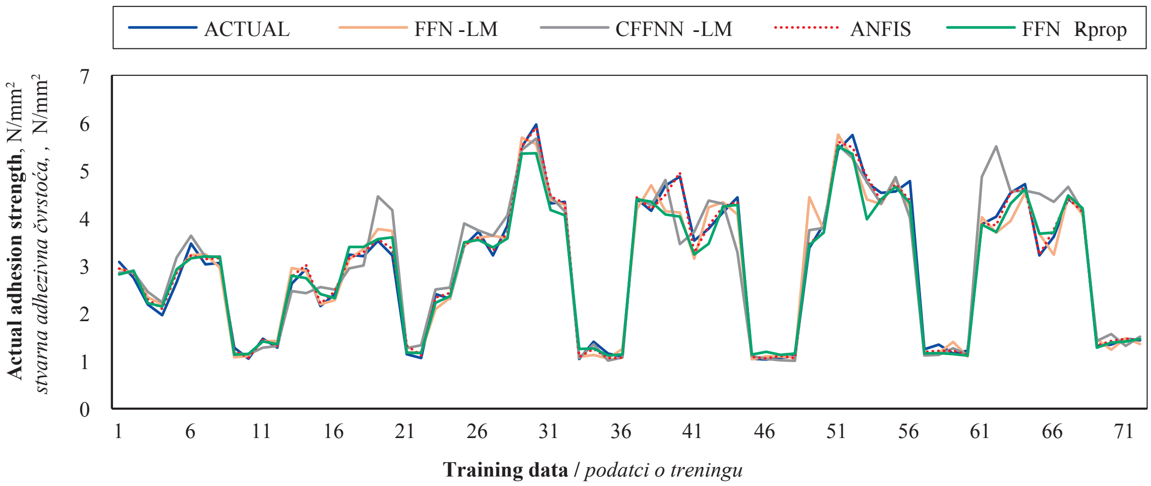



**Figure 17** Comparing ANN and ANFIS values with actual values (testing)
**Slika 17.** Usporedba ANN i ANFIS vrijednosti sa stvarnim vrijednostima (testiranja)

Table 3 presents the training and testing evaluation results in ANN and ANFIS, with determination coefficient ($R^2$), Mean Square Error (*MSE*), Mean Absolute Percentage Error (*MAPE*) and Root Mean Square Error (*RMSE*). In this table, *MSE*, *MAPE* and *RMSE* values give the average results of 5 different groups with the K-Fold technique. In addition, the determination coefficent values were added to the best results obtained.

Tiryaki *et al*. (2016) predicted the bond strength of solid wood exposed to heat treatment using ANN. In this model, as a result of testing, they found the *RMSE* value of 0.217 and the *MAPE* value of 6.253 %. In this study, Anfis testing *RMSE* and *MAPE* values were low-

**Table 3** Results of performance evaluation criteria for ANNs and ANFIS models
**Tablica 3.** Rezultati kriterija ocjenjivanja uspješnosti za modele ANN i ANFIS

| Modelling | $R^2$ | *MSE* | *RMSE* | *MAPE*, % |
|---|---|---|---|---|
| FFNN-LM(training) | 0.9811 | 0.1406* | 0.315* | 7.65* |
| FFNN-LM(testing) | 0.9559 | 0.1806* | 0.4096* | 9.586* |
| FFNN- Rprop (training) | 0.9775 | 0.068* | 0.2552* | 8.024* |
| FFNN- Prop (testing) | 0.9700 | 0.1584* | 0.3782* | 9.938* |
| CFFNN-LM (training) | 0.9808 | 0.0422* | 0.196* | 5.454* |
| CFFNN-LM (testing) | 0.9730 | 0.158* | 0.3808* | 9.672* |
| Anfis (training) | 0.9917 | 0.004 | 0.064 | 2.22 |
| Anfis (testing) | 0.9929 | 0.014 | 0.12 | 3.60 |

*5 test group average values / *srednje vrijednosti pet ispitnih grupa* er. Esteban *et al.* (2009) predicted the bond strength of particle boards using ANN thickness, density, moisture, swelling and absorption. In this study, the test results were MAPE 7.86 %, while the $R^2$ value was 0.85. In our study, on the other hand, higher *MAPE* values were obtained in all models with $R^2$ values and a better *MAPE* result was obtained in Anfis models.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

Due to the heterogeneous properties of the wooden materials, the prediction of the adhesion strength is an important area of research in wood industry. In this research, the adhesion strength was predicted using ANN, FL and ANFIS. According to the proposed model results:

- FFNN, CFNN, FIS and ANFIS were used to predict the adhesion strength.
- The best estimate of adhesion strength in the ANN models was obtained for 32 neurons.
- In ANN-based models, TrainLM and TrainRp provided reasonable results compared to TrainCFG.
- The coefficient of determination values in the ANFIS model was obtained by creating 324 rules using the Gauss membership function. Additionally, testing in the ANFIS model showed the highest coefficient of determination in estimating adhesion strength. In this model, the results of *MAPE* 2.22 % (training) and 3.60 % (testing) seem to be a reasonable result. Additionally, *RMSE* and *MSE* results indicate that fuzzy logic can be applied in this area.
- The ANN model provided significant results for tangensoidal function in the Levemberg Marquardt algorithm.
- In the ANN models, the lowest *MAPE* value was 5.45 % in the FFNN training data, while the *RMSE* value was 0.196.
- The ANFIS model was used for the first time in the wood industry field in estimating varnish adhesion strength. The model was successful in performance predictions in both training and testing.

This result shows that artificial intelligence models can be improved using high-dimensional datasets in the future. Moreover, the life span of the wooden material can be increased, while decreasing the processing time for wooden material. Furthermore, the combination of the different artificial intelligence models can increase the prediction accuracy of the adhesion strength.

**Acknowledgements** – Zahvala

Kenan KILIÇ: experimental study; İbrahim Karaman: ANN, ANFIS, FIS, and Cevdet Söğütlü: Literature, grammar and regression.

## 5 REFERENCES
## 5. LITERATURA

1. Bardak, S.; Tiryaki, S.: Nemli, G.; Aydın, A., 2016: Investigation and neural network prediction of wood bonding quality based on pressing conditions. International Journal of Adhesion and Adhesives, 68: 115-123. https://doi.org/10.1016/j.ijadhadh.2016.02.010
2. Budakci, M.; Akkuş, M.; 2011: Modeling the strength of the veneer adhesion strength on some wood-based panels by artificial neural networks. Journal of Polytechnic, 14: 63-71.
3. Budakci, M., 2006: Design and production of a pneumatic adhesion testing device. Journal of Polytechnic, 9 (1): 53-58. https://doi.org/10.2339/2006.9.1.53-58
4. Ceylan, İ., 2008: Determination of drying characteristics of timber by using artificial neural networks and mathematical models. Drying Technology, 26 (12): 1469-1476. https://doi.org/10.1080/07373930802412132
5. Cha, J. K., Pearson, R. G., 1994: Stress analysis and prediction in 3-layer laminated veneer lumber: response to crack and grain angle. Wood and Fiber Science, 26 (1): 97-106.
6. Chen, M.-S., Liou, R., 1999: An efficient learning method of fuzzy inference system, in the following: FUZZ-IEEE'99. 1999 IEEE International Fuzzy Systems. In: Proceedings of the FUZZ-IEEE'99, 1999 IEEE International Fuzzy Systems (Cat. No.99CH36315), (2): 634-638. https://doi.org/10.1109/FUZZY.1999.793016
7. Dongel, N.; Kureli, I.; Sogutlu, C., 2008: The effect of dry heat for the colour and gloss changes on the wood and wood-based floor covering materials. Journal of Polytechnic, 11 (3): 255-263. https://doi.org/10.2339/2008.11.3.255-263
8. Esteban, L. G.; García Fernández, F.; de Palacios, P.; Conde, M., 2009: Artificial neural networks in variable process control: application in particleboard manufacture. Forest Systems, 18 (1): 92-100. https://doi.org/10.5424/fs/2009181-01053
9. Hauptmann, M.; Müller, U.; Obersriebnig, M.; Gindl-Altmutter, W.; Beck, A.; Hansman, C., 2013: The optical appearance of wood related to nanoscale surface roughness. BioResources, 8: 4038-4045. https://doi.org/10.15376/biores.8.3.4038-4045
10. Hedayat, A.; Davila, H.; Barfrosh, A. A.; Sepanloo, K., 2009: Estimation of research reactor core parameters using cascade feed forward artificial neural networks. Progress in Nuclear Energy, 51: 709-718. https://doi.org/10.1016/j.pnucene.2009.03.004
11. Hounmenou, C. G.; Gneyou, K. E.; Kakaï, R. L. G., 2021: Formalism of the general mathematical expression of multilayer perceptron neural networks. Preprints.org, 2021050412. https://doi.org/10.20944/preprints202105.0412.v1
12. Kılıç, M., 2009: The effects of steaming of beech (*Fagus orientalis* L.) and sapele (*Entandrophragma cylindricum*) woods on the adhesion strength of varnish. Journal of Applied Polymer Science, 113: 3492-3497. https://doi.org/10.1002/app.30180
13. Kilic, K.; Söğütlü, C., 2020: Determination of the gloss values of some varnishes applied on the natural aged wood. Journal of Polytechnic, 23 (4): 1423-1431. https://doi.org/10.2339/politeknik.764261
14. Kumar, K.; Thakur, G. S. M., 2012: Advanced applications of neural networks and artificial ıntelligence: A Review. International Journal of Information Technology

and Computer Science, 4 (6): 57-68. https://doi.org/10.5815/ijitcs.2012.06.08
15. Londhe, S. N.; Deo, M. C., 2003: Wave tranquillity studies using neural networks. Marine Structures, 16: 419-436. https://doi.org/10.1016/j.marstruc.2003.09.001
16. Marra, A. A., 1992: Technology of wood bonding: principles in practice. New York: Van Nostrand Reinhold.
17. Mendel, J. M., 1995: Fuzzy logic systems for engineering: a tutorial. In: Proceedings of the IEEE, 83: 345-377. https://doi.org/10.1109/5.364485
18. Ozsahin, S., 2013: Optimization of process parameters in oriented strand board manufacturing with artificial neural network analysis. European Journal of Wood and Wood Products, 71: 769-777. https://doi.org/10.1007/s00107-013-0737-9
19. Özgenç, Ö.; Bilici, E.; Durmaz, S.; Söğütlü, C.; Emik, S., 2022: Enhancing-weathering durability of pre-protected and unprotected wood by using bark extracts as natural UV absorbers in waterborne acrylic coating. Journal of Coatings Technology and Research, 19: 303-321. https://doi.org/10.1007/s11998-021-00528-3
20. Paliwal, M.; Kumar, U. A., 2009: Neural networks and statistical techniques: Review of applications. Expert Systems with Applications, 36: 2-17. https://doi.org/10.1016/j.eswa.2007.10.005
21. Söğütlü, C.; Nzokou, P.; Koc, I.; Tutgun, R.; Döngel, N., 2016: The effects of surface roughness on varnish adhesion strength of wood materials. Journal of Coatings Technology and Research, 13: 863-870. https://doi.org/10.1007/s11998-016-9805-5
22. Tiryaki, S.; Aydın, A., 2014a: An artificial neural network model for predicting compression strength of heat-treated wood and comparison with a multiple linear regression model. Construction and Building Materials, 62: 102-108. https://doi.org/10.1016/j.conbuildmat.2014.03.041
23. Tiryaki, S.; Malkoçoğlu, A.; Özşahin, Ş., 2014b: Using artificial neural networks for modeling surface roughness of wood in the machining process. Construction and Building Materials, 66: 329-335. https://doi.org/10.1016/j.conbuildmat.2014.05.098
24. Tiryaki, S.; Bardak, S.; Aydın, A., 2016: Modeling of wood bonding strength based on soaking temperature and soaking time by means of artificial neural networks. Modeling of wood bonding strength based on soaking temperature and soaking time by means of artificial neural networks, 4: 153-157. https://doi.org/10.18201/ijisae.2016SpecialIssue-146964
25. Vitosytė, J.; Ukvalbergienė, K.; Keturakis, G., 2012: The effects of surface roughness on adhesion strength of coated ash (*Fraxinus excelsior* L.) and birch (*Betula* L.) wood. Materials Science, 18: 347-351. https://doi.org/10.5755/j01.ms.18.4.3094
26. Wadkar, D. V.; Karale, R. S.; Wagh, M. P., 2021: Application of cascade feed forward neural network to predict the coagulant dose. Journal of Applied Water Engineering and Research, 10 (2): 87-100. https://doi.org/10.1080/23249676.2021.1927210
27. Yang, H.; Cheng, W.; Han, G., 2015: Wood modification at high temperature and pressurized steam: a relational model of mechanical properties based on a neural network. BioResources, 10 (3): 5758-5776.
28. Yapici, F.; Ozcifci, A.; Akbulut, T.; Bayir, R., 2009: Determination of the modulus of rupture and modulus of elasticity on flakeboard with fuzzy logic classifier. Materials and Design, 30: 2269-2273. https://doi.org/10.1016/j.matdes.2008.09.002
29. Zhao, J.; Bose, B. K., 2002: Evaluation of membership functions for fuzzy logic-controlled induction motor drive. In: Proceedings of the 28th Annual Conference of the Industrial Electronics Society IECON. 2 (1): 229-234. https://doi.org/10.1109/IECON.2002.1187512
30. ***ASTM D4541 2009: Standard test method for pull-off strength of coatings using portable adhesion testers.
31. ***TS EN 24624 1996: Paints and varnishes – Tensile Test, TSE, Ankara.

**Corresponding address:**

**İBRAHIM KARAMAN**

Yozgat Bozok University, Yozgat Vocational School, Computer Technology Department, 66200, Yozgat, TURKEY, e-mail: ibrahim.karaman@bozok.edu.tr

Hilal Singer[1], Şükrü Özşahin[2]

# Analysis of Key Attributes of Wooden Toys via an Interval-Valued Spherical Fuzzy Analytic Hierarchy Process

# Analiza ključnih svojstava drvenih igračaka primjenom sfernoga neizrazitog analitičkog hijerarhijskog procesa s intervalnim vrijednostima

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 12. 4. 2022.
Accepted – prihvaćeno: 15. 9. 2022.
UDK: 674.5
https://doi.org/10.5552/drvind.2023.0033



**ABSTRACT** • *The evaluation of wooden toys is a complicated process and can be overwhelming for decision-makers in the presence of many conflicting criteria. Hence, this study proposes a fuzzy decision-making model to identify and prioritize the key attributes of wooden toys. For this purpose, the interval-valued spherical fuzzy analytic hierarchy process (AHP), which is one of the fuzzy multicriteria decision-making methods, is applied to obtain weight vectors. Firstly, the wooden toy evaluation problem is formulated as a multicriteria decision-making problem. Then five main criteria and twenty subcriteria are defined with the help of experts. The decision-making team carries out the pairwise comparisons of the criteria. As a result, the priority weights are computed and the ranking order of the criteria is revealed. Additionally, the validity of the obtained results is supported by conducting a comparative analysis between other popular fuzzy methods: interval type-2 fuzzy AHP, interval-valued Pythagorean fuzzy AHP, and spherical fuzzy AHP. According to the modeling results, the most important criteria are "absence of small parts and sharp edges", "free of harmful wood preservatives and paints", "workmanship quality", "contribution to psychomotor development", and "contribution to cognitive development". The proposed framework can be adapted to similar decision processes for the evaluation or improvement of toys. Consequently, the findings of this research will help manufacturers, designers, and consumers in making conscious decisions.*

**KEYWORDS:** *analytic hierarchy process, expert perspective, fuzzy logic, multicriteria decision-making, wooden toy*

**SAŽETAK** • *Ocjenjivanje drvenih igračaka složen je proces i za donositelje odluka može biti vrlo težak ako postoji mnogo proturječnih kriterija. Stoga je u ovom istraživanju predložen neizraziti model donošenja odluka za prepoznavanje i određivanje ključnih svojstava drvenih igračaka. Pritom je za dobivanje pondera primijenjen sferni neizraziti analitički hijerarhijski proces (AHP), koji je jedna od neizrazitih višekriterijskih metoda odlučivanja. Problem vrednovanja drvene igračke najprije je formuliran kao višestruki problem odlučivanja. Zatim je uz pomoć*

[1] Author is researcher at Bolu Abant Izzet Baysal University, 1Department of Industrial Engineering, Bolu, Turkey. https://orcid.org/0000-0003-0884-2555
[2] Author is researcher at Karadeniz Technical University, 1Department of Industrial Engineering, Trabzon, Turkey. https://orcid.org/0000-0001-8216-0048

*stručnjaka definirano pet glavnih kriterija i 20 potkriterija. Tim za donošenje odluka proveo je usporedbu kriterija u parovima. Kao rezultat toga izračunani su ponderi prioriteta i definiran redoslijed kriterija. Komparativnom analizom dodatno je provedena provjera rezultata s rezultatima dobivenim drugim dvjema popularnim neizrazitim metodama: intervalnim tip 2 neizrazitim AHP-om i Pitagorinim neizrazitim AHP-om s intervalnim vrijednostima. Prema rezultatima modeliranja, najvažnijim su se pokazali kriteriji „bez sitnih dijelova i oštrih rubova", „bez štetnih premaznih materijala", „kvaliteta izrade", „doprinos psihomotoričkom razvoju" i „doprinos kognitivnom razvoju". Predočeni se okvir može prilagoditi za slične procese odlučivanja u ocjenjivanju i poboljšanju igračaka. Slijedom toga, rezultati ovog istraživanja pomoći će proizvođačima, dizajnerima i korisnicima igračaka u donošenju ispravnih odluka.*

**KLJUČNE RIJEČI:** *analitički hijerarhijski proces, stručna perspektiva, neizrazita logika, višestruko odlučivanje, drvena igračka*

## 1 INTRODUCTION
## 1. UVOD

Toys can be defined as products designed for use in learning or playing by children. Symbolic play materials, manipulative toys, art and craft materials, problem-solving toys, and cause-and-effect toys are some of these products. A wide variety of raw materials are used for the manufacture of toys. Wood is one of the most popular raw materials owing to its safety aspects, aesthetic appearance, and durability (Mercan, 2018).

The unique characteristics of wood have considerably contributed to the increase in demand for wooden toys. The purchasing process consists of four main stages: (i) need (problem) recognition, (ii) information retrieval, (iii) alternative evaluation, and (iv) final decision (Oblak *et al*., 2017). Evaluating wooden toys can be a confusing experience because alternatives need to be evaluated against many conflicting criteria. Decision-makers may be subjective and uncertain about their preference levels owing to incomplete information. Hence, selection criteria should be analyzed for the unbiased assessment of alternatives.

Although the need for research on the weighting of toy attributes is acknowledged, the number of studies focusing on this topic is insufficient. According to Fallon and Harris (1989), the most important attributes are safety and teaching new skills. Duracell (2005) has elucidated that costs, product quality, and children's desires possess substantial influences on toy selection decisions. Al Kurdi (2017) has reported that safety, durability, flexibility, and product category affect the decision-making process. Scherer *et al*. (2017) have employed the conjoint analysis technique to analyze the key attributes of bio-based sand toys. According to the researchers, the most important attribute is toy price. Richards *et al*. (2020) have reported that consumers give more importance to the educational qualities of toys. Mai (2021) has detected that the most important factors influencing the selection of green toys are design, material reliability, and the degree of environmental friendliness.

The importance of product selection criteria is not identical in decision-making problems. In order to obtain reliable and informative results, the opinions of different experts should be gathered and modeled through a scientific technique (Singer and Özşahin,

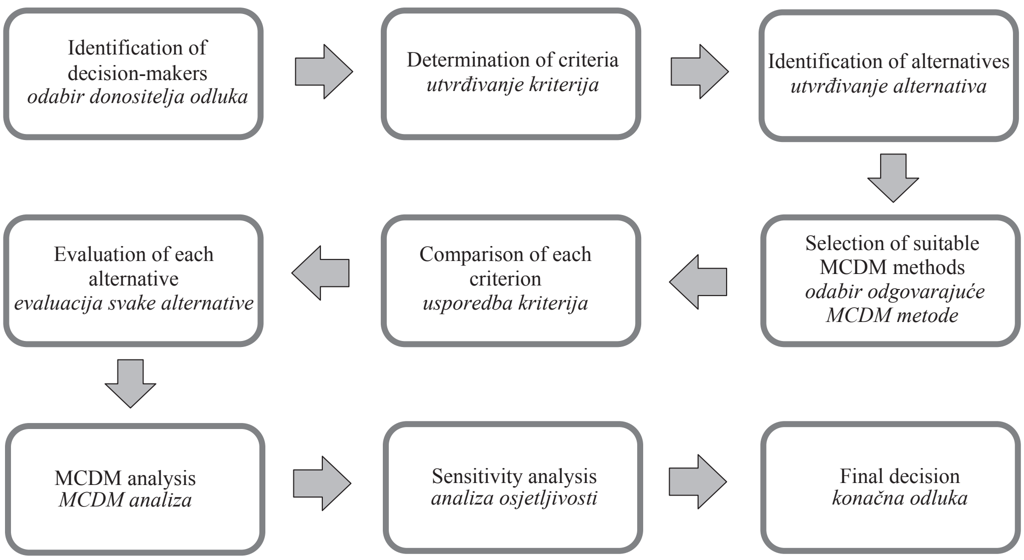



**Figure 1** MCDM process
**Slika 1.** Proces višekriterijskog odlučivanja

2021). One of the most popular scientific techniques is multicriteria decision-making (MCDM). This technique analyzes complex decision situations and processes by various decision support tools. The principal purposes of the MCDM technique are to prioritize multiple conflicting criteria and to choose the best alternative from a candidate set based on comparison matrices. Figure 1 illustrates the main procedure of MCDM models (Kim and Chung, 2013).

There are several weighting methods for MCDM. The analytic hierarchy process (AHP) usually displays more practical and significant properties than the others. The popularity of the AHP method can be attributed to its simplicity, ease of use, flexibility, hierarchical structure, and consistency tests (Alelaiwi, 2019). This method assesses the relative importance of decision elements by employing a 1-9 discrete scale. Pairwise comparison matrices are created and analyzed to obtain weight vectors. When conducting AHP modeling in practice, performance ratings can lead to unrealistic and misleading impressions. Decision-makers cannot assign precise scores to comparison judgments owing to the complexity of decision problems, the subjectivity of some criteria, and the limitation of thinking (Kar, 2015; Shameem *et al*., 2020). The fuzzy set theory can express and treat uncertain situations. Hence, the fuzzy AHP approach is more useful for modeling the vague thoughts of respondents and reasoning the quantitative degree of each decision element (Ashtiani and Abdollahi Azgomi, 2015; Mahjouri *et al*., 2017).

The fuzzy set theory considers approximate reasoning to facilitate decision-making. The relative significance of criteria and the suitability of alternatives are represented via linguistic labels and fuzzy numbers. Fuzzy conclusions are transformed into crisp values to sort or rank decision elements (Balogun *et al*., 2015). The standard fuzzy set assigns one membership point from the interval [0, 1] to each element. In hesitant decision situations, membership degrees can be inadequate in describing the statements of respondents (Wang and Li, 2018). Therefore, different fuzzy theories have been proposed in the literature. The spherical fuzzy set is one of the recent fuzzy extensions addressing the membership, non-membership, and hesitancy degrees of elements. This fuzzy set offers flexibility in generating the priorities of criteria and alternatives under the indefinite environment (Ashraf and Abdullah, 2020; Gül, 2020). Hence, the AHP method has been updated with the spherical fuzzy set to obtain robust results against uncertainties.

The spherical fuzzy AHP method has brought new insights into the solution of many problems such as renewable energy location selection (Kutlu Gündoğdu and Kahraman, 2020), manufacturing system selection (Mathew *et al*., 2020), prioritization of laminate flooring selection criteria (Singer and Özşahin, 2021), Covid-19 crisis management (Demir and Turan, 2021), and sustainable supplier selection (Unal and Temur, 2022). Interval-valued approaches take into account more uncertain information (Srinivas and Singh, 2018; Song *et al*., 2019). Hence, the present study utilizes the interval-valued spherical fuzzy AHP method. Several decision problems such as hospital performance assessment (Kutlu Gündoğdu and Kahraman, 2021), transportation system evaluation (Duleba *et al*., 2021), and financial accounting fraud detection (Hamal and Senvar, 2022) have been solved by this method. The results have demonstrated that the interval-valued spherical fuzzy AHP excellently expresses human preferences.

The consequences of wooden toy selection decisions affect children. Hence, it is necessary to weigh up evaluation factors before making such decisions. To the best of our knowledge, wooden toy selection criteria have not been explored and analyzed in any other study. Therefore, the objectives of the current study are to identify the key attributes of wooden toys, to analyze each attribute from experts' perspectives, and to bridge the knowledge gap by employing the interval-valued spherical fuzzy AHP method. This paper provides different viewpoints because the evaluation of wooden toys is considered a complex MCDM problem and the application of the proposed method is new in the field of wood science.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Interval-valued spherical fuzzy set
### 2.1. Sferni neizraziti skup s intervalnim vrijednostima

The spherical fuzzy set is an extension of the previous fuzzy sets (Figure 2). This new extension consists of membership, non-membership, and hesitancy functions (Kutlu Gundogdu and Kahraman, 2019). The interval-valued spherical fuzzy set is more effective in coping with uncertainties and gives the advantage to model the opinions of different decision-makers. This fuzzy set is defined by Eq. 1 (Balin, 2020).

$$\tilde{s} = \left\{ x, \left( [\mu_{\tilde{s}}^{-}(x), \mu_{\tilde{s}}^{+}(x)], [v_{\tilde{s}}^{-}(x), v_{\tilde{s}}^{+}(x)], [\pi_{\tilde{s}}^{-}(x), \pi_{\tilde{s}}^{+}(x)] \right) \middle| x \in X \right\} \quad (1)$$

$[\mu_{\tilde{s}}^{-}(x), \mu_{\tilde{s}}^{+}(x)]$, $[v_{\tilde{s}}^{-}(x), v_{\tilde{s}}^{+}(x)]$, and $[\pi_{\tilde{s}}^{-}(x), \pi_{\tilde{s}}^{+}(x)]$ are the lower (−) and upper (+) limits of membership, non-membership, and hesitancy, respectively. The squared sum of $\mu_s + (x)$, $v_s + (x)$, and $\pi_s + (x)$ is between 0 and 1. The following equations are used to calculate refusal degrees (Kutlu Gündoğdu and Kahraman, 2021):

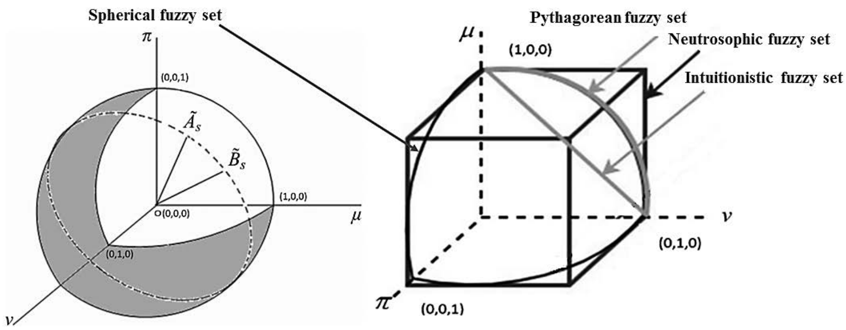



**Figure 2** Geometrical interpretation of spherical fuzzy set
**Slika 2.** Geometrijski prikaz sfernoga neizrazitog skupa

$$\varphi_{\tilde{s}}^{+} = \sqrt{1-\left(\left(\mu_{\tilde{s}}^{+}(x)\right)^{2}+\left(v_{\tilde{s}}^{+}(x)\right)^{2}+\left(\pi_{\tilde{s}}^{+}(x)\right)^{2}\right)} \quad (2)$$

$$\varphi_{\tilde{s}}^{-} = \sqrt{1-\left(\left(\mu_{\tilde{s}}^{-}(x)\right)^{2}+\left(v_{\tilde{s}}^{-}(x)\right)^{2}+\left(\pi_{\tilde{s}}^{-}(x)\right)^{2}\right)} \quad (3)$$

The basic algebraic operations on $\tilde{s}_1$ and $\tilde{s}_2$ numbers are elucidated below (Duleba *et al*., 2021).

$$\tilde{s}_1 \oplus \tilde{s}_2 = \left\{ \begin{array}{l} \left[ \begin{array}{l} \left((\mu_1^-)^2+(\mu_2^-)^2-(\mu_1^-)^2(\mu_2^-)^2\right)^{1/2}, \\ \left((\mu_1^+)^2+(\mu_2^+)^2-(\mu_1^+)^2(\mu_2^+)^2\right)^{1/2} \end{array} \right], \left[v_1^- v_2^-, v_1^+ v_2^+\right], \\ \left[ \begin{array}{l} \left(\left(1-(\mu_2^-)^2\right)(\pi_1^-)^2+\left(1-(\mu_1^-)^2\right)(\pi_2^-)^2-(\pi_1^-)^2(\pi_2^-)^2\right)^{1/2}, \\ \left(\left(1-(\mu_2^+)^2\right)(\pi_1^+)^2+\left(1-(\mu_1^+)^2\right)(\pi_2^+)^2-(\pi_1^+)^2(\pi_2^+)^2\right)^{1/2} \end{array} \right] \end{array} \right\} \quad (4)$$

$$\tilde{s}_1 \otimes \tilde{s}_2 = \left\{ \begin{array}{l} \left[\mu_1^- \mu_2^-, \mu_1^+ \mu_2^+\right], \left[ \begin{array}{l} \left((v_1^-)^2+(v_2^-)^2-(v_1^-)^2(v_2^-)^2\right)^{1/2}, \\ \left((v_1^+)^2+(v_2^+)^2-(v_1^+)^2(v_2^+)^2\right)^{1/2} \end{array} \right], \\ \left[ \begin{array}{l} \left(\left(1-(v_2^-)^2\right)(\pi_1^-)^2+\left(1-(v_1^-)^2\right)(\pi_2^-)^2-(\pi_1^-)^2(\pi_2^-)^2\right)^{1/2}, \\ \left(\left(1-(v_2^+)^2\right)(\pi_1^+)^2+\left(1-(v_1^+)^2\right)(\pi_2^+)^2-(\pi_1^+)^2(\pi_2^+)^2\right)^{1/2} \end{array} \right] \end{array} \right\} \quad (5)$$

$$\lambda \cdot \tilde{s} = \left\{ \begin{array}{l} \left[ \begin{array}{l} \left(1-\left(1-(\mu^-)^2\right)^{\lambda}\right)^{1/2}, \\ \left(1-\left(1-(\mu^+)^2\right)^{\lambda}\right)^{1/2} \end{array} \right], \left[(v^-)^{\lambda}, (v^+)^{\lambda}\right], \\ \left[ \begin{array}{l} \left(\left(1-(\mu^-)^2\right)^{\lambda}-\left(1-(\mu^-)^2-(\pi^-)^2\right)^{\lambda}\right)^{1/2}, \\ \left(\left(1-(\mu^+)^2\right)^{\lambda}-\left(1-(\mu^+)^2-(\pi^+)^2\right)^{\lambda}\right)^{1/2} \end{array} \right] \end{array} \right\} \quad (6)$$

$$\tilde{s}^{\lambda} = \left\{ \begin{array}{l} \left[(\mu^-)^{\lambda}, (\mu^+)^{\lambda}\right], \left[ \begin{array}{l} \left(1-\left(1-(v^-)^2\right)^{\lambda}\right)^{1/2}, \\ \left(1-\left(1-(v^+)^2\right)^{\lambda}\right)^{1/2} \end{array} \right], \\ \left[ \begin{array}{l} \left(\left(1-(v^-)^2\right)^{\lambda}-\left(1-(v^-)^2-(\pi^-)^2\right)^{\lambda}\right)^{1/2}, \\ \left(\left(1-(v^+)^2\right)^{\lambda}-\left(1-(v^+)^2-(\pi^+)^2\right)^{\lambda}\right)^{1/2} \end{array} \right] \end{array} \right\} \quad (7)$$

## 2.2 Interval-valued spherical fuzzy analytic hierarchy process

## 2.2. Sferni neizraziti analitički hijerarhijski proces s intervalnim vrijednostima

The AHP method is used to analyze complex decision situations and processes. The procedure of this method starts by structuring any problem in a hierarchal manner. The AHP schema comprises objectives (peak level), criteria (intermediate level), and alternatives (bottom level) (Figure 3) (Singer and Özşahin, 2022).

The elements of the same level are compared by employing a nine-point scale. Decision-makers' judgments are transferred to pairwise comparison matrices. The inconsistency level of each matrix is estimated through consistency indices. Once the performance scores of decision elements are divided by column sums, the row averages of final matrices are taken to obtain weights and priority orders (Ahammed and Azeem, 2013; Özşahin *et al*., 2019).

The conventional AHP method uses crisp numbers for pairwise comparisons. However, precise scores may be improper or insufficient due to the inevitable uncertainty in the decision-making process. Fuzzy approaches effectively reflect the vagueness of human thinking through a set of possible values (Dožić *et al*., 2018; Shameem *et al*., 2020). In this study, the interval-valued spherical fuzzy AHP method is used as a linguistic preference measurement tool. The steps of this method can be expressed as follows (Kutlu Gündoğdu and Kahraman, 2021):

Step 1: Pairwise comparison matrices are created based on the linguistic evaluations of decision-makers using the scale given in Table 1.

$$D = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & \tilde{a}_{nn} \end{bmatrix} \quad (8)$$

where $n$ refers to the number of criteria and $\tilde{a}_{ij}$ is an interval-valued spherical fuzzy number representing the relative importance between criteria.

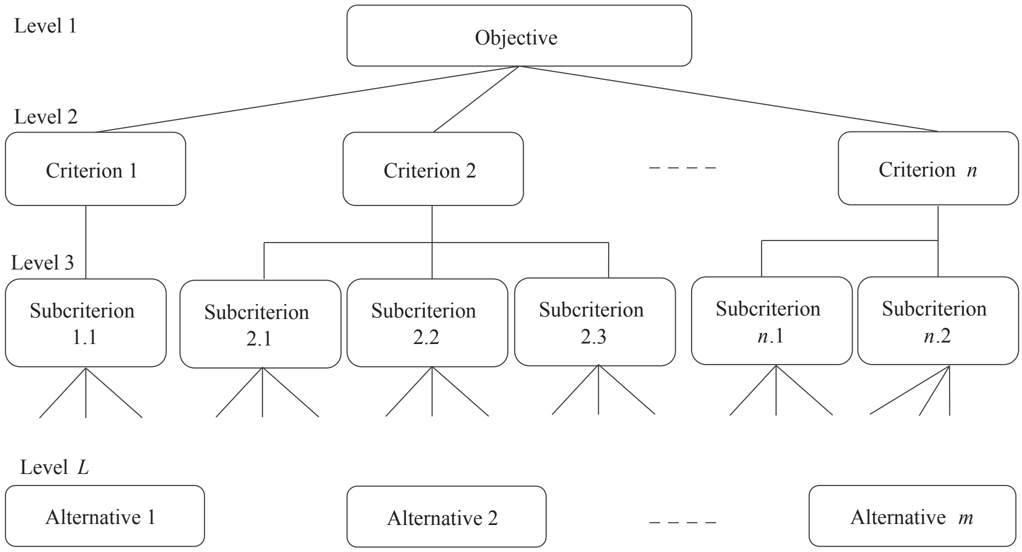



**Figure 3** A multilevel decision hierarchy
**Slika 3.** Hijerarhija višekriterijskog odlučivanja

**Table 1** Fuzzy rating scale
**Tablica 1.** Neizrazita ljestvica ocjenjivanja

| **Linguistic term** *Lingvistički termin* | **Interval-valued spherical fuzzy number** *Sferni neizraziti broj s intervalnim vrijednostima* | **Score index** *Indeks rezultata* |
|---|---|---|
| Absolutely more importance (AMI) *apsolutno visoka važnost (AMI)* | ([0.85,0.95],[0.10,0.15],[0.05,0.15]) | 9 |
| Very high importance (VHI) / *vrlo velika važnost (VHI)* | ([0.75,0.85],[0.15,0.20],[0.15,0.20]) | 7 |
| High importance (HI) / *velika važnost (HI)* | ([0.65,0.75],[0.20,0.25],[0.20,0.25]) | 5 |
| Slightly more importance (SMI) / *nešto veća važnost (SMI)* | ([0.55,0.65],[0.25,0.30],[0.25,0.30]) | 3 |
| Equal importance (EI) / *jednaka važnost (EI)* | ([0.50,0.55],[0.45,0.55],[0.30,0.40]) | 1 |
| Slightly low importance (SLI) / *neznatno niža važnost (SLI)* | ([0.25,0.30],[0.55,0.65],[0.25,0.30]) | 1/3 |
| Low importance (LI) / *niska važnost (LI)* | ([0.20,0.25],[0.65,0.75],[0.20,0.25]) | 1/5 |
| Very low importance (VLI) / *vrlo niska važnost (VLI)* | ([0.15,0.20],[0.75,0.85],[0.15,0.20]) | 1/7 |
| Absolutely low importance (ALI) *apsolutno niska važnost (ALI)* | ([0.10,0.15],[0.85,0.95],[0.05,0.15]) | 1/9 |

Step 2: Score indices are assigned to pairwise comparisons to apply the AHP consistency test. Respondents' judgments are checked using Eq. 9. Consistency ratios under 0.10 indicate that comparison results are acceptable.

$$consistency\,ratio = \frac{\left(\frac{\lambda_{max} - n}{n-1}\right)}{random\,consistency} \quad (9)$$

Here, $\lambda_{max}$ is the largest eigenvalue of matrix $D$ and random consistency is the mean consistency index of randomly generated matrices (Stein and Mizzi, 2007). The random consistency values proposed by Saaty (1977) for different values of $n$ can be seen in Table 2.

Step 3: Fuzzy weights are calculated using the following equation:

$$\tilde{w}_i^s = \left\{ \begin{array}{l} \left[ \left[ \left(1-\prod_{i=1}^{n}\left(1-(\mu_i^-)^2\right)^{w_i}\right)^{1/2}, \left(1-\prod_{i=1}^{n}\left(1-(\mu_i^+)^2\right)^{w_i}\right)^{1/2} \right], \left[\prod_{i=1}^{n}(v_i^-)^{w_i}, \prod_{i=1}^{n}(v_i^+)^{w_i}\right], \right. \\ \left. \left[ \left(\prod_{i=1}^{n}\left(1-(\mu_i^-)^2\right)^{w_i} - \prod_{i=1}^{n}\left(1-(\mu_i^-)^2-(\pi_i^-)^2\right)^{w_i}\right)^{1/2}, \left(\prod_{i=1}^{n}\left(1-(\mu_i^+)^2\right)^{w_i} - \prod_{i=1}^{n}\left(1-(\mu_i^+)^2-(\pi_i^+)^2\right)^{w_i}\right)^{1/2} \right] \right] \end{array} \right\} \quad (10)$$

where $w = 1/n$

**Table 2** Random consistency index
**Tablica 2.** Indeks slučajne konzistencije

| ***n*** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| Random consistency value *Indeks slučajne konzistencije* | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

Step 4: Fuzzy conclusions are defuzzied according to Eq. 11.

$$S\left(\tilde{w}_i^s\right)=\frac{\left(\mu^-\right)^2+\left(\mu^+\right)^2-\left(v^-\right)^2-\left(v^+\right)^2-\left(\pi^-/2\right)^2-\left(\pi^+/2\right)^2}{2}+1 \qquad (11)$$

Step 5: Crisp weights are obtained using Eq. 12.

$$w_i=\frac{S\left(\tilde{w}_i^s\right)}{\sum_{i=1}^{n} S\left(\tilde{w}_i^s\right)} \qquad (12)$$

## 2.3 Decision framework
## 2.3. Okvir za odlučivanje

In the present study, the key attributes of wooden toys are analyzed by employing an expert knowledge-based decision-making approach. The research methodology comprises three main stages. In the first stage, the most important criteria are identified based on literature research and expert interviews. Then an interval-valued spherical fuzzy AHP-based model is devised to obtain weight vectors. In the last stage, the prioritization procedure is initiated to determine the importance of each criterion. The steps of this study are shown in Figure 4.

The expert team is comprised of practitioners and academicians in Turkey. The experts are selected by considering their experience, knowledge, and published record on the research topic. Several criteria are discovered from the literature (Fallon and Harris, 1989; Duracell, 2005; Al Kurdi, 2017; Scherer *et al.*, 2017; Mercan, 2018; Richards *et al.*, 2020; Mai, 2021). The list of criteria is refined and expanded by the experts. The hierarchy is structured with one objective, five main criteria, and twenty subcriteria. The hierarchical structure of the problem is portrayed in Figure 5. The objective of the decision-making process is elucidated at the top level of the hierarchy, while the main criteria and their subcriteria are listed at the middle and bottom levels, respectively.

The main criteria of the problem are "economic properties", "developmental supports", "quality properties", "safety properties", and "functional properties". The subcriteria of "economic properties" are identified as "affordability", "longevity", "minimum coating requirement", and "product origin". The subcriteria of "developmental supports" are determined as "contribution to cognitive development", "contribution to psychomotor development", "contribution to social-

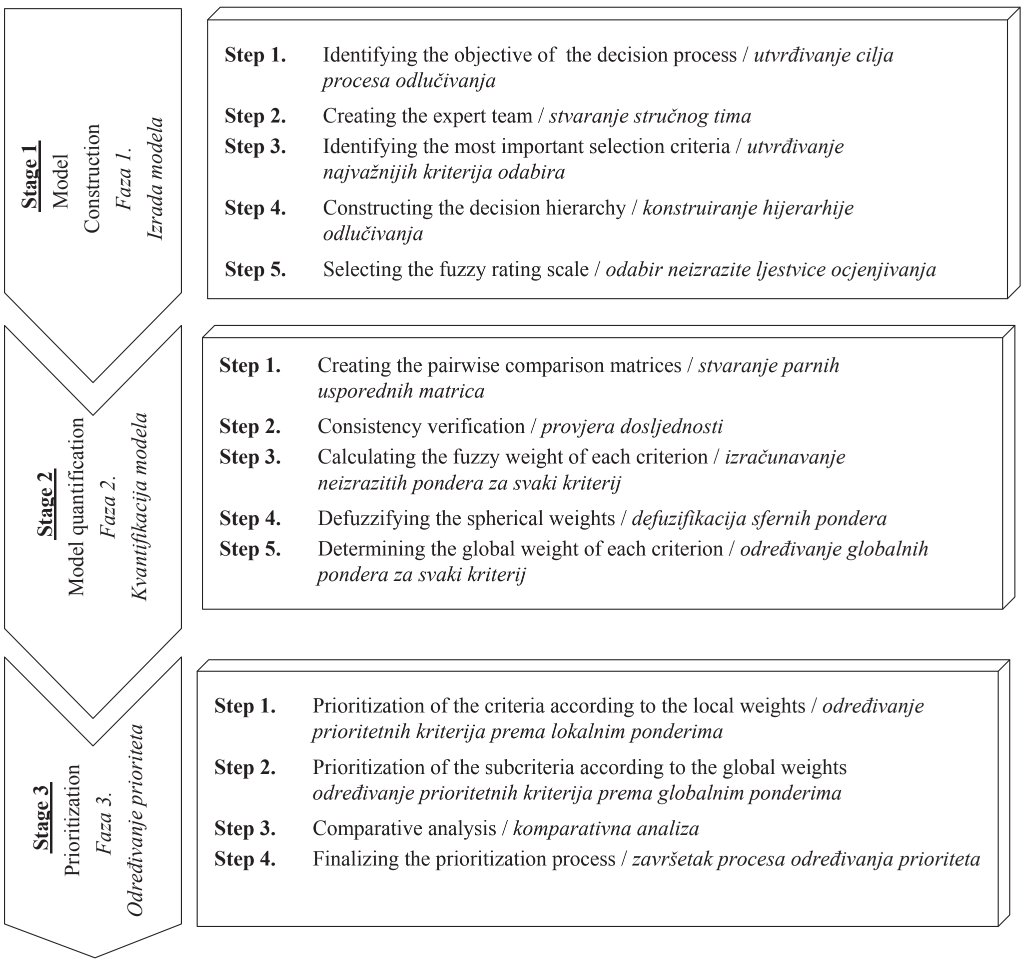



**Figure 4** Steps of this study
**Slika 4.** Koraci u ovom istraživanju

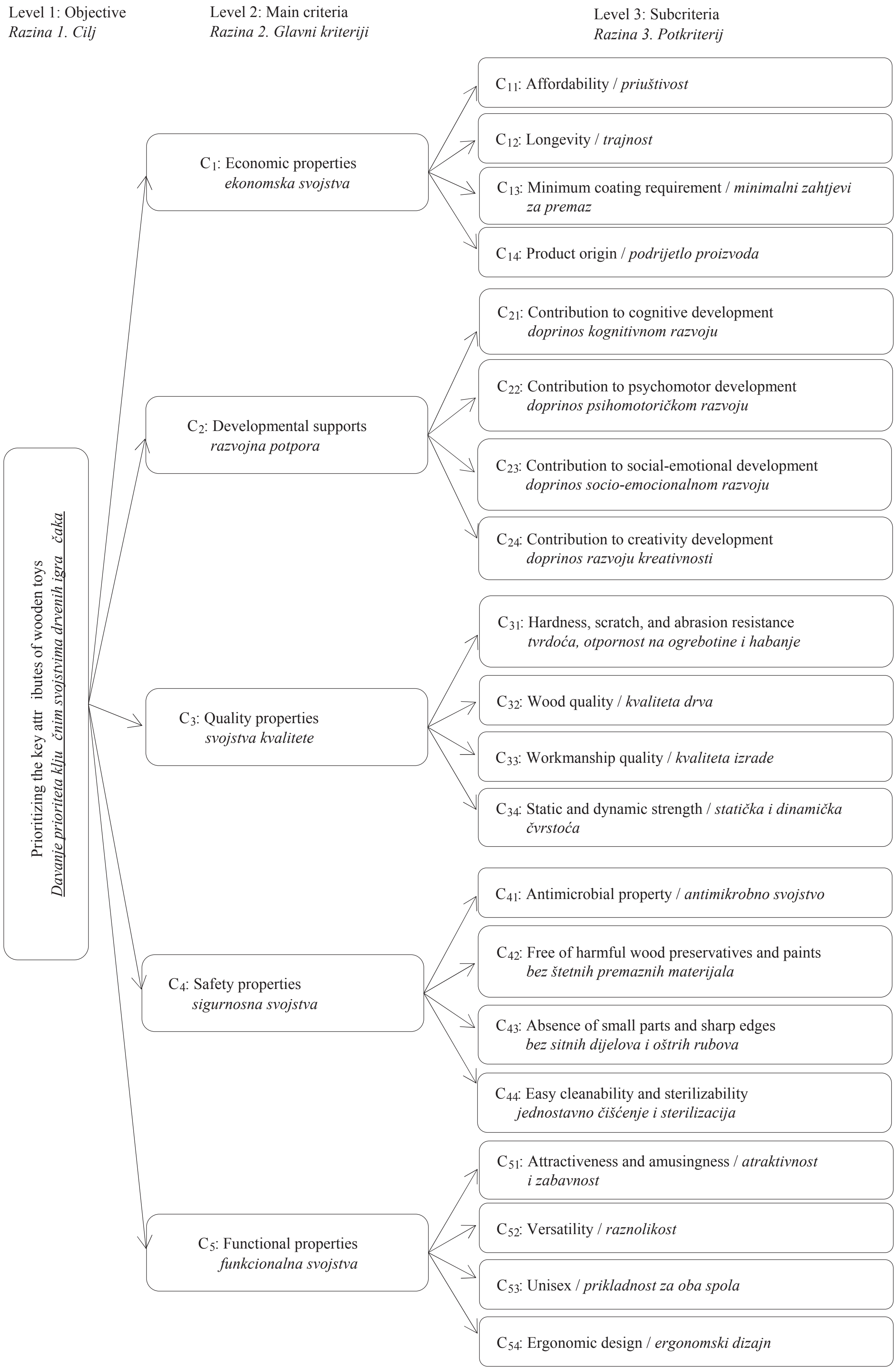



**Figure 5** Hierarchical structure of the problem
**Slika 5.** Hijerarhijska struktura problema

emotional development", and "contribution to creativity development". The subcriteria of "quality properties" are defined as "hardness, scratch, and abrasion resistance", "wood quality", "workmanship quality", and "static and dynamic strength". The subcriteria of "safety properties" are identified as "antimicrobial property", "free of harmful wood preservatives and paints", "absence of small parts and sharp edges", and "easy cleanability and sterilizability". Lastly, the subcriteria of "functional properties" are determined as "attractiveness and amusingness", "versatility", "unisex", and "ergonomic design".

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

The experts are requested to express their preference between every pair of criteria. The fuzzy AHP questionnaires are filled out according to the verbal labels given in Table 1. The consensus-building process is applied to execute collaborative decision-making. The experts' responses are compiled, and then the second round of questionnaires is initiated. After three rounds of opinion consolidation, the experts' final consensus is received. The linguistic preferences are converted to the corresponding interval-valued spherical fuzzy numbers. The main criteria are compared with respect to the objective, while the subcriteria are evaluated against the relevant main criterion. After the pairwise comparison matrices are determined to be consistent, the interval-valued spherical fuzzy AHP is applied to weight the criteria. The matrices used to determine the priorities of the criteria are presented in Tables 3-8.

As an example, the priority calculation of "economic properties" will be elucidated. The fuzzy weight of this criterion is computed as follows:

$$\mu = \begin{bmatrix} \sqrt{1-\left(\left(1-0.50^2\right)^{0.2}\right)\times\left(\left(1-0.20^2\right)^{0.2}\right)\times\left(\left(1-0.25^2\right)^{0.2}\right)\times\left(\left(1-0.15^2\right)^{0.2}\right)\times\left(\left(1-0.25^2\right)^{0.2}\right)}, \\ \sqrt{1-\left(\left(1-0.55^2\right)^{0.2}\right)\times\left(\left(1-0.25^2\right)^{0.2}\right)\times\left(\left(1-0.30^2\right)^{0.2}\right)\times\left(\left(1-0.20^2\right)^{0.2}\right)\times\left(\left(1-0.30^2\right)^{0.2}\right)} \end{bmatrix}$$

$$= [0.30, 0.35]$$

$$v = \begin{bmatrix} \left(0.45^{0.2}\times 0.65^{0.2}\times 0.55^{0.2}\times 0.75^{0.2}\times 0.55^{0.2}\right), \\ \left(0.55^{0.2}\times 0.75^{0.2}\times 0.65^{0.2}\times 0.85^{0.2}\times 0.65^{0.2}\right) \end{bmatrix} = [0.58, 0.68]$$

$$\pi = \begin{bmatrix} \sqrt{\begin{matrix} \left(\left(1-0.50^2\right)^{0.2}\right)\times\left(\left(1-0.20^2\right)^{0.2}\right)\times\left(\left(1-0.25^2\right)^{0.2}\right)\times\left(\left(1-0.15^2\right)^{0.2}\right) \\ \times\left(\left(1-0.25^2\right)^{0.2}\right)-\left(\left(1-0.50^2-0.30^2\right)^{0.2}\right)\times\left(\left(1-0.20^2-0.20^2\right)^{0.2}\right)\times \\ \left(\left(1-0.25^2-0.25^2\right)^{0.2}\right)\times\left(\left(1-0.15^2-0.15^2\right)^{0.2}\right)\times\left(\left(1-0.25^2-0.25^2\right)^{0.2}\right) \end{matrix}}, \\ \sqrt{\begin{matrix} \left(\left(1-0.55^2\right)^{0.2}\right)\times\left(\left(1-0.25^2\right)^{0.2}\right)\times\left(\left(1-0.30^2\right)^{0.2}\right)\times\left(\left(1-0.20^2\right)^{0.2}\right) \\ \times\left(\left(1-0.30^2\right)^{0.2}\right)-\left(\left(1-0.55^2-0.40^2\right)^{0.2}\right)\times\left(\left(1-0.25^2-0.25^2\right)^{0.2}\right)\times \\ \left(\left(1-0.30^2-0.30^2\right)^{0.2}\right)\times\left(\left(1-0.20^2-0.20^2\right)^{0.2}\right)\times\left(\left(1-0.30^2-0.30^2\right)^{0.2}\right) \end{matrix}} \end{bmatrix}$$

$$= [0.24, 0.31]$$

**Table 3** Comparison matrix for the main criteria
**Tablica 3.** Matrica usporedbe za glavne kriterije

| Criterion / *Kriterij* | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $\tilde{w}^s$ | $S(\tilde{w}^s)$ | $w$ |
|---|---|---|---|---|---|---|---|---|
| $C_1$ | EI | LI | SLI | VLI | SLI | ([0.30, 0.35], [0.58, 0.68], [0.24, 0.31]) | 0.69 | 0.132 |
| $C_2$ | | EI | EI | SLI | SMI | ([0.52, 0.60], [0.35, 0.43], [0.26, 0.33]) | 1.13 | 0.218 |
| $C_3$ | | | EI | LI | SMI | ([0.48, 0.56], [0.38, 0.46], [0.27, 0.34]) | 1.07 | 0.206 |
| $C_4$ | | | | EI | VHI | ([0.66, 0.76], [0.22, 0.28], [0.21, 0.26]) | 1.43 | 0.275 |
| $C_5$ | | | | | EI | ([0.38, 0.45], [0.48, 0.57], [0.25, 0.32]) | 0.88 | 0.169 |

**Table 4** Comparison matrix for "economic properties"
**Tablica 4.** Matrica usporedbe za kategoriju „ekonomska svojstva"

| **Criterion** / *Kriterij* | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $\tilde{w}^s$ | $S(\tilde{w}^s)$ | $w$ |
|---|---|---|---|---|---|---|---|
| $C_{11}$ | EI | SMI | HI | SLI | ([0.52, 0.61], [0.33, 0.40], [0.25, 0.32]) | 1.16 | 0.282 |
| $C_{12}$ | | EI | SMI | LI | ([0.41, 0.48], [0.45, 0.53], [0.26, 0.33]) | 0.94 | 0.228 |
| $C_{13}$ | | | EI | LI | ([0.32, 0.37], [0.57, 0.67], [0.25, 0.32]) | 0.71 | 0.173 |
| $C_{14}$ | | | | EI | ([0.59, 0.69], [0.26, 0.32], [0.24, 0.30]) | 1.31 | 0.318 |

**Table 5** Comparison matrix for "developmental supports"
**Tablica 5.** Matrica usporedbe za kategoriju „razvojna potpora"

| **Criterion** / *Kriterij* | $C_{21}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ | $\tilde{w}^s$ | $S(\tilde{w}^s)$ | $w$ |
|---|---|---|---|---|---|---|---|
| $C_{21}$ | EI | SLI | HI | SMI | ([0.52, 0.61], [0.33, 0.40], [0.25, 0.32]) | 1.16 | 0.283 |
| $C_{22}$ | | EI | HI | SMI | ([0.57, 0.66], [0.27, 0.33], [0.25, 0.31]) | 1.27 | 0.309 |
| $C_{23}$ | | | EI | SLI | ([0.32, 0.37], [0.57, 0.67], [0.25, 0.32]) | 0.71 | 0.174 |
| $C_{24}$ | | | | EI | ([0.42, 0.49], [0.43, 0.51], [0.27, 0.33]) | 0.96 | 0.234 |

**Table 6** Comparison matrix for "quality properties"
**Tablica 6.** Matrica usporedbe za kategoriju „svojstva kvalitete"

| **Criterion** / *Kriterij* | $C_{31}$ | $C_{32}$ | $C_{33}$ | $C_{34}$ | $\tilde{w}^s$ | $S(\tilde{w}^s)$ | $w$ |
|---|---|---|---|---|---|---|---|
| $C_{31}$ | EI | LI | VLI | LI | ([0.31, 0.35], [0.61, 0.72], [0.23, 0.30]) | 0.65 | 0.154 |
| $C_{32}$ | | EI | SLI | SMI | ([0.52, 0.61], [0.33, 0.40], [0.25, 0.32]) | 1.16 | 0.277 |
| $C_{33}$ | | | EI | HI | ([0.63, 0.73], [0.24, 0.30], [0.22, 0.28]) | 1.37 | 0.328 |
| $C_{34}$ | | | | EI | ([0.46, 0.53], [0.42, 0.51], [0.24, 0.31]) | 1.01 | 0.241 |

**Table 7** Comparison matrix for "safety properties"
**Tablica 7.** Matrica usporedbe za kategoriju „sigurnosna svojstva"

| **Criterion** / *Kriterij* | $C_{41}$ | $C_{42}$ | $C_{43}$ | $C_{44}$ | $\tilde{w}^s$ | $S(\tilde{w}^s)$ | $w$ |
|---|---|---|---|---|---|---|---|
| $C_{41}$ | EI | LI | VLI | EI | ([0.38, 0.43], [0.56, 0.66], [0.26, 0.34]) | 0.77 | 0.184 |
| $C_{42}$ | | EI | SLI | HI | ([0.55, 0.64], [0.32, 0.39], [0.24, 0.30]) | 1.21 | 0.291 |
| $C_{43}$ | | | EI | VHI | ([0.66, 0.76], [0.22, 0.29], [0.21, 0.27]) | 1.43 | 0.342 |
| $C_{44}$ | | | | EI | ([0.38, 0.43], [0.56, 0.66], [0.26, 0.34]) | 0.77 | 0.184 |

**Table 8** Comparison matrix for "functional properties"
**Tablica 8.** Matrica usporedbe za kategoriju „funkcionalna svojstva"

| **Criterion** / *Kriterij* | $C_{51}$ | $C_{52}$ | $C_{53}$ | $C_{54}$ | $\tilde{w}^s$ | $S(\tilde{w}^s)$ | $w$ |
|---|---|---|---|---|---|---|---|
| $C_{51}$ | EI | SMI | HI | SLI | ([0.52, 0.61], [0.33, 0.40], [0.25, 0.32]) | 1.16 | 0.285 |
| $C_{52}$ | | EI | EI | SLI | ([0.40, 0.45], [0.50, 0.60], [0.28, 0.36]) | 0.85 | 0.209 |
| $C_{53}$ | | | EI | LI | ([0.39, 0.44], [0.54, 0.64], [0.26, 0.35]) | 0.79 | 0.195 |
| $C_{54}$ | | | | EI | ([0.57, 0.66], [0.27, 0.33], [0.25, 0.31]) | 1.27 | 0.311 |

The defuzzfied value of ([0.30, 0.35], [0.58, 0.68], [0.24, 0.31]) is obtained as below.

$$S = \frac{(0.30)^2 + (0.35)^2 - (0.58)^2 - (0.68)^2 - (0.24/2)^2 - (0.31/2)^2}{2} + 1 = 0.69$$

After the normalization operation is applied to the resulting weight vector, the crisp weight of "economic properties" is revealed as 0.132. As can be seen in Figure 6, the sequence of the main criteria is "safety properties" (0.275) > "developmental supports" (0.218) > "quality properties" (0.206) > "functional properties" (0.169) > "economic properties" (0.132). The obtained ranking result indicates that "safety properties" deserves the highest priority in wooden toy selection.

The crisp weights obtained from the pairwise comparison matrix of "economic properties" are presented in Figure 7. The subcriterion "product origin" (0.318) has the highest weight value and is prioritized

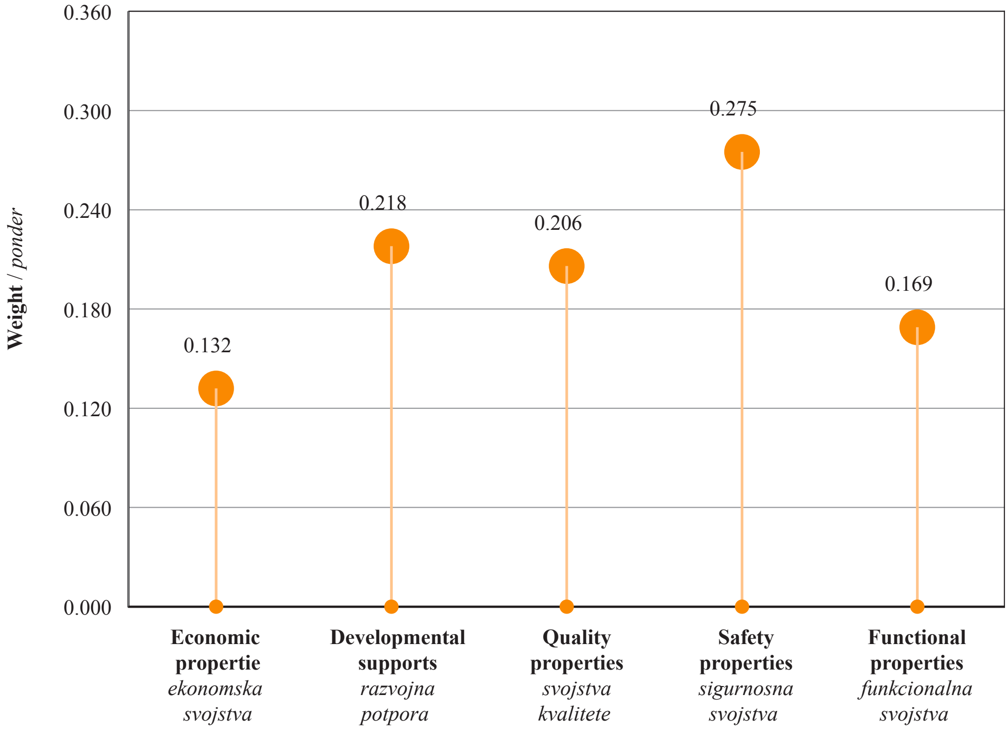



**Figure 6** Modeling results for the main criteria
**Slika 6.** Rezultati modeliranja za glavne kriterije

as the most important one. Many consumers regard this criterion as a sign of product reliability (Kaynak *et al.*, 2000). Hence, consumer perceptions and purchase likelihood are significantly influenced by the origin of toys. The criteria "affordability" (0.282) and "longevity" (0.228) come in second and third, respectively, while "minimum coating requirement" (0.173) emerges as the least important subcriterion.

Figure 8 demonstrates the weight distribution of the subcriteria within the "developmental supports" category. The most important subcriterion of this category is "contribution to psychomotor development"

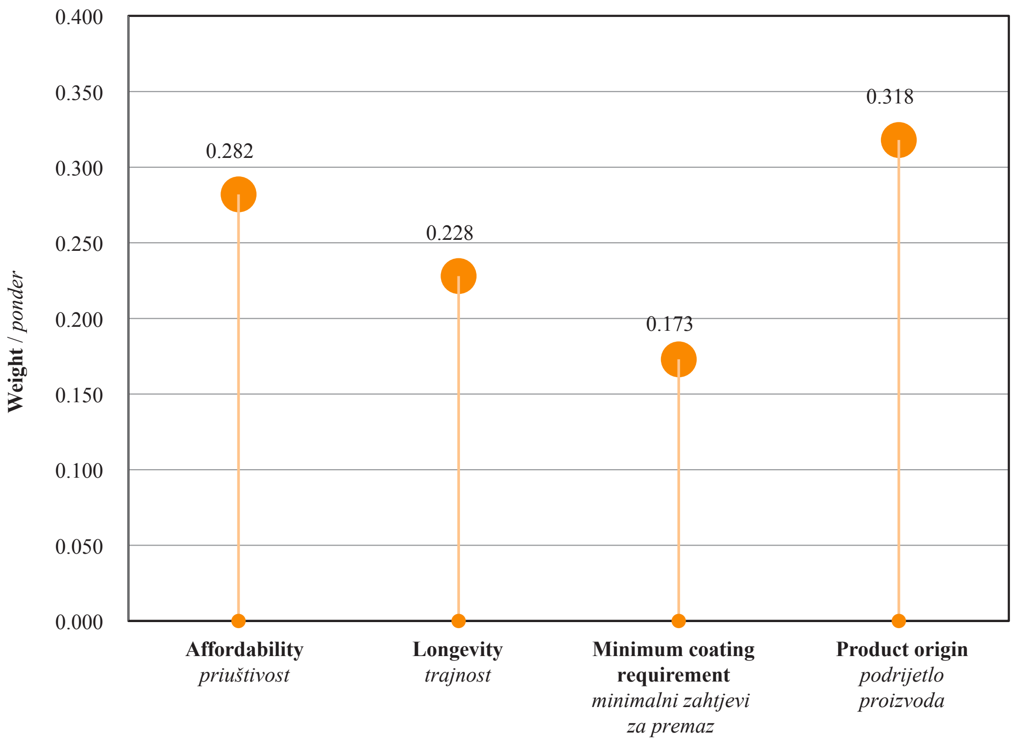



**Figure 7** Modeling results for "economic properties"
**Slika 7.** Rezultati modeliranja za kategoriju „ekonomska svojstva"

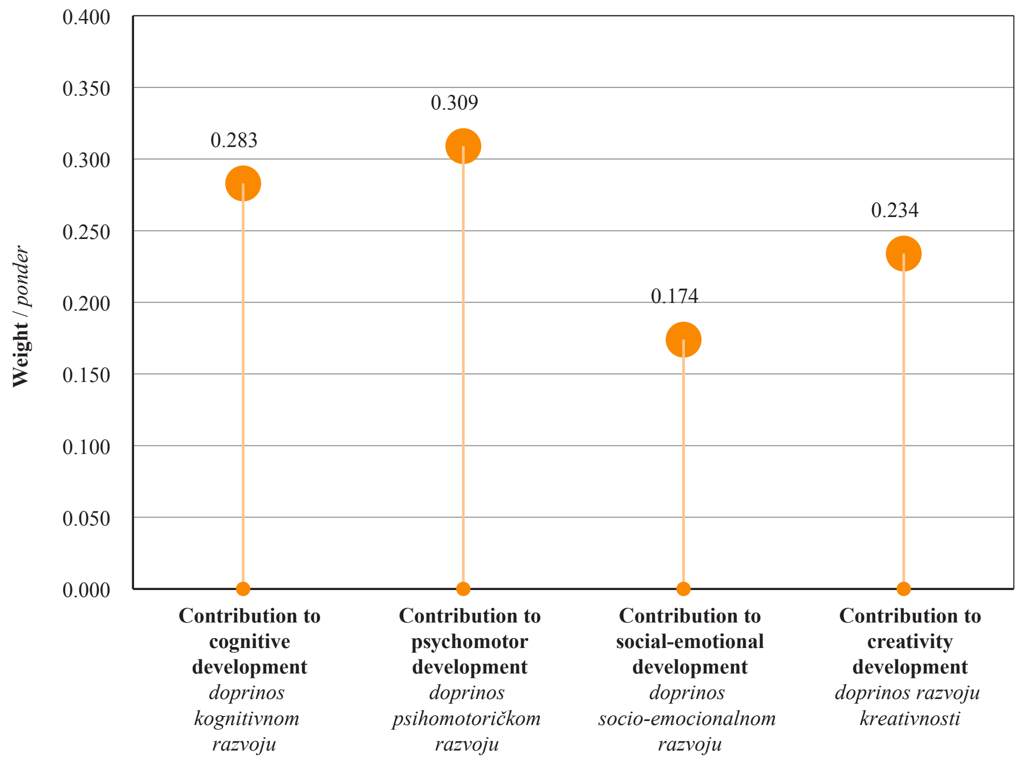



**Figure 8** Modeling results for "developmental supports"
**Slika 8.** Rezultati modeliranja za kategoriju „razvojna potpora"

(0.309). The expert team has highlighted that children playing with wooden toys can learn to control their muscles in the psychomotor aspect and their movements can acquire agility, strength, and speed. The second important subcriterion is "contribution to cognitive development" (0.283). The subcriterion "contribution to creativity development" (0.234) is positioned at the third rank, while "contribution to social-emotional development" (0.174) is at the end of the local priority list.

When the weights in Figure 9 are ranked in descending order, it is observed that "workmanship quality" (0.328) is the most considerable subcriterion within the "quality properties" category. Poor quality can

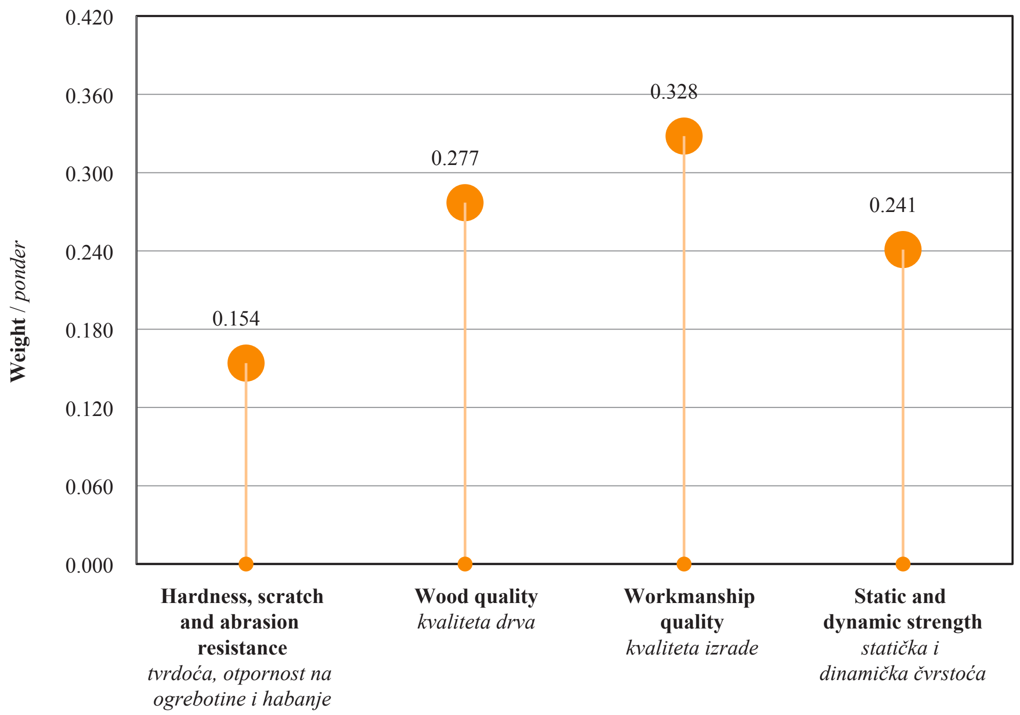



**Figure 9** Modeling results for "quality properties"
**Slika 9.** Rezultati modeliranja za kategoriju „svojstva kvalitete"

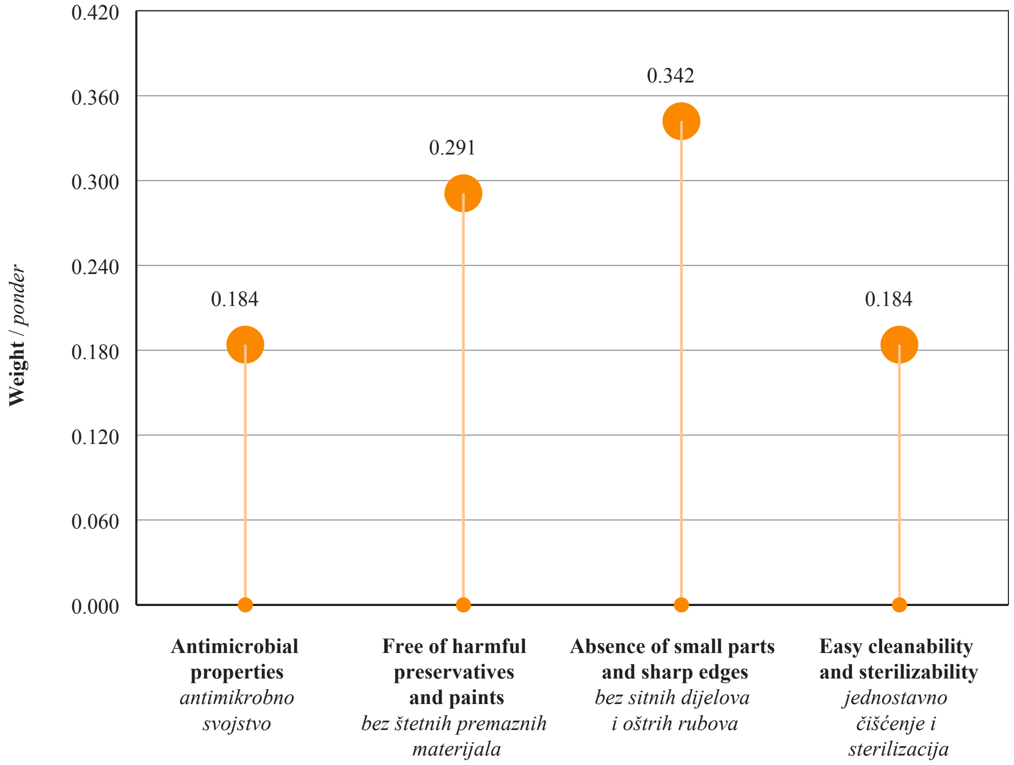



**Figure 10** Modeling results for "safety properties"
**Slika 10.** Rezultati modeliranja za kategoriju „sigurnosna svojstva"

cause permanent or latent product failures and negatively affect the appearance of products (Azemovic *et al*., 2014). The subcriteria "wood quality" (0.277) and "static and dynamic strength" (0.241) obtain the second and third ranks, respectively. The least significant subcriterion appears to be "hardness, scratch, and abrasion resistance" (0.154).

The modeling results for the "safety properties" category are presented in Figure 10. The priority order of the subcriteria of this category is as follows: "ab-

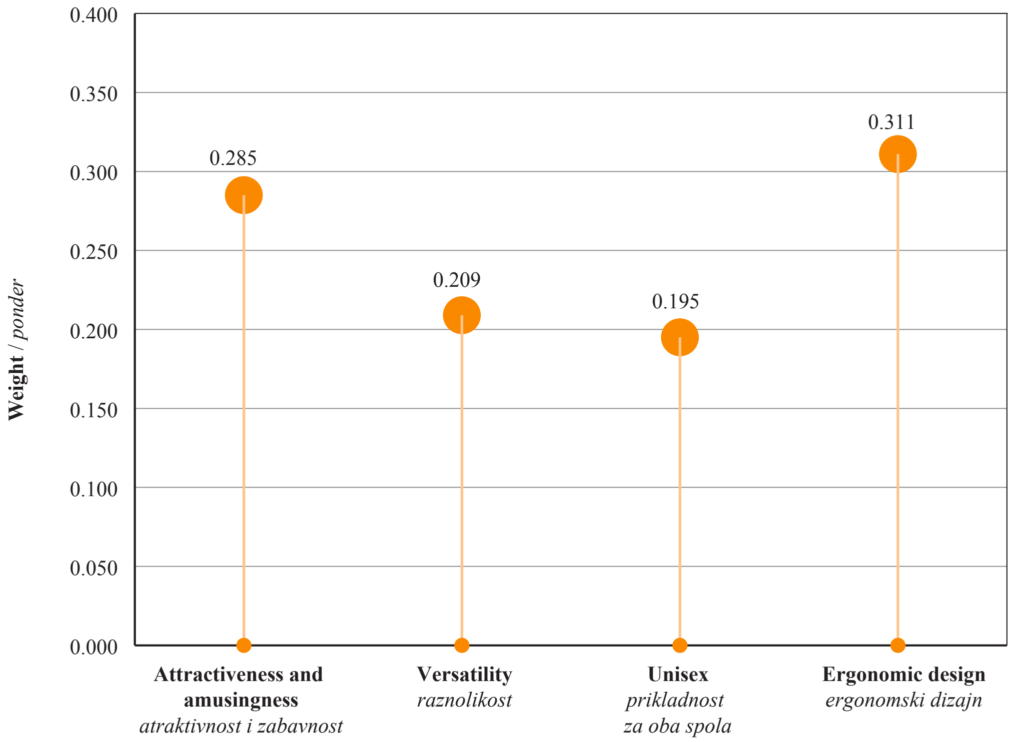



**Figure 11** Modeling results for "functional properties"
**Slika 11.** Rezultati modeliranja za kategoriju „funkcionalna svojstva"

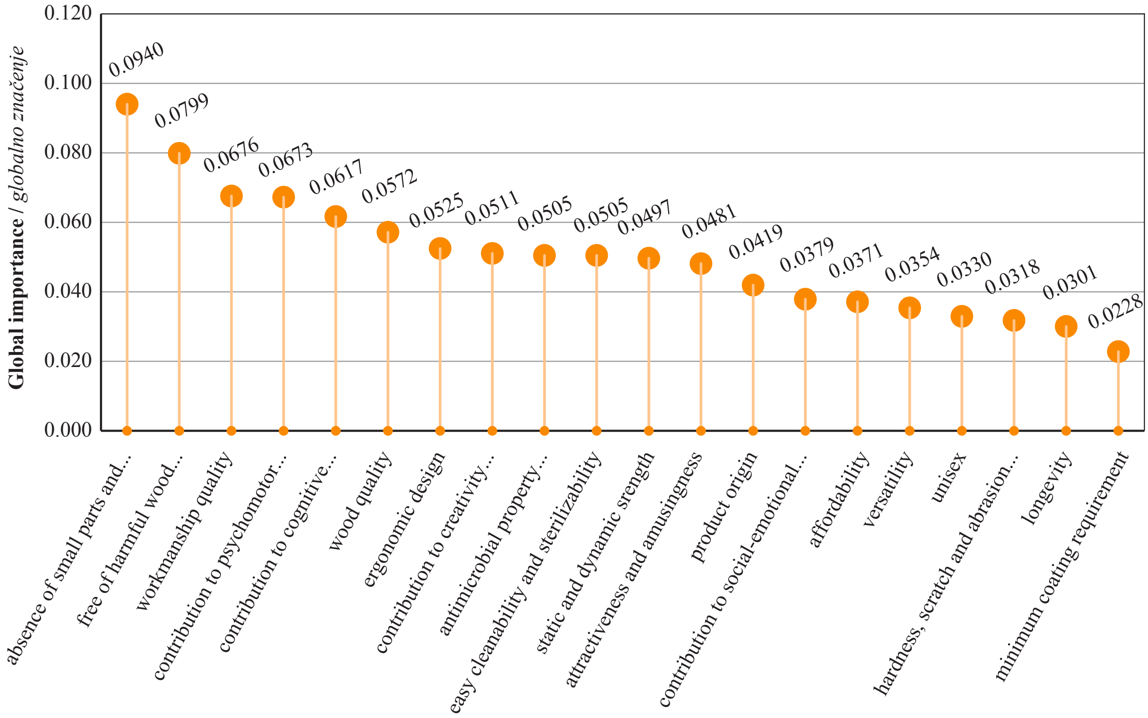



**Figure 12** Global importance of subcriteria
**Slika 12.** Globalno značenje potkriterija

sence of small parts and sharp edges" (0.342) > "free of harmful wood preservatives and paints" (0.291) > "antimicrobial property" (0.184) = "easy cleanability and sterilizability" (0.184). The ranking result means that the experts give more importance to "absence of small parts and sharp edges" than to others. Some toys can be dangerous. Hence, alternatives should be carefully evaluated and then ranked from safest to least safe.

According to Figure 11, "ergonomic design" (0.311) is the most important subcriterion within the "functional properties" category. Good ergonomic design improves product usability and user satisfaction. It ensures that children can utilize toys correctly without causing harm to themselves. The criterion "attractiveness and amusingness" (0.285) has the second-highest weight value, while "versatility" (0.209) is the third-highest weighted subcriterion.

The local weights derived from the comparison matrices are multiplied to reveal the global importance of the subcriteria. Figure 12 demonstrates the global priority for each subcriterion. The top five subcriteria and their global weight are as follows: {absence of small parts and sharp edges, 0.0940}, {free of harmful wood preservatives and paints, 0.0799}, {workmanship quality, 0.0676}, {contribution to psychomotor development, 0.0673}, and {contribution to cognitive development, 0.0617}. Decision-makers should focus primarily on these subcriteria in evaluating different wooden toys.

The reliability and accuracy of decision-making models are generally examined by conducting a comparative analysis. Hence, the data gathered from the experts are tested by three popular fuzzy methods: interval type-2 fuzzy AHP, interval-valued Pythagorean fuzzy AHP, and spherical fuzzy AHP. Figure 13 demonstrates the changes in the global weights of the subcriteria. As can be seen in the figure, "absence of small parts and sharp edges", "free of harmful wood preservatives and paints", "workmanship quality", "contribution to psychomotor development", and "contribution to cognitive development" hold the top five ranks. The weights assigned to the criteria by the methods are not the same; however, the ranking position of the criteria mostly remains the same. The applied methods consider different assumptions and scales. Hence, the differences in the results can be attributed to these factors. The interval-valued spherical fuzzy AHP is a more recent method that considers membership, non-membership, and hesitancy at the same time, and provides a more comprehensive range of membership function definitions. Consequently, the decision framework has strong robustness and feasibility.

The decision-making process associated with choosing wooden toys is complex due to the uncertainty, subjectivity, and conflicting factors. Decision-makers are confronted with many alternatives, which should be evaluated and compared initially. Hence, the identification and prioritization of selection criteria are essential. As pointed out previously, there is no information on the usage of the MCDM technique to specify and analyze the key attributes of wooden toys. Hence, this study provides a novel, comprehensive,

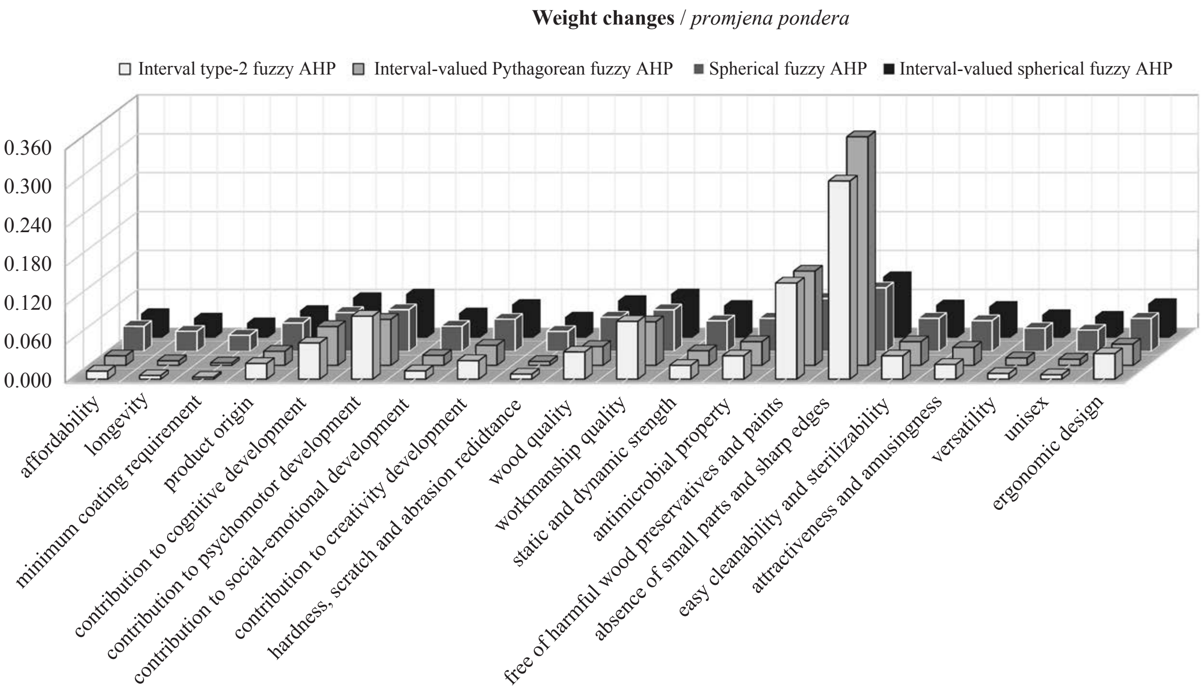



**Figure 13** Comparison of different fuzzy AHP outputs
**Slika 13.** Usporedba različitih neizrazitih izlaznih vrijednosti AHP-a

and valuable guide to assist consumers, designers, and manufacturers in determining the best options.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

This study identifies and prioritizes the key attributes of wooden toys from experts' perspectives. A review of the relevant academic literature and expert interviews are conducted to identify decision criteria. At the end of this process, twenty subcriteria are finalized under five main criteria. A three-level hierarchical model is devised for the prioritization purpose. The required data is gathered from experts who have experience with the research topic. The main criteria and subcriteria used in the study are assigned weights by employing an interval-valued spherical fuzzy AHP approach. According to the modeling results, the most significant main criterion is "safety properties" (27.5 %). The overall priority results demonstrate that "absence of small parts and sharp edges" (9.40 %), "free of harmful wood preservatives and paints" (7.99 %), "workmanship quality" (6.76 %), "contribution to psychomotor development", and "contribution to cognitive development" (6.17%) deserve a higher priority in the decision-making process.

Our research endeavor is different from the previous studies. The originality and value of this paper can be elucidated as follows: (i) identification, classification, and prioritization of the key attributes of wooden toys for the first time; (ii) comprehensive and quantitative analysis of selection criteria; (iii) consideration of uncertainties and hesitations for solving the problem; (iv) examination of the problem from experts' perspectives; (v) first implementation of the interval-valued spherical fuzzy set in the field of wood science. In this research, it is assumed that wooden toy selection criteria are mutually exclusive. Further research may apply the fuzzy cognitive map to examine the interdependency among these criteria. Consumers' preferences can be examined under the fuzzy MCDM environment. The performance of different options can be rated under the criteria to rank them from the best to the worst or to sort them into predefined ordered classes.

## 5 REFERENCES
## 5. LITERATURA


1. Ahammed, F.; Azeem, A., 2013: Selection of the most appropriate package of solar home system using analytic hierarchy process model in rural areas of Bangladesh. Renewable Energy, 55: 6-11. https://doi.org/10.1016/j.renene.2012.12.020
2. Alelaiwi, A., 2019: Evaluating distributed IoT databases for edge/cloud platforms using the analytic hierarchy process. Journal of Parallel and Distributed Computing, 124: 41-46. https://doi.org/10.1016/j.jpdc.2018.10.008
3. Ashraf, S.; Abdullah, S., 2020: Emergency decision support modeling for COVID-19 based on spherical fuzzy information. International Journal of Intelligent Systems, 35 (11): 1601-1645. https://doi.org/10.1002/int.22262
4. Ashtiani, M.; Abdollahi Azgomi, M., 2015: A multi-criteria decision-making formulation of trust using fuzzy analytic hierarchy process. Cognition, Technology and Work, 17 (4): 465-488. https://doi.org/10.1007/s10111-014-0310-2

5. Azemovic, E.; Horman, I.; Busuladžic, I., 2014: Impact of planing treatment regime on solid fir wood surface. Procedia Engineering, 69: 1490-1498. https://doi.org/10.1016/j.proeng.2014.03.146
6. Balin, A., 2020: A novel fuzzy multi-criteria decision-making methodology based upon the spherical fuzzy sets with a real case study. Iranian Journal of Fuzzy Systems, 17 (4): 167-177. https://doi.org/10.22111/ijfs.2020.5413
7. Balogun, A. L.; Matori, A. N.; Hamid-Mosaku, A. I., 2015: A fuzzy multi-criteria decision support system for evaluating subsea oil pipeline routing criteria in East Malaysia. Environmental Earth Sciences, 74 (6): 4875-4884. https://doi.org/10.1007/s12665-015-4499-z
8. Demir, E.; Turan, H., 2021: An integrated spherical fuzzy AHP multi-criteria method for Covid-19 crisis management in regarding lean six sigma. International Journal of Lean Six Sigma, 12 (4): 859-885. https://doi.org/10.1108/IJLSS-11-2020-0183
9. Dožić, S.; Lutovac, T.; Kalić, M., 2018: Fuzzy AHP approach to passenger aircraft type selection. Journal of Air Transport Management, 68: 165-175. https://doi.org/10.1016/j.jairtraman.2017.08.003
10. Duleba, S.; Kutlu Gündoğdu, F.; Moslem, S., 2021: Interval-valued spherical fuzzy analytic hierarchy process method to evaluate public transportation development. Informatica, 32 (4): 661-686. https://doi.org/10.15388/21-infor451
11. Duracell, 2005: The top ten toys in Europe. Young Consumers, 6 (3): 44-49. https://doi.org/10.1108/17473610510701197
12. Fallon, M. A.; Harris, M. B., 1989: Factors influencing the selection of toys for handicapped and normally developing preschool children. The Journal of Genetic Psychology, 150 (2): 125-134. https://doi.org/10.1080/00221325.1989.9914584
13. Gül, S., 2020: Spherical fuzzy extension of DEMATEL (SF-DEMATEL). International Journal of Intelligent Systems, 35 (9): 1329-1353. https://doi.org/10.1002/int.22255
14. Hamal, S.; Senvar, O., 2022: A novel integrated AHP and MULTIMOORA method with interval-valued spherical fuzzy sets and single-valued spherical fuzzy sets to prioritize financial ratios for financial accounting fraud detection. Journal of Intelligent and Fuzzy Systems, 42 (1): 337-364. https://doi.org/10.3233/jifs-219195
15. Kar, A. K., 2015: A hybrid group decision support system for supplier selection using analytic hierarchy process, fuzzy set theory and neural network. Journal of Computational Science, 6: 23-33. https://doi.org/10.1016/j.jocs.2014.11.002
16. Kaynak, E.; Kucukemiroglu, O.; Hyder, A. S., 2000: Consumers' country-of-origin (COO) perceptions of imported products in a homogenous less-developed country. European Journal of Marketing, 34 (9-10): 1221-1241. https://doi.org/10.1108/03090560010342610
17. Kim, Y.; Chung, E. S., 2013: Fuzzy VIKOR approach for assessing the vulnerability of the water supply to climate change and variability in South Korea. Applied Mathematical Modelling, 37 (22): 9419-9430. https://doi.org/10.1016/j.apm.2013.04.040
18. Al Kurdi, B., 2017: Investigating the factors influencing parent toy purchase decisions: reasoning and consequences. International Business Research, 10 (4): 104-116. https://doi.org/10.5539/ibr.v10n4p104
19. Kutlu Gundogdu, F.; Kahraman, C., 2019: Extension of WASPAS with spherical fuzzy sets. Informatica, 30 (2): 269-292. https://doi.org/10.15388/Informatica.2019.206
20. Kutlu Gündoğdu, F.; Kahraman, C., 2020: A novel spherical fuzzy analytic hierarchy process and its renewable energy application. Soft Computing, 24 (6): 4607-4621. https://doi.org/10.1007/s00500-019-04222-w
21. Kutlu Gündoğdu, F.; Kahraman, C., 2021: Hospital performance assessment using interval-valued spherical fuzzy analytic hierarchy process. In: Studies in Fuzziness and Soft Computing, Kahraman, C.; Kutlu Gündoğdu, F. (eds.). Springer, Cham, 349-373. https://doi.org/10.1007/978-3-030-45461-6_15
22. Mahjouri, M.; Ishak, M. B.; Torabian, A.; Manaf, L. A.; Halimoon, N., 2017: The application of a hybrid model for identifying and ranking indicators for assessing the sustainability of wastewater treatment systems. Sustainable Production and Consumption, 10: 21-37. https://doi.org/10.1016/j.spc.2016.09.006
23. Mai, N. H., 2021: Investigating about consumers' attitudes to green children's toys products in Vietnam. International Journal of Trade, Economics and Finance, 12 (2): 54-57. https://doi.org/10.18178/ijtef.2021.12.2.693
24. Mathew, M.; Chakrabortty, R. K.; Ryan, M. J., 2020: A novel approach integrating AHP and TOPSIS under spherical fuzzy sets for advanced manufacturing system selection. Engineering Applications of Artificial Intelligence, 96: 103988. https://doi.org/10.1016/j.engappai.2020.103988
25. Mercan, C., 2018: The role of wooden toys in child development and design suggestions for wooden toys. Master Thesis, Hacettepe University, Ankara, Turkey, 118 pp.
26. Oblak, L.; Barčić, A. P.; Klarić, K.; Kuzman, M. K.; Grošelj, P., 2017: Evaluation of factors in buying decision process of furniture consumers by applying AHP method. Drvna industrija, 68 (5): 37-43. https://doi.org/10.5552/drind.2017.1625
27. Özşahin, Ş.; Singer, H.; Temiz, A.; Yildirim, İ., 2019: Selection of softwood species for structural and non-structural timber construction by using the analytic hierarchy process (AHP) and the multiobjective optimization on the basis of ratio analysis (MOORA). Baltic Forestry, 25 (2): 281-288. https://doi.org/10.46490/vol25iss2pp281
28. Richards, M. N.; Putnick, D. L.; Bornstein, M. H., 2020: Toy buying today: considerations, information seeking, and thoughts about manufacturer suggested age. Journal of Applied Developmental Psychology, 68: 101134. https://doi.org/10.1016/j.appdev.2020.101134
29. Saaty, T. L., 1977: A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, 15 (3): 234-281. https://doi.org/10.1016/0022-2496(77)90033-5
30. Scherer, C.; Emberger-Klein, A.; Menrad, K., 2017: Biogenic product alternatives for children: consumer preferences for a set of sand toys made of bio-based plastic. Sustainable Production and Consumption, 10: 1-14. https://doi.org/10.1016/j.spc.2016.11.001
31. Shameem, M.; Kumar, R. R.; Nadeem, M.; Khan, A. A., 2020: Taxonomical classification of barriers for scaling agile methods in global software development environment using fuzzy analytic hierarchy process. Applied Soft Computing Journal, 90: 106122. https://doi.org/10.1016/j.asoc.2020.106122
32. Singer, H.; Özşahin, Ş., 2021: Prioritization of laminate flooring selection criteria from experts' perspectives: a spherical fuzzy AHP-based model. Architectural Engineering and Design Management. https://doi.org/10.1080/17452007.2021.1956421

33. Singer, H.; Özşahin, Ş., 2022. Prioritization of factors affecting surface roughness of wood and wood-based materials in CNC machining: a fuzzy analytic hierarchy process model. Wood Material Science and Engineering, 17 (2): 63-71. https://doi.org/10.1080/17480272.2020.1778079
34. Song, C.; Zhao, H.; Xu, Z.; Hao, Z., 2019: Interval-valued probabilistic hesitant fuzzy set and its application in the Arctic geopolitical risk evaluation. International Journal of Intelligent Systems, 34 (4): 627-651. https://doi.org/10.1002/int.22069
35. Srinivas, R.; Singh, A. P., 2018: Impact assessment of industrial wastewater discharge in a river basin using interval-valued fuzzy group decision-making and spatial approach. Environment, Development and Sustainability, 20 (5): 2373-2397. https://doi.org/10.1007/s10668-017-9994-9
36. Stein, W. E.; Mizzi, P. J., 2007: The harmonic consistency index for the analytic hierarchy process. European Journal of Operational Research, 177 (1): 488-497. https://doi.org/10.1016/j.ejor.2005.10.057
37. Unal, Y.; Temur, G. T., 2022: Sustainable supplier selection by using spherical fuzzy AHP. Journal of Intelligent & Fuzzy Systems, 42 (1): 593-603. https://doi.org/10.3233/jifs-219214
38. Wang, R.; Li, Y., 2018: Picture hesitant fuzzy set and its application to multiple criteria decision-making. Symmetry, 10 (7): 1-29. https://doi.org/10.3390/sym10070295

**Corresponding address:**

**HILAL SINGER**
Bolu Abant Izzet Baysal University, Department of Industrial Engineering, Golkoy Campus, 14030 Bolu, TURKEY, e-mail: hilal.singer@hotmail.com; hilal.singer@ibu.edu.tr

Nadir Ersen[1], Uğur Can Usta[2], Bahadir Cagri Bayram[3], İlker Akyüz[4]

# Intermediate Role of Presenteeism in Relationship Between Organizational Stress and Organizational Silence: A Research on Forest Industry Employees

# Posredna uloga prezentizma u odnosu između organizacijskog stresa i organizacijske šutnje: istraživanje o zaposlenicima u drvoprerađivačkoj industriji

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 29. 6. 2022.
Accepted – prihvaćeno: 3. 10. 2022.
UDK: 630*8
https://doi.org/10.5552/drvind.2023.0046



**ABSTRACT •** *The purpose of this study is to investigate the mediating role of presenteeism in the relationship between organizational stress and organizational silence of 305 forest products employees in İstanbul and Kocaeli, Turkey. According to our literature review, although some important studies about presenteeism, stress, and silence can be found, this study is the first to explore the mediating role of presenteeism in the relationship between organizational stress and organizational silence in forest products sector. The research was designed as a field study and conducted using a questionnaire. The questionnaire involved forest industry employees' demographic data, Organizational Stress Scale, Organizational Silence Scale, and Stanford Presenteeism Scale. Data were analyzed in SPSS and AMOS, incorporating statistical tests such as exploratory and confirmatory factor analysis, correlation analysis, and structural equation modeling. Results of the analyzed data showed that presenteeism had a significant moderating effect on the relationship between organizational stress and organizational silence. Moreover, organizational stress had a positive effect on presenteeism, while organizational silence had a negative effect. Organizational stress had no effect on organizational silence. Therefore, managers should develop strategies for coping with stress to reduce presenteeism behavior of their employees and identify organizational stress factors causing organizational silence.*

**KEYWORDS:** *stress, silence, presenteeism, forest products sector*

[1] Author is researcher at Artvin Çoruh University, Artvin Vocational School, Department of Forestry, Artvin, Turkey. https://orcid.org/0000-0003-3643-1390
[2] Author is researcher at Bursa Technical University, Faculty of Forest, Department of Forest Industry Engineering, Bursa, Turkey. https://orcid.org/0000-0002-0097-5786
[3] Author is researcher at Kastamonu University, Faculty of Forest, Department of Forest Industry Engineering, Kastamonu, Turkey. https://orcid.org/0000-0002-8563-0233
[4] Author is researcher at Karadeniz Technical University, Faculty of Forest, Department of Forest Industry Engineering, Trabzon, Turkey. https://orcid.org/0000-0003-4241-1118

**SAŽETAK** • *Cilj ovog istraživanja bilo je rasvjetljavanje posredničke uloge prezentizma u odnosu između organizacijskog stresa i organizacijske šutnje 305 zaposlenika u drvoprerađivačkoj industriji u Istanbulu i Kocaeliji u Turskoj. Iako su u literaturi pronađena neka važna istraživanja o prezentizmu, stresu i šutnji, ovo je istraživanje prvo koje se bavi posredničkom ulogom prezentizma u odnosu između organizacijskog stresa i organizacijske šutnje u drvoprerađivačkom sektoru. Istraživanje je pripremljeno kao terensko i provedeno je putem ankete. Anketa je obuhvatila demografske podatke zaposlenika u drvoprerađivačkoj industriji, razinu organizacijskog stresa, razinu organizacijske šutnje i standfordsku razinu prezentizma. Podatci su analizirani u SPSS-u i AMOS-u statističkim testovima kao što su eksplorativna i konfirmatorna faktorska analiza, korelacijska analiza i modeliranje strukturnih jednadžbi. Rezultati analiziranih podataka pokazali su da je prezentizam imao znatan posrednički utjecaj na odnos između organizacijskog stresa i organizacijske šutnje. Štoviše, organizacijski je stres pozitivno utjecao na prezentizam, dok je organizacijska šutnja imala negativan utjecaj na nj. Organizacijski stres nije utjecao na organizacijsku šutnju. Stoga bi menadžeri trebali razviti strategije za suočavanje sa stresom kako bi smanjili prezentističko ponašanje svojih zaposlenika i identificirali čimbenike organizacijskog stresa koji uzrokuju organizacijsku šutnju.*

**KLJUČNE RIJEČI:** *stres, šutnja, prezentizam, drvoprerađivački sektor*

## 1 INTRODUCTION
## 1. UVOD

Employees are the most important element that companies have in order to keep them in business. The productivity of employees, which is important for companies, directly affects the performance of the organization. Therefore, ensuring employee productivity is one of the organizational goals. Employee performance can vary due to many factors. Stress is also accepted as a concept that affects the productivity of the individual (Şahin, 2020).

All jobs might be a potential source of stress because every job has its own working conditions. Work-related social psychological stress might be considered as organizational stress. Organizational stress is defined as "an ongoing transaction between an individual and the environmental demands associated primarily and directly with the organization within which he or she is operating". Organizational stress factors include role ambiguity and conflict, cultural and political environment, coaching and/or management style, lack of participation in the decision-making process, inadequate communication channels, lack of participation in the decision-making process, etc. (Fletcher *et al*., 2006; Rumbold and Didymus, 2021).

There are many factors that cause silence. Such reasons include stress, lack of experience, structural and cultural hierarchy, lack of support, fears and suspicions, fear of being labeled or stigmatized or viewed negatively, fear of losing contact, feelings of emptiness and fear of punishment (Saeidipour *et al*., 2021). Silence occurs when employees in the organization do not express their thoughts and it is an undesirable phenomenon in an organization. Due to organizational silence, employees withhold their useful ideas, and this can have negative effects on their motivation and attitude. In addition, at the individual level, silence can create a feeling of emptiness, lack of control and anomalies (such as mobbing) in the organization (Managheb *et al*., 2018; Saeidipour *et al*., 2021; Mousa *et al*., 2021).

Silence behavior might be exhibited intentionally, purposefully, actively and consciously. This situation leads to the formation of different forms of organizational silence (Yalçınsoy, 2017). Knoll and van Dick (2013) discussed organizational silence in a four-dimensional structure: quiescent silence, opportunistic silence, acquiescent silence and prosocial silence. Quiescent silence is briefly defined as "suffering in silence". Acquiescent silence is withholding work-related ideas, information, or opinions, due to resignation. Prosocial silence is withholding work-related ideas, information, or opinions, based on altruistic or cooperative motives. Opportunistic silence is defined as strategically withholding work-related ideas, information or opinions in order to gain an advantage for oneself (Knoll and van Dick, 2013).

One of the factors affecting the productivity of employees is presenteeism. Presenteeism is the loss of productivity of employees due to health problems or other events that negatively affect employees, even though they are physically at the workplace (Yang *et al*., 2017). Maestas *et al*. (2021) reported that presenteeism causes an average productivity loss of 20 % and workers with high absence rates and presenteeism have more than 80 % probability of leaving the job in 3 years. In studies conducted in different countries, it has been reported that presenteeism causes 30 % - 90 % loss of productivity (Lohaus and Habermann, 2019; Knani, 2022). In addition, at the organizational level, presenteeism increases direct and indirect costs and reduces global performance; at the individual level, it negatively impacts employees' physical and mental health (Knani, 2022).

The purpose of this study is to determine the mediating role of presenteeism in the relationship between organizational stress and organizational silence. In addition, the effect of organizational stress on organizational silence and presenteeism and the effect of presenteeism on organizational silence were investigated.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

The research focuses on employees in the forest products sector (furniture, timber, particleboard, coating, wooden packaging) operating in the provinces of Istanbul and Kocaeli in Turkey. The reason for the selection of employees in the forest products sector in Istanbul and Kocaeli is as follows: Based on TOBB Industry Database, the number of enterprises operating in forest products in Istanbul and Kocaeli is 9596, which accounts for approximately 41 % of all enterprises operating in this sector in Turkey (TOBB, 2021).

The total number of employees in the forest products sector in Turkey was taken as the research universe. Based on TOBB data, the number of employees in the forest products sector in Turkey is 350346 (TOBB, 2021). The following sample determination formula was used to determine the total number of participants to whom the surveys would be applied (Dorman *et al.*, 1990):

$$n = \frac{N \cdot p \cdot q \cdot Z^2}{(N-1) \cdot d^2 + p \cdot q \cdot Z^2} \quad (1)$$

Where $n$ is sample size, $N$ is universe size (350346 employees in the forest products sector), $p$ is probability of the occurrence of the characteristic to be measured in the universe (this ratio was taken as 50 % because this study was multi-purpose), $q$ is 1-$q$ (improbability of the occurrence of the characteristic to be measured in the universe), $Z$ is confidence coefficient ($Z$-score at 95% confidence interval was taken as 1.96), and $d$ is accepted sampling error (6 % taken).

As a result, the sample size was determined to be 267 employees. In order to increase the validity and reliability of the study, the sample number was kept high. For this purpose, the survey study was conducted with 335 employees, but 305 surveys were assessed. The research was carried out between June 2021 and October 2021.

The research was planned as a field study and the survey technique was used to obtain the data. Survey forms were submitted to the employees directly. The survey form used in the research consists of 4 parts. The first part contains statements related to the demographic characteristics of the participants. The second part contains statements about organizational stress. The "Organizational Stress scale" was created using the job stress scale developed by Balcı (1993) and the studies conducted by Akova and Işık (2008), Soysal (2009) and Çökük (2018) and it consists of 14 statements. The third part uses the "Organizational Silence scale" developed by Knoll and van Dick (2013) and consists of 20 statements. The scale was translated into Turkish by Çavuşoğlu and Köse (2019) and validity and reliability analyses were performed. The fourth part uses the "Standford Presenteeism scale" developed by Koopman *et al.* (2002) and it contains 6 statements. The scale was translated into Turkish by Coşkun (2012) and validity and reliability analyses were performed. The statements in the scales were designed according to a 5-point Likert scale (5 = Strongly Agree, 4 = Agree, 3 = Undecided, 2 = Disagree, 1 = Strongly Disagree).

According to the purpose of the research, 4 main hypotheses and 4 sub-hypotheses were formed. The hypotheses of the research are as follows;

$H_1$: Organizational stress has a positive effect on organizational silence.

$H_{1a}$: Organizational (internal) stress has a negative effect on organizational silence.

$H_{1b}$: Organizational (external) stress has a positive effect on organizational silence.

$H_2$: Organizational stress has a positive effect on presenteeism.

$H_{2a}$: Organizational (internal) stress has a positive effect on presenteeism.

$H_{2b}$: Organizational (external) stress has a negative effect on presenteeism.

$H_3$: Presenteeism has a negative effect on organizational silence.

$H_4$: Presenteeism has a mediating role in the relationship between organizational stress and organizational silence.

The IBM SPSS Statistics 15 packaged software and AMOS 22.0 packaged software were used in the analysis of the data. Explanatory Factor Analysis was used to determine how many dimensions, used in the scale expressions in the study, were separated, and Confirmatory Factor Analysis was used to determine the accuracy of the dimensions. The percentage and frequency distribution of the demographic characteristics of the participants and the arithmetic mean of the participants' opinions on the statements about organizational stress factors, presenteeism and organizational silence were calculated. Pearson correlation analysis was used to determine the relationship between "organizational stress scale and dimensions" and "organizational silence and presenteeism scales and dimensions". Path Analysis was used to determine organizational stress and the effect of its dimensions on organizational silence and presenteeism. Path Analysis was also used to determine the mediating role of presenteeism in the relationship between organizational stress and organizational silence.

**Table 1** Statements used in scales
**Tablica 1.** Iskazi primijenjeni za izradu ljestvica

| **Questions** *Pitanje* | **Organizational stress scale** *Razina organizacijskog stresa* | **Presenteeism scale** *Razina prezentizma* | **Organizational silence scale** *Razina organizacijske šutnje* |
|---|---|---|---|
| Q1 | The restlessness and gossip in the workplace lead to stress. *Nemir i ogovaranje na radnome mjestu dovode do stresa.* | Despite my health problems, I was able to complete difficult tasks in my work. *Unatoč zdravstvenim problemima, uspio sam obaviti teške zadatke na poslu.* | I remained silent at work fearing negative consequences. *Na poslu sam šutio zbog straha od negativnih posljedica.* |
| Q2 | The conflict with senior managers leads to stress. *Sukob s voditeljima dovodi do stresa.* | Despite my health problems, I was able to focus on achieving my professional goals. *Unatoč zdravstvenim problemima, mogao sam se usredotočiti na ostvarenje svojih profesionalnih ciljeva.* | I remained silent at work fearing the disadvantages of speaking. *Na poslu sam šutio zbog straha od pogrešaka u istupu.* |
| Q3 | The conflict with subordinates leads to stress. *Sukob s podređenima dovodi do stresa.* | Despite my health problems, I have enough energy to complete all my tasks. *Unatoč zdravstvenim problemima, imam dovoljno energije da obavim sve svoje zadatke.* | I remained silent at work so as not to be vulnerable to my colleagues or superiors. *Na poslu sam šutio kako se ne bih pokazao ranjivim pred kolegama ili nadređenima.* |
| Q4 | Incompatibility with colleagues leads to stress. *Nekompatibilnost s kolegama dovodi do stresa.* | Because of my health problems, it was much more difficult to deal with work-related stresses. *Zbog zdravstvenih problema bilo mi je mnogo teže nositi se sa stresom na poslu.* | I remained silent to avoid conflicts *Šutio sam kako bih izbjegao sukobe.* |
| Q5 | The inadequacy of the physical working environment and tools leads to stress. *Neadekvatnost fizičkoga radnog okruženja i alata dovodi do stresa.* | Because of my health problems, I could not enjoy my job. *Zbog zdravstvenih problema nisam mogao uživati na poslu.* | I remained silent at work because I did not want to be seen as a troublemaker. *Na poslu sam šutio jer nisam želio da me radna okolina doživljava problematičnim.* |
| Q6 | The lack of senior management support in decisions leads to stress. *Nedostatak potpore voditelja pri donošenju odluka dovodi do stresa.* | Despite my health problems, I felt hopeless about finishing certain work-related tasks. *Unatoč zdravstvenim problemima, osjećao sam se beznadno glede dovršavanja određenih radnih zadataka.* | I remained silent at work because other people at work said nothing. *Na poslu sam šutio jer ni ostali nisu ništa govorili.* |
| Q7 | Inadequate and lack of direct participation in the decision-making process lead to stress. *Neadekvatno sudjelovanje i isključivanje iz procesa donošenja odluka dovodi do stresa.* | | I remained silent at work because I do not want to embarrass others. *Na poslu sam šutio jer ne želim osramotiti druge.* |
| Q8 | Inadequate staff in terms of quality and quantity leads to stress. *Nekvalitetno osoblje i njihov nedovoljan broj dovodi do stresa.* | | I remained silent at work because I do not want others to get into trouble. *Na poslu sam šutio jer ne želim da drugi upadaju u nevolje.* |
| Q9 | Inequality in staff assignments and evaluations leads to stress. *Nejednakost pri dodjeljivanju i evaluaciji zadataka dovodi do stresa.* | | I remained silent at work because I did not want to damage relationships with my co-workers or superiors. *Na poslu sam šutio jer nisam želio narušiti odnose s kolegama ili nadređenima.* |
| Q10 | The confusion in the bureaucracy leads to stress. *Neorganiziranost u birokraciji dovodi do stresa.* | | I remained silent at work not to lose my knowledge advantage. *Na poslu sam šutio da ne izgubim prednost u znanju.* |
| Q11 | Political repressions about the works lead to stress. *Političke represije nad radom dovode do stresa.* | | I remained silent at work because of the concern that others could take an advantage of my ideas. *Na poslu sam šutio zbog bojazni da bi drugi mogli iskoristiti moje ideje.* |

| **Questions** *Pitanje* | **Organizational stress scale** *Razina organizacijskog stresa* | **Presenteeism scale** *Razina prezentizma* | **Organizational silence scale** *Razina organizacijske šutnje* |
|---|---|---|---|
| Q12 | The difference of political opinion in the work environment leads to stress. *Različitost političkih stajališta u radnom okruženju dovodi do stresa.* | | I remained silent at work because I wanted others to understand the consequences of their mistakes. *Na poslu sam šutio jer sam želio da drugi nauče koje su posljedice njihovih pogrešaka.* |
| Q13 | Religious differences and repressions in the work environment lead to stress. *Vjerske razlike i represija u radnom okruženju dovode do stresa.* | | I remained silent at work because my superiors do not deserve my involvement. *Na poslu sam šutio jer moji nadređeni ne zaslužuju moj angažman.* |
| Q14 | The frequency of inspections leads to stress. *Učestale kontrole dovode do stresa.* | | I remained silent at work because I did not want to do additional work. *Na poslu sam šutio jer nisam želio dodatni posao.* |
| Q15 | | | I remained silent at work because I could not find anyone (a sympathetic ear) who shared my thoughts. *Na poslu sam šutio jer nisam mogao pronaći nikoga tko dijeli moje razmišljanje.* |
| Q16 | | | I remained silent at work because my superiors were not open to offers, concerns, and the like. *Na poslu sam šutio jer nadređeni nisu bili otvoreni za ponude, dvojbe i sl.* |
| Q17 | | | I kept silent at work because I thought nothing will change. *Na poslu sam šutio jer sam mislio da se ništa neće promijeniti.* |
| Q18 | | | I remained silent at work because I did not expect to participate (be involved). *Na poslu sam šutio jer nisam očekivao da ću biti uključen u proces.* |
| Q19 | | | I remained silent at work because of bad experiences I have had with speaking up on critical issues in the past. *Na poslu sam šutio jer sam u prošlosti imao loša iskustva zbog govorenja o kritičnim problemima.* |

## 3 RESULTS
## 3. REZULTATI

Male employees made up the majority of the survey respondents. The vast majority of participants were younger than 41. Most participants were married. The vast majority of participants had a salary lower than 4000 Turkish liras. The graduation rate of the participants was poor. The majority of participants had less than 11 years' experience in the workforce. The majority of the participants worked in the furniture or wood-based board sector. The vast majority of participants were workers.

The Cronbach Alpha internal consistency test was used to test the reliability of the scales and their dimensions used in the research. As seen in Table 5, Cronbach's Alpha values of organizational stress, presenteeism and organizational silence scales were 0.927, 0.884 and 0.958, respectively. Cronbach's Alpha values of the dimensions of the scales vary between 0.833 and 0.936. Based on these values, it can be said that the scales used are reliable.

Before applying the exploratory factor analysis to the scales, it was first determined whether the data showed a normal distribution. Skewness and kurtosis values should be between -1.5 and + 1.5 (Tabachnick and Fidell, 2013). When Table 5 was examined, it was seen that the skewness and kurtosis values of the scales were between -1.5 and + 1.5, meaning that the data were found to have a normal distribution.

After it was determined that the data showed normal distribution, Kaiser-Meyer-Olkin (KMO) measurement and Bartlett's Sphericity Test were applied to analyze whether the scales were suitable for factor analysis, and the results are given in Table 2, 3 and 4. Based on the KMO values and the Bartlett test results of the scales, it was determined that the data were suitable for factor analysis (KMO: 0.913 and Bartlett Test: 0.000 for organizational stress scale, KMO: 0.773 and Bartlett Test: 0.000 for presenteeism scale, and KMO: 0.945 and Bartlett Test: 0.000 for organizational silence scale). When applying factor analysis, attention was paid to factors such as factor loads greater than 0.30, factor load difference between adjacent items equal to or greater than 0.10, and the use of Varimax rotation method (Karaman *et al*., 2017).

As a result of the factor analysis, it was found that the organizational stress scale was collected from 2 factors and the results are given in Table 2. There are 9 statements in the first factor (Organizational (Internal) Stress), and 5 statements in the second factor (Organizational (External) Stress). These two factors explain 64.382 % of the total variance. The factor loads of the first factor vary between 0.611 and 0.787, whereas the factor loads of the second factor vary between 0.621 and 0.872.

Presenteeism scale was determined to consist of 2 factors (Table 3). There are 3 statements in the first factor (Completing Work) and 3 statements in the second factor (Avoiding Distraction). The scale of presenteeism is similar to the literature data. These two factors explain 81.178 % of the total variance. The factor loads vary between 0.838 and 0.920.

As a result of the factor analysis of the organizational silence scale, it was determined that the factor load difference between the adjacent items in the 7th statement was less than 0.10 (2nd factor: 0.531 and 3rd factor: 0.580) and this statement was removed. After the statement was removed, factor analysis was applied again, and the analysis results are given in Table 4. The original scale consists of 4 dimensions. In this study, the scale consisted of 3 dimensions and the dimensions of prosocial and acquiescent silence were gathered under a single dimension. This dimension has also been renamed as the prosocial and acquiescent silence. These three factors explain 69.888 % of the total variance. The factor loads of the first factor (Quiescent Silence) vary between 0.631 and 0.826, the factor loads of the second factor (Opportunistic Silence) vary between 0.694 and 0.806, and the factor loads of the third factor (Prosocial and Acquiescent Silence) vary between 0.643 and 0.768.

In order to determine the accuracy of the structure obtained as a result of the explanatory factor analysis, confirmatory factor analysis was applied to the study scales. Some statements were modified to improve the results of the organizational stress and organizational silence scales covariance among residual values (for example, between 1 and 2 in the organizational stress scale and between 4 and 5 in the organizational silence scale). In other words, new covariances were created for statements with high covariance among residual values. Confirmatory factor analysis results of the scales are given in Figures 1.

When the fit indices of the models were examined, the fit index values of the organizational silence

**Table 2** Exploratory factor analysis results of organizational stress
**Tablica 2.** Rezultati eksplorativne faktorske analize organizacijskog stresa

| **Factors** / *Čimbenici* | **Number of questions** *Broj pitanja* | **Factor load** *Faktorsko opterećenje* | **Explained variance** *Objašnjena varijanca* | **Total explained variance** *Ukupni postotak objašnjene varijance* |
|---|---|---|---|---|
| Factor 1: Organizational (internal) stress *organizacijski (unutarnji) stres* | 9 (1-9) | 0.611-0.787 | 51.963 | 64.382 |
| Factor 2: Organizational (external) stress *organizacijski (vanjski) stres* | 5 (10-14) | 0.621-0.872 | 12.419 | |
| Kaiser-Meyer-Olkin (KMO) | 0.773 | | | |
| Bartlett's Test of Sphericity (*p*) | 0.000 | | | |

**Table 3** Exploratory factor analysis results of presenteeism
**Tablica 3.** Rezultati eksplorativne faktorske analize prezentizma

| **Factors** / *Čimbenici* | **Number of questions** *Broj pitanja* | **Factor load** *Faktorsko opterećenje* | **Explained variance** *Objašnjena varijanca* | **Total explained variance** *Ukupni postotak objašnjene varijance* |
|---|---|---|---|---|
| Factor 1: Completing work *dovršavanje posla* | 3 (1-3) | 0.859-0.920 | 54.955 | 81.178 |
| Factor 2: Avoiding distraction *izbjegavanje ometanja* | 3 (4-6) | 0.838-0.899 | 26.223 | |
| Kaiser-Meyer-Olkin (KMO) | 0.913 | | | |
| Bartlett's Test of Sphericity (p) | 0.000 | | | |

**Table 4** Results of exploratory factor analysis of organizational silence
**Tablica 4.** Rezultati eksplorativne faktorske analize organizacijske šutnje

| **Factors** / *Čimbenici* | **Number of questions** *Broj pitanja* | **Factor load** *Faktorsko opterećenje* | **Explained variance** *Objašnjena varijanca* | **Total explained variance** *Ukupni postotak objašnjene varijance* |
|---|---|---|---|---|
| Factor 1: Quiescent silence *mirna šutnja* | 6 (1-6) | 0.631-0.826 | 57.072 | 69.888 |
| Factor 2: Opportunistic silence *oportunistička šutnja* | 3 (7-9) | 0.694-0.806 | 7.542 | |
| Factor 3: Prosocial and acquiescent silence *prosocijalna i popustljiva šutnja* | 9 (10-19) | 0.643-0.768 | 5.275 | |
| Kaiser-Meyer-Olkin (KMO) | 0.945 | | | |
| Bartlett's Test of Sphericity (*p*) | 0.000 | | | |

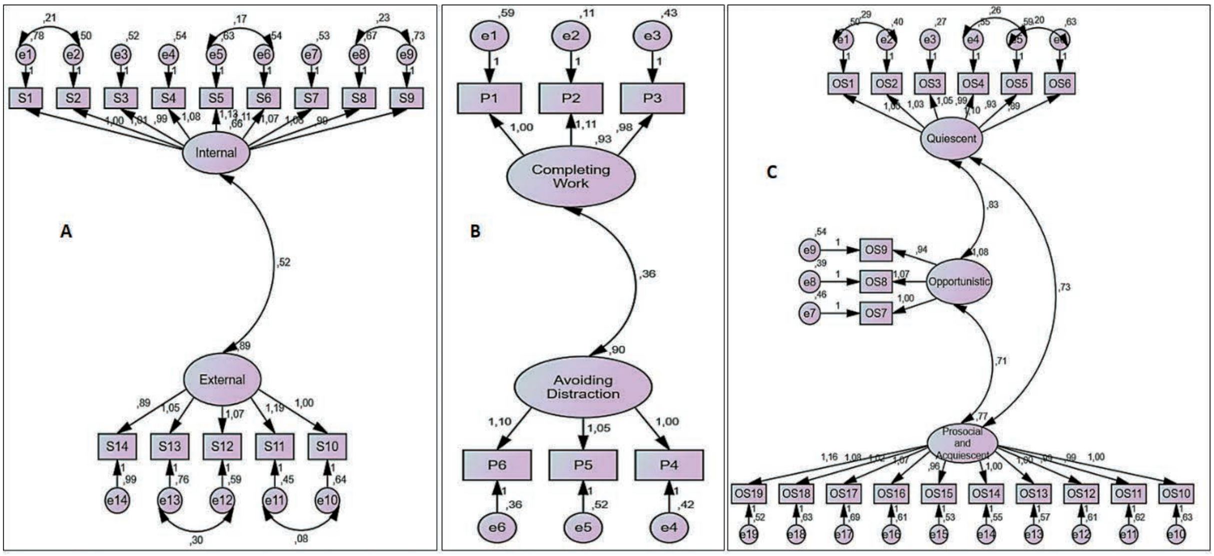



**Figure 1** Confirmatory factor analysis models: A) organizational stress; B) presenteeism; C) organizational silence
**Slika 1.** Modeli konfirmatorne faktorske analize: A) organizacijski stres; B) prezentizam; C) organizacijska šutnja

model were as follows: $x^2$/df = 3.754, GFI = 0.880, CFI = 0.926, RMSEA = 0.097. The fit index values of the presenteeism model were: $x^2$/df = 3.523, GFI = 0.969, CFI = 0.980, RMSEA = 0.093. The fit index values of the organizational silence model were: $x^2$/df = 2.645, GFI = 0.879, CFI = 0.947, RMSEA = 0.075. According to the literature, $x^2$/df value should be less than 5, RMSEA value should be less than 0.10, CFI and GFI value should be less than 0.85 (Byrne and Campbell, 1999; Schermelleh-Engel *et al*., 2003; Kline, 2011; Çokluk *et al*., 2014). The values of the models are among the generally acceptable values. These values confirm the validity of the scales of organizational stress, presenteeism and organizational silence.

The arithmetic mean values of the answers given to the scales by the employees participating in the research are given in Table 5. The following classification was used in the interpretation of the arithmetic

**Table 5** Descriptive statistical values of scales and scale dimensions
**Tablica 5.** Deskriptivne statističke vrijednosti i dimenzije razina

| **Scales and scale dimensions** / *Razine i njihove dimenzije* | **Mean** | **Skewness** | **Kurtosis** | **Cronbach's Alpha** |
|---|---|---|---|---|
| Organizational stress / *organizacijski stres* | 3.3159 | -0.212 | -0.651 | 0.927 |
| Organizational (internal) stress / *organizacijski (unutarnji) stres* | 3.4255 | -0.348 | -0.725 | 0.919 |
| Organizational (external) stress / *organizacijski (vanjski) stres* | 3.1185 | -0.048 | -0.891 | 0.882 |
| Presenteeism / *prezentizam* | 3.0057 | 0.010 | -0.533 | 0.884 |
| Completing work / *dovršavanje posla* | 2.9807 | 0.150 | -1.031 | 0.873 |
| Avoiding distraction / *izbjegavanje ometanja* | 3.0306 | -0.029 | -1.024 | 0.833 |
| Organizational silence / *organizacijska šutnja* | 2.6399 | 0.066 | -0.589 | 0.958 |
| Quiescent silence / *mirna šutnja* | 2.6258 | 0.026 | -0.898 | 0.931 |
| Opportunistic silence / *oportunistička šutnja* | 2.7785 | 0.056 | -0.896 | 0.936 |
| Prosocial and acquiescent silence / *prosocijalna i popustljiva šutnja* | 2.6067 | 0.180 | -0.560 | 0.872 |

means of the scales: 1.00-1.79: very low, 1.80-2.59: low, 2.60-3.39: medium, 3.40-4.19: high, 4.20-5.00: very high (Özdamar, 2003).

As seen in Tables 5, organizational stress level of the participants is close to high. Presenteeism level of the participants is moderate. Organizational silence level of the participants is close to low. Organizational (external) stress has the highest arithmetic mean among organizational stress dimensions. Avoiding distraction has the highest arithmetic mean among the presenteeism dimensions. Opportunistic silence has the highest arithmetic mean among the organizational silence dimensions. However, both the organizational silence scale and the dimensions of organizational silence have a mean score close to low. It is seen that the mean scores of the dimensions of each scale are close to each other.

There is a positive relationship between “organizational stress” and “was silence is weak, whereas the relationship between organizational stress and presenteeism is moderate. There is also a negative relationship between presenteeism and organizational silence and this relationship is moderate. When the relations between the scales and the dimensions were examined, a positive relationship was determined between “organizational stress” and “avoiding distraction and prosocial and acquiescent silence”. There is a negative relationship between presenteeism and dimensions of organizational silence, whereas there is a positive relationship between presenteeism and dimensions of organizational stress. There is a positive relationship between organizational silence and organizational (external) stress, whereas there is a negative relationship between organizational silence and completing work (Table 6).

A structural equation model was created to determine the effects of organizational stress and its dimensions on presenteeism and organizational silence. The effect of presenteeism on organizational silence was also investigated. Structural equation modeling was used to determine the mediating role of presenteeism in the relationship between organizational stress and organizational silence. The models are given in Figure 2 and the analysis results are given in Table 7 and 8.

When the model designed to determine the effects of organizational stress and its dimensions on presenteeism and organizational silence and effect of presenteeism on organizational silence was examined, the fit index values of the models were at an acceptable level [Model 1: $x^2$/df = 3.236, GFI = 0.748, CFI = 0.853, RMSEA = 0.087; Model 2: $x^2$/df = 3.832, GFI = 0.823, CFI = 0.880, RMSEA = 0.098; Model 3: $x^2$/df = 3.221, GFI = 0.792, CFI = 0.894, RMSEA = 0.087; Model 4: $x^2$/df = 2.940, GFI = 0.766, CFI = 0.873, RMSEA = 0.081; Model 5: $x^2$/df = 2.904, GFI = 0.862, CFI = 0.920, RMSEA = 0.080].

According to the fit indices of the model designed to determine whether presenteeism has a mediating effect between organizational stress and organizational silence, it might be said that this model is also acceptable [Model 6: $x^2$/df = 2.963, GFI = 0.724, CFI = 0.843, RMSEA = 0.082].

**Table 6** Correlation analysis of relationship between scales and their dimensions
**Tablica 6.** Korelacijska analiza odnosa između razina i njihovih dimenzija

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| 1: Organizational stress<br>*1: Organizacijski stres* | 1 | | | | | | | | |
| 2: Internal stress<br>*2: Unutarnji stres* | 0.937** | 1 | | | | | | | |
| 3: External stress<br>*3: Vanjski stres* | 0.846** | 0.608** | 1 | | | | | | |
| 4: Presenteeism<br>*4: Prezentizam* | 0.306** | 0.340** | 0.177** | 1 | | | | | |
| 5: Completing work<br>*5: Dovršavanje posla* | 0.110 | 0.187** | -0.035 | 0.820** | 1 | | | | |
| 6: Avoiding distraction<br>*6: Izbjegavanje ometanja* | 0.391** | 0.371** | 0.324** | 0.826** | 0.355** | 1 | | | |
| 7: Organizational silence<br>*7: Organizacijska šutnja* | 0.116* | 0.065 | 0.166** | -0.202** | -0.23** | -0.103 | 1 | | |
| 8: Quiscenet silence<br>*8: Mirna šutnja* | 0.067 | 0.025 | 0.113 | -0.188** | -0.184** | -0.126* | 0.900** | 1 | |
| 9: Opportunistic silence<br>*9: Oportunistička šutnja* | 0.098 | 0.077 | 0.106 | -0.148* | -0.156** | -0.089 | 0.831** | 0.700** | 1 |
| 10: Prosocial and acquiescent silence<br>*10: Prosocijalna i popustljiva šutnja* | 0.136* | 0.075 | 0.194** | -0.194** | -0.247** | -0.074 | 0.944** | 0.734** | 0.708** |

**Correlation is significant at the 0.01 level; *Correlation is significant at the 0.05 level.
***Korelacija je značajna na razini 0,01; *korelacija je značajna na razini 0,05.*

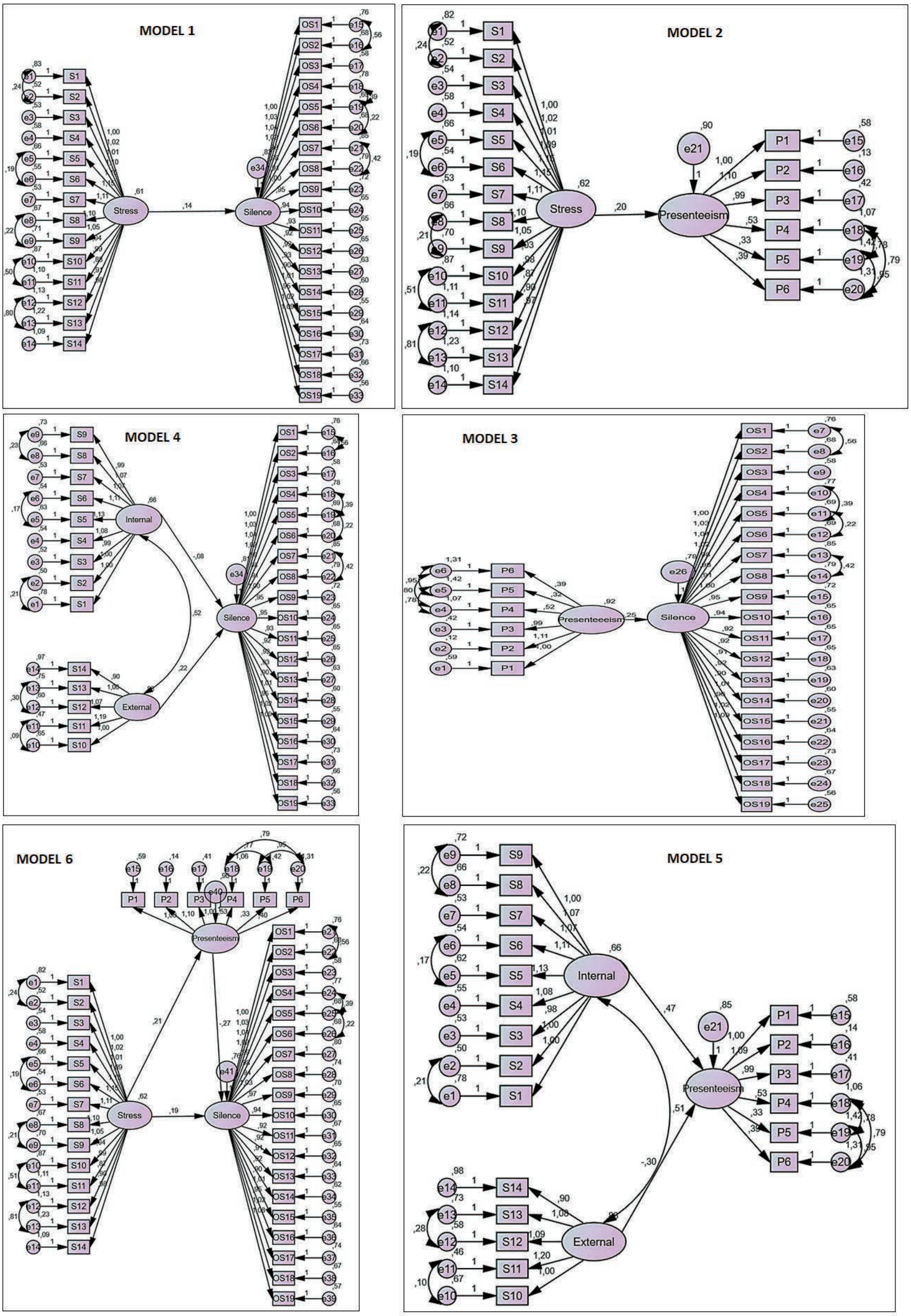



**Figure 2** Structural equation models (Model 1: model of the effect of organizational stress on organizational silence; Model 2: model of the effect of organizational stress on presenteeism; Model 3: model of the effect of presenteeism on organizational silence; Model 4: model of the effect of dimensions of organizational stress on organizational silence; Model 5: model of the effect of dimensions of organizational stress on presenteeism; Model 6: model of constructed regarding the mediating role of presenteeism in the relationship between organizational stress and organizational silence)

**Slika 2.** Modeli strukturnih jednadžbi (model 1: model učinka organizacijskog stresa na organizacijsku šutnju; model 2: model učinka organizacijskog stresa na prezentizam; model 3: model utjecaja prezentizma na organizacijsku šutnju; model 4: model utjecaja dimenzija organizacijskog stresa na organizacijsku šutnju; model 5: model utjecaja dimenzija organizacijskog stresa na prezentizam; model 6: model konstruiran s obzirom na posredničku ulogu prezentizma u odnosu između organizacijskog stresa i organizacijske šutnje)

**Table 7** Results of hypotheses about scales and their dimensions
**Tablica 7.** Rezultati hipoteza o razinama i njihovim dimenzijama

| **Hypotheses** *Hipoteza* | **Relationship** / *Odnos* | | | ***β*** | ***t*-statistics** | ***p* value** | **Results** *Rezultat* |
|---|---|---|---|---|---|---|---|
| $H_1$ | Organizational stress *organizacijski stres* | → | Organizational silence *organizacijska šutnja* | 0.118 | 1.867 | 0.062 | Reject *odbijena* |
| $H_{1a}$ | Organizational (internal) stress *organizacijski (unutarnji) stres* | → | Organizational silence *organizacijska šutnja* | -0.069 | -0.744 | 0.457 | Reject *odbijena* |
| $H_{1b}$ | Organizational (external) stress *organizacijski (vanjski) stres* | → | Organizational silence *organizacijska šutnja* | 0.227 | 2.350 | 0.019 | Accept *prihvaćena* |
| $H_2$ | Organizational stress *organizacijski stres* | → | Presenteeism *prezentizam* | 0.167 | 2.606 | 0.009 | Accept *prihvaćena* |
| $H_{2a}$ | Organizational (internal) stress *organizacijski (unutarnji) stres* | → | Presenteeism *prezentizam* | 0.393 | 4.017 | 0.000 | Accept *prihvaćena* |
| $H_{2b}$ | Organizational (external) stress *organizacijski (vanjski) stres* | → | Presenteeism *prezentizam* | -0.284 | -2.931 | 0.003 | Accept *prihvaćena* |
| $H_3$ | Presenteeism *prezentizam* | → | Organizational silence *organizacijska šutnja* | -0.259 | -4.110 | 0.000 | Accept *prihvaćena* |

**Table 8** Results of mediation effect
**Tablica 8.** Rezultati medijacije

| | | | ***β*** | ***S.E*** | ***C.R.*** | ***p*** |
|---|---|---|---|---|---|---|
| Organizational stress *organizacijski stres* | → | Presenteeism *prezentizam* | 0.169 | 0.079 | 2.627 | 0.009 |
| Presenteeism *prezentizam* | → | Organizational silence *organizacijska šutnja* | 0.166 | 0.061 | -4.481 | 0.000 |
| Organizational stress *organizacijski stres* | → | Organizational silence *organizacijska šutnja* | -0.287 | 0.073 | 2.650 | 0.008 |

The standardized β coefficients, t-statistics, p values and hypothesis results of the models are given in Table 7. As shown in Table 7, the organizational stress and organizational (internal) stress dimension have no effect on the organizational silence. The organizational (external) stress dimension has an effect on the organizational silence. Organizational stress and its dimensions have an effect on presenteeism. Presenteeism also has an effect on organizational silence. Both the effect of organizational (external) stress on presenteeism and the effect of presenteeism on organizational silence were negative. Other effects were positive. For this reason, $H_{1b}$, $H_2$, $H_{2a}$, $H_{2b}$ and $H_3$ hypotheses were accepted. $H_1$ and $H_{1a}$ hypotheses were rejected.

Based on Table 8, it was concluded that presenteeism has a mediating role in the relationship between organizational stress and organizational silence. In other words, the $H_4$ hypothesis was accepted.

## 4 DISCUSSION
## 4. RASPRAVA

Stress, which has become a part of life, can negatively affect individual and organizational life when it is excessive and intense. It is thought that stress will increase the probability of employees leaving the organization and cause organizational silence. There are several studies on the relationship between the organizational stress and organizational silence in the literature. Dileep Kumar *et al*. (2015) said that employee silence increases the stress level. Dedahanov *et al*. (2016) reported that individuals experience stress when they withhold information. Çakır Yıldız and Güneş (2017) stated that individuals under stress at workplaces prefer to remain silent about the events in the organization and are hesitant to express their opinions. A study on Iranian insurance staff found that job stress has no significant effect on organizational silence but the effect of job stress on organizational silence was confirmed (Norouzi and Aghbelaghi, 2020). Mantı (2020) stated that the things that can be done to reduce organizational stress can also affect organizational silence. There are also studies showing the relationship between organizational stress and presenteeism and supporting the findings of this study. In a study conducted in 2016, it was determined that the degree of presenteeism has a positive effect on the relationship between perceived job stress and happiness (Chia and Chu, 2016). El-Kurdy *et al*. (2022) reported that presenteeism has a negative non-significant correlation with stress. In some studies, stress has been identified as a critical factor in triggering presenteeism (Coutu *et al*., 2015; Lauzier *et al*., 2017; Yang *et al*., 2017; Kim *et al*., 2019; Mohamed *et al*., 2021; Jiang *et al*., 2021). There are studies showing that presenteeism has an effect on organizational silence. For example, in the study of Yıldırım and Oruç (2019), a negative relationship was found between “presenteeism” and “acquiescent and protective silence". In another study, it was determined that presenteeism significantly affected the dimensions of organizational silence (Karagöz ve Uzunbacak, 2020). There is no previous study on the mediating role of presenteeism in the relationship between organizational stress and organizational silence.

## 5 CONCLUSIONS
## 5. ZAKLJUČAK

It was discovered that people working in the forest products sector were under considerable stress. Although the stress level of the participants is high, the level of presenteeism of the participants is low. Individuals under stress prefer to remain silent about the events taking place in the organization. It was discovered that organizational stress factors caused presenteeism. While organizational (internal) stress factors affect the presenteeism level positively, organizational (external) stress factors negatively affect the presenteeism level. It was discovered that the participants did not remain silent as the level of presenteeism decreased. Presenteeism had a mediating effect on organizational silence. Organizational stress factors causing organizational silence might be identified. Active participation of employees in decision-making processes should be supported so that they do not remain silent about the issues in the organization. Companies might reorganize their organizational culture and working habits in order to eliminate presenteeism. The research findings were limited to individuals working in the forest products sector in Istanbul and Kocaeli provinces in Turkey. The lack of studies on the relationship between "organizational stress" and "organizational silence and presenteeism", and the mediating role of presenteeism in the relationship between organizational silence and organizational silence, limited the comparison of research findings with different or similar research results. To see the situation in different sectors, similar studies should be carried out with different samples. Although there are studies on presenteeism, organizational stress and organizational silence in different sectors, there is no study on the relationship between presenteeism, organizational stress and organizational silence for the forest products sector. Moreover, this study is the first to explore the mediating role of presenteeism on the relationship between organizational stress and organizational silence. This study is a significant contribution that can fill the gap in the existing literature.

## 6 REFERENCES
## 6. LITERATURA


1. Akova, O.; Işık, K., 2008: Stress management in hotel business: research in five-star hotel business in Istanbul. Kocaeli Üniversitesi Sosyal Bilimler Enstitüsü Dergisi, 15: 17-44.
2. Balcı, A., 1993: Work stress scale of university academic staff. Ankara Üniversitesi Eğitim Bilimleri Fakültesi Dergisi, 26 (1): 315-334.
3. Byrne, B.; Campbell, T. L., 1999: Cross-cultural comparisons and the presumption of equivalent measurement and theoretical structure: a look beneath the surface. Journal of Cross-Cultural Psychology, 30 (5): 555-574. https://doi.org/10.1177/0022022199030005001
4. Chia, Y. M.; Chu, M. J. T., 2016: Moderating effects of presenteeism on the stress-happiness relationship of hotel employees: A note. International Journal of Hospitality Management, 55: 52-56. https://doi.org/10.1016/j.ijhm.2016.02.005
5. Çakır Yıldız, N.; Güneş, M. Ş., 2017: Impact of organizational stress on organizational silence and burnout measure: a survey study on pharmacy workers. Uygulamalı Sosyal Bilimler Dergisi, 1 (1): 45-66.
6. Çavuşoğlu, S.; Köse, S., 2019: Adaptation of the organizational silence scale to Turkish. Bolu Abant İzzet Baysal Üniversitesi Sosyal Bilimler Enstitüsü Dergisi, 19 (2): 365-387. https://doi.org/10.11616/basbed.v19i47045.485266
7. Çokluk, Ö.; Şekercioğlu, G.; Büyüköztürk, Ş., 2014: Sosyal bilimler için çok değişkenli istatistik SPSS ve LİSREL uygulamaları. Ankara: Pegem Akademi, ISBN: 978-605-5885-67-0.
8. Çökük., 2018: The measurement of organizational stress level and its relationship with demographic variables: a public organization sample. Akademik Yaklaşımlar Dergisi, 9 (2): 59-83.
9. Coşkun, Ö., 2012: Evaluation of factors for absenteeism and presenteeism at two work place. PhD Thesis, Ankara University, Health Sciences Institute.
10. Coutu, M. F.; Corbiere, M.; Durand, M. J.; Nastasia, I.; Labrecque, M. E.; Berbiche, D.; Albert, V., 2015: Factors associated with presenteeism and psychological distress using a theory-driven approach. Journal of Occupational and Environmental Medicine, 57 (6): 617-626. https://doi.org/10.1097/JOM.0000000000000459
11. Dedahanov, A. T.; Lee, D. H.; Rhee, J., 2016: Silence as a mediator between organizational factors and stress. Journal of Managerial Psychology, 31 (8): 1251-1264. https://doi.org/10.1108/JMP-09-2014-0265
12. Dileep Kumar, M.; Alagappar, P. N.; Govindarajo, N., 2015: The impact of organizational silence on job stress, organisational commitment and intention to leave among expatriate employees. Australian Journal of Basic and Applied Sciences, 9 (29): 1-8.
13. Dorman, J. S.; LaPorte, R. E.; Stone, R. A.; Trucco, M., 1990: Worldwide differences in the incidence of type I diabetes are associated with amino acid variation at position 57 of the HLA-DQ beta chain. Proceedings of the National Academy of Sciences, 87 (19): 7370-7374. https://doi.org/10.1073/pnas.87.19.7370
14. El-Kurdy, R.; El-Nemer, A.; Yousef, A.; Elsaidy, W.; Hamdan-Mansour, A., 2022: The moderation effect of affective commitment on the relationship between job stress and presenteeism among obstetric healthcare workers during COVID-19 pandemic. Open Nursing Journal, 16 (1): 1-8. https://doi.org/ 10.2174/18744346-v16-e2203090
15. Fletcher, D.; Hanton, S.; Mellalieu, S. D., 2006: An organizational stress review: conceptual and theoretical issues in competitive sport. In: Hanton, S.; Mellalieu, S. D. (eds.). Literature reviews in sport psychology. New York: Nova Science Publishers, pp. 321-373, ISBN: 1-59454-904-4.
16. Jiang, H.; Jia, H.; Zhang, J.; Li, Y.; Song, F.; Yu, X., 2021: Nurses'occupational stress and presenteeism: the

mediating role of public service motivation and the moderating role of health. International Journal of Environmental Research and Public Health, 18 (7): 3523. https://doi.org/10.3390/ijerph18073523
17. Karagöz, Ş.; Uzunbacak, H. H., 2020: The effect of presenteeism on organizational silence: a study in tourism sector. Türk Turizm Araştırmaları Dergisi, 4 (3): 1941-1957. https://doi.org/10.26677/TR1010.2020.459
18. Karaman, H.; Atar, B.; Çobanoğlu Aktan, D., 2017: The comparison of factor extraction methods used in exploratory factor analysis. Gazi Üniversitesi Gazi Eğitim Fakültesi Dergisi, 37 (3): 1173-1193. https://doi.org/10.17152/gefad.309356
19. Kim, J.; Kim, Y. K.; Leem, S. H.; Won, J. U., 2019: Association between job-related stress and experience of presenteeism among Korean workers stratified on the presence of depression. Annals of Occupational and Environmental Medicine, 31: 1-15. https://doi.org/10.35371/aoem.2019.31.e26
20. Kline, R. B., 2011: Principles and practice of structural equation modeling. New York: The Guilford Press, ISBN: 978-1606238769.
21. Knani, M., 2022: What motivates tourism and hospitality employees to practice presenteeism?. Journal of Hospitality and Tourism Management, 52: 198-207. https://doi.org/10.1016/j.jhtm.2022.06.017
22. Knoll, M.; van Dick, R., 2013: Do I hear the whistle...? A first attempt to measure four forms of employee silence and their correlates. Journal of Business Ethics, 113 (2): 349-362. https://doi.org/10.1007/s10551-012-1308-4
23. Koopman, C.; Pelletier, K. R.; Murray, J. F.; Sharda, C. E.; Berger, M. L.; Turpin, R. S.; Hackleman, P.; Gibson, P.; Holmes, D. M.; Bendel, T., 2002: Stanford presenteeism scale: health status and employee productivity. Journal of Occupational Environmental Medicine, 44: 14-20. https://doi.org/10.1097/00043764-200201000-00004
24. Lauzier, M.; Melançon, S.; Cote, K., 2017: The effect of perceived stress on absenteeism and presenteeism behaviors: The mediating role of health status. Canadian Journal of Behavioural Science, 49 (4): 221-230. https://doi.org/10.1037/cbs0000081
25. Lohaus, D.; Habermann, W., 2019: Presenteeism: A review and research directions. Human Resource Management Review, 29 (1): 43-58. https://doi.org/10.1016/j.hrmr.2018.02.010
26. Maestas, N. A.; Mullen, K. J.; Rennane, S., 2021: Absenteeism and presenteeism among American workers. Journal of Disability Policy Studies, 32 (1): 13-23. https://doi.org/10.1177/1044207320933211
27. Managheb, S.; Razmjooei, P.; Gharbi, M.; Hosseini, M.; Amirianzadeh, M., 2018: Mediating role of organizational silence in the relationship between organizational climate and job performance. Amazonia Investiga, 7 (12): 72-86.
28. Mantı, M., 2020: The relationship between academicians' organizational stress and organizational silence behaviours. Master Thesis, Pamukkale University, Institute of Educational Sciences.
29. Mohamed, L. K.; Dorgham, S. R.; Eid, W. M., 2021. Job stress and presenteeism prevalence among nursing staff during the outbreak of pandemic coronavirus disease 2019. Egyptian Journal of Health Care, 21 (1): 1299-1316. https://doi.org/ 10.21608/EJHC.2021.196303
30. Mousa, M.; Abdelgaffar, H. A.; Aboramadan, M.; Chaouali, W., 2021: Narcissistic leadership, employee silence and organizational cynicism: a study of physicians in Egyptian public hospitals. International Journal of Public Administration, 44 (15): 1309-1318. https://doi.org/10.1080/01900692.2020.1758719
31. Norouzi, H.; Aghbelaghi, D. T., 2020: The effect of job plateau and job stress on organizational silence of Iran insurance personnel. Journal of Sustainable Human Resource Management, 2 (2): 221-236. https://doi.org/10.22080/SHRM.2020.2974
32. Özdamar, K., 2003: Modern bilimsel araştırma yöntemleri. Eskişehir: Kaan Kitabevi, ISBN: 9789756787069.
33. Rumbold, J. L.; Didymus, F. F., 2021: Organizational stress in competitive sport. In: Zenko, Z.; Jones, L. (eds.). Essentials of exercise and sport psychology: an open access textbook. Society for Transparency, Openness and Replication in Kinesiology, pp. 710-733. https://doi.org/10.51224/B1030
34. Şahin, M., 2020: Örgütsel sessizlik. In: Erer, B.; Şahin, M. (eds.). İş hayatında örgüt düşmanı davranışlar. Konya: Eğitim Yayınevi, pp. 103-117, ISBN: 978-605-74877-6-6.
35. Saeidipour, B.; Akbari, P.; Alizade, Z., 2021: The role of organizational silence & organizational mobbing on the turnover intention. International Journal of Ethics & Society, 3 (1): 59-69. https://doi.org/ 10.52547/ijethics.3.1.59
36. Schermelleh-Engel, K.; Moosbrugger, H.; Müller, H., 2003: Evaluating the fit of structural equation models: tests of significance and descriptive goodness-of-fit measures. Methods of Psychological Research, 8 (2): 23-74.
37. Soysal, A., 2009: Organizational stressors on workers working in different sectors: a survey in Kahramanmaraş and Gaziantep. Süleyman Demirel Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, 14 (2): 333-359.
38. Tabachnick, B. G.; Fidell, L. S., 2013: Using multivariate statistics. Boston: Pearson, ISBN: 978-0205849574.
39. Yalçınsoy, A., 2017: Organizational silence and its consequences. The Journal of Social Science, 1 (1): 1-19. https://doi.org/10.30520/tjsosci.342211
40. Yang, T.; Guo, Y.; Ma, M.; Li, Y.; Tian, H.; Deng, J., 2017: Job stress and presenteeism among Chinese healthcare workers: the mediating effects of affective commitment. International Journal of Environmental Research and Public Health, 14 (9): 978. https://doi.org/10.3390/ijerph14090978
41. Yıldırım, M. H.; Oruç, Ş., 2019: The research on the relationship between presenteeism and organizational silence. İşletme Araştırmaları Dergisi, 11 (2): 758-774. https://doi.org/10.20491/isarder.2019.634
42. ***TOBB, 2021: "The Union of Chambers and Commodity Exchanges of Turkiye" (online), https://sanayi.tobb.org.tr/yeni_kod_liste70.php (Accessed May 22, 2021).

**Corresponding address:**

**NADIR ERSEN**
Artvin Çoruh University, Artvin Vocational School, Department of Forestry, Artvin, TURKIYE,
e-mail: nadirersen20@artvin.edu.tr

Gökay Nemli[1], Uğur Aras[2], Hülya Kalaycıoğlu[1], Süleyman Kuştaş[3]

# Potential Use of Olive Stone Residues in Particleboard Production

# Mogućnost uporabe ostataka koštica masline u proizvodnji ploča iverica

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 4. 7. 2022.
Accepted – prihvaćeno: 20. 10. 2022.
UDK: 630*83; 674.812
https://doi.org/10.5552/drvind.2023.0047



**ABSTRACT** • *In this study, the effect of using olive stone residues (OSR) on some properties of particleboard was investigated. For this purpose, particle boards were manufactured from particles of white poplar (Populus Alba L.), which were partially substituted with OSR particles in amounts of 10 %, 20 % and 30 %. In addition, boards containing 30 % OSR, which had previously been chemically modified with NaOH solution, were produced. Phenol formaldehyde adhesive was used in the production of the boards. Chemical properties of wood and OSR particles (pH, alcohol benzene solubility, amount of ash), physico-mechanical properties (density, moisture content thickness swelling, modulus of rupture, modulus of elasticity and internal bond strength) and formaldehyde emission values of boards were determined. Water absorption and thickness swelling values were generally decreased with the increase in the use of OSR. When the effect of OSR usage on bending strength, modulus of elasticity, and perpendicular tensile strength values were examined, a decrease in the values was observed except for the 10 % OSR usage ratio. As a result of the application of alkali pretreatment, an increase in thickness swelling values was observed, while the values of mechanical properties increased. Scanning electron microscopy (SEM) analysis results showed more spaces between particles with an increasing OSR usage ratio. Formaldehyde emission values decreased with the increasing amount of OSR. Formaldehyde emission values increased slightly with the application of alkaline pretreatment. Based on the findings of this study, we can conclude that OSR can be used at particularly low ratio in particleboard production.*

**KEYWORDS:** *olive stone residues, particleboard, physical and mechanical properties, formaldehyde emissions*

**SAŽETAK** • *U istraživanju je ispitan učinak iskorištenja ostataka koštica masline (OSR) na neka svojstva ploča iverica. Za potrebe eksperimenta izrađene su ploče od iverja drva bijele topole (Populus alba L.) koje je djelomično zamijenjeno košticama masline u količini od 10, 20 i 30 %. Osim toga, izrađene su ploče s 30 % ostataka koštica masline prethodno modificiranih otopinom NaOH. Pri izradi ploča upotrijebljeno je fenol-formaldehidno ljepilo. Utvrđena su kemijska svojstva drva i ostataka koštica masline (pH, topljivost u smjesi alkohola i benzena, sadržaj pepela) te fizičko-mehanička svojstva (gustoća, sadržaj vode, debljinsko bubrenje, modul loma, modul elastičnosti i čvrstoća raslojavanja) i vrijednosti emisije formaldehida proizvedenih ploča. Upijanje vode i debljinsko bubrenje u osnovi je smanjeno zbog povećanja udjela ostataka koštica masline. Pri ispitivanju utjecaja udjela*

[1] Authors are researchers at Karadeniz Technical University, Faculty of Forestry, Department of Forest Industrial Engineering, Trabzon, Turkey. https://orcid.org/0000-0002-8172-1875, https://orcid.org/0000-0002-1807-4353
[2] Author is researcher at Karadeniz Technical University, Arsin Vocational School, Materials and Materials Machining Technologies, Furniture and Decoration, Arsin, Trabzon, Turkey. https://orcid.org/0000-0002-1572-0727
[3] Author is researcher at Sakarya University of Applied Sciences, Pamukova Vocational Junior College, Materials and Materials Machining Technologies, Paper Technology, Pamukova, Sakarya, Turkey. https://orcid.org/0000-0002-8358-603X

*ostataka koštica masline na čvrstoću na savijanje, modul elastičnosti i vlačnu čvrstoću okomito na ploču uočeno je smanjenje tih vrijednosti ploča, osim pri udjelu ostataka koštica masline od 10 %. Kao rezultat alkalne predobrade uočeno je povećanje vrijednosti debljinskog bubrenja, ali i povećanje vrijednosti mehaničkih svojstava ploča. Rezultati pretražne elektronske mikroskopije (SEM) pokazali su da se s povećanjem udjela ostataka koštica masline povećava prostor između čestica. Vrijednosti emisije formaldehida smanjile su se s povećanjem udjela ostataka koštica masline, ali su blago porasle uz alkalnu predobradu. Na temelju rezultata ovog istraživanja možemo zaključiti da se ostatci koštica masline u malom udjelu mogu iskoristiti u proizvodnji ploča iverica.*

**KLJUČNE RIJEČI:** *ostatci koštica masline, ploča iverica, fizička i mehanička svojstva, emisija formaldehida*

## 1 INTRODUCTION
## 1. UVOD

Particleboards are materials obtained by mixing wood particles with synthetic adhesives and pressing at high temperatures and pressure. Their most important advantages are their low cost, ability to be produced in the desired thickness and size and high mechanical resistance values (Nishimura, 2015).

Particleboards (PB) are composites that have been developed with the increasing demand for wood-based materials and have become the primary raw material for furniture production in a short time. Today, industries such as pulp and thermal energy recovery plants demand the same type of raw materials as low-value logs and round or splitting woods used in wood composite production. This has led to increased competition and the shortage of such wood raw materials caused their prices to skyrocket. The use of lignocellulosic alternative resources in production of PB will be an important way out to reduce competition for the particleboard industry and to avoid problems in the future raw material supply -environmentally friendly and continuous supply at low cost (Trischler, 2016; Borysiuk *et al.,* 2019).

In addition to the studies using recycled wood materials for this purpose (Li *et al.,* 2004; Wang *et al.,* 2008; Azambuja *et al.,* 2018), the following materials were also studied: kenaf (Kalaycioglu and Nemli, 2006), kiwi wastes (Nemli *et al.,* 2003), flax and hemp (Sam-Brew and Smith, 2015), sugarcane bagasse and green coconut (Fiorelli *et al.,* 2019), bamboo (De Almeida *et al.,* 2017), rice husk (Nicolao *et al.,* 2020), pinecones (Buyuksari *et al.,* 2010) and wood composites production with lignocellulosic wastes such as wheat and canola straws (Mo *et al*., 2003; Kord *et al.,* 2016), sunflowers stalks (Tas and Kul, 2020) and walnut shells (Pirayesh *et al*., 2012). Also, studies were carried out on the evaluation of wood bark (Blanchet *et al*., 2000; Medved *et al*., 2019) in particleboard production. In this respect, studies have been increasing due to the necessity of using forest resources more efficiently and lignocellulosic materials being a good alternative for particleboard production.

According to the International Olive Council (IOC) data of 2021, the total olive oil production in the world was 3.1 million tons. European Union countries are leading in the production of olive oil (about 2 million tons). In Turkey, 227500 tons of olive oil is produced annually, and Turkey is third in olive oil production (IOC, 2020).

After the olive squeezing process, 50 % liquid and 30 % solid waste remains. Solid wastes include broken olive seeds, squeezed residues, leaves, branches, etc. and the disposal of these wastes other than oil creates environmental problems (Monteiro *et al.,* 2009). Organic waste generated during the processing of agricultural products creates storage problems in factories, and when mixed with water and soil, it causes serious environmental issues and greenhouse gas emissions (Sharma *et al.,* 2019). Evaluation of this waste is necessary economically and to eliminate its harmful effects on the environment. It has been determined that OSRs used in various polymer-based composite studies show good physical and mechanical properties (Ayrilmis and Buyuksari, 2010; Banat and Fares, 2015; Kaya *et al.,* 2018). Elbir *et al*. (2012) determined that the use of OSR increased the resistance to fungal rot in particleboards. It has been determined that OSRs are especially suitable for particleboards to be used indoors where they provide the necessary strength properties (Farag *et al*., 2020).

Alkaline treatment is one of the most frequently used methods for modifying the fiber and particle surface and increases the amount of reactive OH groups in the material (Ndazi *et al*., 2007a). The hydroxyl groups increase, and better bonding occurs between lignocellulosic fibers and particles with the alkali pretreatment process. (Lopattananon *et al*., 2008). For this purpose, alkali pretreatment was applied to OSRs in this study.

In producing wood-based composites, formaldehyde-based glues are mostly used due to their various advantages and ease of use. However, during and after production, formaldehyde decomposition, which is a problem in terms of environment and health, occurs in the produced plates and this process can last for years. Formaldehyde, depending on the amount to which humans are exposed (>0.1ppm), causes allergic diseases such as tearing, irritation of the respiratory system and mucous membranes, skin disorders, cough, exhaustion, rash, and it can also lead to cancer. For this reason, reducing the amount of free formaldehyde amount is an important criterion, especially for the panels used indoors (Salthammer *et al*., 2010; Kim *et al.,* 2011; Song *et al.,* 2015). This study investigated the possibilities of using OSRs as substitutes for the production of particleboards.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Production of boards
### 2.1. Izrada ploča

White Poplar (*Populus alba* L.) logs with a diameter of 16 cm were used in the production of trial boards. The OSR used in this study was supplied from the Pirina A.Ş. privately owned company in Turkey, Aydın. Phenol formaldehyde (PF) resin (solid content: 40 %) is a product of Polisan Chemical Factory in Kocaeli, Turkey. The PF adhesive was used based on the oven-dried chip weight. The white poplar logs were at first debarked. In the rough chipping process, A laboratory type, two-blade coarse hacker from Vecoplan-hacker (Germany) was used. It was then passed through a Robert Hildebrand (Germany) ring type flaker machine with six hammers and sixteen knives with a blade ring. Algemaier (Germany) branded four-stage shaker sieve was used to sift the resulted particles. Those that pass through a 3 mm sieve and remain on a 1.5 mm sieve are in the middle layer, and those that pass through a 1.5 mm mesh sieve and remain on a 0.5 mm sieve are sieved to be used in the production of the outer layer. The sieved particles were dried in an OSR laboratory type drying oven at 100 °C to 1 % moisture content. In the gluing process, the glue was sprayed on the particles with an air gun and the particles were regularly mixed by hand to achieve a homogeneous gluing. A total of ten boards were produced with two replications, with dimensions of 550 mm × 550 mm × 12 mm. On the other hand, OSR was used in the middle layer with and without pre-treatment (NaOH). The OSR to be pretreated was subjected to 1 % NaOH extraction for 24 hours. Then the particleboards were conditioned at a temperature of (20±2) °C and (65±5) % relative air humidity. The specifications for all board types produced are shown in Tables 1 and 2.

**Table 1** Production conditions of particleboards
**Tablica 1.** Uvjeti izrade ploča iverica

| | |
|---|---|
| Target density, g/cm$^3$ / *Ciljana gustoća,* g/cm$^3$ | 0.650 |
| Core layer / surface layer, %<br>*Središnji sloj / površinski sloj,* % | 60:40 |
| Phenol formaldehyde (surface/core), %<br>*Fenol-formaldehid (površina/sredina),* % | 11/9 |
| Board thickness, mm / *Debljina ploče,* mm | 12 |
| Pressure, kg/cm$^2$ / *Tlak,* kg/cm$^2$ | 25 |
| Press temperature, °C / *Temperatura prešanja,* °C | 150 |
| Press time, min / *Vrijeme prešanja,* min | 6 |

### 2.2 Chemical properties of wood and OSR particles
### 2.2. Kemijska svojstva drva i ostataka koštica masline

The preparation of the particles for chemical analysis was carried out in accordance with the TAPPI T 257 cm-02 (TAPPI, 2002) standard. Wood samples were ground in a laboratory-type Willey mill. Then, they were sieved in a vibrating laboratory type sieve with 40 mesh (425 µ) and 60 mesh (250 µ) sieves. The fraction that passed through the 40 mesh sieve and remained on the 60 mesh sieve was used in the analyses. Finally, the moisture content of the prepared wood samples was determined. Alcohol-benzene solubility and ash content tests of the samples were performed using the standards TAPPI 204-97 (TAPPI, 2007) and TAPPI 211 om-02 (TAPPI, 2002), respectively. The pH values were measured in an extract solution made by 5 g wood flour added to 150-ml distilled water and boiled for 24 h. The pH values of the filtered solutions were determined by means of a pH meter (Kalaycıoğlu *et al*., 2005; Colak *et al*., 2007).

### 2.3 Physical and mechanical properties of particleboards
### 2.3. Fizička i mehanička svojstva ploča iverica

Moisture (MC) EN 322 (1993), density (D) EN 323 (1993), thickness swelling (TS) EN 317 (1993), modulus of rupture (MOR) and modulus of elasticity (MOE) EN 310 (1993) and internal bond strength (IB) EN 319 (1993) for particleboard samples were determined. The results were evaluated according to EN 312 (2010) and twenty test samples were prepared for each test.

**Table 2** Production scheme of particleboards
**Tablica 2.** Shema izrade ploča iverica

| **Board types**<br>*Vrsta ploče* | ***Populus Alba* particle, %**<br>*Populus alba, iverje, %* | **Olive stone reduce, %**<br>*Ostatak koštica masline, %* |
|---|---|---|
| A | 100 | - |
| B | 90 | 10 |
| C | 80 | 20 |
| D | 70 | 30 |
| E | 70 | 30 (treatment) |

### 2.4 Formaldehyde emission
### 2.4. Emisija formaldehida

The perforator method (ISO 12460-5, 2015) was used to determine the formaldehyde emission values (FE). In this method, free formaldehyde in the board is determined by extraction. The formaldehyde emission amounts of the samples were determined by using the measured absorbance values. The absorbance values of these solutions were measured photometrically at 412 nm in a UV Spectrometer device.

### 2.5 Statistical analysis
### 2.5. Statistička analiza

SPSS 20 package program was used for the statistical analysis. One-Way ANOVA (analysis of variance) was used to evaluate the data obtained from the experiments. If the effect was significant with the Newman-Keuls test, the mean values were compared.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

### 3.1 Chemical properties
### 3.1. Kemijska svojstva

Chemical analysis of the samples used are given in Table 3. According to the results of statistical analysis, the difference between the pH and alcohol-benzene solubility of the wood samples was found to be statistically significant ($p<0.001$). The pH value also increased with the pretreatment of OSRs with basic NaOH. The pH of the tree species should be between 4 – 5.5 for good adhesion (Cao *et al.,* 2017). The pH value of the pretreated OSRs was high for production (6.59). According to the results, it was determined that the amount of extractive substance of OSRs was much higher. The results obtained in similar studies show that olive stones contain high phenolic compounds (3.56-11.32 mg/g DM) (Erbil *et al*., 2012). It has been determined that the pretreatment application greatly reduces the amount of extractive material.

Alkali treatment applications remove some extractives, especially oil and wax compounds, from the lignocellulosic material (Troedec *et al.,* 2008; Carvalho *et al.,* 2010). Previous studies also stated that it can decompose lignin and hemicelluloses under room temperature conditions with alkali treatment (Ndazi *et al.,* 2007b). It was determined that 1 % NaOH pretreatment did not affect the ash content values, while the difference in ash content between poplar wood and olive waste was found to be statistically significant. The ash content of OSRs was higher than that of white poplar particles.

### 3.2 Physical and mechanical properties
### 3.2. Fizička i mehanička svojstva

Average values of physical properties and results of Newman-Keus analysis are given in Figure 1. It was determined that MC values varied between 7.71 % and 8.18 %. The M values of the boards comply with the values specified in the standard. In addition, it was determined that the use of OSR had no effect on the density of the boards and values close to the targeted density were obtained.

The amount of thickness swelling (TS) increased depending on the soaking time of the boards. The lowest TS values of boards were obtained from the board groups using 30 % OSR after 2 hours and 24 hours of water soaking, while the highest values of boards were determined in the control groups. With the use of OSR rate of 30 %, there was a 31 % decrease in swelling rates compared to the control group. Extractives (phenol, tannin, etc.) found in wood reduce the rate of water absorption as they show water repellent properties (Cameron and Pizzi, 1986; Baharoglu *et al.,* 2013). In addition, oils and waxy compounds in wood form a thin film layer and provide resistance to water (Nasser, 2012).

Swelling the crystalline structure in cellulose during alkali treatment can facilitate water penetration into the boards (Gwon *et al.,* 2010). The TS values increased in the alkali pre-treated OSR boards. The thickness swelling values of the boards were higher than the standards specified in EN 312 (2010).

Average values of mechanical properties and results of Newman-keuls analysis are given in Figure 2. It was determined that 20 % and 30 % OSR negatively affected MOR, MOE and IB values. There was no significant decrease in mechanical properties at 10 % usage rate. According to the EN 312 (2010) standard, the re-

**Table 3** Chemical properties of wood and OSR particles
**Tablica 3.** Kemijska svojstva drva i ostataka koštica masline

| **Chemical properties, %**<br>*Kemijska svojstva, %* | ***Populus alba* L.** | **Olive stone**<br>*Koštice masline* | **Olive stone (treatment)**<br>*Koštice masline (tretirane)* |
|---|---|---|---|
| pH | 5.96 (0.02)$^{A*}$ | 5.01 (0.21)$^{B}$ | 6.59 (0.11)$^{C}$ |
| Solubility in alcohol-benzene<br>*topljivost u smjesi alkohola i benzena* | 2.55 (0.20)$^{A}$ | 24.63 (0.81)$^{B}$ | 4.83 (0.43)$^{C}$ |
| Ash / *pepeo* | 1.19 (0.07)$^{A}$ | 7.54 (0.14)$^{B}$ | 7.47 (0.14)$^{B}$ |

* Numbers in parenthesis are standard deviation. Means within a column followed by the same capital letter are not significantly different at 5 % level of significance

** Brojevi u zagradama standardne su devijacije. Srednje vrijednosti unutar stupca uz koje je navedeno isto veliko slovo ne razlikuju se značajno na razini značajnosti od 5 %.*

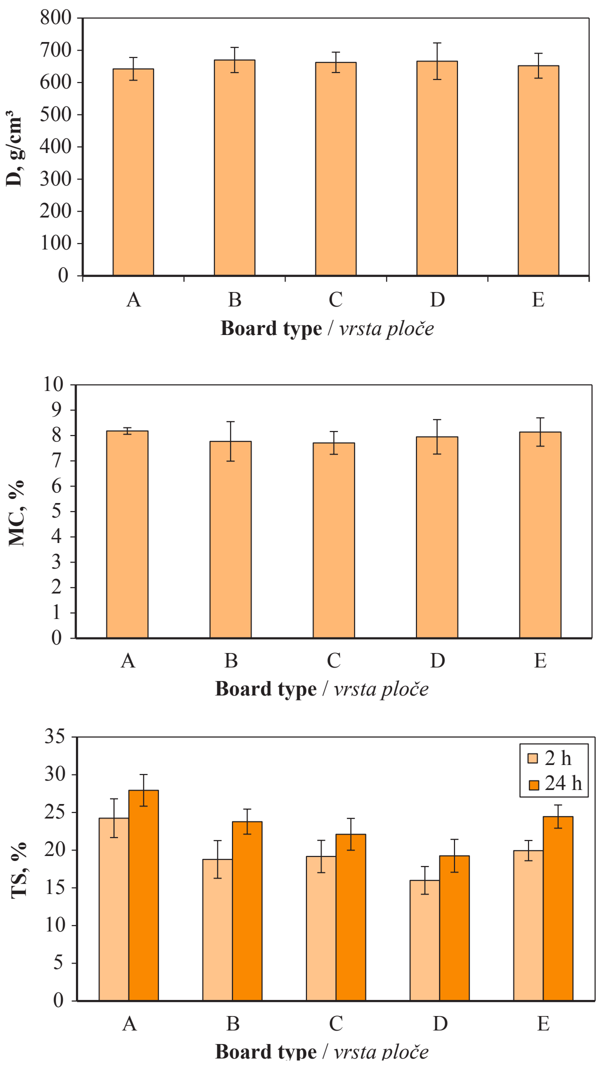



**Figure 1** Effect of OSR amount on physical properties of boards
**Slika 1.** Utjecaj količine ostataka koštica masline na fizička svojstva ploča

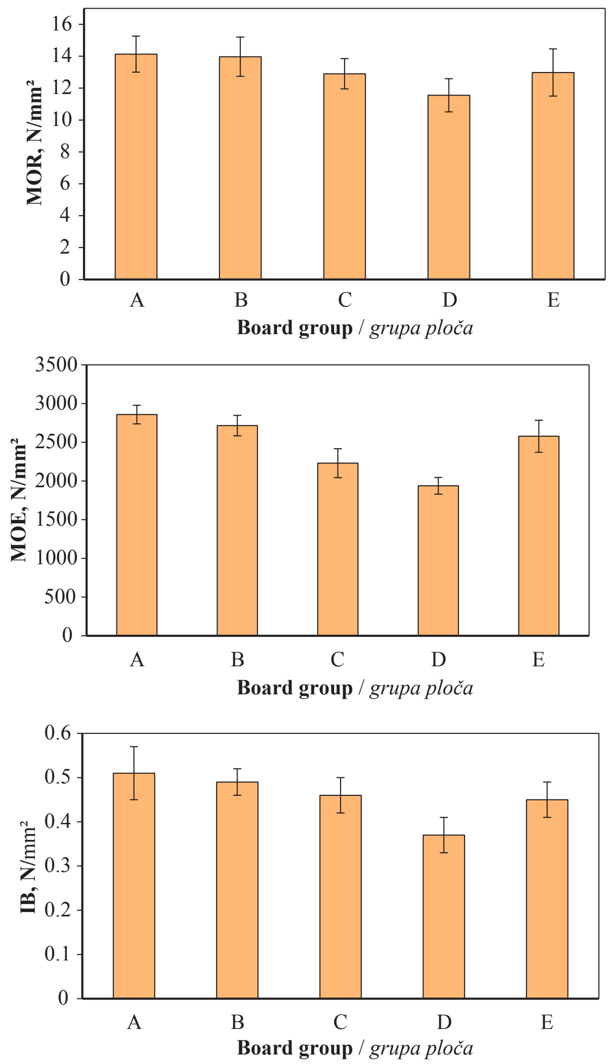



**Figure 2** Effect of OSR amount on mechanical properties of boards
**Slika 2.** Utjecaj količine ostatka koštica masline na mehanička svojstva ploča

quired MOR value for general purpose and interior equipment such as furniture is 12.5 N/mm² and 13 N/mm², respectively, while the MOE value is 1800 N/mm².

Except for the board group using 30 % OSR without pre-treatment, all boards meet these requirements. According to the EN 312 (EN 2010) standard, the required IB value for general purpose and interior equipment such as furniture is 0.28 N/mm² and 0.40 N/mm², respectively. In general, all board groups meet the required IB resistance values. The adhesive properties are negatively affected by the increase of extractives in the raw material used, resulting in lower strength properties. The increase in the amount of OSRs used in wood composites may adversely affect the mechanical properties due to the increase of gaps in the board structure (Aras *et al*., 2022).

Hashim *et al.* (2010) determined that particle geometry is effective in bending and internal bond strength. With the use of particles with a long and thin geometry and a uniform structure, the particles provide a better bonding contact and more homogeneous structure (Cosereanu *et al.,* 2015). Due to the different geometry and blunt chip shape of OSR, less adhesion surface may be provided and internal bonding may decrease.

The high extractive substance content of OSRs, especially layering oils and waxes, can prevent adequate glue penetration during gluing. The alkaline pretreatment is carried out to cause the removal of the oil and wax layer on the surface, making the surfaces rough and hydrophilic. The bond strength is affected by the covalent bonding between the hydroxyl groups of the wood material and the polar groups of the glue, as well as the adhesion of the glue by penetrating the material on the surface (Mo *et al.,* 2001). In addition, it can be said that the fact that the pH values of OSRs are higher than the appropriate pH (4-5) for adhesion negatively affects the board properties.

Scanning electron microscopy (SEM) analysis was carried out to determine the internal microstructure of the boards and the analysis results are given in

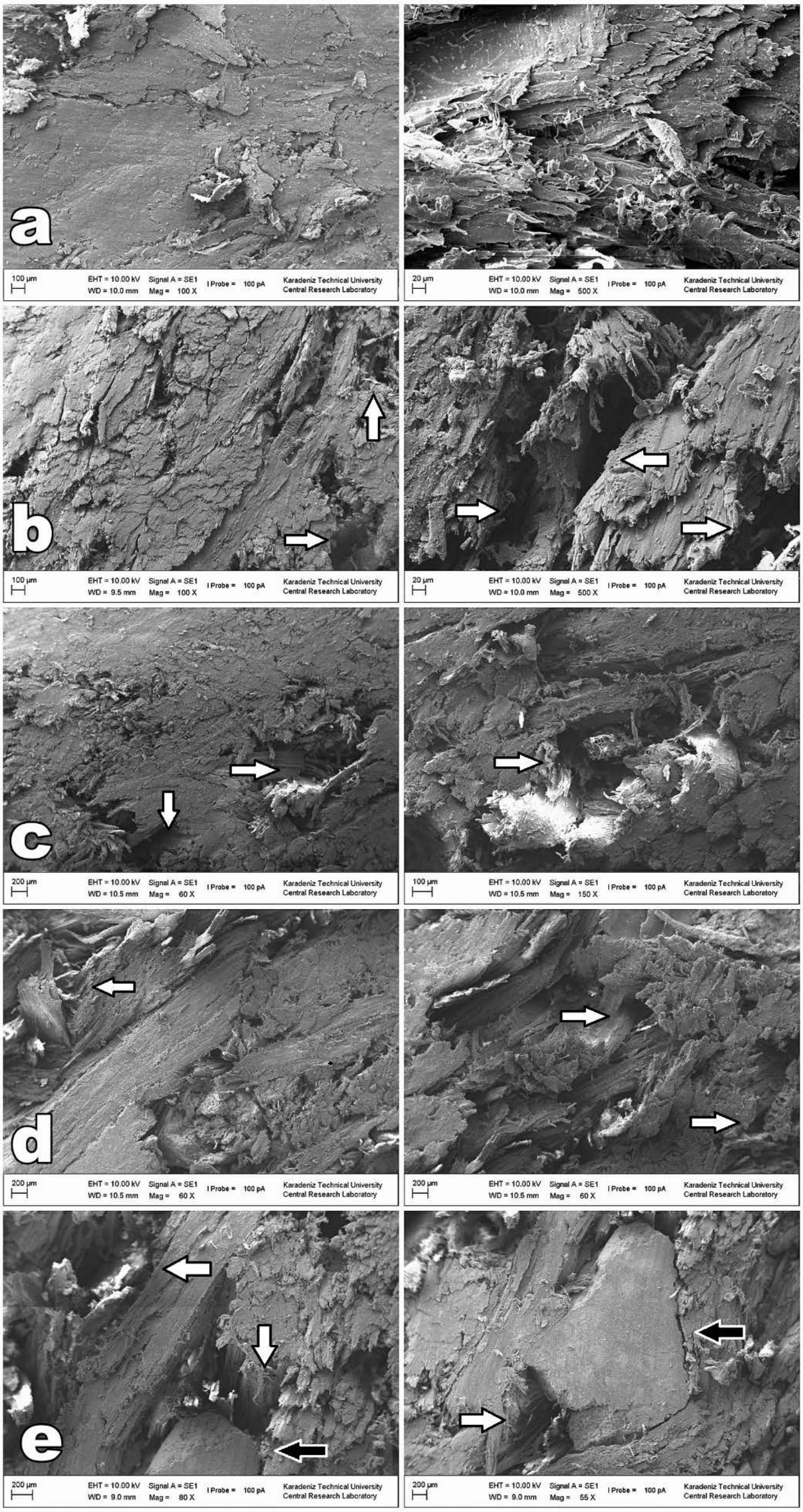



**Figure 3** SEM images of cross-sectional surface of boards: a) control boards, b) particleboard with 10 % OSR, c) particleboard with 20 % OSR, d) particleboard with 30 % OSR, e) particleboard with 30% OSR-treatment
**Slika 3.** SEM slike poprečnog presjeka ploča: a) kontrolne ploče, b) ploča iverica s 10 % OSR-a, c) ploča iverica s 20 % OSR-a, d) ploča iverica s 30 % OSR-a, e) ploča iverica s 30 % tretiranog OSR-a

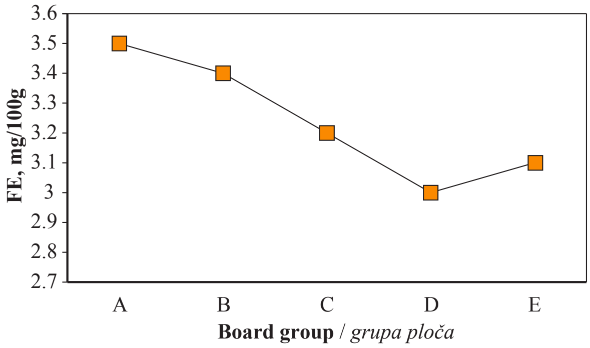



**Figure 4** The effect of OSR amount on formaldehyde emission of boards
**Slika 4.** Utjecaj količine ostataka koštica masline na emisiju formaldehida ploča

Figure 3. The white arrows in the Figures show the gaps formed in the boards, while the black arrows show the OSRs. It seems that with the increase in the use of OSR, the space ratio in the board increases and the adhesive bonding decreases. Also, there was less bonding between particle and lignocellulosic material in board groups using OSR.

### 3.3 Formaldehyde emission
### 3.3. Emisija formaldehida

The effect of using OSR on the FE of the boards is given in Figure 4. The produced boards have E1 FE class values (≤ 8 mg / 100 g) (ISO 12460-5 2015). The lowest FE values were obtained from the untreated board group using 30 % OSR. Hydrolysis-resistant flavonoid methylene bonds are formed after the pressing process of the boards because of the high content of phenolic compounds in the extractives. Thus, due to the increase in the reactivity of the extractive material, the FE values are significantly reduced (Pizzi, 1983; Pizzi and Mittal, 2017). For this reason, if the extractives and adhesives are treated at appropriate rates, it is possible to get emission values close to the E0 and super E0 formaldehyde classes (Stefani *et al*., 2008; Navarrete *et al*., 2012). In other words, OSR high phenolic compound content acts as a formaldehyde scavenger. Similar results were obtained in various studies (Pirayesh *et al.,* 2013; Bekhta *et al.,* 2019). On the other hand, FE values increased in boards produced using pre-treated OSR. This may be because of the removal of the extractives, as well as the spectrometric detection of aldehydes formed due to alkaline pretreatment.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

This study aimed to create an alternative raw material source by evaluating OSRs, which have a significant waste potential in particleboard production. It was determined that the obtained results are suitable for producing particleboards with PF. With the increase in OSR addition to the boards, dimensional stability increased while formaldehyde emission decreased. However, increasing the amount of OSR affected the mechanical properties negatively. There was no significant change in mechanical properties when using 10 % OSR. The results showed that OSR could be used as an alternative raw material in particleboard production. The use of such lignocellulosic materials may be necessary as an alternative to declining forest resources. Also, using these waste materials with no industrial value can contribute to environmental development.

### Acknowledgements – Zahvala

This work was supported by Scientific Research Project Coordination Unit of Karadeniz Technical University. Project number: FHD-2018-7299.

## 5 REFERENCES
## 5. LITERATURA

1. Aras, U.; Kalaycıoğlu, H.; Yel, H.; Kuştaş, S., 2022: Utilization of olive mill solid waste in the manufacturing of cement-bonded particleboard. Journal of Building Engineering, 49: 104055. https://doi.org/10.1016/j.jobe.2022.104055
2. Atoyebi, O. D.; Osueke, C. O.; Badiru, S.; Gana, A. J.; Ikpotokin, I.; Modupe, A. E.; Tegene, G. A., 2019: Evaluation of particle board from sugarcane bagasse and corn cob. International Journal of Mechanical Engineering and Technology, 10 (1): 1193-1200.
3. Ayrilmis, N.; Buyuksari, U., 2010: Utilization of olive mill sludge in manufacture of lignocellulosic/polypropylene composite. Journal Material Science, 45 (5): 1336-1342. https://doi.org/10.1007/s10853-009-4087-2
4. Azambuja, R. D. R.; Castro, V. G. D.; Trianoski, R.; Iwakiri, S., 2018: Recycling wood waste from construction and demolition to produce particleboards. Maderas: Ciencia y Tecnología, 20 (4): 681-690. http://dx.doi.org/10.4067/S0718-221X2018005041401
5. Baharoglu, M.; Nemli, G.; Sari, B.; Birturk, T.; Bardak, S., 2013: Effects of anatomical and chemical properties of wood on the quality of particleboard. Composites Part B: Engineering, 52: 282-285. https://doi.org/10.1016/j.compositesb.2013.04.009
6. Banat, R.; Fares, M. M., 2015: Olive oil waste filled high density polyethylene bio-composite: mechanical, morphological and water absorption properties. Journal of Composite Materials, 5 (5): 133-141. https://doi.org/10.5923/j.cmaterials.20150505.05
7. Bekhta, P.; Sedliačik, J.; Kačík, F.; Noshchenko, G.; Kleinová, A., 2019: Lignocellulosic waste fibers and their application as a component of urea-formaldehyde adhesive composition in the manufacture of plywood. European Journal of Wood and Wood Products, 77 (4): 495-508. https://doi.org/10.1007/s00107-019-01409-8
8. Blanchet, P.; Cloutier, A.; Riedl, B., 2000: Particleboard made from hammer milled black spruce bark residues. Wood Science and Technology, 34 (1): 11-19. https://doi.org/10.1007/s002260050003
9. Borysiuk, P.; Jenczyk-Tolloczko, I.; Auriga, R.; Kordzikowski, M., 2019: Sugar beet pulp as raw material for particle-

board production. Industrial Crops and Products, 141: 111829. https://doi.org/10.1016/j.indcrop.2019.111829
10. Buyuksari, U.; Ayrilmis, N.; Avci, E.; Koc, E., 2010: Evaluation of the physical, mechanical properties and formaldehyde emission of particleboard manufactured from waste stone pine (*Pinus pinea* L.) cones. Bioresource Technology, 101 (1): 255-259. https://doi.org/10.1016/j.biortech.2009.08.038
11. Cameron, F. A.; Pizzi, A., 1986: Tannin-ınduced formaldehyde release depression in urea-formaldehyde particleboard. ACS Symposium Series, 316 (15): 198-201. https://doi.org/10.1021/bk-1986-0316.ch015
12. Cao, M.; Li, T.; Liang, J.; Du, G., 2017: The influence of pH on the melamine-dimethylurea-formaldehyde co-condensations: A quantitative 13C-NMR study. Polymers, 9 (3): 109. https://doi.org/10.3390/polym9030109
13. Carvalho, K. C. C.; Mulinari, D. R.; Voorwald, H. J. C.; Cioffi, M. O. H., 2010: Chemical modification effect on the mechanical properties of hips/coconut fiber composites. BioResources, 5 (2): 1143-1155.
14. Çolak, S.; Çolakoğlu, G.; Aydin, I.; Kalaycioğlu, H., 2007: Effects of steaming process on some properties of eucalyptus particleboard bonded with UF and MUF adhesives. Building and Environment, 42 (1): 304-309. https://doi.org/10.1016/j.buildenv.2005.08.013
15. Cosereanu, C. N.; Brenci, L. M. N.; Zeleniuc, O. I.; Fotin, A. N., 2015: Effect of particle size and geometry on the performance of single-layer and three-layer particleboard made from sunflower seed husks. BioResources, 10 (1): 1127-1136.
16. De Almeida, A. C.; De Araujo, V. A.; Morales, E. A. M.; Gava, M.; Munis, R. A.; Garcia, J. N.; Barbosa, J. C., 2017: Wood-bamboo particleboard: Mechanical properties. BioResources, 12 (4): 7784-7792. https://doi.org/10.15376/biores.12.4.7784-7792
17. Elbir, M.; Moubarik, A.; Rakib, E. M.; Grimi, N.; Amhoud, A.; Miguel, G.; Hanine, H.; Artaud, J.; Vonloot, P.; Mbarki, M., 2012: Valorization of Moroccan olive stones by using it in particleboard panels. Maderas: Ciencia y Tecnología, 14 (3), 361-371. http://dx.doi.org/10.4067/S0718-221X2012005000008
18. Farag, E.; Alshebani, M.; Elhrari, W.; Klash, A.; Shebani, A., 2020: Production of particleboard using olive stone waste for interior design. Journal of Building Engineering, 29: 101119. https://doi.org/10.1016/j.jobe.2019.101119
19. Fiorelli, J.; Bueno, S. B.; Cabral, M. R., 2019: Assessment of multilayer particleboards produced with green coconut and sugarcane bagasse fibers. Construction and Building Materials, 205: 1-9. https://doi.org/10.1016/j.conbuildmat.2019.02.024
20. Gwon, J. G.; Lee, S. Y.; Chun, S. J.; Doh, G. H.; Kim, J. H., 2010: Effects of chemical treatments of hybrid fillers on the physical and thermal properties of wood plastic composites. Composites Part A: Applied Science and Manufacturing, 41 (10): 1491-1497. https://doi.org/10.1016/j.compositesa.2010.06.011
21. Hashim, R.; Saari, N.; Sulaiman, O.; Sugimoto, T.; Hiziroglu, S.; Sato, M.; Tanaka, R., 2010: Effect of particle geometry on the properties of binderless particleboard manufactured from oil palm trunk. Materials & Design, 31 (9): 4251-4257. https://doi.org/10.1016/j.matdes.2010.04.012
22. Kalaycioglu, H.; Deniz, I.; Hiziroglu, S., 2005: Some of the properties of particleboard made from paulownia. Journal of Wood Science, 51 (4): 410-414. https://doi.org/10.1007/s10086-004-0665-8
23. Kalaycıoglu, H.; Nemli, G., 2006: Producing composite particleboard from kenaf (*Hibiscus cannabinus* L.) stalks. Industrial Crops and Products, 24 (2): 177-180. https://doi.org/10.1016/j.indcrop.2006.03.011
24. Kaya, N.; Atagur, M.; Akyuz, O.; Seki, Y.; Sarikanat, M.; Sutcu, M.; Seydibeyoglu, M. O.; Sever, K., 2018: Fabrication and characterization of olive pomace filled PP composites. Composites Part B: Engineering, 150: 277-283. https://doi.org/10.1016/j.compositesb.2017.08.017
25. Kim, K. H.; Jahan, S. A.; Lee, J. T., 2011: Exposure to formaldehyde and its potential human health hazards. Journal of Environmental Science and Health Part C, 29 (4): 277-299. https://doi.org/10.1080/10590501.2011.629972
26. Kord, B.; Zare, H.; Hosseinzadeh, A., 2016: Evaluation of the mechanical and physical properties of particleboard manufactured from canola (*Brassica napus*) straws. Maderas: Ciencia y Tecnología, 18 (1): 09-18. http://dx.doi.org/10.4067/S0718-221X2016005000002
27. Lopattananon, N.; Payae, Y.; Seadan, M., 2008: Influence of fiber modification on interfacial adhesion and mechanical properties of pineapple leaf fiber-epoxy composites. Journal of Applied Polymer Science, 110 (1): 433-443. https://doi.org/10.1002/app.28496
28. Li, W.; Shupe, T. F.; Hse, C. Y., 2004: Physical and mechanical properties of flakeboard produced from recycled CCA-treated wood. Forest Products Journal, 54 (2): 89-94.
29. Medved, S.; Tudor, E. M.; Barbu, M. C.; Jambreković, V.; Španić, N., 2019: Effect of pine (*Pinus Sylvestris*) bark dust on particleboard thickness swelling and internal bond. Drvna industrija, 70: 141-147. https://doi.org/10.5552/drvind.2019.1902
30. Mo, X.; Hu, J.; Sun, X. S.; Ratto, J. A., 2001: Compression and tensile strength of low-densitystraw-protein particleboard. Industrial Crops and Products, 14 (1): 1-9. https://doi.org/10.1016/S0926-6690(00)00083-2
31. Mo, X.; Cheng, E.; Wang, D.; Sun, X. S., 2003: Physical properties of medium-density wheat straw particleboard using different adhesives. Industrial Crops and Products, 18 (1): 47-53. https://doi.org/10.1016/S0926-6690(03)00032-3
32. Monteiro, S.; Lopes, F.; Ferreira, A.; Nascimento, D., 2009: Natural-fiber polymer-matrix composites: cheaper, tougher, and environmentally friendly. Journal Material Science, 61: 17-22. https://doi.org/10.1007/s11837-009-0004-z
33. Nasser, R. A., 2012: Physical and mechanical properties of three-layer particleboard manufactured from the tree pruning of seven wood species. World Applied Sciences Journal, 19 (5): 741-753. https://doi.org/10.5829/idosi.wasj.2012.19.05.2764
34. Navarrete, P.; Pizzi, A.; Tapin-Lingua, S.; Benjelloun-Mlayah, B.; Pasch, H.; Rode, K.; Delmotte, R.; Rigolet, S., 2012: Low formaldehyde emitting biobased wood adhesives manufactured from mixtures of tannin and glyoxylated lignin. Journal of Adhesion Science and Technology, 26 (10-11): 1667-1684. https://doi.org/10.1163/156856111X618489
35. Ndazi, B. S.; Karlsson, S.; Tesha, J. V.; Nyahumwa, C. W., 2007a: Chemical and physical modifications of rice husks for use as composite panels. Composites Part A: Applied Science and Manufacturing, 38 (3): 925-935. https://doi.org/10.1016/j.compositesa.2006.07.004
36. Ndazi, B. S.; Nyahumwa, C.; Tesha, J., 2007b: Chemical and thermal stability of rice husks against alkali treatment. BioResources, 3 (4): 1267-1277.
37. Nemli, G.; Kırcı, H.; Serdar, B.; Ay, N., 2003: Suitability of kiwi (*Actinidia sinensis* Planch.) prunings for particleboard

manufacturing. Industrial Crops and Products, 17 (1): 39-46. https://doi.org/10.1016/S0926-6690(02)00057-2
38. Nicolao, E. S.; Leiva, P.; Chalapud, M. C.; Ruseckaite, R. A.; Ciannamea, E. M.; Stefani, P. M., 2020: Flexural and tensile properties of biobased rice husk-jute-soybean protein particleboards. Journal of Building Engineering, 30: 101261. https://doi.org/10.1016/j.jobe.2020.101261
39. Nishimura, T., 2015: Chipboard, oriented strand board (OSB) and structural composite lumber. In: P. Ansel, M. (eds.). Wood Composites. Woodhead Publishing, Cambridge, United Kingdom. https://doi.org/10.1016/B978-1-78242-454-3.00006-8
40. Pirayesh, H.; Khazaeian, A.; Tabarsa, T., 2012: The potential for using walnut (*Juglans regia* L.) shell as a raw material for wood-based particleboard manufacturing. Composites Part B: Engineering, 43 (8): 3276-3280. https://doi.org/10.1016/j.compositesb.2012.02.016
41. Pirayesh, H.; Khanjanzadeh, H.; Salari, A., 2013: Effect of using walnut/almond shells on the physical, mechanical properties and formaldehyde emission of particleboard. Composites Part B: Engineering, 45 (1): 858-863. https://doi.org/10.1016/j.compositesb.2012.05.008
42. Pizzi, A., 1983: Wood adhesives: chemistry and technology. Marcel Dekker, New York. https://www.routledge.com/Wood-Adhesives-Chemistry-and-Technology---Volume 2/Pizzi/p/book/9780367451127
43. Pizzi, A.; Mittal, K. L., 2017: Handbook of adhesive technology. CRC press, Boca Raton, United States. https://doi.org/10.1201/9781315120942
44. Salthammer, T.; Mentese, S.; Marutzky, R., 2010: Formaldehyde in the indoor environment. Chemical Reviews, 110 (4): 2536-2572. https://doi.org/10.1021/cr800399g
45. Sam-Brew, S.; Smith, G. D., 2015: Flax and Hemp fiber-reinforced particleboard. Industrial Crops and Products, 77: 940-948. https://doi.org/10.1016/j.indcrop.2015.09.079
46. Song, W.; Cao, Y.; Wang, D.; Hou, G.; Shen, Z.; Zhang, S., 2015: An investigation on formaldehyde emission characteristics of wood building materials in Chinese standard tests: Product emission levels, measurement uncertainties and data correlations between various tests. PLoS One, 10 (12): 1-38. https://doi.org/10.1371/journal.pone.0144374
47. Stefani, P. M.; Pena, C.; Rueseckaite, R. A.; Piter, J. C.; Mondragon, I., 2008: Processing conditions analysis of eucalyptus globulus plywood bonded with resol tannin adhesives. Bioresource Technolgy, 99: 5977-5980. https://doi.org/10.1016/j.biortech.2007.10.013
48. Trischler, J., 2016: Strategic raw material supply for the particleboard-producing industry in Europe: Problems and challenges. PhD Thesis, Linnaeus University Press, Växjö, Sweden.
49. Troedec, M. L.; Sedan, D.; Peyratout, C.; Bonnet, J. P.; Smith, A.; Guinebretiere, R.; Gloaguen, V.; Krausz, P., 2008: Influence of various chemical treatments on the composition and structure of hemp fibres. Composites Part A: Applied Science and Manufacturing, 39 (3): 514-522. https://doi.org/10.1016/j.compositesa.2007.12.001
50. Wang, S. Y.; Yang, T. H.; Lin, L. T.; Lin, C. J.; Tsai, M. J., 2008: Fire-retardant-treated low-formaldehyde-emission particleboard made from recycled wood-waste. Bioresource Technolgy, 99 (6): 2072-2077. https://doi.org/10.1016/j.biortech.2007.03.047
51. ***EN 310:1993. Wood based panels, determination of modulus of elasticity in bending and bending strength. European Committee for Standardization, Brussels, Belgium.
52. ***EN 317: 1993. Particleboards and fiberboards, determination of swelling in thickness after immersion. CEN, Brussels, Belgium.
53. ***EN 319: 1993. Particleboards and fiberboards, determination of tensile strength perpendicular to plane of the board. CEN, Brussels, Belgium.
54. ***EN 322: 1993. Wood-based panels. Determination of moisture content. CEN, Brussels, Belgium.
55. ***EN 323: 1993. Wood-based panels. Determination of density. CEN, Brussels, Belgium.
56. ***EN 312: 210. Particleboards-specifications. CEN, Brussels, Belgium.
57. ***International Olive Council (IOC), 2021: World olive oil and table olive figures. https://www.internationaloliveoil.org/what-we-do/economic-affairs-promotion-unit/#figures
58. ***ISO 12460-5: 2015. Wood-based panels – Determination of formaldehyde release. Part 5: Extraction method (called the perforator method). ISO, Geneva, Switzerland.
59. ***TAPPI T 204-97: 2007. Solvent extractives of wood and pulp. TAPPI Press, Atlanta, USA.
60. ***TAPPI T 211 om-02: 2002. Ash in wood, pulp, paper and paperboard. TAPPI Press. Atlanta, USA.
61. ***TAPPI T 257 cm-02: 2012. Sampling and preparing wood for analysis. TAPPI Press, Atlanta, USA.
62. Taş, H. H.; Kul, F. M., 2020: Sunflower (*Helianthus Annuus*) stalks as alternative raw material for cement bonded particleboard. Drvna industrija, 71 (1): 41-46. https://doi.org/10.5552/drvind.2020.1907
63. ***The International Olive Oil Council. Available online: http://www.internationaloliveoil.org/ (Accessed Sep. 20, 2020)

**Corresponding address:**

**UĞUR ARAS**

Karadeniz Technical University, Arsin Vocational Junior College, Materials and Materials Machining Technologies, Furniture and Decoration, Arsin, Trabzon, TURKEY, e-mail: uguraras.86@gmail.com

since 1913

tvin.

Osman Goktas[1], Yasar Tahsin Bozkaya[2], Mehmet Yeniocak[1]

# Coloration of Lacquered Coatings for Furniture Production with Herbal Dyes and Determining Weathering Resistance

# Obojenje lakova za namještaj s biljnim bojilima i određivanje njihove otpornosti na vremenske utjecaje

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 6. 7. 2022.
Accepted – prihvaćeno: 21. 12. 2022.
UDK: 667.613.2; 667.6
https://doi.org/10.5552/drvind.2023.0050



**ABSTRACT** • *The main goal of the study is to produce eco-friendly furniture dyes by using bio-colorants and to determine the color stability of these dyes in outdoor conditions. In this regard, dye extracts obtained from red beet (Beta vulgaris), safflower (Carthamus tinctorius L.), and purple cabbage (Brassica oleracea), as a bio-colorant source, were applied to MDF test panels by mixing with water-based synthetic lacquer coatings. Also, three different synthetic dyes were applied to MDF test panels in order to compare the results with eco-friendly natural dyes. Natural dyes were mixed with metal and natural mordants such as iron sulfate, aluminum sulfate and vinegar. Lacquer coated test panels, coated with natural and synthetic dyes, were exposed to outdoor conditions for 50 days in Denizli/Turkey in order to assess the change in color. As a result, the maximum color stability occurred in the test panels lacquer coated with synthetic black dye, while the minimum color stability occurred in the test panels lacquer coated with synthetic light blue dye. It was determined that the thickness of the color coating layer applied to test panels increases color stability. It was also observed that the color stability performance of natural dyes is as good as that of synthetic dyes.*

**KEYWORDS:** *furniture industry, lacquer coating, natural dyes, weathering, color changes*

**SAŽETAK** • *Glavni cilj istraživanja bio je proizvesti ekološki prihvatljiva bojila za namještaj upotrebom prirodnih bojila te utvrditi postojanost boje tih bojila u vanjskim uvjetima. Kao izvor bojila upotrijebljeni su ekstrakti dobiveni iz cikle (Beta vulgaris), šafranike (Carthamus tinctorius L.) i crvenog kupusa (Brassica oleracea), koji su se nakon miješanja s vodenim lakovima nanosili na MDF ploče. Osim toga, na MDF ploče nanesena su i tri različita sintetička bojila radi usporedbe s rezultatima ekološki prihvatljivih prirodnih bojila. Prirodna su se bojila miješala s metalnim i prirodnim fiksatorima kao što su željezov sulfat, aluminijev sulfat i ocat. Ploče lakirane prirodnim i sintetskim bojilima 50 dana su izložene vanjskim vremenskim uvjetima u Denziliju, u Turskoj, kako bi se utvrdila promjena boje. Rezultati su pokazali da je najveća stabilnost boje postignuta na ispitnim pločama lakiranima sintetskim crnim bojilom, a najmanju stabilnost boje pokazale su ispitne ploče lakirane sintetskim svjetloplavim*

[1] Authors are researchers at Mugla Sitki Kocman University, Faculty of Technology, Department of Woodworking Industrial Engineering, Mugla, Turkey. https://orcid.org/0000-0001-7459-1104, https://orcid.org/0000-0002-8757-5688
[2] Author is researcher at Yonga Mobilya, Denizli, Turkey. https://orcid.org/0000-0003-4395-5176

*bojilom. Utvrđeno je da debljina filma premaza nanesenoga na ispitne ploče povećava stabilnost boje. Također je uočeno da je stabilnost boje prirodnih bojila jednako dobra kao i stabilnost sintetskih bojila.*

**KLJUČNE RIJEČI:** *proizvodnja namještaja, lak, prirodna bojila, izlaganje vremenskim uvjetima, promjene boje*

## 1 INTRODUCTION
## 1. UVOD

People are exposed to numerous types of pollutants such as volatile organic compounds (VOCs) in modern environment. VOCs are generally composed of typical solvents such as ethylbenzene, glycol ethers, methanol, methyl ketone, methyl isobutyl ketone, toluene and xylene and are counted among the most important chemicals lowering the indoor and outdoor air quality. Solvents dissolve dyes (Singh *et al*., 2016). However, they can lead to nausea, headache, irritation of eyes, nose and throat, allergy, mucosa membrane irritation, malaise, drowsiness, asthma, dermatitis, allergic rhinitis, pneumonia, allergy, fertility and development problems, kidney, lung and cardio damages, and even cause cancer on humans (Dalsan, 2021). According to Salthammer (1998), about 150 distinct VOCs are utilized in the wood treatment and coating business. Lacquer coated furniture and other colored wood-based products are among the important sources of VOCs (WHO, 1987; Uçgun,1998; Tong *et al*., 2019). These solvents have been proven to even induce miscarriages in expectant mothers, birth deformities, and learning problems to children (Wolfe, 2021). Additionally, children are particularly undefended to the effects of VOCs due to their relatively high respiratory rates, immature immune systems, close proximity to the ground, and their preference for mouth breathing over nasal breathing.

Eco-friendly bio-colorants obtained from biological sources do not contain VOCs. Bio-colorants are mainly made of pigments such as anthocyanidin, carotenoids, etc. In the past few years, based on the consumer preference as well as legislative action, the availability and use of bio-colorants has greatly increased (Zhu *et al*., 2021), which has continued the delisting of approved artificial dyes (Grüll *et al*., 2014). The current consumers prefer bio-colorants because they are healthier and are products of higher quality.

As a result of rising VOC emissions and their negative effects on air quality, Tong *et al*. (2019) offered to use cleaner dyes such as waterborne dyes and green coatings that can avoid the evaporation of a large amount of solvents discharged to the atmosphere. Green Peace efforts do not only affect private behavior but also the behavior of the major cities and businesses. So, the importance of using natural sources and aesthetic products increases day by day (Salthammer *et al*., 2002; Bechtold *et al*., 2007). Recently, there has been an increased interest in natural dyes on a global scale due to public awareness of their therapeutic and medical capabilities and the benefits they provide, as well as the widely acknowledged extreme toxicity of synthetic colors. Natural dyes are those that exist in nature, like plants, insects, animals, and minerals. Of all natural colors, most people favor plant-based colorants due to their medicinal properties (Chaitanya, 2014). The first technological advances have been made recently to bring natural dyes, pigments, and colorants to a more industrial scale, both in Europe and elsewhere in the world (Cardon, 2010).

In the recent years, efforts have been made to reduce and control indoor air pollution caused by furniture and wood-based product painting. The use of natural dyes is one of the alternative approaches to this problem. These dyes are made from plants and animals that have non-toxic, non-carcinogenic and biodegradable features. There are some studies about developing environmentally friendly wood stains obtained from natural dye plants. In this regard, plant colorants such as laurel (*Laurus nobilis* L.), oleander (*Nerium Oleander* L.) (Goktas *et al*., 2009b), walnut shell (*Juglans regia*) (Goktas *et al*. 2008), madder root (*Rubia tinctorium* L.) (Goktas *et al*., 2009a), have been investigated for their eligibility in wooden products and color stability of wood samples. Peker *et al*. (2013) studied the "Usage opportunities of natural dye extracted from acorn (*Quercus ithaburensis* Decaisne) in furniture industry upper surface treatment". Ozen *et al*. (2014) used *Punica granatum* and *Morus nigra* extracts as natural dyes for wood material and investigated their ability to color the materials. Goktas *et al*. (2015) investigated walnut husk on wood materials and determined the leaching performance of bio-based natural dyes. Yeniocak *et al*. (2015) studied the use of red beetroot (*Beta vulgaris*) on a natural color wood and determined its color stability under UV exposure. Yeniocak *et al*. (2017) also determined the impact of liquid glass ($SiO_2$) on natural dye-stained wood capacity to maintain its color. Velho *et al*. (2017) studied natural dyes and investigated their structure and use in polymers. Zhu *et al*. (2021) studied "staining of wood veneers with anti-UV property using the natural dye extracted from *Dalbergia cohinchinensis*".

In this study, the main goal is to use bio-colorants as an alternative to lacquer coating, which is used to manufacture babies and children's furniture. Currently, there is limited information about the natural weathering color resistance of plant-based dyes applied on MDF panels. Natural weathering is the most precise way for examining coating durability and properties as they would be expected to be used in the actual building (Grüll *et al*. 2014). The aim of this study is to determine the usability of natural dyes obtained from red beetroot (*Beta vulgaris* L.), safflower (*Carthamus tinctorius* L.), and purple cabbage (*Brassica oleracea*), which are VOCs free extracts used as eco-friendly colorants in painting of MDF panels, and evaluate their resistance to outdoor conditions.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 MDF boards
### 2.1. MDF ploče

MDF material is used as a substrate in the production of most children's room lacquered furniture. The easy processing of MDF material, its dimensional change stability and its compatibility with lacquer coating were the main reasons for its selection for tests samples. In this study, E1 quality MDF (Çamsan / Turkey) samples for all tests were prepared in dimensions of 100 mm × 100 mm × 10 mm. For each treatment group, five test samples were prepared.

### 2.2 Natural Colorants
### 2.2. Prirodna bojila

#### 2.2.1 Red beetroot
#### 2.2.1. Cikla

The Amaranthaceae family of plants, which includes red beets (*Beta vulgaris* L.), is one of the ten foods with the highest antioxidant properties. The phenolic elements, especially the betalains, named red beets, have antioxidant properties. Red beets are water-soluble and have nitrogen-containing color pigments known as betalains. Betalains are divided into two groups - betacyanins and betaxanthins. While betaxanthins have yellow-orange color pigments, betacyanins have red-purple cabbage color pigments. This diversity results from the various chemical structures and methods of synthesis. They are very good at retaining free radicals and preventing disorders linked to oxidative stress because of their significant antioxidant action. Additionally, due to their eligibility for use over a wide pH range (3-7) and their ability to naturally produce the correct hue, betalains can also be used as food coloring. Red beetroots, as natural colorants, were procured from the local market in Mugla, Turkey.

#### 2.2.2 Safflower
#### 2.2.2. Šafranika

Safflower (*Carthamus tinctorius* L.) is an annual oil plant also known as false saffron, parrot food, or painter's safflower. It is an herbaceous plant belonging to the genus Carthamus. Safflower, which can be 60 to 70 centimeters tall, blooms yellow, red and orange flowers in July and September, depending on the variety (Karadağ, 2007). It contains a dyestuff called carthamin, which is used as herbal medicine, and in food, paint, varnish, and cosmetics industries. Safflower, as a natural colorant, was procured from the local market in Mugla, Turkey.

#### 2.2.3 Purple cabbage
#### 2.2.3. Crveni kupus

Purple cabbage (*Brassica oleracea*) is a cabbage variety of the cruciferous family with large and thick layers of red and purple leaves, grown as an autumn vegetable. It usually turns blue when cooked. In order to preserve its red color, vinegar or an acidic fruit is added to it. Purple cabbage is a suitable food colorant. Purple cabbage exhibits a wide range of colors, from red to blue. depending on the pH of the medium (Ahmadiani *et al*., 2014). Purple cabbage, as a natural colorant, was procured from the local market in Mugla, Turkey.

#### 2.2.4 Synthetic colorants
#### 2.2.4. Sintetska bojila

In this study, three different synthetic dyes were also used to compare their behavior with bio colorants. They were, namely: black acrylic dye (Cassati Co.), blue synthetic dye and light blue synthetic dye (İzosan Co.). Bio-colorants were used for the coloration of a synthetic white water-based lacquer dye (Hydrolack-Dewilux DYO Co./ Turkey) for top surface coating.

### 2.3 Mordant agents
### 2.3. Fiksatori

Mordants agents were used to get efficient chemical bonding of dye on wood material and to provide colorization. Mordant agents were iron (III) sulfate ($Fe_2(SO_4)_3.7H_2O$ (technical grade 96 percent purity (Merck)), Aluminum Sulfate, Octadecahydrate ($Al_2(SO_4)_3.18H_2O$ (puriss. p.a. Fluka / Kimetsan Co.) and grape vinegar (Fersan Co).

### 2.4 Preparation of dyestuff
### 2.4. Priprema sredstva za bojenje

The preparation of the dyestuff was carried out by the authors according to the optimum conditions during the experimental process. Distilled water was used to extract the dry plant materials. A pot was used to exact the plant materials with the 1:10 g mass ratio of plant material to liquid water volume. The extraction process was completed in 60 minutes at the water boiling temperature of approximately 100 °C and the mixtures were stirred manually. Manual stirring during the extraction period was sufficient to distribute the plant material throughout the liquid due to the high liquor ratio. Make up water was added at the end of the extraction process to restore the beginning water volume.

Application conditions of colorants and mordant ratios are given in Table 1. Aqueous solutions were mordaned with 3 % iron (III) sulfate, 5 % aluminum sulfate and 10 % grape vinegar to ensure that the extracted dyes adhered to the applied substrate (to increase retention amount), stabilize their color, and produce color alternatives.

## 2.5 Dyeing test samples
## 2.5. Bojenje uzoraka

Natural dye solutions (20 g) were mixed with water-based lacquer dye (100 g) to get top coating coloration. Then mordants were added to the mixtures for the final application of MDF test samples. In order to measure the efficiency of mordants, some coated MDF samples were prepared without adding mordant. Natural dyes and mordants mixtures were added to water-based lacquer dye and then applied to MDF test samples by air pressure spray gun. The ratios of mixture are given in Table 1. In the study, two opaque paint coating layers were applied to the test samples. One of them was the base coat and the other was the top coat. The average thickness of the base coat was 0.20 mm and the average thickness of the top coat was 0.08 mm. Between the base and the top layer coating, 220 grit sandpaper was used for surface levelling. After the primer and top coat painting application process, the samples were kept at room temperature for 24 hours to dry. For each test group, five pieces were used.

## 2.6 Natural Weathering
## 2.6. Izlaganje prirodnim vremenskim uvjetima

Outdoor weathering tests were carried out in Denizli / Turkey (28° 30' – 29° 30' E";37° 12' – 38°12' N", at 354 m above sea level) for 50 days from July 8, 2018 to August 26, 2018. Denizli weather condition data was provided from the meteorology department in Denizli. Table 2 displays the meteorological conditions during the weathering processes. In accordance with EN 927-3 (2012), the samples were put roughly 1 m above the ground, exposed to external circumstances, at 45° inclinations and facing south. Prior to the measurements, the samples were stabilized at a temperature

**Table 1** Application ratios of dyes and mordants
**Tablica 1.** Omjeri bojila i fiksatora pri nanošenju

<table>
<tr><th>Colorants / Bojila</th><th>Mordants<br>Fiksatori</th><th>Ratios, %<br>Omjeri, %</th><th>Lacquer dye, g<br>Lak, g</th><th>Natural colorant ratio, %<br>Omjer prirodnog bojila, %</th><th>Synthetic colorant ratio, %<br>Omjer sintetskog bojila, %</th><th>Repetition<br>Ponavljanje</th></tr>
<tr><td rowspan="4">Red beetroot<br>cikla (<u>Beta vulgaris</u>)</td><td>Control<br>kontrolni uzorak</td><td>0</td><td rowspan="15">100</td><td rowspan="12">20</td><td></td><td rowspan="15">5</td></tr>
<tr><td>iron (III) sulfate<br>željezov (III) sulfat</td><td>3</td><td></td></tr>
<tr><td>Aluminum sulfate<br>aluminijev sulfat</td><td>5</td><td></td></tr>
<tr><td>Vinegar / ocat</td><td>10</td><td></td></tr>
<tr><td rowspan="4">Safflower<br>šafranika (<u>Carthamus tinctorius</u> L.)</td><td>Control<br>kontrolni uzorak</td><td>0</td><td></td></tr>
<tr><td>iron (III) sulfate<br>željezov (III) sulfat</td><td>3</td><td></td></tr>
<tr><td>Aluminum sulfate<br>aluminijev sulfat</td><td>5</td><td></td></tr>
<tr><td>Vinegar / ocat</td><td>10</td><td></td></tr>
<tr><td rowspan="4">Purple cabbage<br>crveni kupus<br>(<u>Brassica oleracea</u>)</td><td>Control<br>kontrolni uzorak</td><td>0</td><td></td></tr>
<tr><td>iron (III) sulfate<br>željezov (III) sulfat</td><td>3</td><td></td></tr>
<tr><td>Aluminum sulfate<br>aluminijev sulfat</td><td>5</td><td></td></tr>
<tr><td>Vinegar / ocat</td><td>10</td><td></td></tr>
<tr><td>Synthetic colorant (black)<br>sintetsko bojilo (crno)</td><td>-</td><td>-</td><td rowspan="3"></td><td rowspan="3">20</td></tr>
<tr><td>Synthetic colorant (light blue)<br>sintetsko bojilo (svjetloplavo)</td><td>-</td><td>-</td></tr>
<tr><td>Synthetic colorant (blue)<br>sintetsko bojilo (plavo)</td><td>-</td><td>-</td></tr>
</table>

**Table 2** An overview of on-site weather conditions during exposure
**Tablica 2.** Pregled mjesnih vremenskih uvjeta tijekom izlaganja

| **Denizli / Turkey 2018** | **July** / *Srpanj* | **August** / Kolovoz |
|---|---|---|
| Average temperature, °C / *prosječna temperatura*, °C | 27.6 | 27 |
| Highest temperature, °C / *najviša temperatura*, °C | 43.9 | 44.4 |
| Lowest temperature, °C / *najniža temperatura*, °C | 12.6 | 11.6 |
| Average rainy days / *prosječan broj kišnih dana* | 2.5 | 2 |
| Average monthly total rainfall, mm<br>*prosječna mjesečna količina oborina*, mm | 13.0 | 8.4 |

of (20±2) °C and a relative humidity of 65 %. Table 2 provides an overview of the weather patterns for 50 days of weather conditions.

Following the process of natural weathering, the color variables *L**, *a**, and *b** were identified. A colorimeter was used to gauge the specimen hues both before and after weathering. According to CIELab (1986), color and gloss characteristics of the test panels were assessed using a spectrophotometer 600d (Konica Minolta, Japan). The apparatus was set up with a D65 light source and a 10° observation angle (ISO 2470, CIELab-76). The *CIEL*a*b** method was used to determine these factors, where the *L** axis denotes lightness, while the *a** and *b** axes denote chromaticity coordinates. In this method, the +*a** factors indicate red color, the -a* factors represent green color, the +*b** factors represent yellow color, and the -*b** factors represent blue color. The *L** value ranges from 0 (black) to 100 (white). Each specimen had its parameters *L**, *a**, and *b** as well as gloss measured at the start of the experiment and 50 days afterwards. For each treatment group, five duplicates were produced. Before and after natural weathering, color measurements of the test samples were made from a single point.

The following equation was used to determine the total color changes in accordance with *CIElab* (1986):

$$\Delta a^* = a_f^* - a_i^* \quad (2)$$

$$\Delta b^* = b_f^* - b_i^* \quad (3)$$

$$\Delta L^* = L_f^* - L_i^* \quad (4)$$

$$\Delta E^* = \quad (5)$$

Where Δ*a**, Δ*b**, and Δ*L** represent the changes between the initial and final interval values. Δ*E** represents the total surface color change of the tested panels.

## 2.7 Statistical analysis
## 2.7. Statistička analiza

Based on the measurements obtained, the results were examined using the statistical software SPSS. The variance analysis was carried out once the test data were uploaded to the computer. The Duncan test was performed at a 95 % statistical confidence level. The homogeneity groups (HG) of experimental data were used for the statistical analysis. The difference that can be deemed statistically significant is denoted by a different letter in HG.

# 3 RESULTS AND DISCUSSION
# 3. REZULTATI I RASPRAVA

## 3.1 Color changes
## 3.1. Promjene boje

The descriptive statistical values of the weathering performances of MDF test panels that were coated with natural dye stuffs and synthetic paints are given in Table 3.

According to Table 3, the highest total color change (Δ*E**=29.912) was observed on the MDF test panels colored by synthetic light blue paint. The lowest (Δ*E**0.388) color change was observed on the test panels colored with synthetic black paint. In terms of the layer thicknesses of the synthetic dyes applied to the test piece surfaces, the black, blue and light blue synthetic dyes thicknesses were measured as 0.10 mm, 0.09 mm and 0.06 mm, respectively. These results showed that there is a positive relationship between the layer thickness of the dye and its color stability. It has been estimated that the reason for the greater color change in synthetic light blue paint than in natural dyes is due to the diluted and reduced thin layers. The synthetic black dye has the lowest color change value as expected, because synthetic dyes contain more chemical substances that increase color resistance. The same observations were made by other researchers. Grüll *et al.* (2011, 2014) reported that, for the same coating materials, in all cases darker pigmentation and higher film thickness led to higher durability during artificial and natural weathering. When comparing the bio and synthetic colorants in general, it is seen that the color change values of the synthetic colorants are small, except for the light blue paint. It is believed that the low color change values in synthetic dyes is the consequence of protective substances already present in them.

When the color change values of the plants are compared with each other, it is seen that samples dyed with safflower, red beetroot and purple cabbage pigment have ΔE*=15.58, 3.71 and 3.08, respectively. Exposure to the harsh conditions of the external environment has also been a major reason for the color change observed in the case of natural colorants in this study. The high color changes obtained from these plant-based bio-colorants compared to synthetic colorants can be seen as a

**Table 3** Color changes of MDF panels exposed to a 50-day outdoor weathering
**Tablica 3.** Promjene boje MDF ploča izloženih 50 dana vanjskim vremenskim uvjetima

| **Colorants** *Bojila* | **Mordants** *Fiksatori* | **Before weathering test** *Prije izlaganja vremenskim uvjetima* | | | **After 50 days of natural weathering test** *Nakon 50 dana izlaganja prirodnim vremenskim uvjetima* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ***L**** | ***a**** | ***b**** | **Δ*L**** | **Δ*a**** | **Δ*b**** | **Δ*E**** | ***SD*** | *P* (*p*<**0.05)** |
| Safflower[c] *šafranika*[c] | C[c] | 89.8 | -2.4 | 20 | 4.0 | 2.8 | -16.7 | 17.402 [j] | 0.55 | |
| | IS[a] | 84.7 | -0.6 | 14 | 7.54 | 0.7 | -8.5 | 11.406 [h] | 0.53 | |
| | AS[b] | 90.8 | -2.6 | 19.3 | 3.46 | 1.7 | -16.3 | 16.792 [ıj] | 0.25 | |
| | V[b] | 90.9 | -2.9 | 19 | 304 | 1.9 | -16.4 | 16.754 [ıj] | 0.41 | |
| Purple cabbage[b] *cikla*[b] | C[a] | 91.9 | -1.0 | 3.1 | 1.7 | 0.4 | -0.8 | 1.886 [b] | 0.24 | |
| | IS[d] | 88.0 | -1.5 | 2.1 | 4.4 | 1.8 | 2.6 | 5.388 [g] | 0.17 | |
| | AS[c] | 91.3 | -1.0 | 2.5 | 2.8 | 0.2 | -0.1 | 2.800 [cd] | 0.20 | |
| | V[b] | 91.2 | -0.9 | 2.9 | 2.0 | 0.1 | -1.0 | 2.268 [c] | 0.12 | |
| Red beetroot[b] *crveni kupus*[b] | C[b] | 92.0 | -0.3 | 5.9 | 1.36 | -0.6 | -3.2 | 3.700 [e] | 0.24 | * |
| | IS[a] | 87.8 | 0.3 | 7.1 | 1.84 | 0.9 | 1.6 | 2.690 [cd] | 0.14 | |
| | AS[c] | 91.5 | -0.3 | 6.7 | 1.6 | -0.5 | -.36 | 3.954 [e] | 0.21 | |
| | V[d] | 91.9 | -0.6 | 6.8 | 1.86 | -0.2 | -4.0 | 4.502 [f] | 0.66 | |
| SP (black)[a] *SP (crno)*[a] | - | 23.7 | -0.8 | 0 | 0 | 0.2 | 0.3 | 0.388 [a] | 0.14 | |
| SP (light blue)[d] *SP (svjetloplavo)*[d] | - | 53.5 | 0.8 | -17.4 | 26.4 | -2.1 | 13.9 | 29.912 [k] | 0.62 | |
| SP (blue)[a] *SP (plavo)*[a] | - | 84.0 | -1.5 | 0.7 | 0.1 | 0.5 | -0.4 | 0.724[a] | 0.33 | |

C – Control (without mordant), IS – Iron (III) sulfate, As – Aluminum sulfate, V – Vinegar, SP – Synthetic Paint; [a,b,c,d, e] values having the same letter are not significantly different and vice versa (for Tukey test); *SD* – Standard deviation; *Significance level of 0.05 (for ANOVA)
*C – kontrolni uzorak (bez fiksatora), IS – željezov (III) sulfat, As – aluminijev sulfat, V – ocat, SP – sintetsko bojilo;* [a,b,c,d, e] *vrijednosti koje imaju isto slovo nisu značajno različite, i obrnuto (Tukey test); SD – standardna devijacija; * razina značajnosti od 0,05 (ANOVA)*

negative phenomenon. However, a lower color change can be expected if these bio-colorants are primarily used in interior furniture and wood-based products.

The highest color change observed for safflower dyes is in line with literature data. This feature is linked to the chromophore Carthamin's weak light fastness and great susceptibility to pH and oxygen (Obara and Onodera, 1979), which causes complete deterioration of historical fabrics.

Beetroot is reported to be a source of natural colorants but its color stability can be an obstacle for industry use. Betacyanins, like other naturally occurring plant pigments, have low stability, low tinctorial, and are prone to color fading during processing and storage, which restricts their development and use (Nistor *et al*., 2017). The presence of betalains, one of the natural color pigments, and anthocyanins in beetroot can be used to explain the discoloration (Saenz *et al*., 2012). It was also underlined that there are several sorts of processes in which betalains might degrade. Isomerization, deglycosylation, hydrolysis, decarboxylation, and dehydrogenation reactions are some of these processes. Different chromatic and structural alterations in betalains result from each reaction (Herbach *et al*., 2006). It has been noted that light, oxygen, water activity, pH, and temperature have a significant impact on the stability of betalains. Betalains degraded more rapidly than anticipated when temperature and time increased (Güneser, 2016). According to Delgado *et al*. (2000), the concentration of pigments, pH and water activity, oxygen, light, metallic ions, enzymes, temperature, and the duration and circumstances of processing and storage are the main variables determining the durability of natural colorants in foods. Using the beetroot plant as a natural colorant in outdoor furniture and wood-based products can bring disadvantages in terms of color change. However, it is expected that this colorant can be used with less color change for interior products.

Considering the color change of mordants, the color changes are developed from the highest to the lowest in aluminum sulfate, vinegar, control (without mordant) and iron sulfate, respectively. However, except for iron (III) sulfate, the other three mordant options were in the same homogeneity group. This result shows that mordants are not necessary to provide color stability, except for color options, which is an advantage. There are studies in the literature about coloring wood material with natural dyes that were mixed with metal mordants (Goktas *et al*., 2009a, Goktas *et al*., 2009b, Yeniocak *et al*., 2017). They used iron (III) sulfate and aluminum sulfate as metal and vinegar as natural mordant. No negative effects of metal mordants on color change were observed in the above studies. The fact that the negative effects of metal mordants on color change were not observed in those studies are in line with this study. The fact that mordants do not have negative effects on color change is an advantage as this provides more color combinations.

# 4 CONCLUSIONS
# 4. ZAKLJUČAK

This paper investigated the usability of natural plants as colorants that are eco-friendly products for furniture industry in the lacquer coating of MDF and their color stability resistance in outdoor weather conditions. The weathering performance of MDF test panels coated with natural dye stuffs and synthetic dyes was examined so that the panels were exposed to a 50-day outdoor weathering and then the color factors, $L^*$, $a^*$, $b^*$ and $\Delta E^*$ were determined.

The highest color change ($\Delta E^*$=29.91) was observed on the MDF test panels colored by synthetic light blue paint. The lowest color change ($\Delta E^*$=0.38) was observed on the test panels colored with synthetic black paint. In this case, there is a positive relationship between the layer thickness of the paint and its color stability. In other words, the increase in the layer thickness also contributes to the increase in the color change resistance.

The color change in mordants is arranged from the highest to the lowest as aluminum sulfate, vinegar, control (without mordant) and iron sulfate, respectively. However, except for iron (III) sulfate, the other three mordant options were in the same homogeneity group. This result showed mordants are not necessary in terms of color stability, except for color options, which is quite an advantage.

To conclude, this paper suggests that the use of sustainable and environmentally friendly products in the furniture industry may decrease the load in one of the major pollution discharge issues. The main problem here is that synthetic dyes contain compounds that are harmful to the environment and human health. The aim of this study was to use natural colorants instead of synthetic colorants, which are harmful to both human beings and the environment. VOCs cannot be completely avoided because the basic coating material used is still a synthetic material. However, only substances harmful to the environment and human health, brought into living environments by means of synthetic colorants, have been eliminated. In other words, by using natural dyes as an alternative in the coloring process in furniture industry, only the hazardous chemicals that originate from synthetic colorants can be eliminated. In this sense, the development of colorants and coatings that are completely free of harmful chemicals should be the target of future studies for the furniture industry.

**Acknowledgements** – Zahvala

This investigation was funded by Mugla Sitki Kocman University's Scientific Research Unit under project number 17/113. Some of the data was taken from Yasar Tahsin Bozkaya's master's thesis, for which he was awarded a master's degree from the Mugla Sitki Kocman University Institute of Science.

# 5 REFERENCES
# 5. LITERATURA

1. Ahmadiani, N.; Robbins, R. J.; Collins, T. M.; Giusti, M. M., 2014: Anthocyanins contents, profiles, and color characteristics of red cabbage extracts from different cultivars and maturity stages. Journal of Agricultural and Food Chemistry, 62 (30): 7524-7531. https://doi.org/10.1021/jf501991q
2. Bechtold, T.; Ali, A. M.; Mussak, R., 2007: Natural dyes for textile dyeing: A comparison of methods to assess the quality of Canadian golden rod plant material. Dyes and Pigments, 75 (2): 287-293. https://doi.org/10.1016/j.dyepig.2006.06.004
3. Cardon, D., 2010: Natural dyes, our global heritage of colors (online). In: Proceedings of 12th Biennial Symposium, 6-9 October, Lincoln Nebraska, https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1011&context=tsaconf (Accessed Jun. 11, 2021).
4. Chaitanya, L. G., 2014: Food coloring: the natural way. Research Journal of Chemical Sciences, 4 (2): 87-96.
5. Delgado-Vargas, F.; Jimenez, A. R.; Pardes-Lopez, O., 2000: Natural pigments: carotenoids, anthocyanins and betalains-characteristics, biosynthesis, processing and stability. Critical Reviews in Food Science and Nutrition, 40: 173-289. https://doi.org/10.1080/10408690091189257
6. Goktas, O.; Baysal, E.; Ozen, E.; Mammadov, R.; Duru, E. M., 2008: Decay resistance and color stability of wood treated with juglans regia extract. Wood Research, 53 (3): 27-36.
7. Goktas, O.; Ozen, E.; Baysal, E.; Mammadov, R.; Alma, M. H.; Sonmez, A., 2009a: Color stability of wood treated with madder root (*Rubia tinctorium* L.) extract after lightfastness test. Wood Research, 54 (1): 37-44.
8. Goktas, O.; Ozen, E.; Duru, M. E.; Mammadov, R., 2009b: Determination of the color stability of an environmentally-friendly wood stain derived from oleander (*Nerium Oleander* L.) leave extracts under UV exposure. Wood Research, 54 (2): 63-72.
9. Goktas, O.; Yeniocak, M.; Uğurlu, M.; Ozen, E.; Colak, M.; Yeniocak, S., 2015: Investigation of leaching performance of wood materials colored with walnut husk. CBU Journal of Science, 11 (3): 391-400.
10. Grüll, G.; Truskaller, M.; Podgorski, L.; Georges, V.; Bollmus, S.; Jermer, J., 2011: Woodexter Work Package 3 interaction of wood and coatings effect on the performance of wood products report on natural weathering trials. Holzforschung Austria, Vienna (HFA-Report No. FFG 443).
11. Grüll, G.; Tscherne, F.; Spitaler, I.; Forsthuber, B., 2014: Comparison of wood coating durability in natural weathering and artificial weathering using fluorescent UV-lamps and water. European Journal of Wood and Wood Products, 72 (3): 367-376. https://doi.org/10.1007/s00107-014-0791-y
12. Güneser, O., 2016: Pigment and color stability of beetroot betalains in cow milk during thermal treatment. Food chemistry. 196: 220-227. https://doi.org/10.1016/j.foodchem.2015.09.033
13. Herbach, K. M.; Florian, C. S.; Reinhold, C., 2006: Betalain stability and degradation – structural and chromatic aspects. Journal of Food Science, 71 (4): 41-R50.
14. Karadağ, R., 2007: Türk Halı Kilim ve Kumaşlarında Kullanılan Doğal Boyarmaddeler. Arış Dergisi, (2): 38-51.

15. Nistor, O.; Seremet (Ceclu), L.; Andronoiu, D. G.; Rudi, L.; Botez, E., 2017: Influence of different drying methods on the physicochemical properties of red beetroot (*Beta vulgaris* L. var. Cylindra). Food Chemistry, 236: 59-67. https://doi.org/10.1016/j.foodchem.2017.04.129
16. Obara, H.; Onodera, J. I., 1979: Structure of Carthamine. Chemistry Letters, 8: 201-204.
17. Ozen, E.; Yeniocak, M.; Colak, M.; Goktas, O.; Koca, I., 2014: Colorability of wood material with Punica granatum and *Morus nigra* Extracts. BioResources, 9 (2): 2797-2807.
18. Peker, H.; Atilgan, A.; Ulusoy, H.; Goktas, O., 2013: Usage opportunities of the natural dye extracted from acorn (*Quercus ithaburensis* Decaisne) in the furniture industry upper surface treatment. International Journal of Physical Sciences, 7(40): 5552-5558. https://doi.org/10.5897/IJPS12.479
19. Saenz, C.; Cancino, B.; Robert, P., 2012: Red betalains from *Opuntia* spp.: Natural colorants with potential applications in foods. Israel Journal of Plant Sciences, 60: 291-299.
20. Salthammer, T.; Bednarek, M.; Fuhrmann, F.; Funaki, R.; Tanabe, S. I., 2002: Formation of organic indoor air pollutants by UV-curing chemistry. Journal of Photochemistry and Photobiology A: Chemistry, 152: 1-9. https://doi.org/10.1016/S1010-6030(02)00212-5
21. Salthammer, T.; Schwarz, A.; Fuhrmann, F., 1998: Emission of reactive compounds and secondary products from wood-based furniture coatings. Atmospheric Environment, 33: 75-84. https://doi.org/10.1016/S1352-2310(98)00128-9
22. Singh, P.; Chauhan, S. R., 2016: Carbonyl and aromatic hydrocarbon emissions from diesel engine exhaust using different feedstock: a review. Renewable and Sustainable Energy Reviews, 63: 269-291. https://doi.org/10.1016/j.rser.2016.05.069
23. Tong, R. P.; Zhang, L.; Yang, X. Y.; Liu, J. F.; Zhou, P. N.; Li, J. F., 2019: Emission characteristics and probabilistic health risk of volatile organic compounds from solvents in wooden furniture manufacturing. Journal of Cleaner Production, 208: 1096-1108. https://doi.org/10.1016/j.jclepro.2018.10.195
24. Uçgun, I.; Ozdemir, N.; Metintas, M.; Metintas, S.; Erginel, S.; Kolsuz, M., 1998: Prevalence of occupational asthma among automobile and furniture painters in the center of Eskişehir (Turkey): the effects of atopy and smoking habits on occupational asthma. Allergy, 53(11): 1096-1100. https://doi.org/10.1111/j.1398-9995.1998.tb03822.x
25. Velho, S. R.; Brum, L. F.; Petter, C. O.; dos Santos, J. H. Z.; Šimunić, Š.; Kappa, W. H., 2017: Development of structured natural dyes for use into plastics. Dyes and Pigments, 136: 248-254. https://doi.org/10.1016/j.dyepig.2016.08.021
26. Wolfe, L., 2021: Is it safe to paint or be around paint fumes during pregnancy? (online). www.babycenter.com (Accessed Jun. 11, 2021).
27. Yeniocak, M.; Goktas, O.; Aliyazicioglu, S.; Colak, M.; Yeniocak, S.; Ozen, E.; Ugurlu, M., 2017: Determination of the effect of liquid glass ($SiO_2$) on color stability of wood stained by natural dyes. Drvna industrija, 68 (4): 351-357.
28. Yeniocak, M.; Goktas, O.; Colak, M.; Ozen, E.; Ugurlu, M., 2015: Natural coloration of wood material by red beetroot (*Beta vulgaris*) and determination color stability under UV exposure. Maderas: Ciencia y Tecnologia, 17 (4): 711-722.
29. Zhu, T.; Sheng, J.; Chen, J.; Ren, K.; Wu, Z.; Wu, H.; Lin, J., 2021: Staining of wood veneers with anti-UV property using the natural dye extracted from *Dalbergia cohinchinensis*. Journal of Cleaner Production, 284: 124770. https://doi.org/10.1016/j.jclepro.2020.124770
30. ***CIE (Commission Internationale de l'Eclairage), 1986: Colorimetry. 2nd ed., Publication CIE No. 15.2. Commission Internationale de l'Eclairage, Vienna.
31. ***Dalsan (online), www.dalsan.com.tr (Accessed Jun. 11, 2021).
32. ***EN 927-3, 2012: Paints and varnishes – coating materials and coating systems for exterior wood. Part 3: Natural weathering test.
33. ***ISO 2470, 2008: Measurement of diffuse blue reflectance factor. Part 2: Outdoor daylight conditions (D65 Brightness).
34. ***WHO, 1987: Air Quality Guidelines for Europe. WHO Regional Publications, European Series, No. 23, WHO Regional Office for Europe, Copenhagen.

**Corresponding address:**

**Assoc. Prof. MEHMET YENİOCAK**
Mugla Sitki Kocman University, Faculty of Technology, Department of Woodworking Industrial Engineering, Mugla, TURKEY, e-mail: myeniocak@mu.edu.tr

Çağlar Altay[1]

# Weathering Performance of Oriental Beech (*Fagus orientalis* L.) Wood Impregnated with Glycerol and Glyoxal

# Posljedice izlaganja vremenskim utjecajima drva kavkaske bukve (*Fagus orientalis L.*) impregnirane glicerolom i glioksalom

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 25. 7. 2022.
Accepted – prihvaćeno: 23. 11. 2022.
UDK: 630*84; 674.048;
https://doi.org/10.5552/drvind.2023.0054



**ABSTRACT** • *This study aimed to improve some surface properties such as color, gloss, and surface roughness changes of Oriental beech (Fagus orientalis L.) wood impregnated with some water repellent chemicals such as glycerol (GR) and glyoxal (GX) after weathering. Oriental beech wood specimens were impregnated with a 4 % aqueous solution of GR, GX, and a mixture of GR and GX (1:1; weight : weight) (GR+GX) and then exposed to weathering in Muğla Province in Turkey. Results showed that ΔL* values of all wood specimens were decreased after weathering. Moreover, the decreases in the control specimen were higher than in the impregnated wood specimens. Oriental beech wood specimens showed a greenish and yellowish tendency, giving -Δa* and +Δb* values, respectively. Total color changes of GR impregnated Oriental beech was the lowest after weathering. The gloss of all Oriental beech test specimens decreased after weathering. The control specimen gave the lowest value in all three surface roughness parameters ($R_a$, $R_z$ and $R_q$) after weathering. Among the impregnated specimens, the groups impregnated with GR had, in general, the highest value in all three roughness degrees and showed the most negative results in surface roughness.*

**KEYWORDS:** *glycerol, glyoxal, oriental beech, surface properties, impregnation*

**SAŽETAK** • *Cilj ovog istraživanja bilo je poboljšanje nekih svojstava, npr. promjene boje, sjaja i hrapavosti površine drva kavkaske bukve (Fagus orientalis L.) impregnirane vodoodbojnim kemikalija kao što su glicerol (GR) i glioksal (GX) nakon izlaganja vremenskim utjecajima. Uzorci drva kavkaske bukve impregnirani su 4 %-tnom vodenom otopinom glicerola, glioksala i mješavine glicerola i glioksala (1 : 1; v : v) (GR + GX) te su zatim izloženi vremenskim uvjetima u provinciji Muğla u Turskoj. Rezultati su pokazali da su vrijednosti ΔL* svojstava svih uzoraka drva nakon izlaganja vremenskim uvjetima smanjene. Nadalje, smanjenje tih vrijednosti na kontrolnim je uzorcima bilo veće nego na impregniranima. Uzorci drva kavkaske bukve pokazali su tendenciju povećanja zelenoga (-Δa*) i žutog tona (+Δb*). Nakon izlaganja vremenskim utjecajima ukupne promjene boje ispitivanog drva kavkaske bukve impregniranoga glicerolom bile su najmanje. Sjaj svih uzoraka ispitivanog drva smanjio se nakon izlaganja vremenskim utjecajima. Pri izlaganju vremenskim uvjetima i nakon toga kontrolni je uzorak imao najmanju hrapavost površine za sva tri parametra hrapavosti (Ra, Rz i Rq). Od impregniranih uzoraka najveće*

[1] Author is researcher at Aydın Adnan Menderes University, Aydın Vocational School, Department of Interior Design, Aydın, Turkey. https://orcid.org/0000-0003-1286-8600

*vrijednosti svih triju parametara hrapavosti imali su uzorci impregnirani glicerolom, koji su pokazali i najlošije rezultate hrapavosti površine.*

**KLJUČNE RIJEČI:** *glicerol, glioksal, drvo kavkaske bukve, svojstva površine, impregnacija*

## 1 INTRODUCTION
## 1. UVOD

Many elements add value to wood, which is a renewable resource. Wood is environmentally friendly, widely available, has low energy consumption during preparation, good heat and sound insulation, superior weight/resistance ratio compared to other building materials (Tomak, 2011). As a result of all these features, wooden material has found thousands of uses from past to present (Bozkurt and Göker, 1996). Although wood material has all these positive features, it also has some undesirable negative features. For wood material, outdoor conditions are one of these negative features; in other words, «weathering» is seen as an important risk factor. Weathering is defined as the color change, surface roughness, and cracks that occur on the surface with the effect of sunlight (UV), humidity (rain and snow), and temperature. As a result of these effects, some changes occur in the color, chemical, and physical structure of the wood material (Feist and Hon, 1984; Williams, 2005; Kılıç and Hafızoğlu, 2009). Since untreated wood material does not have a resistant structure against weathering, wood impregnation is highly recommended. Although wood species with high biological durability remain intact for many years at the place of use, tree species with low biological durability must be impregnated to increase their lifetime (Kartal and Imamura, 2004). The negative properties of wood material can be reduced with some protective measures and impregnation techniques. The wood material can become resistant to these effects to some extent with precautions that can be taken without the use of chemicals, but if the risk factors are severe and continuous, chemical measures are needed (Kartal and Imamura, 2004).

Chemicals containing toxic biocides such as arsenic and chromium in their compositions have negative effects on the environment at the point of disposal of wood materials that have completed their useful life, as well as their toxicity during the life of wood, and this causes environmental pressures (Gezer, 2003; Humar *et al.,* 2005). The use of arsenic-containing CCA wood material and its re-use while at rest have been limited since 2003 by the Waste Management and Regulatory Authority (PMRA) in Canada and the Environmental Protection Organization (EPA) in the United States, and this decision has been made by the European Union Countries and Western European Wood Protection Agency. It has also been accepted by the Institute (WEI-IEO) (Gezer, 2003; Tomak, 2011). According to the studies of the Forest Products Laboratory (FPL) in the U.S. state of Wisconsin, based on average 30-year service life, approximately 6 million $m^3$ of impregnated solid wood is involved in the solid waste cycle (Humar *et al.,* 2005). The evaluation or disposal of such a large amount of impregnated wood material that has completed its service life requires serious and costly studies (Felton and De Groot, 1996). Considering all these problems and increasing environmental concerns in recent decades, the use of impregnation materials that have toxic effects on the environment, humans, and all living things has been limited and the wood protection industry has been compelled to develop new and environmentally friendly alternatives of impregnation methods (Kartal and Imamura, 2004). Newly developed impregnation agents include boron compounds, alkyl ammonium compounds (quats), and copper-based systems. In addition, there are isothiazolinone, chlorothalonil, thiazole, carbamate, triazole, copper naphthenate, and oxine copper and water repellent substances among the oily impregnation substances (Kartal and Imamura, 2004).

Water repellents are intended to control or prevent the water uptake of wood. By creating a water-repellent barrier in the wood, the water uptake rate can be significantly reduced. Depending on the materials used and their amounts, water-repellent substances fill the cell spaces and are stored on the outer surfaces and partially on the inner surfaces. Thus, the wood surface shows hydrophobic properties, and the water uptake rate is reduced (Koski, 2008). Specimens impregnated with water-repellent substances, when exposed to water, swell over time like untreated wood. However, the swelling time is 5-6 times longer than that of normal wood (Yıldız, 1988). Although water repellants do not completely reduce water absorption, they are one of the most effective materials for using wood in outdoor conditions. Water-repellent substances protect the wood against fungi and discoloration by reducing the amount of moisture needed for the growth of fungi and microorganisms in the wood (Williams and Feist, 1999). Temiz *et al.,* (2007) determined that the impregnation of wood surfaces with linseed and tall oil reduced the color change caused by external weather conditions and the leaching of lignin with rainwater. Hansmann *et al.,* (2006) stated that wood impregnated with different melamine-formaldehyde resins after accelerated weathering showed a more positive effect in terms of color stability compared to the control specimen. In this study, glycerol and glyoxal were preferred as water repellents. The chemical company Sigma Aldrich supplied the glycerol (GR; 99.5%) and glyoxal (GX; 40 wt% in $H_2O$) used as chemicals to resist water. A substance called glycerol (GR) has three functional groups that can interact with carboxylic acids to generate ester linkages. The dialdehyde glyoxal (GX), which has two aldehyde groups, is extremely reactive. Glyoxal is one of the intriguing dialdehydes as a crosslinking agent for wood in relation to the issue of formaldehyde release (Nakano, 1993).Glycerol finds use in a wide range of areas, depending on the purity of the glycerine produced by the breakdown of triglycerides. It can also be used as a paint and resin additive and antifreeze raw material. It is a sugar alcohol, and the hydrophilic alcoholic hydroxyl groups it contains allow it to dissolve easily in water. It has a high boiling point. It is used as a consistency and viscosity regulator, brightener, moisture retainer in industry and is one of the main inputs in many industrial chemicals. In addition, it has anti-freeze properties (Beser Kimya, 2022). On the other hand, Glyoxal is a linear aliphatic dialdehyde containing two aldehyde groups, and it participates in the synthesis of glyoxylic acid. It can be prepared by oxidizing ethanol or acetaldehyde with nitric acid. It is very commonly used in textile and paper production (Merck, 2022).

This study investigated the changes in color, gloss, and surface roughness that occur as a result of exposure of Oriental beech test specimens impregnated with glycerol and glyoxal to natural-weathering conditions for 1 month. Furthermore, glycerol and glyoxal are impregnating agents that reduce the expansion of wood. Therefore, the aim of this study is to determine various surface performance properties of wood treated with these impregnation materials in weathering conditions.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Materials
### 2.1. Materijali

In this study, Oriental beech (Fagus orientalis L.) was used as wood material, and glycerol and glyoxal were used as impregnation materials.

#### 2.1.1 Preparation of test specimens
#### 2.1.1. Priprema ispitnih uzoraka

Oriental beech wood (*Fagus orientalis* L.) specimens measuring 10 mm (radial) × by 100 mm (tangential) × 150 mm (longitudinal) were made from air-dried wood. Before the experiments, wood specimens were maintained for two weeks at 20 °C and 65 % relative humidity. A total of 40 wooden specimens were prepared, 10 of which were from control and impregnated specimens. The average density of oriental beech wood used in the study is 0.59 g/cm$^3$. In addition, there is no significant difference within the whole annual ring in terms of the size and distribution of the trachea in the wood material used in the study. So the annual ring boundaries are not very clear.

### 2.2 Methods
### 2.2. Metode

#### 2.2.1 Impregnation procedure
#### 2.2.1. Postupak impregnacije

The Oriental beech (*Fagus orientalis* L.) wood specimens were impregnated with a 4 % aqueous solution of GR, GX, and a combination of GR and GX (1:1; weight: weight). Oriental beech wood was impregnated in accordance with ASTM D 1413-07el (2007). A total of 30 specimens were impregnated with each aqueous solution. Test specimens were allowed to diffuse in the solution at room temperature for 30 minutes after a pre-vacuum of 760 mm Hg was applied for 30 minutes in accordance with the impregnation method. The following equation was used to compute the retention value of the impregnated Oriental beech:

$$R = \frac{G \cdot C}{V} \cdot 10^3 \text{ (kg/m}^3\text{)} \quad (1)$$

Where;

$G$ – mass of impregnating solution absorbed by wood specimen (g)

Where;

$G$ – $T_2$ -$T_1$

$T_2$ – Wood mass after impregnation (g)

$T_1$ – Wood mass before impregnation (g)

$V$ – Wood volume (cm$^3$)

$C$ – Solution concentration (%)

#### 2.2.2 Color test
#### 2.2.2. Mjerenje boje

The *CIEL*a*b** technique was used to calculate the color parameters $L^*$, $a^*$, and $b^*$. Additionally, an X-Rite SP Series Spectrophotometer was used to measure the color parameters $a^*$, $b^*$, and $L^*$. The measuring spot was adjusted to be equal or not more than one-third of the distance from the center of this area to the receptor field stops. While $a^*$ and $b^*$ are the chromaticity coordinates, the $L^*$ axis controls brightness. Red and green are displayed by the values $+a^*$ and $-a^*$, respectively. Blue is represented by the $-b^*$ parameter, while yellow is represented by the $+b^*$ value. The $L^*$ value ranges from zero (black) to 100 (white) (Zhang, 2003). The color difference, ($\Delta E^*$) was determined for each wood according to ASTM D1536-58T (1964). Color measurements were made parallel to the fibers. Three measurements were taken for each specimen from 3 different points. Equations 2, 3, 4, and 5 were used to determine the changing of colors.

$$\Delta a^* = a_f^* - a_i^* \quad (2)$$

$$\Delta b^* = b_f^* - b_i^* \quad (3)$$

$$\Delta L^* = L_f^* - L_i^* \quad (4)$$

$$\Delta E^* = [(\Delta a^*)^2 + (\Delta b^*)^2 + (\Delta L^*)^2]^{1/2} \quad (5)$$

Where;

$\Delta a^*$, $\Delta b^*$, and $\Delta L^*$ represent the changes between the initial and final interval values. Ten replicates were made for each treatment group.

### 2.2.3 Gloss test
### 2.2.3. Mjerenje sjaja

A measuring tool was used to determine the gloss values of Oriental beech in accordance with ASTM D523-14 (2018). (Micro-TRI-Gloss). Incidence angle of 85 degrees was the selected geometry. Each treatment group received ten replications. Gloss measurements were made parallel to the fibers. A total of 3 measurements were made from 3 different points for each specimen.

### 2.2.4 Surface roughness
### 2.2.4. Hrapavost površine

Roughness was tested using the Mitutoyo Surftest SJ-301 device in line with DIN 4768 (1990) specifications. The three roughness measures are the mean arithmetic deviation of the profile (*Ra*), mean peak-to-valley height (*Rz*), and root mean square (*Rq*). The average distance between the profile and the mean line over the period of the evaluation is known as the $R_a$. The parameter *Rz* can be derived from the five equal lengths of the peak-to-valley values of the profile, and *Rq* is the square root of the arithmetic mean of the squares of the profile deviations from the mean line (Mummery, 1993). Using a stylus with a diamond tip that had a 5 µm radius and a 90° conical angle, the surface roughness profile was examined. The stylus feed rate was 0.5 mm/s[1] throughout an 8 mm specimen length (Zhong *et al*., 2013). For each treatment group, ten replications were made. Surface roughness measurements were made parallel to the fibers. A total of 3 measurements were made from 3 different points for each specimen.

### 2.2.5 Natural weathering test
### 2.2.5. Izlaganje vremenskim uvjetima

10 wood specimens were grouped together in each group. The specimens were exposed to the weathering conditions of Muğla province in December 2021. Table 1 shows the meteorological data of Muğla province in December 2021 (State Meteorological Services Database, 2021). In accordance with ASTM D 358-55 (1970), wood panels were also prepared for exposure to the elements.

### 2.2.6 Statistical analysis
### 2.2.6. Statistička analiza

As a result of the measures, test results were acquired and then examined using the statistical program SPSS. The computer was used to upload the test results and run a variance analysis. At a 95 % statistical level of confidence, the Duncan test was used. The experimental data homogeneity groups (HG) were used for statistical analysis. Statistically significant differences are denoted by different letters in HG (Günbekler *et al*., 2021; Baysal *et al*., 2021; Türkoğlu *et al*., 2020).

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

### 3.1 Color changes
### 3.1. Promjene boje

Color changes values of Oriental beech wood specimens impregnated with GR, GX, and GR+GX are given in Table 2.

Before weathering, the $L^*$ value of the control specimen was found to be 64.42. In the impregnated specimens, the highest $L^*$ value was obtained at 63.63 in the Oriental beech test specimens impregnated with GR+GX, while the lowest $L^*$ value was determined in the Oriental beech test specimens impregnated with GX at 61.60. The $L^*$ values of the impregnated specimens decreased compared to the control specimen. Before weathering, the Oriental beech test specimens showed a tendency to turn reddish and yellowish, giving $+a^*$ and $+b^*$ values, respectively. After natural weathering, the $\Delta L^*$ values of the control and impregnated Oriental beech test specimens decreased. While the maximum reduction was obtained in the control specimens (-3.87), the least decrease was detected in the specimens impregnated with GR+GX. Negative values in $\Delta L^*$ are an indication of depolymerization of lignin in wood (Temiz *et al.,* 2003). Wood specimens become darker due to the decrease in $L^*$ value (Baysal

**Table 1** Weather conditions of Muğla for December 2021
**Tablica 1.** Vremenski uvjeti u provinciji Muğla za prosinac 2021.

| **Weather conditions** / *Vremenski uvjeti* | **December** / *Prosinac* |
|---|---|
| Average temperature, °C / *prosječna temperatura,* °C | 6.7 |
| Maximum temperature, °C / *najviša temperatura,* °C | 16.4 |
| Minimum temperature, °C / *najniža temperatura,* °C | -4.4 |
| Number of rainy days per month / *broj kišnih dana po mjesecu* | 21 |
| Rainfall per month, kg/m$^2$ / *količina padalina po mjesecu,* kg/m$^2$ | 368.7 |
| Average humidity per month, % / *prosječna vlažnost zraka po mjesecu,* % | 87.7 |

**Table 2** Color change values of test specimens after natural weathering
**Tablica 2.** Vrijednosti promjene boje ispitnih uzoraka nakon prirodnog izlaganja vremenskim uvjetima

| **Specimens** *Uzorci* | **Retention, kg/m³** *Retencija, kg/m³* | **Color values before natural weathering** *Vrijednosti boje prije prirodnog izlaganja vremenskim uvjetima* | | | | | | **Color changes values after natural weathering** *Vrijednosti promjene boje nakon prirodnog izlaganja vremenskim uvjetima* | | | **Total color changes** *Ukupna promjena boje* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *L** | | *a** | | *b** | | | | | | |
| | | **Mean** *Srednja vrijednost* | **Standard deviation** *Standardna devijacija* | **Mean** *Srednja vrijednost* | **Standard deviation** *Standardna devijacija* | **Mean** *Srednja vrijednost* | **Standard deviation** *Standardna devijacija* | $\Delta L^*$ | $\Delta a^*$ | $\Delta b^*$ | $\Delta E^*$ | **Homogeneity group** *Homogene grupe* |
| Control *kontrolni uzorak* | - | 64.42 | 9.66 | 10.97 | 1.64 | 10.83 | 3.13 | -3.87 | -1.48 | 11.85 | 12.55 | A |
| GR | 15.38 | 63.27 | 9.49 | 11.22 | 1.68 | 11.75 | 3.20 | -2.30 | -1.99 | 10.98 | 11.39 | A |
| GX | 21.71 | 61.60 | 9.24 | 10.36 | 1.55 | 10.59 | 3.21 | -1.78 | -1.53 | 11.45 | 11.68 | A |
| GR+GX | 19.54 | 63.63 | 9.54 | 11.05 | 1.65 | 11.99 | 3.26 | -0.39 | -1.43 | 11.56 | 11.65 | A |

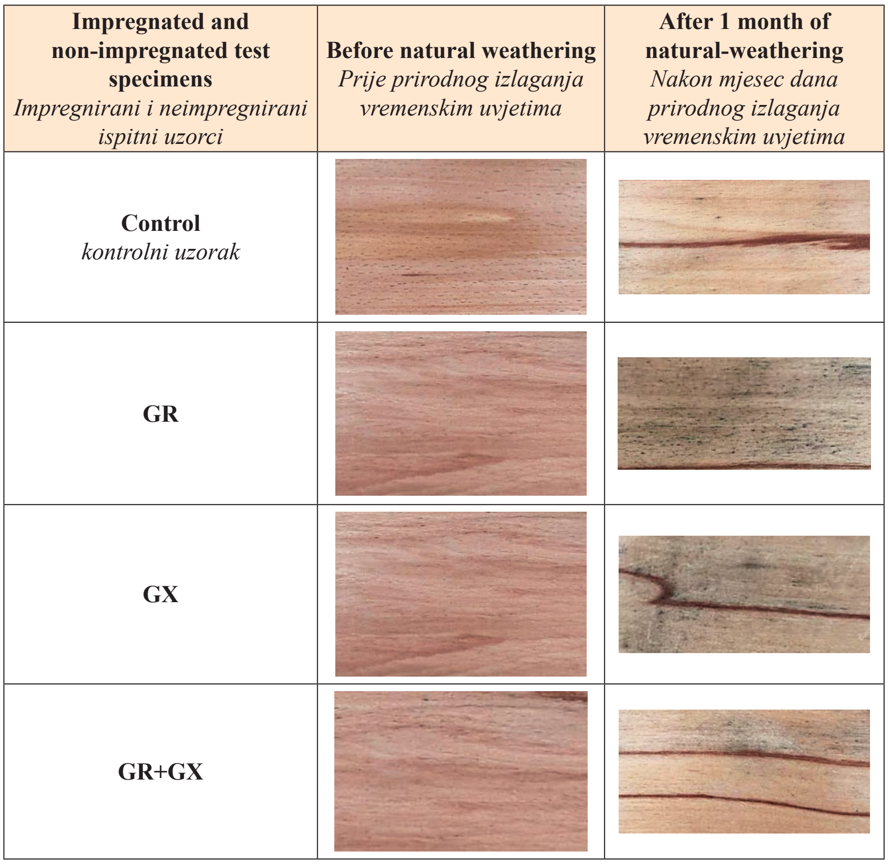



**Figure 1** Color change images of Oriental beech wood specimens impregnated with GR, GX, and GR+GX before and after 1 month of natural weathering
**Slika 1.** Fotografije promjena boje uzoraka drva kavkaske bukve impregniranih s GR, GX i GR+GX prije i nakon prirodnog izlaganja vremenskim uvjetima tijekom jednog mjeseca

*et al.,* 2014). After natural weathering, all specimens showed a greenish and yellowish tendency, giving $-\Delta a^*$ and $+\Delta b^*$ values, respectively. Changes in some chromophoric groups of lignin may be the cause of the rise in the chromaticity coordinate ($\Delta b^*$) (Grelier *et al.*, 2000). According to the results of the total color change ($\Delta E^*$), Oriental beech test specimens impregnated with GR gave the best color stability. However, there was no statistical difference between impregnated Oriental beech specimens. In our study, impregnated specimens showed less discoloration than control specimens after weathering.

Color change images of Oriental beech wood specimens impregnated with GR, GX, and GR+GX before and after natural weathering are given in Figure 1. Additionally, Figure 1 clearly shows that the Oriental beech wood surface is overgrown with mold fungi.

## 3.2 Gloss changes
## 3.2. Promjene sjaja

Values of gloss changes of Oriental beech wood specimens impregnated with GR, GX, and GR+GX are given in Table 3.

In this study, before natural weathering, the highest gloss value was obtained in the control specimens, while the lowest gloss value was obtained in the GR impregnated Oriental beech specimens. With the impregnation process before weathering, the gloss of the specimens was lower than that of the control specimens. After natural weathering, the gloss of all specimens decreased. While the maximum decrease was obtained in the control specimens with -10.49, the least decrease was obtained in the specimens impregnated with GR+GX with -6.33. The gloss reduction in the impregnated specimens was lower than in the control specimens. The deterioration of wood surfaces is caused by the sunlight UV component, temperature and relative humidity (RH) fluctuations throughout the year, air pollution, oxygen levels, and human activities (Williams, 2005). The chemical, physical, and optical properties of wood change over time, resulting in discoloration, gloss loss, and surface roughening. In addition, the three main mechanical qualities of wood are impacted (Denes and Young, 1999). Additionally, it has been suggested that poor glossiness values in impregnated specimens may be the result of the addition of impregnation materials with their chemical structures to the surface of the wood material (Soylamış, 2007). According to Özdemir *et al.* (2015), increased fibers reduce the gloss value and water-based wood treatments enhance surface porosity. In the present study, the surface gloss of the impregnated wood specimens decreased. For this reason, this study is supported by the study of Özdemir *et al.,* (2015).

## 3.3 Surface roughness changes
## 3.3. Promjene hrapavosti površine

Surface roughness changes of Oriental beech wood specimens impregnated with GR, GX, and GR+GX are given in Table 4.

In this study, before natural weathering, the highest value of *Ra* roughness was obtained in specimens impregnated with GR (6.10 µm), while the lowest value was obtained in control specimens (3.65 µm). While the highest value in *Rz* roughness was obtained in specimens impregnated with GR (34.19 µm), the lowest value was obtained in control specimens (21.88 µm). While the highest value in *Rq* roughness was obtained in the specimens impregnated with GX (7.41 µm), the lowest value was obtained in the control specimens (4.58 µm). The impregnation process before natural weathering had an effect on increasing the surface roughness of the specimens in all three roughness values (*Ra*, *Rz*, and *Rq*). Surface roughness is an important factor in determining wood surface. In addition, wood is affected by many factors (Yıldız *et al.,* 2013). The roughness of all specimens increased at *Ra*, *Rz* and *Rq* roughness values after natural weathering. While there was no statistical difference between the control specimens and the specimens impregnated with GX in *Ra* and *Rz* roughness values, a statistical difference was determined compared to the other specimens. While there was no statistical difference in *Rq* roughness value between control specimens and the specimens impregnated with GR, a statistical difference was observed compared to other specimens. Generally, after weathering, the impregnated specimens caused a rougher surface on the wood material. Rough surface wood materi-

**Table 3** Values of gloss changes of test specimens after natural weathering
**Tablica 3.** Vrijednosti promjene sjaja ispitnih uzoraka nakon prirodnog izlaganja vremenskim uvjetima

| **Specimens** *Uzorci* | **Retention, kg/m³** *Retencija,* kg/m³ | **Gloss values before natural weathering** *Vrijednosti sjaja prije prirodnog izlaganja vremenskim uvjetima* 85° | | **Gloss values after natural weathering** *Vrijednosti sjaja nakon izlaganja vremenskim uvjetima* 85° | | **Values of gloss changes after natural weathering, %** *Vrijednosti promjene sjaja nakon prirodnog izlaganja vremenskim uvjetima, %* | |
|---|---|---|---|---|---|---|---|
| | | **Mean** *Srednja vrijednost* | **Standard deviation** *Standardna devijacija* | **Mean** *Srednja vrijednost* | **Standard deviation** *Standardna devijacija* | **85°** | **Homogeneity group** *Homogene grupe* |
| Control *kontrolni uzorak* | - | 5.81 | 0.87 | 5.20 | 1.03 | -10.49 | A |
| GR | 15.38 | 1.13 | 0.16 | 1.03 | 0.21 | -8.84 | AB |
| GX | 21.71 | 1.25 | 0.18 | 1.16 | 0.31 | -7.20 | B |
| GR+GX | 19.54 | 1.42 | 0.21 | 1.33 | 0.69 | -6.33 | B |

Note: GR: Glycerol, GX: Glyoxal, Homogeneity group at 95 % confidence level
*Napomena: GR – glicerol, GX – glioksal; homogene grupe na razini pouzdanosti od 95 %*

**Table 4** Values of surface roughness change of test specimens after natural weathering
**Tablica 4.** Vrijednosti promjene hrapavosti površine ispitnih uzoraka nakon prirodnog izlaganja vremenskim uvjetima

| Specimens *Uzorci* | Retention, kg/m³ *Retencija, kg/m³* | Surface roughness values before natural weathering *Vrijednosti hrapavosti površine prije prirodnog izlaganja vremenskim uvjetima* | | | | | | Surface roughness values after natural weathering *Vrijednosti hrapavosti površine nakon prirodnog izlaganja vremenskim uvjetima* | | | | | | Surface roughness values after natural weathering, % *Vrijednosti hrapavosti površine nakon prirodnog izlaganja vremenskim uvjetima, %* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ***Ra*, µm** | | ***Rz*, µm** | | ***Rq*, µm** | | ***Ra*, µm** | | ***Rz*, µm** | | ***Rq*, µm** | | *Ra* | H.G | *Rz* | H.G | *Rq* | H.G |
| | | Mean | Std. dev. | Mean | Std. dev. | Mean | Std. dev. | Mean | Std. dev. | Mean | Std. dev. | Mean | Std. dev. | | | | | | |
| Control | - | 3.65 | 0.54 | 21.88 | 3.28 | 4.58 | 0.68 | 3.68 | 1.88 | 23.45 | 4.15 | 5.12 | 1.85 | 0.82 | A | 7.17 | A | 11.79 | B |
| GR | 15.38 | 6.10 | 0.91 | 34.19 | 5.12 | 7.14 | 1.07 | 6.87 | 1.93 | 39.79 | 3.53 | 8.24 | 2.69 | 12.62 | C | 16.37 | B | 15.40 | B |
| GX | 21.71 | 5.75 | 0.85 | 33.80 | 5.07 | 7.41 | 1.11 | 5.90 | 1.41 | 36.22 | 4.99 | 9.12 | 3.56 | 2.60 | A | 7.15 | A | 23.07 | C |
| GR + GX | 19.54 | 5.31 | 0.79 | 33.34 | 5.03 | 6.85 | 1.02 | 5.77 | 0.89 | 38.12 | 3.40 | 7.23 | 1.47 | 8.66 | B | 14.33 | B | 5.54 | A |

als require much more sanding than smooth-surfaced wood materials, which causes a decrease in the thickness of the material and thus increases the losses from sanding (Dündar *et al.,* 2008). Wood roughness, however, is a complicated issue. For the evaluation of the surface roughness of wood, a number of parameters, including its anatomical structure, machining properties, growth characteristics, and pre-treatments before machining, should be taken into account (Aydın and Çolakoğlu, 2003; Aydın and Çolakoğlu, 2005; Temiz *et al*., 2005). According to Miklei *et al.* (2017), light irradiation largely caused the middle lamella, which sits between two cell walls and binds the cells together, to deteriorate. This deterioration makes the wood surface more uneven. (Tolvaj *et al.,* 2014).

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

The surface properties such as color, gloss, and surface roughness of Oriental beech wood impregnated with GR, GX, and GR+GX mixtures were investigated after natural weathering. The $L^*$ values of all specimens decreased after natural weathering. All specimens showed a tendency to greenish and blueish, giving negative $\Delta a^*$ and positive $\Delta b^*$ values, respectively. Our results showed total color changes of impregnated Oriental beech was improved compared to the control group, but there were no statistical differences in total color changes between all test specimens and control specimens. In terms of gloss changes, impregnated Oriental beech wood specimens gave better results than the control group after natural weathering.

In conclusion, while total color changes and gloss changes of impregnated Oriental beech were lower than those of the control specimen after weathering, impregnated Oriental beech specimens gave rougher surface compared to the control specimens after natural weathering.

## 5 REFERENCES
## 5. LITERATURA


1. Aydın, I.; Çolakoğlu, G., 2003: Roughness on wood surfaces and roughness measurement methods. Artvin Coruh University Journal of Forestry Faculty, 4 (1-2): 92-102. (in Turkish).
2. Aydın, I.; Çolakoğlu, G., 2005: Effects of surface inactivation, high temperature drying and preservative treatment on surface roughness and colour of alder and beech wood. Applied Surface Science*,* 252 (2): 430-440. https://doi.org/10.1016/j.apsusc.2005.01.022
3. Baysal, E.; Toker, H.; Türkoğlu, T.; Gündüz, A.; Altay, Ç.; Küçüktüvek, M.; Peker, H., 2021: Weathering characteristics of impregnated and coated Calabrian pine wood. Maderas. Ciencia y Tecnologia*,* 2021 (23): 1-10. https://doi.org/10.4067/s0718-221x2021000100431

4. Baysal, E.; Tomak, E. D.; Özbey, M.; Altın, E., 2014: Surface properties of impregnated and varnished Scots pine wood after accelerated weathering. Coloration Technology, 130 (2): 140-146. https://doi.org/10.1111/cote.12070
5. Bozkurt, A. Y.; Göker, Y., 1996: Fiziksel ve Mekanik Ağaç Teknolojisi. İstanbul University Forestry Faculty Publishing, İstanbul, Türkiye, pp. 374 (in Turkish).
6. Denes, A. R.; Young, R. A., 1999: Reduction of weathering degradation of wood through plasmapolymer coating. Holzforschung, 53 (6): 632-640. https://doi.org/10.1515/HF.1999.104
7. Dündar, T.; As, N.; Korkut, S.; Ünsal, O., 2008: The effect of boiling time on the surface roughness of rotary-cut veneers from oriental beech (*Fagus orientalis* L.). Journal of Materials Processing Technology, 199 (1-3): 119-123. https://doi.org/10.1016/j.jmatprotec.2007.07.036
8. Feist, W. C.; Hon, D. N. S., 1984: Chemistry of weathering and protection. The Chemistry of Solid Wood, 207: 401-451.
9. Felton, C. C.; De Groot, R. C., 1996: The recycling potential of preservative-treated wood. Forest Products Journal, 46 (7,8): 37. https://www.proquest.com/openview/54dbaa6344c9737cee5137b4db724b7c/1?pq-origsite=gscholar&cbl=25222 (Accessed Nov. 04, 2022).
10. Grelier, S.; Castellan, A.; Kamdem, D. P., 2000: Photoprotection of copper amine treated wood. Wood and Fiber Science, 32 (2): 196-202.
11. Gezer, E. D., 2003: Kullanım Süresinin Tamamlamış Emprenyeli Ağaç Malzemelerin Yeniden Değerlendirilmesi Olanaklarının Araştırılması. PhD Thesis, Karadeniz Technical University, Trabzon (in Turkish).
12. Günbekler, A. Y.; Toker, H.; Altay, Ç.; Küçüktüvek, M.; Baysal, E., 2021: Increasing the physical and combustion performance of Oriental beech by impregnating borates and coating liquid glass. Polimeros-Ciencia e Tecnologia, 31 (2): 1-8. https://doi.org/10.1590/0104-1428.20210041
13. Humar, M.; Kalan, P.; Šentjurc, M.; Pohleven, F., 2005: Influence of carboxylic acids on fixation of copper in wood impregnated with copper amine based preservatives. Wood Science and Technology, 39 (8): 685-693. https://doi.org/10.1007/s00226-005-0031-z
14. Hansmann, C.; Deka, M.; Wimmer, R.; Gindl, W., 2006: Artificial weathering of wood surfaces modified by melamine formaldehyde resins. Holz als Roh-und Werkstoff, 64 (3): 198-203. https://doi.org/10.1007/s00107-005-0047-y
15. Kılıç, A.; Hafızoğlu, H., 2009: Açık hava koşullarının ağaç malzemenin kimyasal yapısında meydana getirdiği değişimler ve alınacak önlemler. Turkish Journal of Forestry, 8 (2): 175-183 (in Turkish).
16. Kartal, S. N.; Imamura, Y., 2004: Borlu bileşiklerin emprenye maddesi olarak ağaç malzeme ve kompozitlerde kullanımı. In: 3rd International Boron Symposium, September, Eskişehir, Türkiye, 333-338 (in Turkish).
17. Koski, A., 2008: Applicability of crude tall oil for wood protection. PhD Thesis, University of Oulu, Oulu, Finland.
18. Miklečić, J.; Turkulin, H.; Jirouš-Rajković, V., 2017: Weathering performance of surface of thermally modified wood finished with nanoparticles-modified waterborne polyacrylate coatings. Applied Surface Science, 408: 103-109. https://doi.org/10.1016/j.apsusc.2017.03.011
19. Mummery, L., 1993: Surface texture analysis. The handbook. Muhlhausen, Germany: Hommelwerke, pp 106 .
20. Nakano, T., 1993: Reaction of glyoxal and glyoxal/glycol with wood. Wood science and Technology, 28 (1): 23-33. https://doi.org/10.1007/BF00193873
21. Özdemir, T.; Temiz, A.; Aydin, I., 2015: Effect of wood preservatives on surface properties of coated wood. Advances in Materials Science and Engineering, 2015: 631835. https://doi.org/10.1155/2015/631835.
22. Soylamış, D., 2007: The effect of some water repellent impregnated materials on the covering surface applications. Master Thesis, Zonguldak Karaelmas University, Karabük, Türkiye (in Turkish).
23. Tomak, E. D., 2011: Masif Odundan Bor Bileşiklerinin Yıkanmasını Önlemede Yağlı Isıl İşlemin ve Emülsiyon Teknikleri ile Emprenye İşleminin Etkisi. PhD Thesis, Karadeniz Technical University, Trabzon, Türkiye (in Turkish).
24. Temiz, A.; Terziev, N.; Eikenes, M.; Hafren, J., 2007: Effect of accelerated weathering on surface chemistry of modified wood. Applied Surface Science, 253 (12): 5355-5362. https://doi.org/10.1016/j.apsusc.2006.12.005
25. Türkoğlu, T.; Baysal, E.; Altay, Ç.; Toker, H.; Küçüktüvek, M.; Gündüz, A., 2020: Investigating the surface performance of impregated and varnished Calabrian pine wood against waethering. Polimeros-Ciencia e Tecnologia, 30 (4): 1-6. https://doi.org/10.1590/0104-1428.10120
26. Temiz, A.; Eikenes, M.; Yıldız, Ü. C.; Evans, F. G.; Jacobsen, B., 2003: Accelerated weathering test for the evaluation of wood preservative efficacy. In: The Proceedings of the 34th Annual Meeting of The International Research Group on Wood Preservation, 14-18 May 2003, Australia, pp. 1-10.
27. Temiz, A.; Yıldız, U. C.; Aydın, I.; Eikenes, M.; Alfredsen, G.; Çolakoğlu, G., 2005: Surface roughness and colour characteristics of wood treated with preservatives after accelerated weathering test. Applied Surface Science, 250 (1-4): 35-42. https://doi.org/10.1016/j.apsusc.2004.12.019
28. Tolvaj, L.; Molnar, Z.; Magoss, E., 2014: Measurement of photodegradation-caused roughness of wood using a new optical method. Journal of Photochemistry and Photobiology, B: Biology, 134: 23-26. https://doi.org/10.1016/j.jphotobiol.2014.03.020
29. Williams, R. S., 2005: Weathering of wood. In: Handbook of Wood Chemistry and Wood Composites. Rowell, M. Roger (ed.). USDA, Forest Service, Forest Products Laboratory, Madison, WI, pp. 402-451.
30. Williams, R. S.; Feist, W. C., 1999: Water repellents and water repellent preservatives for wood. Department of Agriculture, Forest Service, Forest Products Laboratory, Gen. Tech. Rep. FPL-GTR-109. Madison, WI: U.S.
31. Yıldız, Ü. C., 1988: Çeşitli Ağaç türlerinde su alımının ve çalışmanın azaltılması. Master Thesis, Karadeniz Technical University, Trabzon, Türkiye (in Turkish).
32. Yıldız, S.; Tomak, E. D.; Yıldız, Ü. C.; Ustaömer, D., 2013: Effect of artificial weathering on the properties of heat treated wood. Polymer Degradation and Stability, 98 (8): 1419-1427. https://doi.org/10.1016/j.polymdegradstab.2013.05.004
33. Zhang, X., 2003: Photo-resistance of alkylammonium compound treated wood. Master Thesis, University of British Columbia, Vancouver, BC.
34. Zhong, Z. W.; Hızıroğlu, S.; Chan, C. T. M., 2013: Measurement of the surface roughness of wood based materials used in furniture manufacture. Measurement, 46 (4): 1482-1487. https://doi.org/10.1016/j.measurement.2012.11.041

35. ***ASTM D 358-55, 1970: Standard specification for wood to be used panels in weathering tests of paints and varnishes. Annual Book of ASTM Standard.
36. ***ASTM D1413–07e1, 2007: Standard test method for wood preservatives by laboratory soil-block cultures. Annual Book of ASTM Standard.
37. ***ASTM D1536-58T, 1964: Tentative method of test color difference using the color master differential colorimeter. Annual Book of ASTM Standard.
38. ***ASTM D523-14, 2018: Standard test method for specular gloss. Annual Book of ASTM Standard.
39. ***Beser Kimya, 2022: https://beserkimya.com.tr/category/urun-gruplari/gliserin/ (Accessed Nov. 04, 2022).
40. ***DIN 4768, 1990: Determination of values of surface roughness parameters ra, rz, rmax using electrical contact (stylus) instruments concepts and measuring conditions.
41. ***Merck, 2022: https://www.sigmaaldrich.com/TR/en (Accessed Nov. 04, 2022).
42. ***Turkish State Meteorological Service Database, Meteorological data, 2021, http://www.mgm.gov.tr

**Corresponding address:**

**ÇAĞLAR ALTAY**

Aydın Adnan Menderes University, Aydın Vocational School, Department of Interior Design, Aydın, TURKEY,
e-mail: caglar.altay@adu.edu.tr

Cebrail Açık [1]

# Innovation of Traditional Furniture Surface Decoration Techniques with CNC Laser-Assisted Regression Modeling Production Method: Product Design Study

# Inovacija tradicionalnih tehnika ukrašavanja površine namještaja proizvodnom metodom regresijskog modeliranja podržanom CNC laserom: analiza razvoja proizvoda

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 25. 7. 2022.
Accepted – prihvaćeno: 23. 11. 2022.
UDK: 684.6
https://doi.org/10.5552/drvind.2023.0055



**ABSTRACT** • *Recently, efforts have been made to develop decoration techniques with CNC router machining and contact production machines in the furniture industry. However, this method is insufficient in micro-processes that require precision. In this research, the innovation of traditional furniture surface treatment techniques as a regression modeling production method with laser technology was examined. For this purpose, beech wood was processed in a CNC laser processing machine with a 130-watt carbon dioxide gas tube, and sample product design and manufacture were made. It has been determined that many furniture surface treatment techniques can be applied with the regression modeling method of CAD/CAM supported laser technology.*

**KEYWORDS:** *laser woodworking, mother-of-pearl, filigree, inlay, wood carving*

**SAŽETAK** • *U posljednje se vrijeme tehnike ukrašavanja u industriji namještaja razvijaju uz pomoć CNC glodalica i strojeva s kontaktnom obradom. Međutim, ta metoda nije zadovoljavajuća za fine obrade, za koje je potrebna velika preciznost. U ovom je radu istražena mogućnost inovacije tradicionalnih tehnika ukrašavanja površine namještaja proizvodnom metodom regresijskog modeliranja laserom. Za tu je namjenu CNC laserom s plinskom cijevi ugljikova dioksida snage 130 W izrađen ogledni proizvod od bukovine. Utvrđeno je da se mnoge tehnike obrade površine namještaja mogu primijeniti zajedno s CAD/CAM metodom regresijskog modeliranja podržanom laserom.*

**KLJUČNE RIJEČI:** *laserska obrada drva, majka bisera, filigran, intarzija, rezbarenje drva*

[1] Author is researcher at District Directorate of National Education Onikişubat, Kahramanmaraş, Turkey. https://orcid.org/0000-0002-1094-6946

## 1 INTRODUCTION
## 1. UVOD

Furniture surface decoration is the evaluation of furniture with shapes, pictures and motifs by using various techniques in order to add beauty without disturbing its function. The motifs, figures, symbols and shapes used in decorations are the products of thoughts and behaviors at a certain point in history. Carving is an ornamentation technique in which the excess parts of the motifs drawn on wood are removed with special carving pens or machines and shaped as relief. If the surface depth is 3-4 mm, it is called low carving, and if it is more, it is called high carving. Inlay is an ornamentation technique made by embedding materials such as solid, ivory, wood veneer, mother-of-pearl, metal on solid or coated surfaces according to the motif (URL1). Furniture, which has been developed according to societies and cultures since ancient times, started to change in terms of technology, understanding and use at the beginning of the 20th century. In the 20th century, an industrial society was formed and handicrafts lost their old value. In this period, when architecture and furniture design were in close relationship, many architects also made furniture designs with a holistic method (Gesamkuntswerk) approach. For this reason, it is seen that some furniture design movements and architectural movements overlap and affect each other in the 20th century (Çifçi and Demirarslan, 2021).

Technology has contributed to the development of art movements. Technology becomes a part of culture and innovations and offers the opportunity to reach practical, fast and easy solutions. Time-saving technology can be used as an auxiliary element through mechanical tools. While technology represents power in terms of economy, speed and increasing product quality, it also supports positive efficiency. While art is affected by the development of technology, industry and industrial products also benefit from art and design (Aytepe, 2013).

In the past, there have been some studies on furniture surface decoration arts, especially in the cultural sense. The evaluation of the shells of freshwater mussels, which show a substantial population, collected from Hatay province, in the old Ottoman handicraft mother-of-pearl inlay, in making buttons and ornaments, has been investigated and it has been tried to clarify how they can be evaluated in a wider range (Şereflişan, 2014). Although mother-of-pearl inlays and coppersmithing attract little attention today, other fields are experiencing great difficulties. Gaziantep University, Gaziantep Chamber of Coppersmiths and Sedefçiler and the Ministry of Culture and Tourism are working to protect these areas (Aktürk, 2016). It is aimed to research the place and importance of mother-of-pearl inlay in Gaziantep, its current situation and the products made. It has been determined that there are approximately 50 workshops dealing with the art of mother-of-pearl inlay in the city center, and these workshops are gradually closing. In mother-of-pearl inlay, it is necessary to turn our lost arts into a state policy and to create a budget for our traditional arts in order to eliminate economic concerns and prevent the artifacts left from our traditional arts only in museums (Özdemir and Yıldırım, 2016). The situation of mother-of-pearl inlay workshops in Gaziantep region was investigated. According to the information obtained at the end of the research, while many mother-of-pearl inlay workshops were operating in the past, it has been determined that this number has decreased considerably today. In the following years, it is understood that this profession will be one of the dying professions in Turkey with the closure of the workplaces currently doing this job (Eser and Bal, 2017). The chest, which is a status symbol in the dowry tradition of the Turks, has been examined in terms of its usage and decorations. It is important to transfer traditional Turkish furniture styles and to inspire new designs (Selhan and Usal, 2010). Mother-of-pearl inlay can be applied on large or small furniture in any finished size, usually on small souvenirs and solid wood furniture. Products to be inlaid with mother-of-pearl are generally produced from solid walnut wood. The walnut wood gets a more beautiful color at the end of the darkening process and the inlay process comes to the fore. Apart from walnut wood, hard solids such as rosewood, beech and mahogany are frequently preferred (Tamamoğlu, 2020). The professions of wood carving, wood inlay, mother-of-pearl inlay and filigree were declared national treasures by the Ministry of National Education of the Republic of Turkey (URL2).

With CNC laser, popular operations on wood such as cutting and engraving can be performed. Some parameter studies have been examined in the international literature on these processes. The effects of power, speed, focal distance, air pressure on the machining performance of the machine parameters in laser processing of wood or wood-based materials were studied (Cherif, 1990; Barnekov *et al.,* 1986; Eltawahni *et al.,* 2011; Yuzhı *et al*., 2017; Kudela *et al.,* 2020; Vidholdova *et al*., 2017; Petru *et al*., 2017), as well as the optimization of these parameters (Eltawahni *et al*., 2013; Merchant, 1995; Jiang *et al*., 2021). There have been some studies on the predictive modeling method in laser woodworking (Li *et al*., 2021; Gurau *et al.,* 2017; Li *et al*., 2018). In laser wood engraving, only the patterns created with vector drawing are not processed. Studies have been carried out on the processing of images with photographic properties in laser wood engraving (Jurek and Wagnerová, 2021), and the effects of wood moisture content on laser processing (Rezaei *et al*., 2022).

With the use of CNC machines in furniture production, computer aided design and production systems can work together. In order to produce the parts of the furniture designed with CAD systems in the computer environment, the designs of these parts can be directed to the CAM systems. In laser cutting and engraving processes made on wood and its derivatives, the probability of faulty production is very low compared to the processes made with traditional methods and using cutters in CNC machines. In laser cutting processes made on wood materials, very precise and thin cuts that cannot be made in CNC machines with cutters can be made easily (Karabıyık, 2016). It has been proven that folding furniture can be produced more efficiently with these machines to increase the usability and aesthetics of a space by using CNC router and CNC laser (Oates, 2015). In order to show new applications of compatible mechanisms to folding systems in furniture design and to produce such mechanisms with non-traditional methods, chair, stool and childcare furniture applications have been shown as a result of research on how such structures can be created with folding compatible mechanisms using new methods with laser (Daiel, 2021).

In the studies carried out to date, awareness has been raised that traditional wood decoration techniques are in the category of professions that are gradually disappearing, but sufficient solutions have not been offered. A limited number of studies have been carried out on the wood surface treatment method with CNC router, especially in terms of surface roughness. In addition, in industry the woodworking method with CNC router has had a very positive effect on the continuity of wood surface decoration techniques. Studies have been carried out on wood surface decoration techniques with laser, but these studies have generally remained at the experimental level, and their application in furniture design and production has not been explained. In some studies, only the laser folding furniture production process has been explained. In this study, experimental studies were carried out on a medium-sized CNC laser machine, which is widely used. Beech wood was tested since it is frequently used in industrial production. In line with the findings, furniture surface decoration design and application were made with the predictive modeling method, which is important in industrial production. The design was based on techniques that are about to disappear. An original study was carried out by presenting the materials, machinery, production method, design and manufacturing processes used in an integrated manner in the industrial production sector.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Materials
### 2.1. Materijali

In the study, 18 mm thick beech wood with a density of 0.720 g/cm³ in air-dry state at 12 % moisture conten was used. In material processing, the experimental samples were cut and engraved in a CNC laser machine with a power output of 130 watts, a 50.8 mm focal length lens, carbon dioxide gas, water cooled, 1.5 mm nozzle diameter and 10.6 µm wavelength. Figure 1.a shows the laser processing stage of the CNC laser machine, Figure 1.b shows the example of the laser cutting experiment, and Figure 1.c shows the example of the laser engraving experiment. In addition, 0.02 mm precision digital depth measuring instrument and magnifying glass (5x) were used to measure laser cutting depths in the study.

### 2.2. Method
### 2.2. Metoda

The factorial experimental design allows each of the variable factors to be evaluated with each other. While doing this, in addition to determining the extent of the effect of each variable on the event, different behaviors of the factors that may appear as a result of the interaction of the variables with each other can also be determined. There are many factors that affect laser

a) b) c)

**Figure 1** a) Laser processing step, b) Laser cutting test example, c) Laser engraving test example
**Slika 1.** a) Obrada laserom, b) primjer laserskog rezanja, c) primjer laserskog graviranja

**Table 1** Experiment factor design
**Tablica 1.** Faktori dizajniranog eksperimenta

| **Test factors** / *Varijable testa* | **Levels** / *Razine* | | |
|---|---|---|---|
| | **1** | **2** | **3** |
| Nozzle height *NH*, mm / *visina sapnica NH,* mm | 4.8 | 5.2 | 5.6 |
| Power *P* cut / engrave, W / *snaga P rezanja / graviranja,* W | 25/55 | 50/75 | 100/95 |
| Speed *S* cut / engrave, mm/s / *brzina S rezanja / graviranja,* mm/s | 5/50 | 10/250 | 20/450 |

processing performance. According to the data obtained from the experimental studies carried out so far, it is aimed to determine the effect of the factors that are considered important by keeping some factors constant. These factors are nozzle height (*NH*), feed rate (*S*), and laser processing power (*W*). As seen in Table 1 below, there are 3 variable parameters in the design, and each of them takes 3 different values. According to the specified levels, full factorial design, 27 experiments for laser cutting depth (*CD*) and 27 experiments for laser carving (inlay) depth (*ID*) were performed. The resulting design is the Taguchi orthogonal design and it can be named L27($3^3$). This indicates that the number of experiments is 27; the 3 factors have 3 different levels.

In the tests performed, the data obtained from the experimental samples were analyzed using the 22nd version of the SPSS statistical package program. Analyses were made on the basis of 95 % confidence level. Multiple linear regression analysis was preferred to determine whether there was a significant difference for each analysis made according to the interaction of laser cutting depth and engraving depth dependent variable and independent variables. Preliminary estimates made to achieve optimum yield in production are calculated according to the regression Eq. 1:

$$\hat{Y}=\beta_0+\beta_1X_1+\beta_2X_2+\beta_3X_3 \quad (1)$$

Where:

$\hat{Y}$: Dependent variable (cutting or gouging depth mm value),

$\beta_0$: Constant beta value,

$\beta_1$: 1.independent variable (Nozzle height) beta value,

$X_1$: 1st independent variable (Nozzle height mm) value,

$\beta_2$: beta value of the 2nd independent variable (processing power W),

$X_2$: Value of the 2nd independent variable (cutting speed mm/s),

$\beta_3$: 3rd independent variable (processing speed) beta value,

$X_3$: Indicates the value of the 3rd independent variable (processing speed mm/s).

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

### 3.1 Laser cutting results
### 3.1. Rezultati rezanja laserom

The laser cutting depths (*CD*) obtained according to the test factors of nozzle height (*NH*), feed rate (*S*), laser processing power (*W*) in laser cutting applied to the parallel directions of the wood laser cutting samples are shown in Table 2.

Multivariate linear regression analysis was performed to determine the effects of nozzle height, cutting power and cutting speed on the laser cutting depth of the beech massif. The analysis results of the laser cutting process are shown in Table 3 below.

According to the analysis results in Table 3, the nozzle height negatively and significantly affected the laser cutting depth with an effect size of 15 % ($pr^2$ = 0.148). The laser cutting power positively and significantly affected the laser cutting depth with an effect size of 52 % ($pr^2$ = 0.519). The laser cutting speed, on the other hand, negatively and significantly affected the laser cutting depth with an effect size of 60 % ($pr^2$ = 0.599). It was found that the regression analysis

**Table 2** Laser cutting depths of solid beech materials used in case study
**Tablica 2.** Dubine laserskog rezanja masivne bukovine upotrijebljene u studiji slučaja

| *SN* | *NH*, mm | *P*, W | *S*, mm/s | *CD*, mm | *SN* | *NH*, mm | *P*, W | *S*, mm/s | *D*, mm | *SN* | *NH*, mm | *P*, W | *S*, mm/s | *CD*, mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.8 | 25 | 5 | 5.30 | 10 | 5.2 | 25 | 5 | 6.07 | 19 | 5.6 | 25 | 5 | 4.07 |
| 2 | 4.8 | 25 | 10 | 3.60 | 11 | 5.2 | 25 | 10 | 4.60 | 20 | 5.6 | 25 | 10 | 2.70 |
| 3 | 4.8 | 25 | 20 | 1.40 | 12 | 5.2 | 25 | 20 | 3.20 | 21 | 5.6 | 25 | 20 | 1.70 |
| 4 | 4.8 | 50 | 5 | 11.87 | 13 | 5.2 | 50 | 5 | 10.67 | 22 | 5.6 | 50 | 5 | 7.47 |
| 5 | 4.8 | 50 | 10 | 5.37 | 14 | 5.2 | 50 | 10 | 7.87 | 23 | 5.6 | 50 | 10 | 4.20 |
| 6 | 4.8 | 50 | 20 | 3.73 | 15 | 5.2 | 50 | 20 | 5.50 | 24 | 5.6 | 50 | 20 | 2.40 |
| 7 | 4.8 | 100 | 5 | 14.00 | 16 | 5.2 | 100 | 5 | 13.47 | 25 | 5.6 | 100 | 5 | 9.23 |
| 8 | 4.8 | 100 | 10 | 7.77 | 17 | 5.2 | 100 | 10 | 9.33 | 26 | 5.6 | 100 | 10 | 6.17 |
| 9 | 4.8 | 100 | 20 | 4.40 | 18 | 5.2 | 100 | 20 | 6.93 | 27 | 5.6 | 100 | 20 | 3.57 |

**Table 3** Regression analysis results
**Tablica 3.** Rezultati regresijske analize

| **Variables** *Varijable* | ***Beta(β)*** | ****Beta(β)*** | **Partial correlation (*pr*)** *Parcijalna korelacija (pr)* | **Significance** *Značajnost* |
|---|---|---|---|---|
| Control constant / *kontrolna konstanta* | 8.560 | - | - | 0.000 |
| Nozzle height / *visina sapnice* | -0.224 | -0.216 | -0.385 | 0.000 |
| Cutting power / *snaga rezanja* | 0.058 | 0.538 | 0.721 | 0.000 |
| Cutting speed / *brzina rezanja* | -0.343 | -0.631 | -0.774 | 0.000 |

*Standardized / *standardizirano*

model was 95 % reliable ($p$<0.05), and 72 % of the variation in cutting depth ($R^2_{adjustad}$ = 0.723) was explained by the independent variables. As a result of mathematical modeling of the beech massif, the following regression equation was generated using the data in Table 3, in order to theoretically provide optimum laser cutting and to predict the cutting depth.

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3$$

Depth of cut = 8.560 + (Focal length* - 0.224) + (Cutting Power*0.058) + (Cutting Speed*-0.343)

## 3.2 Laser carving results
## 3.2. Rezultati graviranja laserom

The laser carving (inlay) depths (*ID*) obtained according to the test factors of nozzle height (*NH*), feed rate (*S*), laser processing power (*W*) in laser engraving applied to the parallel directions of the wood laser engraving samples are shown in Table 4.

Multivariate linear regression analysis was performed to determine the effects of focal length, engraving power and engraving speed on the laser engraving depth of the beech massif. Since the effect of nozzle height on laser engraving depth is statistically insignificant, it was not included in the analysis in order not to adversely affect the predictive value of other variables that gave significant results. The analysis results of the laser engraving process, which give significant results, are shown in Table 5.

According to the analysis results in Table 5, laser engraving power positively and significantly affected the laser engraving depth with an effect size of 65 % ($pr^2$ = 0.649). On the other hand, laser engraving speed affected the laser engraving depth negatively and significantly with a 70 % effect size ($pr^2$ = 0.703). It was found that the regression analysis model was 95 % reliable ($p$<0.05), while 80 % of the variation in the engraving depth ($R^2_{adjustad}$ = 0.804) was explained by the independent variables. As a result of the mathematical modeling of the beech massif, the following regression equation was generated using the data in Table 4, in order to theoretically provide the optimum laser engraving and estimate the engraving depth.

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3$$

Carving depth = 2.756 + (Carving Power*0.033) + (Carving Speed*-0.019)

**Table 4** Laser engraving depths of solid beech materials used in case study
**Tablica 4.** Dubine laserskoga graviranja masivne bukovine upotrijebljene u studiji slučaja

| *SN* | *NH*, mm | *P*, W | *S*, mm/s | *CD*, mm | *SN* | *NH*, mm | *P*, W | *S*, mm/s | *D*, mm | *SN* | *NH*, mm | *P*, W | *S*, mm/s | *CD*, mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4.8 | 25 | 50 | 2.07 | 10 | 5.2 | 25 | 50 | 1.70 | 19 | 56 | 25 | 50 | 1.70 |
| 2 | 4.8 | 25 | 100 | 1.10 | 11 | 5.2 | 25 | 100 | 0.83 | 20 | 5.6 | 25 | 100 | 0.87 |
| 3 | 4.8 | 25 | 200 | 0.50 | 12 | 5.2 | 25 | 200 | 0.50 | 21 | 5.6 | 25 | 200 | 0.43 |
| 4 | 4.8 | 50 | 50 | 4.73 | 13 | 5.2 | 50 | 50 | 4.40 | 22 | 5.6 | 50 | 50 | 4.40 |
| 5 | 4.8 | 50 | 100 | 2.57 | 14 | 5.2 | 50 | 100 | 2.33 | 23 | 5.6 | 50 | 100 | 2.23 |
| 6 | 4.8 | 50 | 200 | 1.37 | 15 | 5.2 | 50 | 200 | 1.10 | 24 | 5.6 | 50 | 200 | 1.10 |
| 7 | 4.8 | 100 | 50 | 6.10 | 16 | 5.2 | 100 | 50 | 3.83 | 25 | 5.6 | 100 | 50 | 6.33 |
| 8 | 4.8 | 100 | 100 | 3.60 | 17 | 5.2 | 100 | 100 | 3.03 | 26 | 5.6 | 100 | 100 | 3.73 |
| 9 | 4.8 | 100 | 200 | 1.73 | 18 | 5.2 | 100 | 200 | 1.53 | 27 | 5.6 | 100 | 200 | 1.80 |

**Table 5** Regression analysis results
**Tablica 5.** Rezultati regresijske analize

| **Variables** / *Varijable* | ***Beta(β)*** | ****Beta(β)*** | **Partial correlation (*pr*)** *Parcijalna korelacija (pr)* | **Significance** *Značajnost* |
|---|---|---|---|---|
| Control constant / *kontrolna konstanta* | 2.756 | - | - | 0.000 |
| Carving power / *snaga graviranja* | 0.033 | 0.596 | 0.806 | 0.000 |
| Carving speed / *brzina graviranja* | -0.019 | -0.674 | -0.839 | 0.000 |

*Standardized / *standardizirano*

a) b) c) d)

**Figure 2** Traditional wood surface decoration techniques: a) manual pattern copying stage, b) hand carving stage, c) hand or CNC router Machine engraving stage, d) filigree (wire inlay) engraving stage
**Slika 2.** Tradicionalne tehnike ukrašavanja površine drva: a) faza ručnog kopiranja uzorka, b) faza ručnoga graviranja, c) faza ručnoga ili CNC glodanja, d) faza graviranja intarzija (žičani umetak)

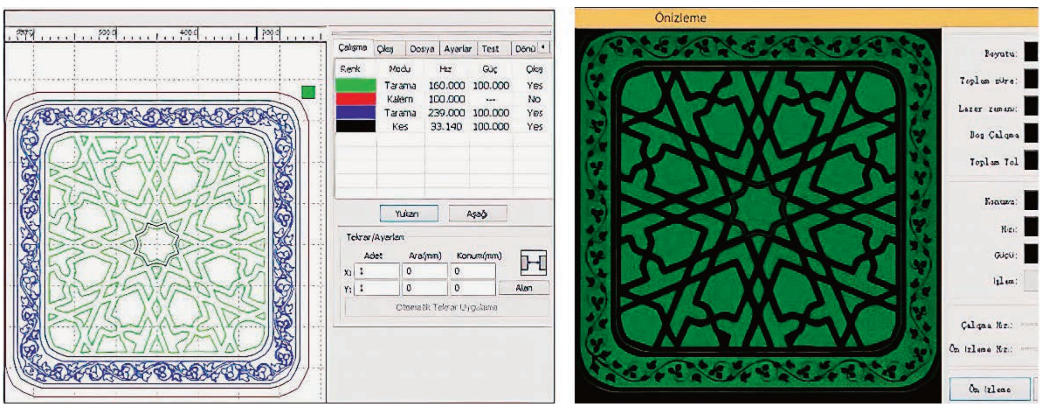
## 3.3 Design and implementation
## 3.3. Dizajn i implementacija

In traditional wood surface treatment, it is first necessary to transfer the motif to the wood surface. Motif transfer is done by free hand or by one of the methods of drawing, pasting or copying with a template (Figure 2a). Then, it is necessary to empty the parts outside the motif or to carve the unnecessary parts. This process is done with hand tools (Figure 2b) or with a vertical boring machine or milling machine (Figure 2c). Along with these machines, although the machine is partly included in the production, handwork is also used. If wire inlay is to be done, since the wire channels are very thin, it should be done by hand with special tools (Figure 2d). In recent years, wood surface treatments in large enterprises have been carried out in CNC router fully automatic machines. The biggest revolution in wood surface processing has been achieved with CNC router production. With these machines, many production stages such as motif transfer and handwork are eliminated. However, all of these applications can be defined as machining and contact mechanical production. CNC laser technology, on the other hand, can be called chipless and contactless chemical production. CNC router and CNC laser woodworking have advantages and disadvantages when compared to each other. These differences may vary according to the operation performed.

In order for the CNC laser machine to work, a computer hardware with CAD (Computer Aided Drawing) and CAM (Computer Aided Manufacturing) drawing and code converter programs is also required as a complement to the laser processing center. CAM processes the drawings made in CAD and converts them into machine codes (Alıcı, 2006). In this study, a case study was conducted to determine the applicability of CNC laser wood surface decoration with regression modeling method. The design and production process steps of CNC laser processes, made of beech solid, poplar, walnut solids, mother-of-pearl and wire, applied to three nesting tables, are explained below.

The edge flower carving motif, "Selçuklu" inlay motif and filigree cutting paths to be applied on the beech massif forming the upper table of the coffee tables were drawn in a CAD (computer aided design) program. The upper table motif was transferred to the CAM (computer aided production) program in the software of the CNC laser machine as vector. The design was completed by determining the production parameter values measured according to the surface of the coffee tabletop. The design ready for production is shown in Figure 3a below, and the preview screen is shown in Figure 3b.

During the process of production parameter settings, the cutting power of the laser machine was applied using a 100 watt power to complete the produc-




a) b)

**Figure 3** a) CNC laser product manufacturing design CAM program interface, b) CAM program Preview Screen
**Slika 3.** a) Dizajn CAM programskog sučelja za CNC obradu laserom, b) pregled zaslona CAM programa

a) b) c) d)

**Figure 4** a) CNC laser tabletop engraving step, b) CNC laser tabletop table inlay step, c) CNC laser tabletop table Filigree (wire Inlay) step, d) CNC laser table stand leg processing
**Slika 4.** a) Graviranje ploče stola CNC laserom, b) izrada intarzije na ploči stola CNC laserom, c) izrada filigrana na ploči stola CNC laserom (žičani umetak), d) obrada nogu stola CNC laserom

tion as soon as possible. Since the walnut, poplar solids and mother-of-pearl thicknesses to be inlaid on the "Selçuklu" motif of the coffee table were designed as 3mm, the speed parameter for carving 3 mm on the table surface was calculated from the carving depth regression formula as follows:

Carving depth = 2.756 + (Carving Power*0.033) + (Carving Speed* - 0.019)

3 mm (Desired engraving depth) = 2.756 + (100 W-Max power*0.033) + (Required speed* - 0.019)

(Required engraving speed*0.019) = 6.056 - 3 mm (Required engraving depth)

Required engraving speed = 3.056/0.019 = 160 mm/s.

Since the edge flower motif of the tabletop and legs was designed as 1.5 mm low surface carving, the required speed parameter was calculated from the carving depth regression formula as follows:

1.5 mm (Desired engraving depth) = 2.756 + (100 W-Max power*0.033) + (Required speed* - 0.019)

(Required engraving speed*0.019) = 6.056 - 1.5 mm (desired engraving depth)

The required engraving speed = 4.556/0.019 = 239 mm/s.

Since for the filigree motif in mother-of-pearl inlay on the middle part of the tabletop and the filigree cutting paths on the edges, the width of the wire to be used was measured as 1.5 mm, the cutting speed parameter required for the cutting depth of the notch where the wire would be embedded was obtained from the cutting depth regression formula as follows:

Depth of cut = 8.560 + (Nozzle height* - 0.224) + (Cutting Force*0.058) + (Cutting Speed* - 0.343)

1.5 mm (desired cutting depth) = 8.560 + (5.2 mm - nozzle height* - 0.224) + (100 W-Max power *0.058) + (cutting speed*0.343)

(Required cutting speed*0.343) = 13.195 - 1.5 mm (desired cutting depth)

The required cutting speed was determined as = 11.695/0.343 = 34 mm/s.

The CAM design, developed with the obtained parameters, was completed and the production phase was started. Figure 4a shows the engraving step for inlay, Figure 4b shows the construction of mother-of-pearl and solid inlays, Figure 4.c shows filigree construction, Figure 4d shows the stages of preparation of the legs of the coffee table.

Figure 5a shows the assembled image of the nest table set, whose design and processing have been completed with the CNC laser-assisted regression modeling; Figure 5b shows the image sanded and adapted tables; and Figure 5c shows the final shape with varnish.

**Figure 5** a) Assembled coffee table, b) sanded version of tables, c) varnished version of integrated tables
**Slika 5.** a) Sastavljeni stolić za kavu, b) brušena verzija stolova, c) lakirana verzija integriranih stolova

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

In this study, the applicability of traditional furniture surface treatment techniques to the manufacturing method based on CNC laser assisted regression modeling was investigated. As a result of the research, it was determined that the regression modeling method can be successfully applied to furniture surface decoration with CNC laser, considering the material, machine and processing parameters. With the preview method for predictive modeling in industrial wood product design, the view of the cutting path in the production process, the length of the cutting path, the working time with laser processing, and the product output data can be determined in advance. Low wood carving, high wood carving, wood and mother-of-pearl inlay carvings can be done successfully with laser processing. Perfect and fast cutting paths can be embroidered on the most complex motifs, especially for filigree inlay. When a good design is made, the color tones ranging from brown to black on the engraving surfaces, depending on the processing power of the laser, add value to the decoration. It processes highly detailed motifs with much more precision than CNC laser, hand engraving and CNC router processing methods. In addition, it has been determined that laser furniture top surface decoration is very suitable for mass production.

A badly managed process of motif design and production parameter in laser wood decoration can have negative effects such as excessive burns on the ornamental surface, loss of adhesion of the combustion surfaces, extra cutting path and energy consumption, more difficult sanding and polishing of the burned surface.

## 5 REFERENCES
## 5. LITERATURA


1. Aktürk, M., 2016: International art symposium and exhibition from the past to the future, 215-231.
2. Alıcı, F., 2006: A research on laser veneer cutting and wood inlay. Master Thesis, Gazi University, Institute of Science and Technology, pp. 173 Ankara.
3. Aytepe, B., 2013: Evaluation of the curriculum design and effectiveness of the application of laser etching method in graphics and ceramics. PhD Thesis, Gazi University Institute of Educational Sciences Department of Applied Arts Education Graphic Education Department, Ankara.
4. Barnekov, V. G.; McMillin, C. W.; Huber, H. A., 1986: Factors influencing laser cutting of wood. Forest Products Journal, 36 (1): 55-58.
5. Cherif, M., 1990: Precision cutting of hardwoods by using a high energy carbon dioxide laser. Master's Thesis, pp. 81, Michigan State University Institute of Science. Metallurgy Mechanics and Materials Science.
6. Cifçi, S. K.; Demirarslan, Z., 2021: An overview of furniture design styles in the 20th century. Electronic Journal of Social Sciences, 20 (79): 1607-1627. https://doi.org/10.17755/esosder.842189
7. Daniel Calvin, D., 2021: Laser forming of compliant mechanisms and nhat-foldable furniture. PhD Thesis, 9341, BYU Scholars Archive Citation.
8. Eltawahni, H. A.; Olabi, A. G.; Benyounis, K. Y., 2011: Investigating the $CO_2$ laser cutting parameters of MDF wood composite material. Optics and Laser Technology, 43: 648-659.
9. Eltawahni, H. A.; Rossini, N. S.; Dassisti, M.; Alrashed, K.; Aldaham, T. A.; Benyounis K. Y.; Evalaution, A. G., 2013: Optimization of laser cutting parameters for plywood materials. Optics and Lasers in Engineering, (51) 1029-1043.
10. Eser, F.; Bal, B. C., 2017: A research on mother of pearl inlay decoration and the situation of mother of pearl inlay workshops in Gaziantep region. Journal of Advanced Technology Sciences, 572-579.
11. Gurau, L.; Petru, A.; Varodi, A.; Timar, M. C., 2017: The influence of $CO_2$ laser beam power output and scanning speed on surface roughness and color changes of beech (*Fagus sylvatica*). BioResources, 12 (4): 7395-7412.
12. Jiang, T.; Yang, C.; Yu, Y.; Bakary, S. D.; Liu, J.; Ma, Y., 2021: Prediction and analysis of surface quality of northeast china ash wood during water-jet assisted $CO_2$ laser cutting. Journal of Renewable Materials, 9 (1): 119-128.
13. Jurek, M.; Wagnerová, R., 2021: Laser beam calibration for wood surface colour treatment. European Journal of Wood and Wood Products, 79: 1097-1107. https://doi.org/10.1007/s00107-021-01704-3
14. Karabıyık, K., 2016: The effects of current digital technologies on furniture design and production. Master's Thesis, pp. 87, Beykent University Graduate School of Natural and Applied Sciences, Department of Interior Architecture, Istanbul.
15. Kudela, J.; Kubovski, I.; Andrejko, M., 2020: Surface properties of beech wood after $CO_2$ laser engraving. Coatings, 10 (1): 77. https://doi.org/10.3390/coatings10010077
16. Li, R.; He, C.; Chen, Y.; Wang, X., 2021: Efects of laser parameters on the width of color change area of poplar wood surface during a single irradiation. European Journal of Wood and Wood Products, 79: 1109-1116. https://doi.org/10.1007/s00107-021-01706-1
17. Li, R.; Xu, W.; Wang, X.; Wang, C., 2018: Modeling and predicting of the color changes of wood surface during $CO_2$ laser modification. Journal of Cleaner Production, 183: 818-823. https://doi.org/10.1016/J.JCLEPRO.2018.02.194
18. Merchant, V. E., 1995: The influence of cutting assist gas and pressure on the laser cutting of lumber products. In: Proceedings of the International Congress on Applications of Lasers & Electro-Optics. ICALEO® '95: Proceedings of the Laser Materials Processing Conference. Orlando, FL, USA. ASME, pp. 128-137. https://doi.org/10.2351/1.5058897
19. Oates, C., 2015: Twofold: Space-Saving Folding Furniture. Faculty of San Diego State University. In: Partial Fulfillment of the Requirements for the Degree Master of Fine Arts.
20. Özdemir, M.; Yıldırım, Ş., 2016: Investigation of Mother-of-Pearl Inlay in Gaziantep. Academic View Journal, 56: 416-440.
21. Petru, A.; Lunguleasa, U., 2017: Color infuence of the laser raster speed on wood pyrography. Pro Ligno, 13 (4): 508-515.

22. Rezaei, F.; Wimmer, R.; Gaff, M.; Gusenbauer, C.; Frömel-Frybort, S.; Kumar Sethy, A.; Corleto, R.; Ditommaso, G.; Niemz, P., 2022: Anatomical and morphological characteristics of beech wood after $CO_2$-laser cutting. Wood Material Science & Engineering, 17 (6): 459-468, https://doi.org/10.1080/17480272.2022.2134820
23. Selhan, S.; Usal, Y., 2010: The Use of Dowry Chest and Traditional Decorations in Turks. ODU Social Sciences Institute Journal of Social Sciences Research, 1 (1):157-167.
24. Şereflişan, H., 2014: Investigation of economical properties of freshwater mussels in Gölbaşı Lake (Hatay). Yunus Research Bulletin, (3): 43-49.
25. Tamiroğlu, H. E., 2020: Application of inlay art and silver inlay technique on ceramic jewelry in gaziantep province. Gazi University Institute of Fine Arts Master Thesis, pp. 96.
26. Vidholdova, Z.; Reinprecht, L.; Igaz, R., 2017: Mold on laser-treated beech. BioResources, 12 (2): 4177-4186.
27. Yuzhi, X.; Baojin, W.; Shen, Y., 2017: Study on laser cutting technology of bamboo. Wood Research, 62 (4): 645-658.
28. ***URL1 http://www.megep.meb.gov.tr/?page=moduller (Accessed Jul. 11, 2022).
29. ***URL2https://ticaret.gov.tr/data/5d41938613b87639ac9e005f/Meslekler%20Listesi.pdf (Accessed Jul. 11, 2022).

**Corresponding address:**

**CEBRAIL AÇIK**
District Directorate of National Education Onikişubat, 46050, Kahramanmaraş, TURKEY,
e-mail: cebrail46@hotmail.com

Henry Eric Magezi, Taner Okan[1]

# A Gravity Model Analysis of Forest Products Trade Between Turkey and European Union Countries

# Gravitacijski model analize trgovine drvnim proizvodima između Turske i zemalja Europske unije

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 15. 8. 2022.
Accepted – prihvaćeno: 21. 12. 2022.
UDK: 630*88
https://doi.org/10.5552/drvind.2023.0057



**ABSTRACT** • *The study aimed to understand the determining factors of the trade between Turkey and the European Union (EU) countries in the forest products sector and assess Turkey's forest product export potential to the EU. The study period was from 2005 to 2020 and focused on HS44, HS47, and HS48 forest product groups. A gravity model was estimated using panel data with the Ordinary Least Squares, Random Effects, and Hausman-Taylor estimation methods. Results indicate that the forest products exports from Turkey to the EU are significantly influenced by the Gross Domestic Product, the population of Turkey and the EU partner, and negatively by the relative forest endowment. The elasticities estimated were then used to predict the export potential of Turkey in the trade of forest products. The findings revealed that the predicted forest export value exceeded Turkey's actual forest products export to Denmark, France, Italy, Luxembourg, Poland, Slovenia and Spain from 2005 to 2020.*

**KEYWORDS:** *forest products trade, gravity model, export potential, Turkey, European Union*

**SAŽETAK** • *Cilj istraživanja bio je proučiti najvažnije čimbenike trgovinskih odnosa Turske i zemalja Europske unije (EU) u sektoru šumarstva i drvne industrije te procijeniti izvozni potencijal drvnih proizvoda iz Turske u EU. Istraživanje je trajalo od 2005. do 2020., a naglasak je bio na skupinama drvnih proizvoda HS44, HS47 i HS48. Gravitacijski model definiran je uz pomoć panel-podataka primjenom ovih metoda: metode najmanjih kvadrata, metode slučajnih efekata i Hausman-Taylorove metode. Rezultati su pokazali da je izvoz drvnih proizvoda iz Turske u EU pod znatnim utjecajem domaće bruto proizvodnje, broja stanovništva Turske i partnera iz EU-a te pod negativnim utjecajem relativne raznovrsnosti drvnih proizvoda. Ujedno su procijenjene elastičnosti primijenjene za predviđanje izvoznog potencijala drvnih proizvoda iz Turske. Utvrđeno je da predviđena vrijednost izvoza od 2005. do 2020. godine premašuje stvarni izvoz drvnih proizvoda iz Turske u Dansku, Francusku, Italiju, Luksemburg, Poljsku, Sloveniju i Španjolsku.*

**KLJUČNE RIJEČI:** *trgovina drvnim proizvodima, gravitacijski model, izvozni potencijal Turske, Europska unija*

[1] Authors are researchers at Istanbul University-Cerrahpaşa, Faculty of Forestry, Department of Forestry Economics, Istanbul, Turkey. https://orcid.org/0000-0003-3170-7159, https://orcid.org/0000-0001-7531-5662

# 1 INTRODUCTION
## 1. UVOD

Before the 1970s, Turkey used to pursue an inward-oriented import-substitution industrialization strategy for the economy. Nevertheless, from the 1980s, Turkey made a drastic turnaround to follow an export-focused growth approach with the majority of the country's economic policies focusing on the integration of the economy to world markets and promotion of export (Karagoz and Saray, 2010). With the increase in the openness of the economy, Turkey has become more critical of its export performance with the focus being the European Union market where it has wanted to be a member since the 1960s.

The EU is by far Turkey's most significant partner in trade in recent years, accounting for 41.3% of Turkey's exports and 33.4 % of Turkey's imports. According to European Commission, Turkey in 2020 ranked as the EU's sixth biggest trade partner with exports worth 62.6 billion Euros to the EU and imports worth 69.9 billion Euro from the EU (European Commission, 2021). This is one of the results of the Customs Union (CU) between Turkey and the EU that provided a significant impetus for trade facilitation and customs reform in Turkey including the modernization of the Turkish Customs Administration (TCA). These improvements are of great economic significance for Turkey and lie at the heart of Turkey's strong export performance over the past decade (World Bank, 2014).

Turkey's volume of exports declined by an unprecedented rate of 17.8 % in 2020 mainly due to Covid-19, whereas its imports contracted by 6.4 %. Turkey's Exports reached USD 170 billion in 2020 across Turkey's highly diversified export markets. In the EU, Germany continued to be Turkey's largest export market with a share of 9.2 % of all exports in 2020. Turkey's second largest export market was the United Kingdom (UK) with a share of 6.2 %, followed by Iraq and Italy (IMF, 2021). Concerning forest products trade, the export figures of the wood and forest products sector for Turkey, as a whole, was $ 4.9 billion in 2013, up by 15.7 % compared to 2012, with UK and Germany being top importers of Turkish wood and forest products in the EU.

Also, the exports of Turkish furniture increased from US $ 684,5 million in 2005 to US $ 2,2 billion in 2015 (Ministry of Trade, 2019). This is mainly due to improvements in capacity, quality and design. In 2015, Turkey exported furniture to 201 countries throughout the world as well as being the fifth largest source of furniture imported to the EU, with Germany and France being the main markets in the EU.

The Global Economic Dynamics (GED) Study 2016 applied the Grubel-Lloyd (GL) index to quantify the extent of bilateral EU-Turkish trade within the forest products sector and showed that in 2014 the GL index of Turkey and the EU in wood and forest products was 0.92. It also showed that the simple and the weighted average bilateral tariffs applied between the EU and Turkey on forestry and wood products are zero percent (GED Study, 2016). Turkey is in a competitive position to supply semi-processed wood products and furniture to the EU due to its relatively low labor costs. Turkish forest product-based industries, such as the panel and furniture industries, have increased their capacity over the last decade, allowing them to take advantage of these regional opportunities (Ministry of Trade, 2019).

In recent times, several studies have attempted to assess the trade between Turkey (in general and some sectors in particular) and the EU and understand the key factors influencing the foreign trade of Turkey. However, the forest products sector has received limited attention in these studies, and its potential with the EU is yet to be fully understood. The trade of forest products is essential for the developed economies, and it is rapidly becoming a significant factor in the economic growth of many developing economies. Consequently, the increase in the demand for forest products has been recorded (Akyüz *et al*., 2020). Lundmark (2010) observed that the increasing use of and demand for forest products relative to the scarcity of forest resources in some countries has led to an increase in the import needs of such countries, at the same time increasing the forest products exports from those with comparatively high forest resources.

Anderson (2011) describes the gravity model as the most recognized empirical model to understand and analyze international trade. The gravity model defines the volume of trade between two partners as a function of push and pull factors, mainly the economic size of the exporting and importing trade partners, and the transactional distance in-between the partners (Patuelli *et al*., 2015).

Even though several studies like those of McCallum (1995), Marku (2014) and Yu Cheng (2016) have discussed the use of the gravity model in the analysis of international trade, just a few studies have estimated the trade flows of forestry products. Using panel data from 2001-2016, Vu *et al*. (2019) employed a gravity model to study the determinants of Vietnam's trade of wood products. Larson *et al*. (2018) estimated the impact of GDP of the importing partner and the exporting partner GDP together with the distance between the trading partners using FAO's dataset. Buongiorno (2016) studied trade flows of forest products, forecasting the trade value for three forestry product types amongst the Trans-Pacific Partnership (TPP) member countries. Buongiorno (2015) estimated a gravity model using OLS and

Fixed Effects methods to study the effects the monetary union introduction in Europe posed to the forest products trade flow. Similarly, Akyüz *et al*. (2010) used the gravity to study the trade of forest products of Turkey and the EU countries from 2000 to 2006. They used a logarithmic specification with a variable for population and three dummy variables for shared border, shared language, and for membership in the EU before 2004.

This study aimed to use the gravity model analysis of Turkey's forest products trade to identify important factors that determine Turkey's forest products exports to the EU. In addition, the study aimed to identify the export potential for Turkey forest products to the EU countries.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Materials
### 2.1. Materijali

The study considered the 28 EU countries as of 2019 (EU-27 and UK from 2020). The data set contains the annual observations from 2005 to 2020. The study obtained annual Gross Domestic Product (GDP) data from the Economic Outlook Database (IMF, 2021). The UN Comtrade database was the source for the forest products trade data for three forest products groups. These followed the HS Codes 2017; HS44: Wood and articles of wood, wood charcoal; HS47: Pulp of wood or other fibrous cellulosic material, recovered (waste and scrap) paper or paperboard; and HS48: Paper and paperboard, articles of paper pulp, paper or paperboard (United Nations, 2021). The geographical distance between the EU capitals and Istanbul instead of Ankara was taken into consideration because it would be an overestimate to use Ankara, as Istanbul is the business hub of Turkey, and nearest to the EU capitals.

For the endowment variable, data was obtained from the FAOSTAT database, where the forest area in each country at a time (t) was used as a proxy for forestry endowment (FAO 2021). The study utsed STATA for the data analysis and the estimation of the Gravity Model.

### 2.2 Methods
### 2.2. Metode

#### 2.2.1 Econometric specification
#### 2.2.1. Ekonometrijska specifikacija

The most fundamental equation of the gravity model is structured as

$$T_{ij} = A\left(\frac{Y_i \cdot Y_j}{DIST_{ij}}\right) \quad (1)$$

Where $T_{ij}$ stands for volume of trade between countries $i$ and $j$, $A$ a constant, $Y_i$ and $Y_j$ for the economic size of countries $i$ and $j$, while $DIST_{ij}$ is for the distance between the countries $i$ and $j$. A log-linear transformation of equation (1) leads to equation (2), which is the basis of

$$logT_{ijt} = logA + logY_{it} + logY_{jt} - logDIST_{ij} \quad (2)$$

Other independent variables have been added to equation (2). Our gravity model specification includes population variables for Turkey and EU country $j$, ($POP_{it}$) and ($POP_{jt}$) at time $t$, respectively. Population variables represent the market size of the countries and the bigger the market, the more it trades; hence the market size is expected to exert a positive sign. The Real Effective Exchange Rate of the Turkish Lira (TL) at time $t$ ($REER_{ijt}$). An increase in the REER represents an appreciation of the TL in real terms. This indicates that Turkey's export is becoming expensive, thus losing its trade competitiveness. The dummy variable for common border ($BORD_{ij}$) is set at one if Turkey has a shared border with the EU country (e.g., McCallum 1995; Akyüz *et al.* 2010). It is expected to affect the trade value positively due to the closeness. ($EURO_j$) is the dummy for EU country j using EURO to capture the effect of the Euro (e.g., Buongiorno 2015) since only 19 out of 28 EU members use it as the official currency. And $LANDLKD_j$ is the dummy for country j being landlocked. Its effect is expected to be negative as it increases the transaction costs of the trade. The study includes an endowment variable ($END_{jit}$) which is the relative forest endowment in terms of the ratio of the forest area of EU partner($j$) to Turkey($i$). Its effect on trade is expected to be negative. Thus, the following gravity model specification:

$$logTRADE_{ijt} = \beta_0 + \beta_1 logGDP_{it} + \beta_2 logGDP_{jt} + \beta_3 logPOP_{it} + \beta_4 logPOP_{jt} - \beta_5 logDIST_{ij} + \beta_6 logEND_{jit} + \beta_7 logREER_{ijt} + \beta_8 BORD_{ij} + \beta_9 EURO_j + \beta_{10} LANDLKD_j + U_{ij} \quad (3)$$

Where $GDP_{it}$ is Gross Domestic Product of Turkey and $GDP_{jt}$ is for the EU country $j$ at a time $t$. We excluded a dummy variable to cater for preferred trade agreements. The World Bank (2014), using a panel data set from 1990 to 2010, observed no significant Bilateral Preferential Trade Framework (BPTF) effect on the trade between Turkey and the EU. As of 1 January 2021, Turkey has an active Free Trade Agreement with the UK but this is out of context for this paper.

#### 2.2.2 Gravity model estimation
#### 2.2.2. Procjena uz pomoć gravitacijskog modela

We used Panel data to estimate the gravity model. a panel data set helps to observe the trend and evolution of the relevant variables over time and to identify the specific time and country effects. Our model estimation begins with a pooled OLS estimation of the empirical specification (3) as a startup estimation for other estimators. Although many papers (e.g., McCallum 1995) have employed the OLS method, it ignores the heterogeneity among countries and tends to provide biased estimations since it does not cater for the individual effects and time effects.

The Random Effects Model (REM) assumes zero correlation amongst the individual effects and independent variables since it presumes a strictly exogenous (uncorrelated with the individual effects) unobserved heterogeneous component (Baltagi, 2001). Contrary, the Fixed Effects Model (FEM) presumes the presence of an unobserved heterogeneous component being constant over time. However, heterogeneity which is common across countries and time can be avoided when panel data is used with fixed effects, thus reducing the possibility for inconsistent estimators.

However, other researchers (e.g., Egger 2002) have opted to use Hausman and Taylor's estimator as a better estimator of panel data than both the REM and FEM. McPherson and Trumbull (2008) observe that the ability of the Hausman-Taylor method to include time-invariant variables in the estimations and its ability to avoid the problem of the country-specific dummy variables necessary in the FEM makes it an ideal estimation method. The Hausman-Taylor estimation also solves the correlation problem amongst the independent variables and the error term, which is common with the REM (McPherson and Trumbull 2008).

### 2.2.3 Estimation of export potential
### 2.2.3. Procjena izvoznog potencijala

The forest products export potential of Turkey is estimated based on the differences between the estimated and actual forest products exports from Turkey to the EU. The estimation of forest products export potential follows:

$$XP_{ijt} = \frac{\sum E_{ijt}}{\sum Ex_{ijt}} \tag{4}$$

Where the forest products export potential of Turkey is $XP_{ijt}$, $\sum E_{ijt}$ is Turkey's estimated forest products export flow, and $\sum Ex_{ijt}$ is Turkey's actual forest products export to the EU. $XP_{ijt}$ greater than 1 shows that the actual forest products exports are less than the estimated forest products exports, which indicates the presence of untapped forest products export potential. Conversely a value less than 1 shows that the actual forest products exports from Turkey are greater than the estimated forest products exports, which indicates exhausted export potential.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

### 3.1 Empirical results
### 3.1. Empirijski rezultati

The summary statistics of the dataset are presented in Table 1. Since there was no missing data, 448 potential observations were obtained for one exporting country, Turkey and 28 partner EU countries, which led to a maximum of 28 pairs and 16 years from 2005-2020. This was uniform for all our variables, which indicated a strongly balanced panel data set.

The Hausman test for the REM against FEM showed that the REM was more consistent and efficient to apply over fixed effects, hence only results of the estimations from the REM are included in the results (Tables 2 and 3). Even though the REM proved consistent and efficient for the study data, when the data were run with country dummy variables and parameter test for EU country and time dummies, variables tested to be significant indicating a presence of

**Table 1** Summary statistics of gravity model
**Tablica 1.** Zbirna statistika gravitacijskog modela

| **Variable** *Varijable* | **Observations** *Broj zapažanja* | **Mean** | **Std. Dev.** | **Minimum** | **Maximum** |
|---|---|---|---|---|---|
| log$TRADE_{ijt}$ | 448 | 17.43 | 1.89 | 4.76 | 20.47 |
| log$EXPORTS_{ijt}$ | 448 | 15.52 | 1.95 | 4.76 | 19.25 |
| log$IMPORTS_{ijt}$ | 441 | 16.89 | 2.34 | 5.05 | 20.41 |
| log$GDP_{it}$ | 448 | 27.36 | 0.17 | 26.94 | 27.58 |
| log$GDP_{jt}$ | 448 | 26.07 | 1.57 | 22.58 | 29.00 |
| log$POP_{it}$ | 448 | 18.14 | 0.07 | 18.03 | 18.25 |
| log$POP_{jt}$ | 448 | 15.88 | 1.39 | 12.91 | 18.24 |
| log$DIST_{ij}$ | 448 | 7.33 | 0.50 | 6.10 | 8.08 |
| log$END_{jit}$ | 448 | -2.38 | 2.16 | -11.03 | 0.31 |
| log$REER_{ijt}$ | 448 | 4.89 | 1.15 | 4.13 | 9.27 |
| $\mathrm{LANDLKD}_j$ | 448 | 0.18 | 0.38 | 0.00 | 1.00 |
| $\mathrm{BORDER}_{ij}$ | 448 | 0.14 | 0.35 | 0.00 | 1.00 |
| $\mathrm{EURO}_j$ | 448 | 0.68 | 0.47 | 0.00 | 1.00 |

**Table 2** Regression results – dependent variable as bilateral trade, 2005–2020
**Tablica 2.** Rezultati regresije – zavisna varijabla *bilateralna trgovina*, 2005. – 2020.

| **log*TRAD*$_{Eij}$t** | **Pooled OLS** | **Random Effects** | **Hausman - Taylor** |
|---|---|---|---|
| Observations | 448 | 488 | 488 |
| *F*/Wald Statistic | 62.81 | 112.93 | 68.92 |
| Prob > *F* | 0.0000 | 0.0000 | 0.0000 |
| $R^2$ | 0.59 | 0.58 | |
| log$GDP_{it}$ | 0.22 | 0.11 | 0.10 |
| log$GDP_{jt}$ | 0.94$^{***}$ | 1.33$^{***}$ | 1.34$^{***}$ |
| log$POP_{it}$ | 2.31$^{**}$ | 2.15$^{***}$ | 3.21$^{***}$ |
| log$POP_{jt}$ | -0.32$^{**}$ | -0.84$^{***}$ | -4.98$^{***}$ |
| log$DIST_{ij}$ | -0.75$^{***}$ | -1.20 | -1.54 |
| log$END_{jit}$ | -0.29$^{***}$ | -0.37$^{***}$ | -3.20$^{***}$ |
| log$REER_{ijt}$ | -0.04 | -0.38 | -0.04 |
| LANDLKD$_j$ | -0.33$^{**}$ | -0.54$^{*}$ | -1.09 |
| BORDER$_{ij}$ | 0.56$^{**}$ | 0.25 | 1.57 |
| EURO$_j$ | -0.36$^{***}$ | -0.25$^{**}$ | -0.27 |
| Constant | -43.71$^{***}$ | -36.00$^{**}$ | -22.03$^{***}$ |
| Hausman test | | | *P* > Chi2 = 0.1519$^{***}$ |

***, **, * Significant at 1 %, 5 % and 10%, respectively / *značajno pri 1 %, 5 % odnosno 10 %*

fixed effects. The presence of both random and fixed effects is the reason the study applied a Hausman –Taylor estimation method. Since the Hausman-Taylor model was found to be most appropriate, the interpretation of the results was based on this model.

### 3.2 Results of gravity equations and bilateral trade
### 3.2. Rezultati gravitacijskih jednadžbi i bilateralne trgovine

Table 2 shows the estimates from the OLS, REM, and the Hausman-Taylor estimation methods of the gravity model from 2005 to 2020 data for Eq. 3.

The estimation of the gravity model gave signs of coefficients that are consistent with economic theory. Table 2 shows that Turkey trades more forest products to more developed EU countries. This was expressed through the positive coefficients on importer GDP and is highly significant at 0.01 level. Although, an increase in the GDP of Turkey's GDP increases the bilateral trade flows, its effect is insignificant on the forest products trade between Turkey and the EU countries. The coefficients on the population of Turkey and the EU partners are both highly significant. It is worth noting that, although the population of Turkey influences the trade positively, the population of the EU partners influences the bilateral forest trade negatively. This could mean that high population levels are expected to decrease the income per capita, which may hinder the demand for forest products by the EU partners.

The relative endowment factor has a negative significant effect on the forest trade between Turkey and the EU partners. The coefficients of the distance between Turkey and the EU partners, the real effective exchange rate, and the dummies for a landlocked EU partner, EURO users and sharing a border with Turkey are consistent with the data on gravity model in literature but were found insignificant in the model.

### 3.3 Results of gravity model estimations and bilateral exports
### 3.3. Rezultati procjene gravitacijskog modela i bilateralnog izvoza

Table 3 shows the estimates from the OLS, REM, and the Hausman-Taylor estimation methods of the gravity model from 2005 to 2020 data for Eq. 3.

The estimation results indicate that forest products exports are positively influenced by the demand (EU partner's GDP) and the supply capacity (Turkey's GDP). This is in line with the prior research, Buongiorno (2016), Buongiorno (2015), and Akyüz *et al.* (2010). However, the impact of Turkey's GDP is not significant. This implies that the EU countries with a higher GDP show a higher demand and more chances of import; however, an increase in the GDP of Turkey does not necessarily trigger additional forest products exports to the EU. This result is rather different from most prior research, where the domestic GDP tends to play a more significant role than that of the trading

**Table 3** Regression results – dependent variable as bilateral Exports, 2005–2020
**Tablica 3.** Rezultati regresije – zavisna varijabla *bilateralni izvoz*, 2005. – 2020.

| **logEXPORTS$_{ijt}$** | **Pooled OLS** | **Random Effects** | **Hausman -Taylor** |
|---|---|---|---|
| Observations | 448 | 488 | 488 |
| *F*/Wald Statistic | 297.80 | 286.36 | 127.02 |
| Prob > *F* | 0.0000 | 0.0000 | 0.000 |
| $R^2$ | 0.70 | 0.69 | |
| log$GDP_{it}$ | 0.06 | 0.15 | 0.33 |
| log$GDP_{jt}$ | 0.26$^{***}$ | 0.58$^{***}$ | 1.19$^{***}$ |
| log$POP_{it}$ | 5.76$^{***}$ | 5.61$^{***}$ | 5.31$^{***}$ |
| log$POP_{jt}$ | 0.89$^{***}$ | 0.54$^{**}$ | 0.11$^{***}$ |
| log$DIST_{ij}$ | -0.14 | -0.23 | -0.96 |
| log$END_{jit}$ | -0.23$^{***}$ | -0.21$^{***}$ | -0.1$^{8***}$* |
| log*REERijt* | -0.03 | -0.03 | -0.02 |
| LANDLKDj | -0.59$^{***}$ | -0.73$^{***}$ | -0.99 |
| BORDERij | 2.47$^{***}$ | 2.23$^{***}$ | 1.78 |
| EUROj | -0.19 | -0.25 | -0.37 |
| Constant | -109.71$^{***}$ | -104.34$^{***}$ | -94.21$^{***}$ |
| Hausman test | | | *P* > Chi2 = 0.2132$^{***}$ |

***, **, * Significant at 1 %, 5 % and 10 %, respectively / *značajno pri 1 %, 5 % odnosno 10 %*

partner as observed by Head and Mayer (2013). In some cases, the increase in Turkey's GDP will tend to increase the per capita income of the population, which raises the domestic demand that can mostly be meet by the domestic supply, resulting in lower exports. This is also observed by Karamuriro (2015).

Following the argument by Olofsson *et al*. (2018), it is likely that the increase in the GDP of Turkey, reflecting times of economic growth, may instead result in Turkey choosing to use more forest products (e.g., roundwood) domestically to support production (e.g., pulp and sawn wood) rather than exporting. This is in line with Aksu *et al*. (2010), who observed that majority of the investments that have led to the significant development of the Turkish forest product sector since 1980 targeted the domestic market more than foreign markets.

The coefficients of the population of both Turkey and the EU partner, as expected, positively influence the forest exports, and are significant at 0.01 percent.

As expected, the distance coefficient is negative and an increase in distance of 1 percent reduces trade by about 0.96 percent. The reason why the coefficient of distance is statistically insignificant may be due to geographical closeness of European countries. This is in line with Anaman and Al-Kharusi (2003), who observed that this might be due to the fact that the majority of European countries are geographically very close.

Although distance between countries harms the export flows, its effects were insignificant. Different theorists like Marku (2014) have also highlighted that globalization has weakened the significance of distance as the determining factor of trade. Borchert and Yotov (2017) also agree that with time the significance of distance in international trade has decreased, possibly reflecting the decreasing communication costs, and technological advances, which are commonly associated with 'globalization. However, the globalization process has not yet been fully achieved, so the importance of distance might have been reduced but it has not yet lost its power.

The EU countries with a shared border with Turkey had more trade than those without a common border. This is consistent with theory but interestingly just with the effect of distance; the effect of a common border is also insignificant according to the estimate of Hausman- Taylor. This may be for the same reason as the distance effect. At the same time, the Euro effect was negative on the forest products exports from Turkey to the EU countries with a coefficient of -0.37 and this can be because in recent years the Turkish lira has been weak compared to Euro. Similarly, the forest products trade with landlocked EU countries was lower than with those that have access to open waters. This is consistent with the literature as access to open waters avails an alternative of water transport, which reduces the transportation costs since the marginal cost of shipping transportation is low (Wu, 2015).

The coefficient of the relative endowment effect was negative, implying that Turkey exported more to EU partners with less forest resource endowments. The negative sign on the endowment factor shows that countries with considerably more forest resources tend to be more self-sufficient, which reduces their demand for foreign forest products. This explains why the exports of forest products from Turkey decrease as forest resources of the EU countries increase. The forest area first affects the country's forest products output and then the demand of forest products in the trading nation as observed by Yu Cheng (2016). This is also in line with Uusivuori and Tervo (2002), who observe that such countries have relatively large net forest products exports. Even though the endowment effect is highly significant, countries can still import forest products irrespective of their abundant forest resources. This is due to the fact that the forest area may not directly translate to productivity.

### 3.4 Results of forest products export potential

### 3.4. Rezultati analize potencijala izvoza drvnih proizvoda

In order to explore the unrealized forest products trade potential of Turkey with its EU partners, trade volumes estimated from the gravity model were compared with the actual trade volumes from 2005 to 2020 and the results of mean values of periods 2005-2009, 2010-2014, and 2015-2020 are given in Table 4.

Turkey's actual forest products exports increased throughout the study period from an average of 396.8 million USD in the period of 2005-2009 to an average of 433.6 million USD and 733.1 million USD in the periods of 2010-2014 and 2015-2020, respectively. Also, the average export potential increased from 320.2 million USD between 2005-2009 to 743.8 million USD over the study period with an average untapped export potential of 10.8 million USD in the period of 2015-2020.

Turkey's predicted exports exceeded its forest products actual exports to Poland, Spain, Italy, France, Slovenia, Luxembourg, and Denmark throughout the study period. This implies that Turkey had untapped forest products export potential with these EU countries from 2005 to 2020.

On the other hand, Turkey's actual forest products exports exceeded the predicted export value with Austria, Bulgaria, Hungary, Ireland, and Lithuania throughout the study from 2005-2020. This implies that Turkey exhausted its forest products export potential with these countries during this period. Akyüz *et al*. (2010) also observed that there were some countries

**Table 4** Turkey's forest products export actual and potential values (1000 USD)
**Tablica 4.** Stvarne i potencijalne vrijednosti izvoza drvnih proizvoda iz Turske (1000 USD)

| Country *Država* | 2005-2009 | | | 2010-2014 | | | 2015-2020 | | |
|---|---|---|---|---|---|---|---|---|---|
| | *XP* | Actual | Potential | *XP* | Actual | Potential | *XP* | Actual | Potential |
| Austria | 0.71 | 2657.233 | 1706.068 | 0.71 | 4013.960 | 2772.556 | 0.78 | 6247.090 | 4780.713 |
| Belgium | 1.58 | 4776.022 | 7480.218 | 0.83 | 10638.412 | 8663.375 | 0.75 | 21180.091 | 16000.602 |
| Bulgaria | 0.23 | 67553.533 | 15232.438 | 0.46 | 51793.270 | 23528.207 | 0.56 | 74433.428 | 41617.799 |
| Croatia | 2.39 | 729.005 | 1338.558 | 1.41 | 1550.169 | 1836.228 | 0.95 | 3492.122 | 3081.759 |
| Cyprus | 0.12 | 38992.255 | 4739.911 | 68.01 | 29455.607 | 7178.427 | 19397.71 | 24631.464 | 11522.889 |
| Czech | 0.98 | 2404.098 | 1692.419 | 1.82 | 1584.929 | 2764.995 | 1.01 | 4810.024 | 4858.124 |
| Denmark | 2.16 | 2627.325 | 5573.901 | 2.95 | 2702.946 | 7845.866 | 2.42 | 5469.842 | 13275.688 |
| Estonia | 1.68 | 188.457 | 252.483 | 1.12 | 882.501 | 374.832 | 0.73 | 956.098 | 675.309 |
| Finland | 0.96 | 1678.996 | 1525.977 | 1.90 | 1279.859 | 2268.554 | 2.03 | 1767.694 | 3513.359 |
| France | 1.37 | 17347.649 | 23392.417 | 1.14 | 27333.499 | 30955.266 | 1.35 | 39415.445 | 53696.415 |
| Germany | 1.26 | 28932.849 | 36626.729 | 0.97 | 45805.860 | 43921.831 | 1.34 | 63867.907 | 84926.321 |
| Greece | 1.04 | 54343.720 | 50865.761 | 1.20 | 51450.387 | 59693.240 | 0.92 | 84433.217 | 74101.156 |
| Hungary | 0.46 | 4150.138 | 1665.529 | 0.47 | 5365.199 | 2422.859 | 0.63 | 7623.816 | 4294.764 |
| Ireland | 0.34 | 7493.055 | 2294.916 | 0.30 | 11940.315 | 3536.833 | 0.40 | 19019.345 | 7611.188 |
| Italy | 1.34 | 20123.519 | 26546.995 | 1.59 | 23788.585 | 36838.936 | 1.32 | 44499.400 | 58563.336 |
| Latvia | 1.37 | 368.467 | 373.958 | 1.39 | 533.719 | 515.318 | 0.69 | 1309.980 | 888.417 |
| Lithuania | 0.39 | 1720.601 | 631.472 | 0.51 | 1832.806 | 937.797 | 0.35 | 4457.175 | 1517.564 |
| Luxembourg | 9.34 | 108.424 | 432.932 | 5.80 | 90.027 | 478.973 | 3.50 | 407.702 | 934.223 |
| Malta | 0.75 | 547.196 | 359.244 | 0.76 | 1108.778 | 837.374 | 0.66 | 2876.567 | 1732.570 |
| Netherlands | 0.98 | 11803.373 | 11600.029 | 1.02 | 16946.609 | 17454.568 | 1.21 | 24857.668 | 30385.016 |
| Poland | 1.72 | 5508.313 | 9512.953 | 2.29 | 6510.124 | 14725.237 | 2.94 | 9428.035 | 26551.856 |
| Portugal | 1.73 | 1775.817 | 2678.754 | 0.87 | 4314.815 | 3656.062 | 0.45 | 15601.605 | 6100.140 |
| Romania | 0.86 | 59347.495 | 50486.438 | 2.37 | 8515.018 | 73421.297 | 2.95 | 46301.985 | 138353.686 |
| Slovakia | 3.37 | 220.900 | 696.940 | 0.41 | 2748.673 | 1042.600 | 0.62 | 3842.385 | 2339.851 |
| Slovenia | 1.46 | 451.170 | 660.313 | 1.38 | 930.645 | 1308.429 | 1.54 | 1125.829 | 1749.426 |
| Spain | 2.02 | 8102.697 | 14928.171 | 1.88 | 9112.649 | 16542.429 | 1.55 | 23292.263 | 36992.285 |
| Sweden | 1.24 | 3437.432 | 3827.142 | 0.87 | 7495.853 | 6267.848 | 0.73 | 13751.790 | 10094.287 |
| UK | 0.97 | 49452.960 | 43073.342 | 0.57 | 103909.497 | 56658.332 | 0.56 | 183969.517 | 103661.891 |
| TOTAL | | 396842.699 | 320196.008 | | 433634.711 | 428448.269 | | 733069.484 | 743820.634 |

*XP* – mean values of export potentials in that period / *XP – srednje vrijednosti izvoznih potencijala u promatranom razdoblju*

where Turkey's actual forest exports exceeded the predicted forest exports. These included only two countries - Bulgaria and Cyprus.

Even though Turkey had exceeded its forest products export potential with Belgium, Portugal, Slovakia, Sweden, Latvia, Greece, Estonia and Croatia at the beginning of the study, gradually this trend changed. The actual forest products exports from Turkey to these countries exceeded the predicted export value in the last periods. On the contrary, there some countries like Romania, Finland, and Czech Republic, where Turkey's actual forest products exports to these countries exceeded the predicted value at the beginning of the study (Table 4).

Similarly, the Turkey's forest products actual exports to Cyprus generally exceeded the predicted exports in the period of 2005-2009. However, in the next periods of 2010-2014 and 2015-2020, there is a huge difference as the predicted export value exceeded the actual forest products exports by an average XP of 68.01 and 19397.71 in the respective periods (Table 4). This increase in the untapped export potential between Turkey and Cyprus can be explained by the big fall in forest products exports from Turkey to Cyprus from 2013. The UN Comtrade database reports that the total forest products exports fell from over 34 million USD in 2013 to just 22,346 USD in 2014 and this fall continued through to 2016 (United Nations, 2021).

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

In this study, gravity models were applied and estimated to analyse the forest products trade between Turkey and EU countries from 2005 to 2020. The findings of the study highlight that the GDP of EU partner countries, and the population of the exporting and importing countries were highly significant determinants of the volume of forest products exports from Turkey to the EU, while the endowment factor of the EU countries relative to Turkey deters the forest products exports from Turkey to the EU countries.

The derived elasticities were applied to analyse the export potential of Turkey to the EU and findings highlight that there is untapped export potential that

Turkey has to utilize to benefit from the foreign forest products trade.

The study provides significant results that can help policy makers to obtain a clearer view on how to improve Turkey's forest products trade with the EU. Emphasis should be given to EU countries with higher GDP and higher GDP growth. Turkey should take full advantage of the deepening bilateral trade relationship with the EU to serve as an instrument for the expansion of forest products trade. Besides, the promotion of forest products exports is important in the economic growth of the country and improves the international competitiveness of its forest sector. As such, more export-focused schemes should be directed to the forest products trade with the EU market.

**Acknowledgements** – Zahvala

This article includes a part of the results from a master's thesis of Henry Eric Magezi titled "Foreign Trade Analysis between Turkey and European Union Countries in Forest Products Sector" under the supervision of Assoc. Prof. Dr. Taner Okan at the Institute of Graduate Studies, Istanbul University-Cerrahpaşa.

## 5 REFERENCES
## 5. LITERATURA

1. Aksu, B.; Hüseyin, K.; Kurtoğlu, A., 2010: The forest products industry in Turkey. African Journal of Business Management, 5 (6): 2363-2369.
2. Akyüz, K. C.; Yıldırım, I.; Balaban, Y.; Gedik, T.; Korkut, S., 2010: Examination of forest products trade between Turkey and European Union countries with gravity model approach. African Journal of Biotechnology, 9 (16): 2375-2380.
3. Akyüz, K. C.; Yıldırım, I.; Ersen, N.; Akyüz, I.; Memiş, D., 2020: Competitiveness of the forest products industry in turkey: the revealed comparative advantage index. Drewno, 63 (205): 155-170. https://doi.org/10.12841/wood.1644-3985.333.09
4. Anaman, K. A.; Al-Kharusi, L. H. S., 2003: Analysis of trade flows between Brunei Darussalam and the European Union. ASEAN Economic Bulletin, 20 (1): 60-73.
5. Anderson, J. E., 2011: The gravity model, annual review of economics. Annual Reviews, 3 (1): 133-160. https://doi.org/10.1146/annurev-economics-111809-125114
6. Baltagi, B. H., 2001: Econometric analysis of panel data, 2nd ed. John Wiley & Sons, New York, USA.
7. Borchert, I.; Yotov, Y. V., 2017: Distance, globalization, and international trade. Economics Letters, 153: 32-38. https://doi.org/10.1016/j.econlet.2017.01.023
8. Buongiorno, J., 2015: Monetary union and forest products trade – The case of the Euro. Journal of Forest Economics, 21 (4): 238-249. https://doi.org/10.1016/j.jfe.2015.09.005
9. Buongiorno, J., 2016: Gravity model of forest products trade: application to forecasting and policy analysis. Forestry, 89 (2): 117-126. https://doi.org/10.1093/forestry/cpw005
10. Egger, P., 2002: An econometric view on the estimation of gravity models and the calculation of trade potentials. The World Economy, 25 (2): 297-312. https://doi.org/10.1111/1467-9701.00432
11. Head, K.; Mayer, T., 2013: Gravity equations: Workhorse, toolkit, and cookbook. CEPII Working Paper, 2013-2027.
12. Karagoz, K.; Saray, M. O., 2010: Trade potential of Turkey with Asia-Pacific Countries: Evidence from panel gravity model. International Economic Studies, 36 (1): 19-26.
13. Karamuriro, H. T., 2015: Determinants of Uganda's export performance; a gravity model approach. International Journal of Economics and Business Research, 4 (2): 45-54. https://doi.org/10.11648/j.ijber.20150402.14
14. Larson, J.; Baker, J.; Latta, G.; Ohrel, S.; Wade, C., 2018: Modeling international trade of forest products: Application of PPML to a gravity model of trade. Forest Products Journal, 68 (3): 303-316.
15. Lundmark, R., 2010: European trade in forests products and fuels. Journal of Forest Economics, 16 (3): 235-251. https://doi.org/10.1016/j.jfe.2009.11.007
16. Marku, M., 2014: The gravity model on EU countries – An econometric approach. European Journal of Sustainable Development, 3 (3): 149. https://doi.org/10.14207/ejsd.2014.v3n3p149
17. McCallum, J., 1995: National borders matters: Canada – U.S. regional trade patterns. The American Economic Review, 85 (3): 615-623.
18. McPherson, M. Q.; Trumbull, W. N., 2008: Rescuing observed fixed effects: Using the Hausman-Taylor method for out-of-sample trade projections. The International Trade Journal, 22 (3): 315-340. https://doi.org/10.1080/08853900802191389
19. Olofsson, C.; Wadsten, J.; Lundmark, J., 2018: European trade and projections in forest-based feed-stocks. Scandinavian Journal of Forest Research, 33 (8): 809-814. https://doi.org/10.1080/02827581.2018.1495255
20. Patuelli, R.; Linders, G.; Metulini, R.; Griffith, D. A., 2015: The space of gravity: Spatial filtering estimation of a gravity model for bilateral trade. Working Paper series 15-27, Rimini Centre for Economic Analysis.
21. Usivuori, J.; Tervo, M., 2002: Comparative advantage and forest endowment in forest products trade: Evidence from panel data of OECD countries. Journal of Forest Economics, 8 (1): 53-75. https://doi.org/10.1078/1104-6899-00004
22. Vu, T. H.; Tian, G.; Zhang, B.; Nguyen, T. V., 2019: Determinants of Vietnam's wood products trade: application of the gravity model. Journal of Sustainable Forestry, 39 (5): 1 445-460. https://doi.org/10.1080/10549811.2019.1682011
23. Wu, H., 2015: Revisiting the distance coefficient in gravity model. New York, USA: Cornel University Library (online). https://arxiv.org/abs/1503.05283 (Accessed May 19, 2021).
24. Yu Cheng, Y., 2016: An influence factor analysis of international trade flow using a gravity model. International Journal of Simulation: Systems, Science & Technology, 1473-8031. https://doi.org/10.5013/IJSSST.a.17.36.23
25. ***European Commission, 2021: European Commission, Directorate-General for Trade 2021, European Union, Trade with Turkey (online). https://webgate.ec.europa.eu/isdb_results/factsheets-/country/details_turkey_en.pdf (Accessed May 15, 2021).
26. ***FAO, 2021: Food and agriculture organization of the United Nations (online). http://www.fao.org/faostat/en/#data/FO (Accessed May 20, 2021).

27. ***GED Study, 2016: Turkey's EU integration at a crossroads. Global Economic Dynamics (GED), Bertelsmann Stiftung. April 2016.
28. ***IMF, 2021: The international monetary fund – economic outlook database (online). https://www.imf.org/en/Data (Accessed May 23, 2021).
29. ***Ministry of Trade, 2019: Industry Furniture, Directorate General of Exports, Ministry of Trade, Republic of Turkey.
30. ***United Nations, 2021: UN Comtrade Database – International Trade Statistics – Import/Export Data (online). https://comtrade.un.org/data (Accessed May 19, 2021).
31. ***World Bank, 2014: Evaluation of the EU-TURKEY Customs Union, Report No. 85830-TR, March 28, 2014.

**Corresponding address:**

**HENRY ERIC MAGEZI**

Istanbul University – Cerrahpaşa, Faculty of Forestry, Department of Forestry Economics, Bahçeköy Merkez Mah., Valide Sultan Caddesi No: 2, 34473, Istanbul, TURKEY, e-mail: henryeric.magezi@ogr.iuc.edu.tr

Lukas Emmerich[1], Christian Brischke[2]

# Impact of Wood Moisture Content on Structural Integrity of Wood Under Dynamic Loads

# Utjecaj sadržaja vode u drvu na strukturnu cjelovitost drva pri dinamičkim opterećenjima

**ORIGINAL SCIENTIFIC PAPER**
**Izvorni znanstveni rad**
Received – prispjelo: 10. 10. 2022.
Accepted – prihvaćeno: 15. 3. 2023.
UDK: 630*82
https://doi.org/10.5552/drvind.2023.0067



**ABSTRACT** • *The majority of mechanical wood properties are negatively affected by wood moisture within the hygroscopic range, disregarding the stress relaxation of wood at very low moisture contents (MC). In contrast, the structural integrity and thus the brittleness of wood appears to be positively affected by moisture. This study aimed at examining the effect of wood MC on the structural integrity of wood between the oven-dry state and MC well above cell wall saturation (CWS), i.e., at approx. 100 %. For both softwood (Picea abies) and hardwoods (Fagus sylvatica and Quercus robur), the structural integrity was assessed on the basis of the Resistance to Impact Milling (RIM) originating from High-Energy Multiple Impact (HEMI) tests. RIM increased with increasing MC in the hygroscopic range, which might be explained by stress relaxation and 'gluing effects' inside the cell wall polymer structure, resulting from a growing network of hydrogen bonds on cell wall level. Increasing MC above CWS caused a slight decrease of RIM in the selected hardwood species, whereas no significant change in RIM was observed when MC varied in the range from CWS to approx. 100 % for the softwood species Norway spruce.*

**KEYWORDS:** *brittleness, High-Energy Multiple Impact (HEMI) test, moisture content, moisture states, resistance to impact milling (RIM)*

**SAŽETAK** • *Sadržaj vode u drvu unutar higroskopskog područja negativno utječe na većinu mehaničkih svojstava drva, bez obzira na popuštanje naprezanja pri vrlo niskom sadržaju vode. Nasuprot tome, čini se da voda u drvu pozitivno utječe na strukturnu cjelovitost, a time i na krtost drva. Cilj ovog istraživanja bio je ispitati utjecaj sadržaja vode u drvu na njegovu strukturnu cjelovitost u području između apsolutno suhog stanja i sadržaja vode znatno većeg od točke zasićenosti vlakanaca, oko 100 %. Strukturna cjelovitost za četinjače (Picea abies) i listače (Fagus sylvatica i Quercus robur) procijenjena je na temelju otpornosti na mljevenje udarcima (RIM), određene primjenom testova višestrukih udaraca visoke energije (HEMI test). S povećanjem sadržaja vode u drvu u higroskopskom se području povećao i RIM, što se može objasniti popuštanjem naprezanja i „efektom lijepljenja" unutar polimerne strukture stanične stijenke zbog povećanja broja vodikovih veza. Povećanje sadržaja vode iznad točke zasićenosti vlakanaca uzrokovalo je blago smanjenje RIM-a odabranih listača, dok je primijećena značajna promjena RIM-a u smrekovine kada je sadržaj vode varirao u rasponu od točke zasićenosti vlakanaca do približno 100 %.*

**KLJUČNE RIJEČI:** *krtost, test višestrukih udaraca visoke energije (HEMI test), sadržaj vode, stanja vlažnosti drva, otpornost na mljevenje udarcima (RIM)*

[1] Authors is researcher at University of Goettingen, Faculty of Forest Sciences and Forest Ecology, Wood Biology and Wood Products, Goettingen, Germany. https://orcid.org/0000-0002-2072-4722
[2] Author is researcher at Thünen Institute of Wood Research, Hamburg, Germany. https://orcid.org/0000-0003-4652-825X

## 1 INTRODUCTION
## 1. UVOD

Wood density and moisture content (*MC*) are the main variables affecting the mechanical properties of wood (Ghelmeziu, 1938; Kollmann, 1951; Wang and Wang 1999; Lachenbruch *et al*., 2010). The stiffness and strength properties of wood are usually positively correlated with wood density (Niemz and Sonderegger, 2003; Niklas and Spatz, 2010; Brischke, 2017), and negatively correlated with wood *MC* in the hygroscopic range, i.e., below cell wall saturation. The latter is often referred to as fibre saturation, which is a somewhat misleading term and does not necessarily represent the moisture state of the wood, from which the mechanical properties and dimensional changes stay unaffected (Brischke and Alfredsen, 2020). However, the latter relationship is more complex. Several mechanical properties show an optimum at 6–12 % wood *MC* and decrease from there with increasing wood *MC* until cell wall saturation (Kretschmann and Green, 1996; Müller, 2015). Below this optimum, stress relaxation of the cellulose fibrils may occur, and provoke an increase in strength and stiffness (Ishimaru *et al*., 2001).

Above cell wall saturation, i.e., when the cell lumens start to get filled with free water, no further changes in mechanical properties are expected, since water bodies inside the cell lumens are not supposed to contribute to the overall stiffness and strength of moist wood (e.g., Hering *et al*., 2012). Solely, at very high moisture loads of the xylem tissue, the incompressibility of the liquid water may enhance its compression strength and derivative properties of the wood. Similar observations were made by Megnis *et al*. (2002) and Ulvcrona *et al*. (2006), who suggested hydraulic effects in Norway spruce (*Picea abies*) wood impregnated with vegetable oils.

Remarkably enhanced structural integrity was observed in wood samples after water pressure impregnation and soaking in a study by Brischke *et al*. (2014), who conducted High-Energy Multiple Impact (HEMI) tests on different timbers for marine applications. The Resistance to Impact Milling (*RIM*) was significantly higher for the majority of wood species under test compared to those obtained with oven-dry specimens. In contrast, the dynamic and static hardness of the matched samples were reduced through wetting. However, intermediate *MC*s between the absolute dry state and water saturation were not the focus of their study. In HEMI tests, small defect-free wood specimens were crushed using steel balls in the bowl of a heavy vibratory disc mill. The fragments obtained were analysed and the degree of integrity (I) as well as a percentage of fine fragments (F, fragments smaller than 1 mm in width) were determined. The *RIM* data can be used to detect traces of wood degradation, e.g., through thermal and chemical modification, fungal decay, gamma irradiation, and salt-induced damage (Brischke *et al*., 2006, 2012; Rapp *et al*., 2006; Despot *et al*., 2007; Welzbacher *et al*., 2011; Kirker *et al*., 2020; Emmerich *et al*., 2021). The *RIM* values obtained in HEMI tests are rather insensitive to wood density variation and macroscopic defects such as checks after weathering (Brischke, 2017). In contrast, the structural integrity of wood, expressed as *RIM*, seems to be affected by wood moisture content, opposite to the well-known relationship between different strength properties of wood and *MC*.

The aim of this study was therefore to examine the impact of changes in the wood *MC* below and above cell wall saturation on the structural integrity of wood. Therefore, three wood species were investigated as examples, representing coniferous, ring-porous, and diffuse-porous hardwoods.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

### 2.1 Preparation and conditioning of wood specimens
### 2.1. Priprema i kondicioniranje uzoraka drva

Axially matched specimens of 5 mm × 20 mm × 10 mm (ax.) were prepared from European beech (*Fagus sylvatica*), English oak (*Quercus robur*), and Norway spruce (*Picea abies*). The specimens were cut from 20 lattices per wood species with a cross-section of 5 mm × 20 mm. Thus, each set of 20 specimens contained one specimen per lattice. In total, 1,300 specimens were prepared from each wood species representing 65 sets, i.e., sets for *n*=5 replicate tests for each target moisture content (*MC*), which was calculated according to Eq. 1. The target *MC* and the respective conditioning regimes are summarised in Table 1.

$$MC = \frac{m_0 - m_{cond}}{m_0} \cdot 100\ [\%] \tag{1}$$

where the moisture content *MC* is calculated on the basis of the initial oven-dry mass before conditioning ($m_0$ after drying at (103±2) °C for 48 h) and the conditioned mass in equilibrium state ($m_{cond}$).

### 2.2 High-Energy Multiple Impact (HEMI) tests
### 2.2. Test višestrukih udaraca visoke energije (HEMI test)

The development and optimisation of the HEMI test was described by Rapp *et al.* (2005) and Brischke *et al.* (2006a, b). In the present study, the following procedure was applied: 20 oven-dried specimens of 10 mm (ax.) × 5 mm × 20 mm were placed in the bowl (140 mm in diameter) of a heavy-vibratory-impact ball mill (Herzog HSM 100-H; Herzog Maschinenfabrik, Osnabrück, Germany) together with one steel ball of 35 mm diame-

**Table 1** Target moisture contents and corresponding conditioning regimes
**Tablica 1.** Ciljani sadržaj vode i odgovarajući režimi kondicioniranja

| **Target moisture content, %** *Ciljani sadržaj vode, %* | **Conditioning regime** / *Režim kondicioniranja* |
|---|---|
| 0 | Oven-drying at 103°C |
| 5 | 23 % RH ($CH_3CO_2K$)*, 20 °C |
| 8 | 43 % RH ($K_2CO_3$)*, 20 °C |
| 12 | 65 % RH, Climate cabinet |
| 15 | 75 % RH (NaCl)*, 20 °C |
| 18 | 85 % RH (KCl)*, 20 °C |
| 25 | 98 % RH ($K_2SO_4$)*, 20 °C |
| 30 | Exposed above a deionised water body, 20°C |
| 30 | Vacuum-pressure impregnation during submersion in water and subsequent re-drying *Vakuumsko-tlačna impregnacija vodom i ponovno naknadno sušenje* |
| 40 | |
| 60 | |
| 80 | |
| 100 | |

*Exposure above respective saturated salt solution or deionised water until constant mass / *izlaganje iznad odgovarajuće zasićene otopine soli ili deionizirane vode do konstantne mase*

ter for crushing the specimens. Three balls of 12 mm diameter and three of 6 mm diameter were added to ensure the impact with smaller wood fragments. The bowl was shaken for 60 s at a rotary frequency of 23.3 $s^{-1}$ and a stroke of 12 mm. The fragments of the 20 specimens were fractionated on a slotted sieve according to ISO 5223 (1996) with a slit width of 1 mm using an orbital shaker at an amplitude of 25 mm and a rotary frequency of 200 $min^{-1}$ for 2 min. Sieving served to identify the fine fragments being smaller than 1 mm, whereas the 20 biggest fragments from the entire fraction were selected visually. Subsequently, the degree of integrity (*I*), fine fraction (*F*) and Resistance to Impact Milling (*RIM*) were calculated according to Eq. 2-4:

$$I = \frac{m_{20}}{m_{\text{all}}} \cdot 100 \text{ [\%]} \tag{2}$$

where the degree of integrity *I* is the ratio of the mass of the 20 biggest fragments $m_{20}$ to the mass of all fractions $m_{all}$ after crushing.

$$F = \frac{m_{\text{fragments<1mm}}}{m_{\text{all}}} \cdot 100 \text{ [\%]} \tag{3}$$

where the fine fraction *F* is the ratio of the mass of fragments < 1 mm to the mass of all fractions $m_{all}$ multiplied by 100.

$$RIM = \frac{(I - 3 \cdot F) + 300}{400} \text{ [\%]} \tag{4}$$

where *RIM* is the resistance to impact milling as a measure for the structural integrity of the material.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

The structural integrity of the tested wood species was significantly affected by wood moisture in the hygroscopic range, as shown in Table 2 and Figure 3. The Resistance to Impact Milling (*RIM*) of all three wood species was linearly positively correlated with the wood moisture content (*MC*), but this effect was wood-species-specific, with beech being less affected than Norway spruce and English oak. In contrast to the hygroscopic range, only the *RIM* of the hardwoods was negatively affected by the wood *MC* above cell wall saturation (CWS), showing a slight logarithmic decrease with increasing *MC*. In contrast, the *RIM* of Norway spruce occurred to be unaffected by the wood *MC* above CWS (Figure 3). The absolute values of the degree of integrity (*I*), the fine fraction percentage (*F*) and the *RIM* as well as their standard deviations are summarised in Table 2. The latter is remarkably low regardless of the *MC*. Even at the highest *MC*, i.e., approximately at 100 %, the coefficients of variation (COV) were less than 2 %.

The effect of wood *MC* on structural integrity was opposite to those on different mechanical properties, as reported by Gerhards (1982), who found negative effects of moisture content in a range between 6 and 20 % on the following in descending order: compressive strength $_{\text{parallel to the grain}}$ > compressive strength $_{\text{perpendicular to the grain}}$ > bending strength > MOE $_{\text{perpendicular to the grain}}$ > shear modulus > tensile strength $_{\text{parallel to the grain}}$ > tensile strength $_{\text{perpendicular to the grain}}$ > MOE $_{\text{parallel to the grain}}$. Similar negative effects of wood *MC* on different mechanical properties have been observed by Wang and Wang (1999), Nocetti *et al*. (2015), and Mvondo *et al*. (2017). At *MC* below 10 %, some mechanical properties such as tensile strength increase with increasing *MC*. The latter is commonly accepted to be the result of stress relaxation (e.g., Kretschmann and Green, 1996; Ishimaru *et al*., 2001). The progressive moistening of wood leads to a decline of different static and dynamic mechanical properties since more

**Table 2** Moisture content (*MC* in %), degree of integrity (*I* in %), fine fraction (*F* in %) and Resistance to Impact Milling (*RIM* in %) depending on wood species (mean values with standard deviation in parentheses)
**Tablica 2.** Sadržaj vode (*MC*, u %), stupanj cjelovitosti (*I*, u %), fina frakcija (*F*, u %) i otpornost na mljevenje udarcima (*RIM*, u %) ovisno o vrsti drva (srednje vrijednosti sa standardnom devijacijom navedene su u zagradama)

| **Wood species** / *Vrsta drva* | ***MC*, %** | ***I*, %** | ***F*, %** | ***RIM*, %** |
|---|---|---|---|---|
| *Quercus robur* L. | 0 (± 0) | 43.9 (± 1.5) | 6.4 (± 0.9) | 81.2 (± 1.0) |
| | 4.1 (± 0.1) | 47.7 (± 2.8) | 6.4 (± 0.9) | 83.9 (± 1.3) |
| | 7.1 (± 0.1) | 51.1 (± 3.9) | 2.7 (± 0.9) | 85.7 (± 1.4) |
| | 11.3 (± 0.2) | 58.3 (± 1.8) | 1.0 (± 0.1) | 88.8 (± 0.4) |
| | 11.9 (± 0.1) | 59.1 (± 2.1) | 1.1 (± 0.6) | 88.9 (± 0.5) |
| | 14.7 (± 0.1) | 63.1 (± 3.8) | 0.6 (± 0.1) | 90.3 (± 1.0) |
| | 18.9 (± 0.2) | 66.8 (± 2.6) | 0.2 (± 0.1) | 91.5 (± 0.6) |
| | 21.9 (± 0.3) | 69.0 (± 4.9) | 0.2 (± 0.0) | 92.1 (± 1.3) |
| | 32.0 (± 0.1) | 78.7 (± 6.8) | 0.1 (± 0.0) | 94.6 (± 1.7) |
| | 41.7 (± 0.4) | 76.1 (± 7.8) | 0.1 (± 0.0) | 93.9 (± 2.0) |
| | 61.7 (± 0.4) | 70.4 (± 4.6) | 0.1 (± 0.0) | 92.5 (± 1.2) |
| | 80.2 (± 1.6) | 67.0 (± 6.1) | 0.1 (± 0.0) | 91.6 (± 1.6) |
| | 98.9 (± 2.9) | 69.9 (± 2.7) | 0.1 (± 0.0) | 92.4 (± 0.7) |
| *Fagus sylvatica* L. | 0 (± 0) | 53.5 (± 2.0) | 1.1 (± 0.1) | 87.5 (± 0.5) |
| | 4.1 (± 0.1) | 55.6 (± 2.0) | 0.6 (± 0.1) | 88.4 (± 0.5) |
| | 7.0 (± 0.1) | 58.3 (± 3.6) | 0.3 (± 0.0) | 89.4 (± 0.9) |
| | 11.4 (± 0.1) | 63.0 (± 4.7) | 0.2 (± 0.1) | 90.6 (± 1.2) |
| | 12.1 (± 0.1) | 62.3 (± 3.9) | 0.1 (± 0.0) | 90.5 (± 1.0) |
| | 15.7 (± 0.1) | 67.0 (± 3.9) | 0.1 (± 0.0) | 91.7 (± 1.0) |
| | 20.7 (± 0.0) | 71.3 (± 2.9) | 0.0 (± 0.0) | 92.8 (± 0.8) |
| | 24.6 (± 0.7) | 77.0 (± 4.1) | 0.1 (± 0.1) | 94.2 (± 1.1) |
| | 32.0 (± 0.2) | 80.9 (± 4.0) | 0.0 (± 0.0) | 95.2 (± 1.0) |
| | 41.1 (± 0.9) | 77.0 (± 6.7) | 0.0 (± 0.0) | 94.2 (± 1.7) |
| | 61.6 (± 0.2) | 71.8 (± 5.2) | 0.0 (± 0.0) | 92.9 (± 1.3) |
| | 81.1 (± 0.7) | 69.8 (± 4.0) | 0.0 (± 0.0) | 92.4 (± 1.0) |
| | 98.8 (± 1.5) | 71.2 (± 6.2) | 0.0 (± 0.0) | 92.8 (± 1.6) |
| *Picea abies* (L.) H. Karst. | 0 (± 0) | 28.1 (± 3.4) | 1.7 (± 0.3) | 80.8 (± 0.8) |
| | 4.8 (± 0.1) | 35.7 (± 3.7) | 1.1 (± 0.2) | 83.1 (± 0.8) |
| | 8.1 (± 0.1) | 37.4 (± 5.1) | 0.9 (± 0.1) | 83.7 (± 1.3) |
| | 12.2 (± 0.1) | 49.5 (± 3.1) | 0.4 (± 0.1) | 87.1 (± 0.8) |
| | 13.2 (± 0.1) | 49.4 (± 1.7) | 0.3 (± 0.1) | 87.1 (± 0.4) |
| | 16.6 (± 0.2) | 56.1 (± 4.2) | 0.4 (± 0.1) | 88.7 (± 1.1) |
| | 21.2 (± 0.3) | 63.7 (± 2.2) | 0.2 (± 0.1) | 90.8 (± 0.6) |
| | 22.8 (± 0.5) | 67.5 (± 3.3) | 0.3 (± 0.2) | 91.7 (± 0.7) |
| | 33.3 (± 0.3) | 72.9 (± 4.3) | 0.2 (± 0.2) | 93.0 (± 1.1) |
| | 41.6 (± 1.6) | 73.0 (± 4.1) | 0.2 (± 0.1) | 93.1 (± 1.0) |
| | 62.5 (± 0.3) | 72.4 (± 3.3) | 0.1 (± 0.0) | 93.0 (± 0.8) |
| | 82.5 (± 0.5) | 74.8 (± 0.8) | 0.1 (± 0.1) | 93.6 (± 0.2) |
| | 100.4 (± 2.7) | 70.9 (± 4.1) | 0.1 (± 0.1) | 92.6 (± 1.0) |

and more water molecules lose the bonds within the hierarchical cell wall structure. The situation is different with the structural integrity of wood. Both, the degree of integrity *I* and the *RIM* increased with increasing *MC* in the hygroscopic range (Figure 1 and Figure 3), which again might be explained to some extent by stress relaxation. In consideration of the fine fraction percentage *F*, which clearly dropped from the oven-dry state to the CWS (Figure 2), 'gluing effects' (Brischke *et al*., 2012) might have a further positive effect on the structural integrity and occur with increasing amount of hydrogen bonds.

In contrast, the values of *I* and *RIM* in English oak and beech decreased slightly with increasing *MC* in a range between CWS and approx. 100 %. The structural integrity of Norway spruce was not significantly affected by *MC* changes above CWS.

Ghelmeziu (1938) conducted comprehensive experiments on numerous factors influencing the Impact Bending Strength (*IBS*) of wood, including the wood *MC*. Since impact bending is among the dominating loads in HEMI tests (Welzbacher *et al*., 2011), one may expect similar interrelationships between wood *MC* and *IBS* and *RIM,* respectively. As shown in Figure 4,

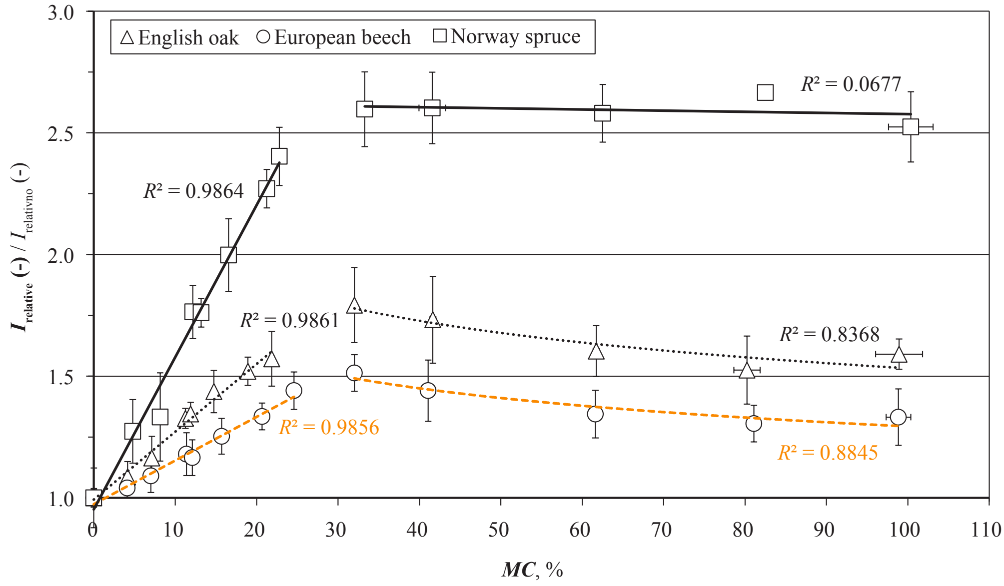



**Figure 1** Relative degree of integrity ($I_{relative}$) depending on *MC* in hygroscopic and over-hygroscopic *MC* range shown for English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.)
**Slika 1.** Relativni stupanj cjelovitosti ($I_{relativno}$) ovisno o sadržaju vode u higroskopskom području i iznad njega za hrastovinu (*Quercus robur* L.), bukovinu (*Fagus sylvatica* L.) i smrekovinu (*Picea abies* (L.) H. Karst.)

Ghelmeziu's data do not demonstrate a clear relationship between *IBS* and wood *MC*, neither below nor above the CWS. While IBS and *RIM* are quite well correlated for a given *MC* in both untreated (Brischke, 2017) and modified wood specimens (Emmerich *et al.*, 2021), they are apparently affected differently by wood *MC*. A general issue with the results of dynamic mechanical testing of wood is their high variability. As Ghelmeziu (1938) and many others have noted, this is particularly valid for the wood's impact bending strength and may have masked a possible relationship between the *IBS* and *MC* data presented in Figure 4. Thus, on opposite to standardised dynamic mechanical testing methods, *RIM* as a measure of the structural integrity turned once more out as an appropriate and sensitive method to detect physical or chemical changes on cell wall level, which in this study originated from deposits of water molecules.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

The structural integrity of wood, as a measure of the resistance of wood against dynamic impacts, seemed

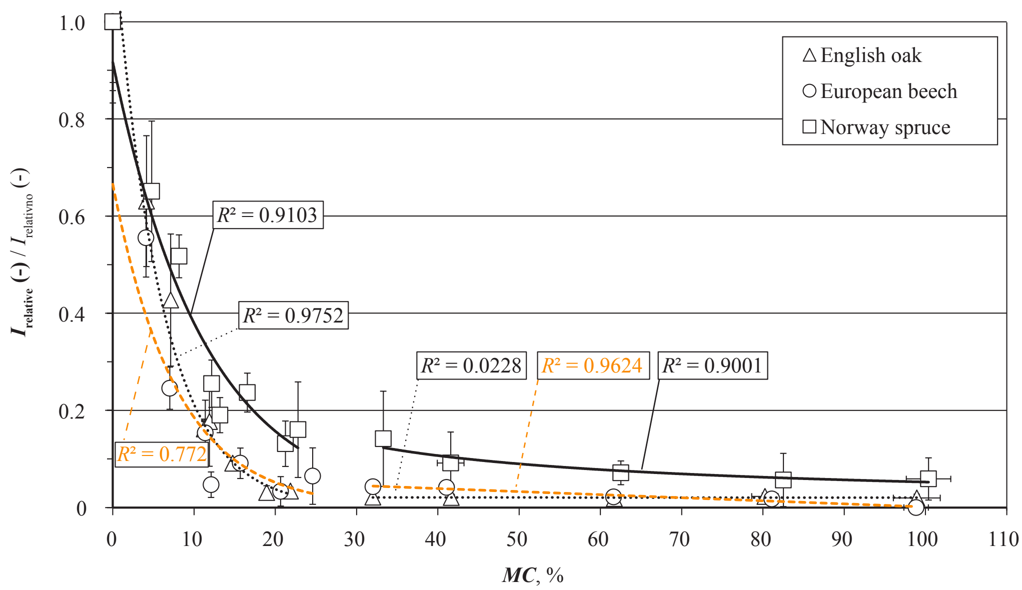



**Figure 2** Relative fine fraction ($F_{relative}$) depending on *MC* in hygroscopic and over-hygroscopic *MC* range shown for English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.)
**Slika 2.** Relativna fina frakcija ($F_{relativno}$) ovisno o sadržaju vode u higroskopskom području i iznad njega za hrastovinu (*Quercus robur* L.), bukovinu (*Fagus sylvatica* L.) i smrekovinu (*Picea abies* (L.) H. Karst.)

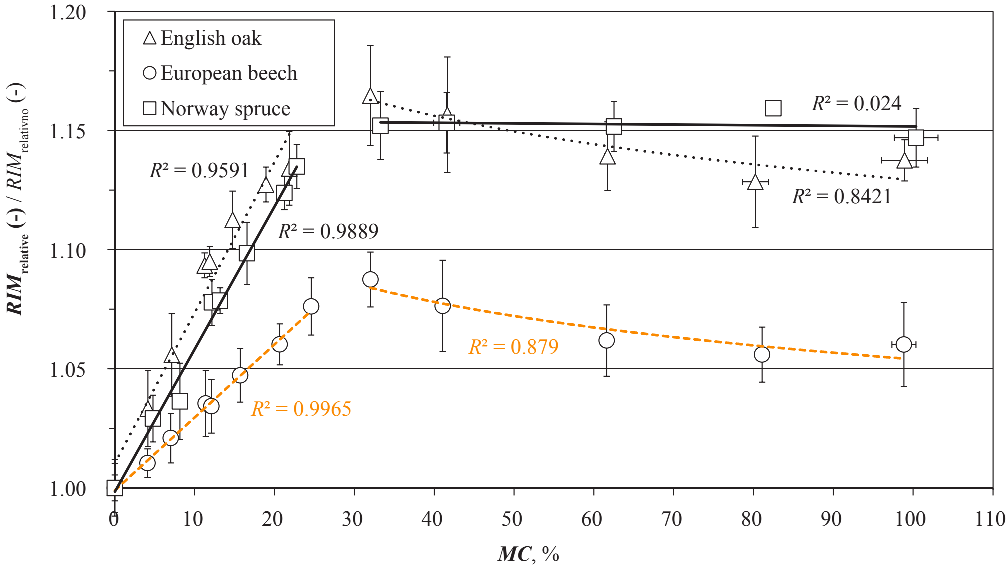



**Figure 3** Relative resistance to impact milling ($RIM_{relative}$) depending on *MC* in hygroscopic and over-hygroscopic *MC* range shown for English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.)

**Slika 3.** Relativna otpornost na mljevenje udarcima ($RIM_{relativno}$) ovisno o sadržaju vode u higroskopskom području i iznad njega za hrastovinu (*Quercus robur* L.), bukovinu (*Fagus sylvatica* L.) i smrekovinu (*Picea abies* (L.) H. Karst.)

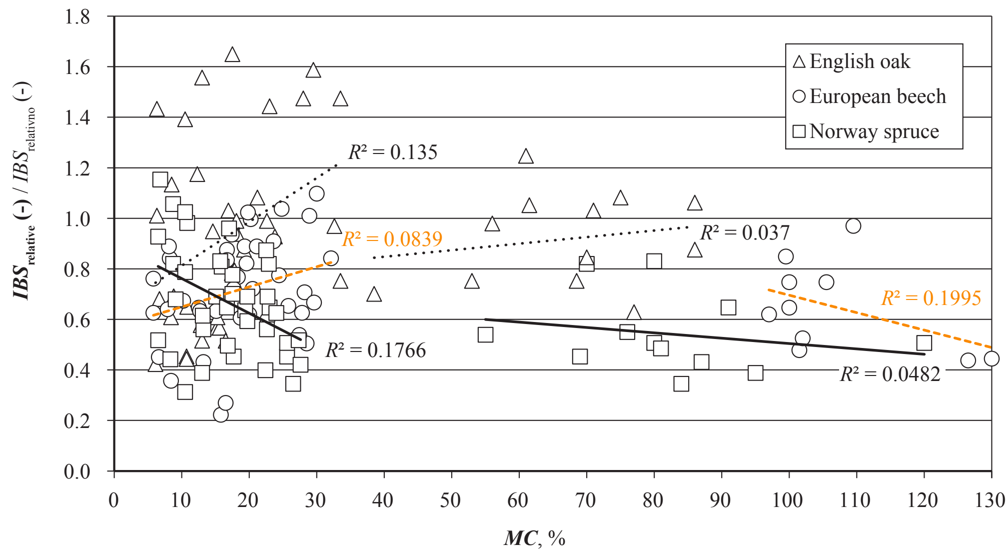



**Figure 4** Relative impact bending strength ($IBS_{relative}$) depending on *MC* in hygroscopic and over-hygroscopic *MC* range shown for English oak (*Quercus robur* L.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) H. Karst.)

**Slika 4.** Relativna udarna čvrstoća ($IBS_{relativno}$) ovisno o sadržaju vode u higroskopskom području i iznad njega za hrastovinu (*Quercus robur* L.), bukovinu (*Fagus sylvatica* L.) i smrekovinu (*Picea abies* (L.) H. Karst.)

to be significantly affected by the wood *MC* in the range from 0 % *MC* to CWS. Such interrelationship between wood *MC* and its behaviour under dynamic loads was derived from a multiple dynamic impact test (HEMI test) and this could hardly be verified in standardised single dynamic impact tests (e.g. impact bending strength). In particular, the structural integrity (*RIM*) increased linearly with increasing wood *MC* up to CWS for both softwoods and hardwoods. Conversely, increasing the wood *MC* from CWS to ca. 100 % caused a slight decrease in *RIM* for the hardwood species, without a significant impact on the *RIM* of Norway spruce. *MC* induced changes in structural integrity (*RIM*) along the hygroscopic range could be explained by stress relaxation and 'gluing effects' resulting from a growing network of hydrogen bonds at the cell wall level.

## 5 REFERENCES
## 5. LITERATURA


1. Brischke, C., 2017: Interrelationship between Static and Dynamic Strength Properties of Wood and its Structural Integrity. Drvna industrija, 68: 53-60.
2. Brischke, C.; Alfredsen, G., 2020: Wood-water relationships and their role for wood susceptibility to fungal decay. Applied Microbiology and Biotechnology, 104: 3781-3795. https://doi.org/10.1007/s00253-020-10479-1
3. Brischke, C.; Koch, S.; Rapp, A. O.; Welzbacher, C. R., 2005: Surface properties of thermally treated wood – Wear, abrasion and hardness. In: Proceedings of the 2nd European Conference on Wood Modification, Göttingen, Germany, 6-7 October, pp. 371-375.
4. Brischke, C.; Iseler, N.; Meyer, L.; Sawyer, G., 2014: Testing the mechanical resistance of timber used for construction in the marine environment. International Wood Products Journal, 5: 39-49. https://dx.doi.org/10.1179/2042645313Y.0000000050
5. Brischke, C.; Welzbacher, C. R.; Huckfeldt, T., 2008: Influence of fungal decay by different basidiomycetes on the structural integrity of Norway spruce wood. Holz als Roh- und Werkstoff, 66: 433-438. https://dx.doi.org/10.1007/s00107-008-0257-1
6. Brischke, C.; Welzbacher, C. R.; Huckfeldt, T.; Schuh, F., 2009: Impact of decay and blue stain causing fungi on the structural integrity of wood. Document IRG/WP 09-10699. International Research Group on Wood Protection, Stockholm.
7. Brischke, C.; Welzbacher, C. R.; Rapp, A. O., 2006: Detection of fungal decay by high-energy multiple impact (HEMI) testing. Holzforschung, 60: 217-222. https://dx.doi.org /10.1515/HF.2006.036
8. Brischke, C.; Zimmer, K.; Ulvcrona, T.; Bollmus, S.; Welzbacher, C. R.; Thomsen, O., 2012: The impact of various modification processes on the structural integrity of wood. In: Proceedings of the 6th European Conference on Wood Modification, Ljubljana, Slovenia, 17-18 September 2012.
9. Despot, R.; Hasan, M.; Brischke, C.; Welzbacher, C. R.; Rapp, A. O., 2007: Changes in physical, mechanical and chemical properties of wood during sterilization by gamma irradiation. Holzforschung, 61: 267-271. https://dx.doi.org /10.1515/HF.2007.064
10. Emmerich, L.; Brischke, C.; Bollmus, S.; Militz, H., 2021: Dynamic strength properties and structural integrity of wood modified with cyclic N-methylol and N-methyl compounds. Holzforschung 75: 932-944. https://doi.org/10.1515/hf-2021-0013
11. Esteves, B.; Pereira, H., 2008: Wood modification by heat treatment: A review. BioResources, 4: 370-404.
12. Gerhards, C. C., 1982: Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. Wood and Fiber Science, 14: 4-36.
13. Ghelmeziu, N., 1938: Untersuchungen über die Schlagfestigkeit von Bauhölzern. Holz als Roh- und Werkstoff, 1: 585-603. https://dx.doi.org /10.1007/BF02639957
14. Hering, S.; Keunecke, D.; Niemz, P., 2012: Moisture-dependent orthotropic elasticity of beech wood. Wood Science Technology, 46: 927-938. https://doi.org/10.1007/s00226-011-0449-4
15. Huckfeldt, T.; Eichhorn, M.; Koch, G.; Welzbacher, C. R.; Brischke, C., 2010: Bewertung von Schäden an dauerhaften Hölzern am Beispiel von Bongossi (*Lophira alata*). Eur. Sanierungskalender, 2010: 95-108.
16. Ishimaru, Y.; Oshima, K.; Iida, I., 2001: Changes in the mechanical properties of wood during a period of moisture conditioning. Journal of Wood Science, 47: 254-261.
17. Kirker, G. T.; Brischke, C.; Passarini, L.; Zelinka, S. L., 2020: Salt damage in wood: Controlled laboratory exposures and mechanical property measurements. Wood and Fiber Science, 52: 44-52.
18. Kretschmann, D. E.; Green, D. W., 1996: Modeling moisture content-mechanical property relationships for clear southern pine. Wood and Fiber Science, 28: 320-337.
19. Lachenbruch, B.; Johnson, G. R.; Downes, G. M.; Evans, R., 2010: Relationships of density, microfibril angle, and sound velocity with stiffness and strength in mature wood of Douglas-fir. Canadian Journal of Forest Research, 40: 55-64. https://dx.doi.org /10.1139/X09-174
20. Megnis, M.; Olsson, T.; Varna, J.; Lindberg, H., 2002: Mechanical performance of linseed oil impregnated pine as correlated to the take-up level. Wood Science and Technology, 36: 1-18. https://doi.org/10.1007/s002260100120
21. Meyer, L.; Brischke, C.; Welzbacher, C. R., 2011: Dynamic and static hardness of wood: method development and comparative studies. International Wood Products Journal, 2 (1): 5-11. https://doi.org/10.1179/2042645311Y.0000000005
22. Müller, D. I. C., 2015: Untersuchung von Holzwerkstoffen unter Schlagbelastung zur Beurteilung der Werkstoffeignung für den Maschinenbau [Investigation of wood composites under impact load to assess the suitability of materials for machine construction]. PhD Thesis, Technical University Chemnitz.
23. Niemz, P.; Sonderegger, W., 2003: Untersuchungen zur Korrelation ausgewählter Holzeigenschaften untereinander und mit der Rohdichte unter Verwendung von 103 Holzarten [Analysis of the correlation between selected wood properties among each other and the density of 103 wood species]. Schweizerische Zeitschrift für das Forstwesen, 154: 489-493.
24. Niklas, K. J.; Spatz, H. C., 2010: Worldwide correlations of mechanical properties and green wood density. American Journal of Botany, 97: 1587-1594.
25. Rapp, A. O.; Brischke, C.; Welzbacher, C. R.; Nilsson, T.; Björdal, C., 2008: Mechanical strength of wood from the Vasa shipwreck. Document IRG/WP 08-20381. International Research Group on Wood Protection, Stockholm.
26. Rapp, A. O.; Brischke, C.; Welzbacher, C. R. 2006: Interrelationship between the severity of heat treatments and sieve fractions after impact ball milling: a mechanical test for quality control of thermally modified wood. Holzforschung, 60: 64-70. https://dx.doi.org /10.1515/HF.2006.012
27. Sandak, J.; Sandak, A.; Riggio, M., 2015: Characterization and monitoring of surface weathering on exposed timber structures with a multi-sensor approach. International Journal of Architectural Heritage, 9: 674-688. https://dx.doi.org /10.1080/15583058.2015.1041190
28. Schweingruber, F. H., 2012: Tree rings: basics and applications of dendrochronology. Springer Science & Business Media.
29. Ulvcrona, T.; Lindberg, H.; Bergsten, U., 2006: Impregnation of Norway spruce (*Picea abies* L. Karst.) wood with hydrophobic oil and dispersion patterns in different tissues. Forestry, 79: 123-134. https://dx.doi.org /10.1093/forestry/cpi064

30. von Pechmann, H., 1953: Untersuchungen über die Bruchschlagarbeit von Rotbuchenholz. Holz als Roh- und Werkstoff, 11: 361-367. https://dx.doi.org /10.1007/BF02607465
31. Wang, S. Y.; Wang, H. L., 1999: Effects of moisture content and specific gravity on static bending properties and hardness of six wood species. Journal of Wood Science, 45: 127-133. https://doi.org/10.1007/BF01192329
32. Welzbacher, C. R.; Rassam, G.; Talaei, A.; Brischke, C., 2011: Microstructure, strength and structural integrity of heat treated beech and spruce wood. Wood Material Science and Engineering, 6: 219-227. https://dx.doi.org/10.1080/17480272.2011.622411
33. Yang, J. L.; Evans, R., 2003: Prediction of MOE of eucalypt wood from microfibril angle and density. Holz als Roh- und Werkstoff, 61: 449-452. https://dx.doi.org /10.1007/s00107-003-0424-3
34. ***ISO International Standardisation Organisation 1996: ISO 5223. Test sieves for cereals. Geneva: International Organization for Standardization.



**Corresponding address:**

**Dr. LUKAS EMMERICH**

University of Goettingen, Faculty of Forest Sciences and Forest Ecology, Wood Biology and Wood Products, Buesgenweg 4, D-37077 Goettingen, GERMANY, e-mail: lukas.emmerich@uni-goettingen.de

Zoran Vlaović, Vid Palalić, Danijela Domljan[1]

# Research of Carbon Biosensors for Application in Seating Furniture: A Review

# Istraživanje ugljičnih biosenzora radi primjene u namještaju za sjedenje – pregled literature

**REVIEW PAPER**
**Pregledni rad**
Received – prispjelo: 1. 2. 2023.
Accepted – prihvaćeno: 9. 5. 2023.
UDK: 684.43
https://doi.org/10.5552/drvind.2023.0089



**ABSTRACT** • *The paper provides a limited overview of existing pressure sensors based on composite technology from carbonized biomass and synthetic materials which could be implemented in seating furniture. Carbon-based pressure sensors have proven to be good for pressure measurement that works on the principle of the piezoresistive effect. Research on materials based on carbonized components of biological origin encourages the development of composite sensors made of different materials, which have different negative and positive properties. Despite the great potential, such sensors are still not sufficiently researched and there is a lot of space for their improvement. Today's rapid development of technologies and frequent work at the computer leads to excessive sitting while working, which is a big problem for human health. Chairs with sensors could be increasingly used in the future, and in combination with the Internet of Things could be used to monitor the sitting habits and health of users. Sensors implemented in seating furniture are one way of monitoring sitting habits, warning users of inappropriate body positions when sitting, and mitigating the negative consequences of long-term improper sitting. The paper analyses research that includes the production and application of sensors made of carbonized bio-materials, which could be used in seating furniture with the aim of monitoring the way of sitting based on the principle of pressure detection. So far, the results have not provided the requested answers. However, they provided an overview of technologies that, with additional research, likely have the potential to be incorporated into seating furniture.*

**KEY WORDS:** *carbonized biomaterials, biosensors, seating furniture, smart seating, health*

**SAŽETAK** • *Rad donosi ograničen pregled postojećih senzora tlaka utemeljenih na tehnologiji kompozita od karbonizirane biomase i sintetskih materijala koji bi se mogli implementirati u namještaj za sjedenje. Senzori tlaka na bazi ugljika pokazali su se dobrima za mjerenje tlaka na načelu piezootporničkog učinka. Istraživanja materijala na bazi karboniziranih komponenata biološkog podrijetla potiču razvoj kompozitnih senzora od različitih materijala koji imaju negativna i pozitivna svojstva. Unatoč velikom potencijalu, takvi senzori još nisu dovoljno istraženi te postoji mnogo prostora za njihovo unaprjeđenje. Današnji brzi razvoj tehnologija i dugotrajan rad za računalom rezultiraju prekomjernim sjedenjem pri radu, što je velik problem za čovjekovo zdravlje. Stolice sa senzorima u budućnosti bi mogle naći sve veću primjenu, a u kombinaciji s mrežnom strukturom Internet stvari mogle bi se iskoristiti za praćenje navika sjedenja i zdravlja korisnika. Senzori implementirani u namještaj za sjedenje jedan*

[1] Authors are associate professor, student and associate professor at University of Zagreb, Faculty of Forestry and Wood Technology, Zagreb, Croatia.

*su od načina praćenja navika sjedenja, upozoravanja korisnika na neodgovarajuće položaje tijela pri sjedenju i za ublažavanje negativnih posljedica dugotrajnoga nepravilnog sjedenja. U radu su analizirana istraživanja koja obuhvaćaju izradu i primjenu senzora od karboniziranih biomaterijala koji bi mogli naći primjenu u namještaju za sjedenje radi praćenja načina sjedenja na načelu detektiranja tlakova. Rezultati zasad nisu dali tražene odgovore. Međutim, dali su pregled tehnologija koje uz dodatna istraživanja vjerojatno imaju potencijala za primjenu u namještaju za sjedenje.*

**KLJUČNE RIJEČI:** *karbonizirani biomaterijali, biosenzori, namještaj za sjedenje, pametno sjedenje, zdravlje*

## 1 INTRODUCTION
## 1. UVOD

It is a time of exponential development of technology and frequent work on the computer, where excessive sitting is a big problem for human health (Oven *et al.*, 2010). Chairs with sensors will be in increasing use, which, in combination with the Internet of Things, can be put to good use in monitoring the habits and health of users, and thus in the prevention of potential diseases.

Piezoresistive pressure sensors have attracted great interest from scientists in today's time of exponential technological development (Tai *et al.,* 2022). Their potential application is present in the development of the latest technologies such as wearable electronics or intelligent systems like robotic sensors, electronic skin, systems for monitoring movement or monitoring physiological information of the human organism (Lei *et al.,* 2022; Zhang *et al.,* 2019). Carbon-based composite pressure sensors have proven to be an excellent means of pressure measurement that functions on the principle of piezoresistive effect (Huang *et al.,* 2017).

The piezoresistive effect represents a change in the electrical resistance of a material (e.g. semiconductor or metal) under mechanical stress. The change in resistance occurs due to a change in the geometry (crystal lattice) and electrical conductivity of the material. It is significantly higher in semiconductors than in metals. Piezoresistive sensors based on silicon semiconductors are commonly used. In such an example, four Si-resistors are pressed into the semiconductor membrane and connected in a Wheatstone bridge. Under the influence of pressure, the diaphragm deforms, thereby changing the electrical resistance of the four resistors. The change in resistance is proportional to the applied pressure. This means that the voltage difference across the Wheatstone bridge is proportional to the applied pressure (Bolf, 2019; Tran *et al.,* 2018).

Various materials based on carbonized components of biological origin have been researched by many authors, and composite sensors made of different materials have been developed based on their findings. Each of them shows different negative and positive properties. Despite the great potential, such sensors are still not sufficiently researched and there is a lot of space for their improvement. Therefore, scientists devoted themselves to finding a suitable material that would adequately replace expensive and non-renewable materials (Bartoli *et al.,* 2022; Liu *et al.,* 2018; Mishra *et al.,* 2021). Given that the search for an ideal material emphasizes naturally renewable, ecological and cheap materials, carbon-rich carbonized biomass was found at the center of the research. In order to produce a high-quality sensor of this type, it is necessary to design a composite material that will be extremely sensitive, long-lasting and stable in different conditions. The functioning of this type of sensor can be influenced by numerous material factors such as electrical conductivity, mechanical properties, stability in different conditions and the range of pressure sensitivity.

When talking about the use of these sensors in furniture, negative properties can be weak flexibility, insufficient sensitivity at relatively low pressures, permanent deformation and low repeatability. Positive properties would be the design of the sensor for working at lower pressures, suitable for those that occur when sitting, then great durability and linear characteristics.

Wood is the most available renewable resource and offers a sustainable solution for making lightweight carbonized materials (Chen, Z. *et al.,* 2020). In modern technology, pressure sensors must often have high sensitivity and a wide linear range. However, there are few who can meet both criteria. The active material of the sensor would have to have a rough surface so that the electrode can respond sensitively to pressure changes. In addition, such a material would have to withstand a high degree of deformation, i.e. maintain good sensitivity in a large pressure range (Huang *et al.,* 2018). Natural wood has a unique 3D microstructure that implies a hierarchy of interconnected channels along its growth direction. Lignin is the most abundant aromatic substance on Earth, and at the same time it is cheap, renewable, environmentally friendly, and available. Carbonized lignin as a conductive component is a suitable material for making a flexible composite with polydimethylsiloxane (PDMS) as a polymer matrix (Wang *et al.,* 2018). Similar to the occurrence of lignin, cellulose is the most common renewable biopolymer (also sustainable, biocompatible, and biodegradable) on Earth, which is mainly obtained from cotton and lignocellulosic biomass (most often wood or grass). For example, sensors based on cellulose paper are increasingly used in "green" electronics due to their wide distribution, low cost, light weight, and excellent flexibility and sustainability (Chen *et al.,* 2018). Lignin and cellulose are suitable components for creating aerogel – a porous material of low density (contains more than 90 % air), which can have excellent mechanical properties, high compressibility, resistance to material fatigue and excellent sensitivity in a wide range of working pressure. Chen *et al.* (2020) investigated an aerogel based on flexible cellulose nanofibers (CNF) connected in a 3D network. In the network created in this way, alkali-lignin (obtained by the alkaline process of cooking cellulose) with its high thermal stability reduces thermal deformation, thus creating a very stable structure.

Light and elastic carbon materials, thanks to their outstanding properties, represent one of the most important candidates for the development of high-performance flexible sensors. In the last few years, a number of carbon materials with low density and high porosity have been synthesized from nanocarbon, such as graphene, graphene oxide, carbon nanotubes (CNT) or their composites. The carbon materials obtained in this way show good mechanical properties, which implies elasticity, and in addition, they have exceptional electrical properties and as such are suitable for making sensors in the increasingly common so-called wearable technology. However, they are non-renewable, and the process of their production is expensive and complex (Chen *et al.,* 2020). Often, when making flexible pressure sensors, materials such as polyurethane (PU) foams and melamine-formaldehyde (MF) foams are used; however, they are also not environmentally friendly due to the way they are manufactured (Li *et al.,* 2021).

On the other hand, biochar can be a good solution for the conductive sensor component due to its ease of production, low cost, and positive attitude towards the environment. However, not every biochar has electrical conductivity, and it depends on many factors. Some of these factors are the mass fraction and density of the powdered carbonized material in the composite, or the pyrolysis temperature in the carbonization process of biomaterials. Marrot *et al.* (2022) obtained results in which the conductivity test showed that pyrolysis at higher temperatures results in higher conductivity of biochar particles at the desired pressure or density of the compacted biochar particles. Understudied electrical conductivity of biochar in composite materials may be a potential for innovation in this area. In addition, polyvinyl alcohol has numerous advantages such as easy processing, high durability, low price, non-toxicity, and favorable insulating properties (Nan and DeVallance, 2017). Noori *et al.* (2020) state that the production of tea is one of the largest productions of beverages in the world. By preparing tea in the extraction process, only a small number of compounds are removed, and a large amount of usable residue remains, which can be used for the purpose of making biochar. Global rice production is increasing to keep pace with the growing global population as well. Rice husk is a by-product in the production of rice, which is obtained by peeling the grain. According to Haffiz *et al.* (2017), rice husk is a cheap and sustainable solution for making a conductive pressure sensor component. Such a conductive component in combination with PDMS forms the active part of the sensor. In recent years, pressure sensors made of carbonized fabric have appeared; they are characterized by excellent flexibility and pressure reading, as well as ease of preparation and low cost. Given that fabrics in the sensor function are still insufficiently researched, Chang *et al.* (2020) investigated a flexible sensor based on carbonized cotton fabric and thermoplastic polyurethane (TPU).

The aim of this paper is to present different types of existing pressure sensors made of carbonized components obtained from biomass, with an emphasis on sensors that have the potential to be installed in seating furniture with the purpose of monitoring the way of sitting based on the principle of pressure detection.

## 2 MATERIALS AND METHODS
## 2. MATERIJALI I METODE

Data for this research was collected from databases of scientific articles with open access from several fields of science (technical and biotechnical, biomedical and health, and natural sciences).

The keywords for the database search were: "biochar pressure sensor" and "carbonized pressure sensor". Databases (such as IEEE Xplore, ACS Publications, ScienceDirect, SpringerLink) were searched during June and July 2022, and included papers published in the last five years (2017-2022). Papers that included sensors made of carbonized organic materials were selected. Papers related to strain sensors were excluded from the overview, as well as papers with pressure sensors in which the combination of conductive component material and resin matrix material (carrier) was repeated.

## 3 RESULTS AND DISCUSSION
## 3. REZULTATI I RASPRAVA

The analysis of pressure sensors based on a carbonized component of organic origin found that there are different types of sensors, but they all have a common feature of working on the principle of piezoresistive effect. Most of them were developed for the purpose of use in wearable devices, i.e. robotic skin or devices for monitoring biosignals in humans.

The manufacturing method and methods of researching their properties can be found in the original articles of the cited authors, while here is a presentation of basic details and results that can be interesting guidelines for future research and application in seating furniture.

### 3.1 Biochar sensor of wood origin and polyvinyl alcohol
### 3.1. Senzor od biougljena drvnog podrijetla i polivinil alkohola

Polymer composites based on electroconductive carbon are considered acceptable materials for pressure and strain sensors based on the piezoresistive principle of operation. Nan and DeVallance (2017) investigated the responses of a pressure sensor as a composite material obtained from a mixture of hardwood biochar and polyvinyl alcohol (PVA). The produced composite PVA/biochar sensors showed piezoresistive properties under pressure. It was observed that, as the biochar content changed within sensor, the electrical response also changed proportionally, i.e. by increasing the proportion of biochar from 8 wt% to 12 wt%, the output voltage increased, as the sensor was subjected to increasing pressure. However, in such situations, one should be careful, because a further increase in the proportion of the substance does not necessarily lead to an improvement in the properties of the sensor, but on the contrary, it may reach a threshold when the sensor becomes unusable. Furthermore, with increasing pressure, the resistance of the PVA/biochar composite sensor gradually decreased. The effect of composite thickness was found to be important, but also complex, as many factors, such as biochar particle size, their amount and spatial distribution, and the electrical and mechanical properties of the PVA/biochar films likely influenced the results. In addition, temperature can affect the electrical response and piezoresistive effect of the PVA/biochar sensor. However, the research results showed that in the temperature range from 25 to 70 °C the sensors were relatively stable. The research showed that there is a basis for further research on the influence of particle size and conductivity properties of biochar, because the electrical response and piezoresistive behavior of polymer materials filled with biochar and carbonized wood material are repeatable and stable.

### 3.2 Biochar sensor made of tea origin and polypropylene
### 3.2. Senzor od biougljena čajnog podrijetla i polipropilena

Noori *et al.* (2020) investigated a composite material based on biochar obtained from exhausted tea leaves and polypropylene. The developed biochar samples proved to be poorly conductive up to low temperatures. A produced powder was dispersed in a polypropylene matrix up to a load of 40 wt%, and a noteworthy conductivity was obtained (Figure 1). However, at such a high level of biochar content, after the initial increase in conductivity, applied pressures above a certain point no longer result in different electrical outputs, which is why the sensors can only be useful for detecting the presence of pressure, but not their values.

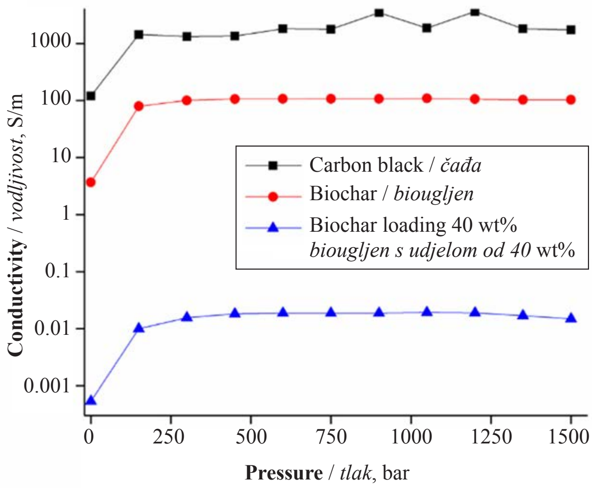



**Figure 1** Electrical conductivity as a function of pressure on fillers and biochar with a loading of 40 wt%, carbon black and tea biochar (Noori *et al.,* 2020)
**Slika 1.** Električna vodljivost kao funkcija pritiska na punila i biougljen s udjelom od 40 wt%, na čađu i biougljen čaja (Noori *et al*., 2020.)

The properties of the produced materials were determined in detail by testing mechanical, thermal, morphological, and electrical characteristics in relation to temperature. The material showed a general improvement in mechanical and thermal properties when the amount of filler was varied instead of the type of filler, as similar concentrations of carbon black and biochar caused similar effects. Electrical conductivity was also studied for a large range of pressures, when the sensor underwent plastic deformation. An increase in conductivity by a whole order of magnitude was observed in the case of biochar loading of 40 wt%. This phenomenon occurs together with plastic deformation, effectively acting as an irreversible overpressure detector. The researched technology could find application in various areas where it would serve as a sensor to detect irregularities due to, for example, impact.

### 3.3 Biocarbon sensor from cellulose fibers
### 3.3. Biougljični senzor od celuloznih vlakana

According to Li *et al.* (2021), it is a major challenge to fabricate compressible aerogels for flexible pressure sensors from cellulose-based materials in an environmentally and cost-effective manner. Carbonized cellulose fiber network (CCFN) and polydopamine (PDA) are materials for a flexible pressure sensor

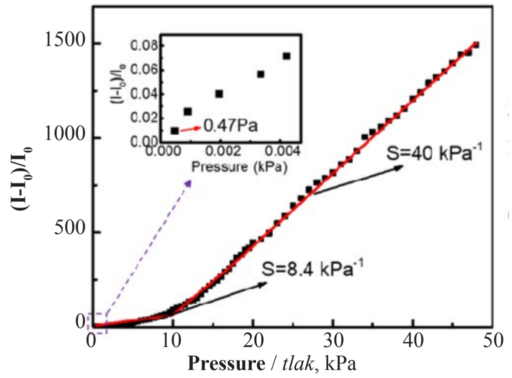



**Figure 2** Relative change in electrical current [$(I-I_0)/I_0$] as a function of pressure ranging from 0 to 50 kPa in PDA/CCFN-based pressure sensor (Reprinted (adapted) with permission from Li *et al.* Copyright 2021 American Chemical Society)
**Slika 2.** Relativna promjena električne struje [$(I-I_0)/I_0$] kao funkcija tlaka u rasponu od 0 do 50 kPa u PDA/CCFN senzoru tlaka (preuzeto s dozvolom iz Li *et al.*, Copyright 2021 American Chemical Society)

obtained in a low-cost, scalable, and environmentally friendly process. This process gives the prepared pressure sensor high compressibility and excellent mechanical durability.

The pressure sensor based on PDA/CCFN has a high sensitivity of 8 $kPa^{-1}$ and 40 $kPa^{-1}$ at pressure ranges of 0–10 kPa and 10–50 kPa, respectively (Figure 2). The sensor has a detection limit of less than 0.5 Pa, a fast response time (for a pressure of 50 Pa: 50 ms and 20 ms for loading and unloading, respectively), and a very good repeatability of 1000 cycles (for a pressure of 20 kPa). The excellent properties of this kind of sensor enable accurate recognition of various human actions, it can monitor fine biomedical signals in humans and more. The development of a flexible cellulose fiber pressure sensor that can be used to map the pressure distribution or as a pixel detector to detect spatially resolved pressure is a new viable approach in fabrication for applications in electronic skin and wearable electronics; however, due to its high sensitivity, it is not applicable in seating furniture.

### 3.4 Carbonized wood sensor with polydimethylsiloxane filling

### 3.4. Senzor od karboniziranog drva s punilom od polidimetilsiloksana

Huang *et al.* (2018) developed a simple procedure for the fabrication of flexible pressure sensors based on carbon using natural wood structures and silicon. The method they developed uses a blade cutting process in a unique multi-channel composite structure with variable surface topography. The authors studied the role of carbon surface microstructures in the pressure sensor by using horizontally and vertically cut composite layers in a vertical piezoresistor configuration.

Due to their rough surface and highly deformable microstructure, the horizontally cut composite sensors exhibit much higher sensitivity and a wider linear range, while exhibiting low hysteresis and good cycle stability. The wide linear range is an outstanding property that enables the sensor to precisely track human physiological signals (e.g. real-time breathing detection), and the high sensitivity property is suitable for measuring epidermal pulse, for example.

### 3.5 Carbonized lignin sensor from corn and polydimethylsiloxane

### 3.5. Senzor od karboniziranog lignina iz kukuruza i polidimetilsiloksana

Wang *et al.* (2018) presented a flexible composite of polydimethylsiloxane and carbonized lignin (PDMS/CL) that is electrically highly sensitive and was made by a simple and inexpensive process. The conductivity of the PDMS/CL composite with one-third part of carbonized lignin is at least 16 times lower than the conductivity of the obtained CL, whose oxygen and hydrogen content were drastically reduced during the simple carbonization process. A relative change in resistance response, built up during an applied stress of 0 to 20 kPa, was found in the pressure-sensitive phase in the range of 0 to 3 kPa. Previous reports on transistor pressure sensors and most other carbon materials sensors indicate significantly lower sensitivity than the 57 $kPa^{-1}$ achieved here, which is very interesting.

The PDMS/CL composite shows excellent and stable pressure frequency response of up to 2.5 Hz. At the same time, the time of response to loading is approximately 60 ms, while the response to unloading occurs in 40 ms. The sensor has exceptional durability, which is manifested by the intensity of the response to repeated compression, which is stable for as many as 100,000 cycles. The paper proved the possible application of lignin in the production of flexible sensors in a relatively cheap process, with good reproducibility and high sensitivity that finds application in wearable electronics (for example, pulse monitoring by delicate pressure changes or muscle movements) and smart systems where force is demanded.

### 3.6 Biocarbon sensor from rice husk and polydimethylsiloxane

### 3.6. Biougljični senzor iz rižine ljuske i polidimetilsiloksana

By using the pyrolysis of plant biomass, biochar is obtained, which can be considered as an alternative source of "green" carbon for the production of pressure sensors based on polymer foams, according to Haffiz *et al*. (2017). In the paper, foams produced by the sugar template method were studied, while biochar obtained by pyrolysis of rice husk in the extraction of liquid fuel was explored as a filler. By static and cyclic loading of a sensor device with biochar/PDMS foam between two copper electrodes, the properties of the pressure sensor were investigated, and the mechanical characteristics were also studied. Tests have shown an inversely proportional relationship between electrical resistance and pressure increase, whereby the biochar/PDMS foams produced in this way show a negative pressure resistance coefficient.

The sensor showed remarkable electrical conductivity, which increased significantly during compression. Mechanical properties during compression showed that this sensor behaves like a typical elastomeric foam. Hysteresis is present during the loading and unloading cycles. The response is in the elastic region during lower stresses with a trend of a slight increase due to the action of higher stresses, and then a sudden increase in deformation at higher stresses. This leads to the fusion of opposite cell walls and a drop in electrical resistance, and an increase in conductivity.

### 3.7 Sensor made of cellulose nanofibers and lignin
### 3.7. Senzor od celuloznih nanovlakana i lignina

Fabrication of wood-derived elastic carbon aerogel with a tracheid-like texture from cellulose nanofibers (CNF) and lignin is a sustainable and simple method presented by Chen *et al.* (2020). Carbon aerogel obtained from wood shows high durability and compressibility, which are excellent mechanical properties. In addition, it has high sensitivity in a wide range of working pressure up to 17 kPa, which enables precise detection of human biosignals.

A flexible, free-standing symmetric solid-state supercapacitor can be made of carbon aerogel, which shows satisfactory results for applications in pressure sensors and flexible electrodes with its electrochemical properties and mechanical flexibility.

### 3.8 Carbonized cotton fabric sensor with thermoplastic polyurethane
### 3.8. Senzor od karbonizirane pamučne tkanine s termoplastičnim poliuretanom

By a simple carbonization process, Chang *et al.* (2020) made an elastic pressure sensor based on fabric and thermoplastic polyurethane (TPU). The influence of carbonization temperature variations (up to 1000 °C) and the concentration of the flexible substrate solution (up to 10 %) on the properties of the sensor was investigated, which was confirmed by tests under different process conditions. After research, it was determined that the pressure sensor made in this way, with fabric carbonized at a temperature between 800 and 900 °C and with a concentration of 6 % thermoplastic polyurethane, has a sensitivity of up to 80 $kPa^{-1}$ (at pressure of 0.5 kPa) and a hysteresis of less than 12 %, which unfortunately does not make it a candidate for use in furniture, but is therefore excellent for use in wearable electronics.

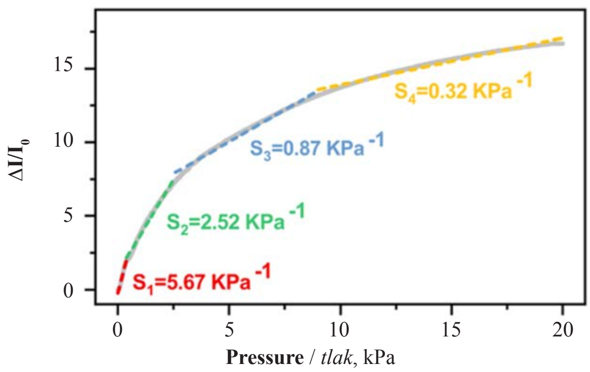



**Figure 3** CCP pressure sensor sensitivity shown as relative change in electric current under pressure load (Reprinted (adapted) with permission from Chen *et al.* Copyright 2018 American Chemical Society)
**Slika 3.** Osjetljivost CCP senzora tlaka prikazana kao relativna promjena električne struje pod tlačnim opterećenjem (preuzeto s dozvolom iz Chen *et al.*, Copyright 2018 American Chemical Society)

### 3.9 Sensor made of carbonized crepe paper with a wavy structure
### 3.9. Senzor od karboniziranog krep-papira valovite strukture

Taking advantage of the porous and corrugated structure of carbonized crepe paper, Chen *et al.* (2018) developed a flexible pressure sensor. The sensor is based on a simple and scalable approach, using screen-printed interdigital electrodes on printing cellulose paper and carbonized crepe paper (CCP). The presented sensor has very good electromechanical properties, including high sensitivity, wide operating pressure range up to 20 kPa (Figure 3), fast response time (less than 30 ms), low detection limit of only 0.9 Pa, and durability greater than 3000 cycles.

The advantages of carbonized crepe paper pressure sensors, according to authors, are flexible substrate and active component (printing paper and crepe paper, respectively), having a microstructure that can be adapted to known papermaking technologies, in order to meet different requirements: simple, scalable, cost-effective and environmentally friendly, produced in the process and, due to the origin of the components, available at a low price and in sufficient quantities. The mentioned advantages enable the sensor to detect pressure changes, for example, caused by the pulse on the hand, breathing, speech, etc., but also to monitor the spatial distribution of pressure in real time. This sensor, like most of the previously described ones, has potential applications in wearable electronics, robotics, healthcare and human-machine interface.

### 3.10 Discussion
### 3.10. Rasprava

The basic difference between the described sensors is in the materials and manufacturing process. According to the materials used to make the conductive component, sensors can be from: carbonized wood and wood substances (lignin, cellulose fibers); carbonized extracted tea leaf; carbonized lignin from corn; carbonized rice flakes; carbonized cotton fabrics; and carbonized crepe paper. The conductive components of all described sensors are made of organic biomass. Considering the growing environmental awareness, the conductive elements of all described sensors can be made from biological waste or excess unused material (residue) from production.

Carbonized organic mass can have excellent electrical conductivity properties, but poor mechanical properties, which is solved by adding conductive material in carrier from different types of synthesized materials. The following polymer matrix materials are usually used as a carrier: polyvinyl alcohol (PVA); polypropylene (PP); polydimethylsiloxane (PDMS); thermoplastic polyurethane (TPU); and polydopamine (PDA).

All described sensors, except for one, are characterized by more or less elastic properties with different changes in electric resistance. In many results presented, the usefulness and operating range of the sensor are partially dependent on the matrix material. Unlike the others, the sensor based on polypropylene matrix is specific in a way that it showed irreversible plastic deformation. It seems that the PP was the reason for the non-reversibility, due to its higher plastic phase than in common epoxy resins, and as a counterexample to the excellent flexibility of the PVA polymer matrix material in one of the papers presented. Such an irreversible pressure sensor could also find application in many sectors, e.g. a sensor for detecting a local shock-induced failure.

All processed papers on “biochar pressure sensor” or “carbonized pressure sensor” are shown in Table 1, where an overview of the used conductive component material, matrix material, sensitivity, operating range, and other summary data are given.

The sensor based on carbonized cotton fabric with TPU matrix showed the best sensitivity (80.59 $kPa^{-1}$). Despite the excellent sensitivity, this sensor has relatively poor durability, i.e. repeatability (endurance) of only 4,000 cycles. The second most sensitive sensor was the one made of carbonized corn lignin and PDMS matrix. It showed a sensitivity of 57 $kPa^{-1}$ and an exceptional repeatability of 100,000 cycles. In addition, the working range of this sensor is above average high, up to 130 kPa. The sensor made of carbonized wood and carrier with PVA has a maximum working range of 0 to 358 kPa. The sensor made of carbonized wood and PDMS showed the highest response speed, lasting 20 ms for loading and the same amount for unloading. According to these data, it is noticeable that all conductive materials are made using different technologies and different processes (carbonization time, temperature, conditions). The processing method to make biocarbon or biochar (i.e. filler) is an important factor in determining the appropriateness of the material used in a sensor.

PDMS seems to be the most suitable matrix material, as it is characterized by high sensitivity, working range, response speed and repeatability. However, according to Ariati *et al.* (2021), the main disadvantage of PDMS is its structural application, which may be extremely specific and reduced. However, the modification of its characteristics, such as transparency, can be interesting for the use in sensors and for some other application. It is also limited by the lack of (covalent) bonds between PDMS and surface modifiers, which lead to the loss of modifiers (Miranda *et al.,* 2022). Given that the positive properties of PDMS are expressed in different sensors, it is necessary to analyze in more detail the correlations between the composite manufacturing procedures and the quantity and quality of the materials used.

According to the mentioned properties and analyses, sensors based on carbonized biomass have great potential for implementation in cutting-edge technological discoveries such as robotic skin and wearable devices for monitoring physiological information in humans. Apart from the previously described purposes of the analyzed sensors, none of the above should be understood as a means of measuring the pressure load in the use of furniture.

In order to have the potential to be used in e.g. seating furniture, the solutions presented here should be developed in such a way as to improve the design of the sensor, which would be a combination of the best known properties. Such sensors do not have to be super-sensitive like those on wearable devices, but they must be robust: be durable enough, have the minimum necessary elasticity, have the best sensitivity in the area of pressures that occur in the given circumstances (e.g. under the sitting bones and surrounding tissue when sitting), have a relatively fast response, be discreet. These would be the parameters that determine the properties of the sensor, as well as the necessity of a simple interface and connectivity with existing devices for displaying output signals.

## 4 CONCLUSIONS
## 4. ZAKLJUČAK

In today’s time of exponential development of technology and frequent work on the computer, excessive sitting is a big problem for human health. Chairs with sensors will be increasingly used, which in combination with the Internet of Things can be put to good

**Table 1** Comparison of properties of analyzed pressure sensors
**Tablica 1.** Usporedba svojstava analiziranih senzora tlaka

| **Paper** *Članak* | **Conductive component material (filler)** *Materijal vodljive komponente (punilo)* | **Filler percentage** *Udio punila* | **Resin matrix material** *Smolasti materijal matrice* | **Sensor dimensions** *Dimenzije senzora* | **Biochar preparation parameters** *Parametri pripreme biougljena* | **Sensitivity** *Osjetljivost,* $kPa^{-1}$ | **Operating range** *Radni raspon,* kPa | **Response speed** *Brzina odaziva,* ms | **Repeatability, no. of cycles** *Ponovljivost, broj ciklusa* |
|---|---|---|---|---|---|---|---|---|---|
| Nan and DeVallance (2017) | carbonized wood *karbonizirano drvo* | 8 wt%, 10 wt% and 12 wt% | polyvinyl alcohol *polivinilni alkohol* | ($D8×0.5\ mm^3$) | n/a | n/a | < 358 | n/a | n/a |
| Noori *et al.* (2020) | carbonized extracted tea leaves *karbonizirani listovi ekstrahiranog čaja* | 40 wt% | polypropylene *polipropilen* | ($6×30×1.0\ mm^3$) | 1000 °C / 30 min | n/a | n/a | n/a | n/a |
| Li *et al.* (2021) | carbonized cellulose fibers *karbonizirana celulozna vlakna* | 23.5 wt% | polydopamine *polidopamin* | n/a | 800 °C / 3 h | 40 | < 50 | loaded / *opterećen*: 50<br>unloaded / *neopterećen*: 20 | 1,000 |
| Huang *et al.* (2018) | carbonized wood *karbonizirano drvo* | approx. 9 wt% | polydimethyl-siloxane *polidimetil-siloksan* | ($3×3×0.5\ mm^3$) | 800 °C | 10.74 | < 100 | loaded / *opterećen*: 20<br>unloaded / *neopterećen*: 20 | 13,000 |
| Wang *et al.* (2018) | carbonized lignin from corn *karbonizirani lignin iz kukuruza* | 33.3 wt% | polydimethyl-siloxane *polidimetil-siloksan* | ($10×10×1.0\ mm^3$) | 900 °C / 2 h | 57 | < 130 | loaded / *opterećen*: 60<br>unloaded / *neopterećen*: 40 | 100,000 |
| Haffiz *et al.* (2017) | carbonized rice husk *karbonizirane rižine ljuskice* | n/a | polydimethyl-siloxane *polidimetil-siloksan* | n/a | 400-500 °C / 75 min | n/a | n/a | n/a | n/a |
| Chen *et al.* (2020) | carbonized cellulose nanofibers *karbonizirana celulozna nanovlakna* | 3 wt%, 5 wt% and 7 wt% | polydimethyl-siloxane *polidimetil-siloksan* | n/a | 800 °C / 2 h | 5.16 | < 16.89 | loaded / *opterećen*: 65<br>unloaded / *neopterećen*: 52 | 30,000 |
| Chang *et al.* (2019) | carbonized cotton fabric *karbonizirana pamučna tkanina* | n/a | thermoplastic polyurethane *termoplastični poliuretan* | n/a | 800-900 °C / 1 h | 80.59 | / | / | 4,000 |
| Chen *et al.* (2018) | carbonized crepe paper *karbonizirani krep-papir* | n/a | polydimethyl-siloxane *polidimetil-siloksan* | ($10×10×1.7\ mm^3$) | up to-900 °C / 7 h | 5.67 [0-0.42 kPa]<br>2.52 [0.42-2.53 kPa] | < 20 | loaded / *opterećen*: 30<br>unloaded / *neopterećen*: 25 | 3,000 |

use in monitoring the users' habits and health. Sensors implemented in seating furniture are one of the solutions for monitoring sitting habits and indirectly mitigating the negative consequences of poor sitting.

This paper analyzes a part of the research that includes the production and application of pressure sensors from carbonized biomaterials. Although the research focused on sensors that can be built into seating furniture, so far, the results have not provided the desired answers. However, the results offer an overview of technologies that, with further research, likely have the potential to be incorporated into seating furniture. Precisely the sensors analyzed in this paper, considering their excellent properties, low manufacturing cost and organic origin of the material, have great potential in the wider application of sensors for monitoring sitting habits.

Analyzed sensors showed excellent sensitivity and as such could be used to monitor sitting habits. Considering their small thickness and simple construction, the sensors could be implemented in chair seats, for example in the layer between the seat foam and the seat base. In the same way, they could be implemented in the backrest or armrests, thus covering all the key parts related to habits, i.e. the quality of sitting. In this way, the chair could remain aesthetically and functionally unchanged, while at the same time being enriched with sensors that monitor the sitting position of the user.

Despite the exceptional sensitivity, the problem of implementing these sensors in seating furniture is their repeatability (durability). Given that numerous changes in pressure load occur during sitting, almost all analyzed sensors would lose their function very quickly. As a possible pilot solution, a sensor based on carbonized lignin and PDMS, characterized by repeatability of 100,000 cycles, could be used. To solve the problem of repeatability, at the expense of sensitivity, the durability of the sensor could be increased. According to previous research, this could be done by adding a larger percentage of the resin matrix to improve the mechanical properties of the sensor. However, this would likely impact the sensitivity and conductivity of the sensor. Nonetheless, sensors produced in this way would have better durability, and considering that furniture involves much higher forces than robotic skin or devices for monitoring physiological signals, the reduced sensitivity should still be sufficient to collect information related to monitoring sitting habits.

During the research of the most suitable bio-sensors for use in seating furniture, unfortunately, not a single paper was directly related to such an application of bio-sensors for any kind of furniture. Therefore, new research is needed, which will focus on the implementation of bio-sensors in furniture for sitting, as well as on the search for possible solutions that would be further improved and adapted to the application in furniture.

## 5 REFERENCES
## 5. LITERATURA

1. Ariati, R.; Sales, F.; Souza, A.; Lima, R. A.; Ribeiro, J., 2021: Polydimethylsiloxane Composites Characterization and Its Applications: A Review. Polymers, 13 (23): 4258. https://doi.org/10.3390/polym13234258
2. Bartoli, M.; Torsello, D.; Piatti, E.; Giorcelli, M.; Sparavigna, A. C.; Rovere, M.; Ghigo, G.; Tagliaferro, A., 2022: Pressure-Responsive Conductive Poly(vinyl alcohol) Composites Containing Waste Cotton Fibers Biochar. Micromachines, 13 (1): 125. https://doi.org/10.3390/mi13010125
3. Bolf, N., 2019. Measurement and regulation technique: Pressure measurement – piezoelectric and piezoresistive sensors (in Croatian). Kemija u industriji: Časopis kemičara i kemijskih inženjera Hrvatske, 68 (7-8): 365-368.
4. Chang, S.; Li, J.; He, Y.; Liu, H., 2020: Effects of carbonization temperature and substrate concentration on the sensing performance of flexible pressure sensor. Applied Physics A: Materials Science and Processing, 126 (1): 1-10. https://doi.org/10.1007/s00339-019-3216-2
5. Chen, S.; Song, Y.; Xu, F., 2018: Flexible and Highly Sensitive Resistive Pressure Sensor Based on Carbonized Crepe Paper with Corrugated Structure. ACS Applied Materials and Interfaces, 10 (40): 34646-34654. https://doi.org/10.1021/acsami.8b13535
6. Chen, Z.; Zhuo, H.; Hu, Y.; Lai, H.; Liu, L.; Zhong, L.; Peng, X., 2020: Wood-Derived Lightweight and Elastic Carbon Aerogel for Pressure Sensing and Energy Storage. Advanced Functional Materials, 30 (17): 1910292. https://doi.org/10.1002/adfm.201910292
7. Haffiz, T. M.; Izzuddin, M. Y. A.; Affidah, D.; Amirul, A.; Ahmad, S.; Islam, M. N.; Zuruzi, A. S., 2017: Biochar: A "green" carbon source for pressure sensors. In: Proceedings of IEEE Sensors, October, pp. 1-3. https://doi.org/10.1109/ICSENS.2017.8233940
8. Huang, Y.; Chen, Y.; Fan, X.; Luo, N.; Zhou, S.; Chen, S. C.; Zhao, N.; Wong, C. P., 2018: Wood Derived Composites for High Sensitivity and Wide Linear-Range Pressure Sensing. Small, 14 (31): 1801520. https://doi.org/10.1002/smll.201801520
9. Huang, W.; Dai, K.; Zhai, Y.; Liu, H.; Zhan, P.; Gao, J.; Zheng, G.; Liu, C.; Shen, C., 2017: Flexible and Lightweight Pressure Sensor Based on Carbon Nanotube/Thermoplastic Polyurethane-Aligned Conductive Foam with Superior Compressibility and Stability. ACS Applied Materials and Interfaces, 9 (48): 42266-42277. https://doi.org/10.1021/acsami.7b16975
10. Lei, X.; Ma, L.; Li, Y.; Cheng, Y.; Cheng, G. J.; Liu, F., 2022: Highly sensitive and wide-range flexible pressure sensor based on carbon nanotubes-coated polydimethylsiloxane foam. Materials Letters, 308: 131151. https://doi.org/10.1016/j.matlet.2021.131151
11. Li, C.; Li, G.; Li, G.; Yu, D.; Song, Z.; Liu, X.; Wang, H.; Liu, W., 2021: Cellulose Fiber-Derived Carbon Fiber Networks for Durable Piezoresistive Pressure Sensing. ACS Applied Electronic Materials, 3 (5): 2389-2397. https://doi.org/10.1021/acsaelm.1c00286
12. Liu, W.; Liu, N.; Yue, Y.; Rao, J.; Cheng, F.; Su, J.; Liu, Z.; Gao, Y., 2018: Piezoresistive Pressure Sensor Based

on Synergistical Innerconnect Polyvinyl Alcohol Nanowires/Wrinkled Graphene Film. Small, 14 (15): 1-8. https://doi.org/10.1002/smll.201704149
13. Marrot, L.; Candelier, K.; Valette, J.; Lanvin, C.; Horvat, B.; Legan, L; DeVallance, D. B., 2022: Valorization of hemp stalk waste through thermochemical conversion for energy and electrical applications. Waste and Biomass Valorization, 13: 2267-2285. https://doi.org/10.1007/s12649-021-01640-6
14. Miranda, I.; Souza, A.; Sousa, P.; Ribeiro, J.; Castanheira, E. M. S.; Lima, R.; Minas, G., 2022: Properties and Applications of PDMS for Biomedical Engineering: A Review. Journal of Functional Biomaterials, 13 (1): 2. https://doi.org/10.3390/jfb13010002
15. Mishra, R. B.; El-Atab, N.; Hussain, A. M.; Hussain, M. M., 2021: Recent Progress on Flexible Capacitive Pressure Sensors: From Design and Materials to Applications. Advanced Materials Technologies, 6 (4): 2001023. https://doi.org/10.1002/admt.202001023
16. Nan, N.; DeVallance, D. B., 2017: Development of poly(vinyl alcohol)/wood-derived biochar composites for use in pressure sensor applications. Journal of Materials Science, 52 (13): 8247-8257. https://doi.org/10.1007/s10853-017-1040-7
17. Noori, A.; Bartoli, M.; Frache, A.; Piatti, E.; Giorcelli, M.; Tagliaferro, A., 2020: Development of pressure-responsive polypropylene and biochar-based materials. Micromachines, 11 (4): 339. https://doi.org/10.3390/MI11040339
18. Owen, N.; Healy, G. N.; Matthews, C. E.; Dunstan, D. W., 2010: Too Much Sitting: The Population Health Science of Sedentary Behavior. Exercise and Sport Sciences Reviews, 38 (3): 105-113. https://doi.org/10.1097/JES.0b013e3181e373a2
19. Tai, G.; Wei, D.; Su, M.; Li, P.; Xie, L.; Yang, J., 2022: Force-Sensitive Interface Engineering in Flexible Pressure Sensors: A Review. Sensors, 22 (7): 2652. https://doi.org/10.3390/s22072652
20. Tran, A.V.; Zhang, X.; Zhu, B., 2018. Mechanical structural design of a piezoresistive pressure sensor for low-pressure measurement: A computational analysis by increases in the sensor sensitivity. Sensors, 18 (7): 2023. https://doi.org/10.3390/s18072023
21. Wang, B.; Shi, T.; Zhang, Y.; Chen, C.; Li, Q.; Fan, Y., 2018: Lignin-based highly sensitive flexible pressure sensor for wearable electronics. Journal of Materials Chemistry C, 6 (24): 6423-6428. https://doi.org/10.1039/c8tc01348a
22. Zhang, L.; Li, H.; Lai, X.; Gao, T.; Liao, X.; Chen, W.; Zeng, X., 2019: Carbonized cotton fabric-based multilayer piezoresistive pressure sensors. Cellulose, 26 (8): 5001-5014. https://doi.org/10.1007/s10570-019-02432-x

**Corresponding address:**

**DANIJELA DOMLJAN**

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, 10000 Zagreb, CROATIA, e-mail: ddomljan@sumfak.unizg.hr

**ORCID ID**

Z. Vlaović https://orcid.org/0000-0002-0855-6842

D. Domljan https://orcid.org/0000-0002-6388-5825

## Upute autorima

### Opće odredbe

Časopis *Drvna industrija* objavljuje znanstvene radove (izvorne znanstvene radove, pregledne radove, prethodna priopćenja), stručne radove, izlaganja sa savjetovanja, stručne obavijesti, bibliografske radove, preglede te ostale priloge s područja biologije, kemije, fizike i tehnologije drva, pulpe i papira te drvnih proizvoda, uključujući i proizvodnu, upravljačku i tržišnu problematiku u drvnoj industriji.

Predaja rukopisa podrazumijeva uvjet da rad nije već predan negdje drugdje radi objavljivanja ili da nije već objavljen (osim sažetka, dijelova objavljenih predavanja ili magistarskih radova odnosno disertacija, što mora biti navedeno u napomeni) te da su objavljivanje odobrili svi suautori (ako rad ima više autora) i ovlaštene osobe ustanove u kojoj je istraživanje provedeno. Cjelokupni sadržaj Drvne industrije dostupan je za skidanje s interneta, tiskanje, daljnju distribuciju, čitanje i ponovno korištenje bez ograničenja sve dok se naznače autor(i) i originalni izvor prema Creative Commons Attribution 4.0 International License (CC BY). Autor(i) zadržavaju izdavačka prava bez ograničenja.

Znanstveni i stručni radovi objavljuju se na engleskom jeziku, uz sažetak na hrvatskome. Također, naslov, podnaslovi i svi važni rezultati trebaju biti napisani dvojezično. Uredništvo osigurava inozemnim autorima prijevod na hrvatski. Ostali se članci uglavnom objavljuju na hrvatskome. Znanstveni i stručni radovi podliježu temeljitoj recenziji najmanje dvaju recenzenata. Izbor recenzenata i odluku o klasifikaciji i prihvaćanju članka (prema preporukama recenzenata) donosi Urednički odbor.

Svi prilozi podvrgavaju se jezičnoj obradi. Urednici će od autora zahtijevati da tekst prilagode preporukama recenzenata i lektora, te zadržavaju i pravo da predlože skraćivanje ili poboljšanje teksta. Autori su potpuno odgovorni za svoje priloge. Podrazumijeva se da je autor pribavio dozvolu za objavljivanje dijelova teksta što su već negdje objavljeni te da objavljivanje članka ne ugrožava prava pojedinca ili pravne osobe. Radovi moraju izvještavati o istinitim znanstvenim ili tehničkim postignućima. Autori su odgovorni za terminološku i metrološku usklađenost svojih priloga. Radovi se šalju elektronički putem poveznice http://journal.sdewes.org/drvind

### Upute

Predani radovi smiju sadržavati najviše 15 jednostrano pisanih A4 listova s dvostrukim proredom (30 redaka na stranici), uključujući i tablice, slike te popis literature, dodatke i ostale priloge. Dulje je članke preporučljivo podijeliti na dva ili više nastavaka. Tekst treba biti u *doc formatu*, u potpunosti napisan fontom *Times New Roman* (tekst, grafikoni i slike), normalnim stilom, bez dodatnog uređenja teksta.

Prva stranica poslanog rada treba sadržavati puni naslov, ime(na) i prezime(na) autora, podatke o zaposlenju autora (ustanova, grad i država) te sažetak s ključnim riječima (duljina sažetka približno 1/2 stranice A4).

Posljednja stranica treba sadržavati titule, zanimanje, zvanje i adresu (svakog) autora, s naznakom osobe s kojom će Uredništvo biti u vezi.

Znanstveni i stručni radovi moraju biti sažeti i precizni. Osnovna poglavlja trebaju biti označena odgovarajućim podnaslovima. Napomene se ispisuju na dnu pripadajuće stranice, a obrojčavaju se susljedno. One koje se odnose na naslov označuju se zvjezdicom, a ostale uzdignutim arapskim brojkama. Napomene koje se odnose na tablice pišu se ispod tablica, a označavaju se uzdignutim malim pisanim slovima, abecednim redom.

Latinska imena trebaju biti pisana kosim slovima (italicom), a ako je cijeli tekst pisan kosim slovima, latinska imena trebaju biti podcrtana.

U uvodu treba definirati problem i, koliko je moguće, predočiti granice postojećih spoznaja, tako da se čitateljima koji se ne bave područjem o kojemu je riječ omogući razumijevanje ciljeva rada.

Materijal i metode trebaju biti što preciznije opisane da omoguće drugim znanstvenicima ponavljanje pokusa. Glavni eksperimentalni podaci trebaju biti dvojezično navedeni.

Rezultati trebaju obuhvatiti samo materijal koji se izravno odnosi na predmet. Obvezatna je primjena metričkog sustava. Preporučuje se upotreba SI jedinica. Rjeđe rabljene fizikalne vrijednosti, simboli i jedinice trebaju biti objašnjeni pri njihovu prvom spominjanju u tekstu. Za pisanje formula valja se koristiti Equation Editorom (programom za pisanje formula u MS Wordu). Jedinice se pišu normalnim (uspravnim) slovima, a fizikalni simboli i faktori kosima (italicom). Formule se susljedno obrojčavaju arapskim brojkama u zagradama, npr. (1) na kraju retka.

Broj slika mora biti ograničen samo na one koje su prijeko potrebne za objašnjenje teksta. Isti podaci ne smiju biti navedeni i u tablici i na slici. Slike i tablice trebaju biti zasebno obrojčane, arapskim brojkama, a u tekstu se na njih upućuje jasnim naznakama ("tablica 1" ili "slika 1"). Naslovi, zaglavlja, legende i sav ostali tekst u slikama i tablicama treba biti napisan hrvatskim i engleskim jezikom.

Slike je potrebno rasporediti na odgovarajuća mjesta u tekstu, trebaju biti izrađene u rezoluciji 600 dpi, crno-bijele (objavljivanje slika u koloru moguće je na zahtjev autora), formata jpg ili tiff, potpune i jasno razumljive bez pozivanja na tekst priloga.

Svi grafikoni i tablice izrađuju se kao crno-bijeli prilozi (osim na zahtjev). Tablice i grafikoni trebaju biti na svojim mjestima u tekstu te originalnog formata u kojemu su izrađeni radi naknadnog ubacivanja hrvatskog prijevoda. Ako ne postoji mogućnost za to, potrebno je poslati originalne dokumente u formatu u kojemu su napravljeni (*excel* ili *statistica* format).

Naslovi slika i crteža ne pišu se velikim tiskanim slovima. Crteži i grafikoni trebaju odgovarati stilu časopisa (fontovima i izgledu). Slova i brojke moraju biti dovoljno veliki da budu lako čitljivi nakon smanjenja širine slike ili tablice. Fotomikrografije moraju imati naznaku uvećanja, poželjno u mikrometrima. Uvećanje može biti dodatno naznačeno na kraju naslova slike, npr. "uvećanje 7500 : l".

Diskusija i zaključak mogu, ako autori žele, biti spojeni u jedan odjeljak. U tom tekstu treba objasniti rezultate s obzirom na problem postavljen u uvodu i u odnosu prema odgovarajućim zapažanjima autora ili drugih istraživača. Valja izbjegavati ponavljanje podataka već iznesenih u odjeljku *Rezultati*. Mogu se razmotriti naznake za daljnja istraživanja ili primjenu. Ako su rezultati i diskusija spojeni u isti odjeljak, zaključke je nužno napisati izdvojeno. Zahvale se navode na kraju rukopisa. Odgovarajuću literaturu treba citirati u tekstu, i to prema harvardskom sustavu (*ime – godina*), npr. (Bađun, 1965). Nadalje, bibliografija mora biti navedena na kraju teksta, i to abecednim redom prezimena autora, s naslovima i potpunim navodima bibliografskih referenci. Popis literature mora biti selektivan, a svaka referenca na kraju mora imati naveden DOI broj, ako ga posjeduje (http://www.doi.org) (provjeriti na http://www.crossref.org).

### Primjeri navođenja literature

Članci u časopisima: Prezime autora, inicijal(i) osobnog imena, godina: Naslov. Naziv časopisa, godište (ev. broj): stranice (od – do). Doi broj.

Primjer

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.

Knjige: Prezime autora, inicijal(i) osobnog imena, godina: Naslov. (ev. izdavač/editor): izdanje (ev. svezak). Mjesto izdanja, izdavač (ev. stranice od – do).

Primjeri

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.

Ostale publikacije (brošure, studije itd.)

Müller, D., 1977: Beitrag zür Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanstalt für Forstund Holzvvirt schaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

Web stranice

***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/department/docs/punctuation/node 00.html. First published 1997 (pristupljeno 27. siječnja 2010).

Autoru se prije konačnog tiska šalje pdf rada. Rad je potrebno pažljivo pročitati, ispraviti te vratiti Uredništvu s listom ispravaka. Autori znanstvenih i stručnih radova besplatno dobivaju po jedan primjerak časopisa. Autoru svakog priloga također se dostavlja besplatan primjerak časopisa.

Dodatne informacije o načinu pisanja znanstvenih radova mogu se naći na web adresi:

**www.ease.org.uk/publications/author-guidelines**

# Instructions for authors

## General terms

The "Drvna industrija" ("Wood Industry") journal publishes scientific papers (original scientific papers, review papers, previous notes), professional papers, conference papers, professional information, bibliographical and survey articles and other contributions related to biology, chemistry, physics and technology of wood, pulp and paper and wood products, including production, management and marketing issues in the wood industry.
Submission of a paper implies that the work has not been submitted for publication elsewhere or published before (except in the form of an abstract or as part of a published lecture, review or thesis, in which case it must be stated in a footnote); that the publication is approved by all co-authors (if any) and by the authorities of the institution where the research has been carried out. The complete content of the journal *Drvna industrija* (Wood Industry) is available on the Internet permitting any users to download, print, further distribute, read and reuse it with no limits provided that the author(s) and the original source are identified in accordance with the Creative Commons Attribution 4.0 International License (CC BY). The authors retain their copyrights.
The scientific and professional papers shall be published in English with summary in Croatian. The titles, headings and all the relevant results shall be also presented bilingually. The Editor's Office shall provide the translation into Croatian for foreign authors. Other articles are generally published in Croatian. The scientific and professional papers will be subject to a thorough review by at least two selected referees. The Editorial Board shall make the choice of reviewers, as well as the decision about the classification of the paper and its acceptance (based on reviewers' recommendations).
All contributions are subject to proofreading. The editors will require authors to modify the text in the light of the recommendations made by reviewers and language advisers, and they reserve the right to suggest abbreviations and text improvements. Authors are fully responsible for the contents of their contributions. It shall be assumed that the author has obtained the permission for the reproduction of portions of text published elsewhere, and that the publication of the paper in question does not infringe upon any individual or corporate rights. Papers shall report on true scientific or technical achievement. Authors are responsible for the terminological and metrological consistency of their contributions. The contributions are to be submitted by the link http://journal.sdewes.org/drvind

## Details

Papers submitted shall consist of no more than 15 single-sided DIN A-4 sheets of 30 double-spaced lines, including tables, figures and references, appendices and other supplements. Longer papers should be divided into two or more continuing series. The text should be written in doc format, fully written using Times New Roman font (text, graphs and figures), in normal style without additional text editing.
The first page of the paper submitted should contain full title, name(s) of author(s) with professional affiliation (institution, city and state), abstract with keywords (approx. 1/2 sheet DIN A4).
The last page should provide the full titles, posts and address(es) of each author with indication of the contact person for the Editor's Office.
Scientific and professional papers shall be precise and concise. The main chapters should be characterized by appropriate headings. Footnotes shall be placed at the bottom of the same page and consecutively numbered. Those relating to the title should be marked by an asterix, others by superscript Arabic numerals. Footnotes relating to the tables shall be printed under the table and marked by small letters in alphabetical order.
Latin names shall be printed in italics and underlined.
Introduction should define the problem and if possible the framework of existing knowledge, to ensure that readers not working in that particular field are able to understand author's intentions.
Materials and methods should be as precise as possible to enable other scientists to repeat the experiment. The main experimental data should be presented bilingually.
The results should involve only material pertinent to the subject. The metric system shall be used. SI units are recommended. Rarely used physical values, symbols and units should be explained at their first appearance in the text. Formulas should be written by using Equation Editor (program for writing formulas in MS Word). Units shall be written in normal (upright) letters, physical symbols and factors in italics. Formulas shall be consecutively numbered with Arabic numerals in parenthesis (e.g. (1)) at the end of the line.
The number of figures shall be limited to those absolutely necessary for clarification of the text. The same information must not be presented in both a table and a figure. Figures and tables should be numbered separately with Arabic numerals, and should be referred to in the text with clear remarks ("Table 1" or "Figure 1"). Titles, headings, legends and all the other text in figures and tables should be written in both Croatian and English.
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.
All graphs and tables shall be black and white (unless requested otherwise). Tables and graphs should be inserted into the text in their original format in order to insert them subsequently into the Croatian version. If this is not possible, original document should be sent in the format in which it was made (excel or statistica format).
The captions to figures and drawings shall not be written in block letters. Line drawings and graphs should conform to the style of the journal (font size and appearance). Letters and numbers shall be sufficiently large to be readily legible after reduction of the width of a figure or table. Photomicrographs should have a mark indicating magnification, preferably in micrometers. Magnification can be additionally indicated at the end of the figure title, e.g. "Mag. 7500:1".
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).:

## Example of references

Journal articles: Author's second name, initial(s) of the first name, year: Title. Journal name, volume (ev. issue): pages (from - to). DOI number.

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).

The paper will be sent to the author in pdf format before printing. The paper should be carefully corrected and sent back to the Editor's Office with the list of corrections made. Each contributor will receive 1 copy of the journal.

Further information on the way of writing scientific papers can be found on the following website:

**www.ease.org.uk/publications/author-guidelines**

**SVEUČILIŠTE U ZAGREBU • FAKULTET ŠUMARSTVA I DRVNE TEHNOLOGIJE**
***UNIVERSITY OF ZAGREB • FACULTY OF FORESTRY AND WOOD TECHNOLOGY***
Svetošimunska 23, 10000 Zagreb, Hrvatska / *Croatia* IBAN: HR0923600001101340148
tel: 00385 1 2352 454 e-mail: dcvetan@sumfak.hr OIB / *VAT ID*: HR07699719217

# PRETPLATNI LIST / *SUBSCRIPTION SHEET*

Izašao je **broj 1** časopisa Drvna industrija, **volumen 74 (2023. godina)**. Pozivamo Vas da obnovite svoju pretplatu ili se pretplatite na časopis, te na taj način pomognete njegovo izlaženje. Cijena sva četiri broja jednog godišta (volumena) je 55,00 EUR bez PDV-a, u Hrvatskoj i inozemstvu. Ukoliko ste suglasni s uvjetima pretplate za jedno godište časopisa, molimo Vas da popunite obrazac za pretplatu i pošaljete ga na našu poštansku ili elektroničku adresu.

***Issue 1, Volume 74 (2023)*** *of the journal* Drvna industrija *is published. We invite you to renew your subscription or subscribe to a journal to support it. The price of all four issues of one year (volume) is 55 EUR without VAT, in Croatia and worldwide. If you agree to the subscription terms for one volume, please complete the subscription form and send it to our postal or e-mail address*

Predsjednik Izdavačkog savjeta
časopisa Drvna industrija
*President of Publishing Council*

izv. prof. dr. sc. Vjekoslav Živković

Glavna i odgovorna urednica
časopisa Drvna industrija
*Editor-In-Chief*

prof. dr. sc. Ružica Beljo Lučić

## PRETPLATA NA ČASOPIS
## *SUBSCRIPTION TO JOURNAL*

DRVNA INDUSTRIJA

Pretplaćujemo se na časopis Drvna industrija u količini od _____ godišnje pretplate (četiri broja).
Cijena jednog godišta (volumena) iznosi 55 EUR, bez PDV-a. Pretplata obuhvaća sve brojeve jednog godišta.
*We subscribe to the journal Drvna industrija in amount of _____ annual subscription(s) (four issues).*
*Price of one volume (year) is 55 EUR, without VAT. The subscription covers all numbers of one volume.*

Hrvatska:
HR0923600001101340148
s naznakom "Za časopis Drvna industrija"
poziv na broj: 3-02-03

EU / World:
Bank: Zagrebačka banka
IBAN: HR0923600001101340148
Swift: ZABA HR 2X

Osoba / *Name*: ______________________________ e-mail: ______________________

Tvrtka, ustanova / *Company, institution*: ____________________________________________

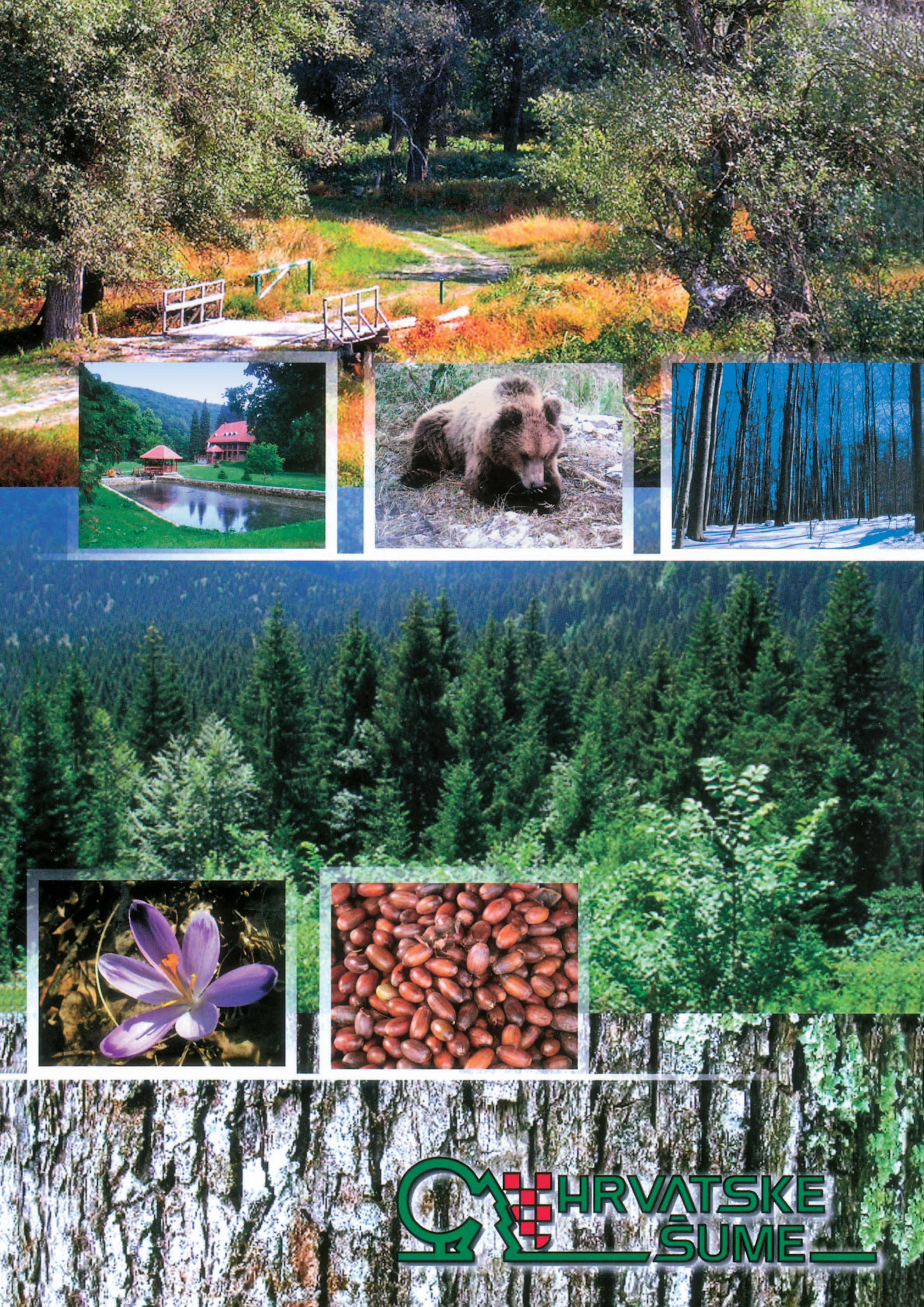
OIB / *VAT ID*: ______________________________ Telefon / *Phone*: ______________

Adresa / *Address*: ______________________________ Pošta. broj: ______________
*(ulica / street)* *Postal code:*

Grad / *City*: ______________________________ Regija / *Region*: ______________________

Država / *Country*: ______________________________


povežite se s prirodom
drvodjelac
Drvodjelac d.o.o.
Petra Preradovića 14, Ivanec, Hrvatska
+385 (0)42 781 922 | www.drvodjelac.hr


HRVATSKE
ŠUME

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:

projektiranje, izrada, procjena, izvođenje i nadzor radova iz područja uzgajanja, uređivanja, iskorištavanja i otvaranja šuma, lovstva, zaštite šuma, hortikulture, rasadničarske proizvodnje, savjetovanja, ispitivanja kvalitete proizvoda, sudskoga vještačenja, izrade i revizije stručnih studija i planova, kontrola projekata i stručne dokumentacije, izgradnja uređaja, izbor opreme, objekata, procesa i sustava, stručno osposobljavanje i licenciranje radova u šumarstvu, lovstvu i preradi drva.

## Zadaci Komore:

- promicanje razvoja struke i skrb o stručnom usavršavanju članova,
- 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.

Članovima Komore izdaje se rješenje, pečat i iskaznica ovlaštenoga inženjera.
Za uspješno obavljanje zadataka te za postizanje ciljeva ravnopravnoga i jednakovrijednoga zastupanja struka udruženih u Komoru, članovi Komore organizirani su u razrede:

- Razred inženjera šumarstva
- Razred inženjera drvne tehnologije

HRVATSKA KOMORA INŽENJERA ŠUMARSTVA I DRVNE TEHNOLOGIJE
Prilaz Gjure Deželića 63
10000 ZAGREB

telefon:
++ 385 1 376-5501
e-mail:
info@hkisdt.hr

www.hkisdt.hr