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Characterization of Engineering Elastic Parameters of Oriented Strand Board (OSB) Manufactured from Poplar (*Populus deltoides*) Strands Using Ultrasonic Contact Pulse Transmission

Karakterizacija parametara elastičnosti ploče s orijentiranim makroiverjem (OSB) proizvedene od iverja drva topole *(Populus deltoides)* uz pomoć ultrazvučnoga kontaktnog prijenosa impulsa

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ABSTRACT • *When using wood and wood-based composites, it is necessary to determine the elastic constants of these engineered materials. Oriented strand board (OSB), as structural wood based panel, plays a significant role in the building sector, but the accessibility of such elastic constants of OSB is mostly limited. For this purpose, this study aimed at determining the elastic wave velocity, stiffness and all elastic constants of OSB made from Poplar (Populus deltoides) strands using ultrasonic through–transmission technique. Laboratory OSBs with the mean density of 760 kg/m^3 were made with the average strand sizes of 0.6 mm in thickness, 120 mm in length and 30 mm in width. 8 % phenol-formaldehyde (PF) resin was used with the pressing conditions of 3.43 N/mm^2, 190 °C and 600 s as pressure, temperature and time of pressing, respectively. The OSBs were assumed as an orthotropic model. Three modulus of elasticity (E_1, E_2, and E_3), three shear modulus (G_{12}, G_{13} and G_{23}), and six Poisson's ratios (ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23}, ν_{32}) were calculated by longitudinal, transversal and quasi-transversal waves velocities. Ultrasonically determined stiffness coefficients of OSB were investigated by representative volume elements*

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(RVE). Therefore, the separation of scales requirement is satisfied, and the measured velocities can be applied to determine the engineering elastic parameters of the examined OSB. The results indicate that modulus of elasticity and shear modulus are in the same order of magnitude in comparison with other references, and the values of Poisson's ratios are valid in ultrasonic range measurement. In conclusion, the ultrasonic contact pulse transmission shows great potential to determine the characterization of elastic wave velocity, stiffness and engineering elastic parameters.

Keywords: *poplar (Populus deltoides); oriented strand bord; engineering parameters; ultrasonic waves*

SAŽETAK • *Za primjenu drva i kompozita na bazi drva iznimno je važno odrediti konstante elastičnosti tih konstrukcijskih materijala. Ploča s orijentiranim makroiverjem (OSB ploča), kao strukturna ploča na bazi drva, ima široku primjenu u građevnom sektoru, a pristup takvim konstantama elastičnosti OSB ploča uglavnom je ograničen. Stoga je cilj ove studije bio odrediti brzinu elastičnog vala, krutost i sve konstante elastičnosti OSB ploča proizvedenih od makroiverja topole (Populus deltoides) primjenom ultrazvučne tehnike. Od iverja prosječne debljine 0,6 mm, duljine 120 mm i širine 30 mm laboratorijski su izrađene OSB ploče srednje gustoće 760 kg/m^3. Upotrijebljena je 8 %-tna fenol-formaldehidna (PF) smola u ovim uvjetima prešanja: tlak je bio 3,43 N/mm^2, temperatura 190 °C, a proces prešanja trajao je 600 s. Pretpostavljeno je da su OSB ploče ortotropni modeli. Na temelju srednjih vrijednosti uzdužne, poprečne i kvazipoprečne brzine valova izračunana su tri modula elastičnosti (E_1, E_2 i E_3), tri modula smicanja (G_{12}, G_{13} i G_{23}) i šest Poissonovih omjera (ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23}, ν_{32}). Ultrazvučno utvrđene krutosti OSB ploča ispitivane su reprezentativnim volumnim elementima (RVE). Dakle, ispunjen je zahtjev za odvajanje skala, a izmjerene se brzine mogu primijeniti za određivanje inženjerskih parametara elastičnosti ispitivanih OSB ploča. Rezultati pokazuju da su moduli elastičnosti i moduli smicanja istog reda veličine u usporedbi s drugim referencama, a vrijednosti Poissonovih omjera vrijede u mjerenjima ultrazvučnog raspona. Zaključno, ultrazvučni kontaktni prijenos impulsa pokazuje velik potencijal za određivanje brzine elastičnih valova, krutosti i konstrukcijskih parametara elastičnosti materijala.*

Ključne riječi: *topola (Populus deltoides); ploča s orijentiranim makroiverjem; konstrukcijski parametri; ultrazvučni valovi*

1 INTRODUCTION
1. UVOD

OSB, as an engineered wood material, has got considerable attention in structural applications in recent years so that today OSB plays a remarkable role in both commercial and residential sectors. OSB is commonly used for wall and roof sheathing, flooring and I-joists. It is also used in different applications such as furniture, reels, pallets and boxes, trailer liners and recreational vehicle flooring (Smulski, 1997; Hiziroglu, 2006). Hence, with increasing applications of OSB, the determination of its mechanical properties is critical for ensuring reliable performance.

Elastic constants of OSB are of substantial importance to both science and technology as they not only describe the mechanical behavior of materials but are also significant for purposes of engineering design. Furthermore, engineering constants are required as input parameters for modern numerical simulation methods such as finite element method (FEM), which is often used in mechanics of engineered materials and civil engineering (Goncalves *et al.*, 2014). As a result, determination of the full set of elastic engineering parameters, including three modulus of elasticity (E_1, E_2 and E_3), three shear modulus (G_{12}, G_{13} and G_{23}), and six Poisson's ratios (ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23}, ν_{32}), is essential for a better understanding of the particular elastic behavior of OSB (Bodig and Jayne, 1993; Ozyhar *et al*., 2013).

The availability of engineering parameters for engineered wood composites such as OSB is often limited and no adequate information can be found in the literatures because some properties such as shear modulus and six Poisson's ratios have never been properly addressed. For this reason, some researchers including Morris *et al*. (1995) used Poisson's ratio of other wood-based panels such as particleboard for simulating the behavior of OSB employing FEM (Morris *et al*., 1995). Besides, the conventional static test is the most common experimental technique to determine elastic properties of materials. Determination of the elastic constants by conventional static tests requires complex and expensive equipment, long test time and several specimens with special shape and dimensions (Kazemi Najafi *et al*., 2005). Measurements of shear modulus and Poisson's ratios are very sophisticated to perform and require very elaborate testing equipment, because it is complex to measure shear stresses and respective strains in the test specimens (Keunecke *et al*., 2007). To overcome these limitations, some researchers such as Bucur (1992, 2006), Bucur and Archer (1984), Kazemi Najafi *et al.* (2005), Keunecke *et al.* (2007), Kohlhauser and Hellmich (2012), Ozyhar *et al.* (2013), Goncalves *et al.* (2014) and Bader *et al.* (2016) proposed ultrasonic waves method as a nondestructive, cheap, fast, simple and flexible technique to determine the elastic constants of wood and wood-based composites. Ultrasonic waves can freely propagate in solids and liquids and are reflected at boundaries of internal flaws or change of medium. Accordingly, they are related to properties of the propagation medium. Therefore, the measurement of acoustical quantities, such as propagation velocities and attenuation, provides information about the elastic properties of the material.

Thus, with taking into account the limitations in availability of elastic constants of OSB, the aim of this study was to characterize elastic wave velocity, stiffness and anisotropic behavior, and also to provide all elastic constants of OSB made from Poplar (*Populus deltoides*) strands by means of ultrasonic waves.

2 THEORETICAL BACKGROUND
2. TEORIJSKE OSNOVE

In an orthotropic material, by the generalized Hook's law, stresses σ_{ij} and strains ε_{ij} are linked by six linear relations $\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl,}$ which define the stiffness matrix C_{ijkl} with nine independent constants: six diagonal terms and three off-diagonal terms:

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ 0 & C_{22} & C_{23} & 0 & 0 & 0 \\ 0 & 0 & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} \quad (1)$$

Where σ, C and ε are stress, stiffness and strain tensors, respectively

The relations between the terms of the stiffness matrix and the ultrasonic wave velocity are well known by the Christoffel's equation (Ozyhar *et al.*, 2013; Bucur, 1992):

$$[\Gamma_{ik} - \rho V^2 \delta_{ik}] = 0, \quad (2)$$

Where Γ_{ik} is Christoffel's tensor, δ_{ik} is the Kronecker delta symbol, V is the wave velocity and ρ is the density of the solid. The eigenvalues and eigenvectors of Christoffel's tensor, and stiffness tensor components can be calculated from the mass density of the material, and from the ultrasonic wave velocities, according to the theory of wave propagation in elastic media (Ozyhar *et al.,* 2013; Bucur, 1992):

$$C_{ij} = V_{ij}^2 \rho \quad (3)$$

Where the first index i of the velocities $V_{i,j}$ designates the wave propagation direction, and the second index j designates the direction of the particle motion induced by the wave, i.e. the polarization direction ($i = j$ for a longitudinal wave; $i \neq j$ for a transversal wave).

Accordingly, the normal stiffness tensor components C_{11}, C_{22}, and C_{33} are related to longitudinal wave velocities V_{11}, V_{22}, and V_{33} (Eq. 4); while the shear stiffness components C_{44}, C_{55}, and C_{66}, which are equal to the shear moduli G_{12}, G_{13}, and G_{23}, respectively, are related to transversal wave velocities V_{12}/V_{21}, V_{13}/V_{31} and V_{23}/V_{32} (Eq. 5). For the determination of off-diagonal terms C_{iijj}, the propagation of ultrasonic waves along non-principal directions in symmetry planes is necessary. For propagation directions in symmetry planes inclined by 45° to the principal directions of materials, the off-diagonal terms are related to wave velocity of the quasi-shear wave with propagation direction in direction $n = \left(\frac{1}{\sqrt{2}} \frac{1}{\sqrt{2}}\right)^T$ (T superscript denotes quasi-transverse mode) and particle motion in the $i - j$ plane. The off-diagonal elasticity components C_{iijj} can be determined by equations 6 (Ozyhar *et al.,* 2013).

$$C_{11} = V_{11}^{\ 2}\rho \qquad C_{22} = V_{22}^{\ 2}\rho \qquad C_{33} = V_{33}^{\ 2}\rho \quad (4)$$

$$\begin{aligned} C_{44} &= (V_{32}^{\ 2}\rho + V_{23}^{\ 2}\rho)\ /2 \\ C_{55} &= (V_{13}^{\ 2}\rho + V_{31}^{\ 2}\rho)\ /2 \\ C_{66} &= (V_{12}^{\ 2}\rho + V_{21}^{\ 2}\rho)\ /2 \end{aligned} \quad (5)$$

$$\begin{aligned} C_{12} &= \sqrt{C_{11} + C_{66} - 2V^2_{12/12}\rho)(C_{22} + C_{66} - 2V^2_{12/12}\rho)} - C_{66} \\ C_{13} &= \sqrt{C_{11} + C_{55} - 2V^2_{13/13}\rho)(C_{33} + C_{55} - 2V^2_{13/13}\rho)} - C_{55} \\ C_{23} &= \sqrt{C_{22} + C_{44} - 2V^2_{23/23}\rho)(C_{33} + C_{44} - 2V^2_{23/23}\rho)} - C_{44} \end{aligned} \quad (6)$$

The compliance tensor S of the orthotropic material is the inverse of the stiffness tensor C, i.e. $C^{-1} = S$. The compliance matrix is directly related to the elastic engineering parameters (Bucur and Archer, 1984):

$$Sij = \begin{bmatrix} S_{11}=1/E_1 & S_{12}=-\nu_{12}/E_2 & S_{13}=-\nu_{13}/E_3 & 0 & 0 & 0 \\ S_{21}=-\nu_{21}/E_1 & S_{22}=1/E_2 & S_{23}=-\nu_{23}/E_3 & 0 & 0 & 0 \\ S_{31}=-\nu_{31}/E_2 & S_{32}=-\nu_{32}/E_2 & S_{33}=1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44}=1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55}=1/G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66}=1/G_{12} \end{bmatrix} \quad (7)$$

Three Young's moduli *of* E_1, E_2, E_3 refer to the principal directions of materials, three shear moduli G_{12}, G_{13}, G_{23} refer to principal planes of materials (symmetry), and out of six Poisson's ratios n_{12}, n_{21}, n_{13}, n_{31}, n_{23}, n_{32}, the first index of Poisson's ratio refers to the (passive) strain and the second index refers to the active strain. Bucur and Archer (1984) have described in detail the conversion between the components of the compliance matrix and the components of the stiffness matrix.

3 MATERIALS AND METHODS
3. MATERIJALI I METODE

3.1 Materials
3.1. Materijali

Poplar (*Populus deltoides*) trees, as a fast-growing species and widely planted in Iran, with an average DHB of 20-25 cm, were harvested from Chamestan Educational Forest, Noor, Iran. Logs were cut into 120 cm length and debarked by hand (Figure 1). The average wood density was 0.39 g/cm^3. The morphological characteristics and chemical composition of Poplar wood are listed in Table 1.

3.2. Panel manufacturing
3.2. Proizvodnja ploča

The veneers with thickness of 0.6 mm were prepared from poplar wood and then cut into strands with 30 mm width and 120 mm length by circular saw. The strands were dried at (105±5) °C in an oven to reach moisture content of 2.5-3 %. Phenol-formaldehyde

Figure 1 Harvesting and debarking Poplar tree
Slika 1. Sječa, izrada i otkoravanje drva topole

Table 1 Morphological characteristics and chemical composition of Poplar wood (Ramazani *et al.,* 2013)
Tablica 1. Morfološka svojstva i kemijski sastav drva topole (Ramazani *et al.,* 2013.)

Properties / *Svojstva*	**Poplar** *Topola*
Anatomical / *Anatomska*	
Fiber length / *duljina vlakna*, mm	0.76 (0.087)*
Fiber lumen diameter / *promjer lumena vlakna*, μm	15.67 (1.81)
Fiber overall diameter / *promjer vlakna,* μm	23.00 (2.5)
Fiber wall thickness / *debljina stijenke vlakna*, μm	3.6 (0.59)
Chemical / *Kemijska*	
Cellulose / *celuloza,* %	51
Lignin / *lignin,* %	22.3
Extractives / *ekstraktivne tvari*, %	5.1
Ash / *pepeo*, %	0.7

[a] Dissolved in alcohol-acetone. / *Otopljeno u alkohol-acetonu.*
* Values in parenthesis are the standard deviation. / *Vrijednosti u zagradama standardne su devijacije.*

(PF) resin was used at a level of 8 % based on oven-dry weight of wood strands to produce the panels. No wax or other additives were used. The characteristics of the PF resin are given in Table 2.

Table 2 Properties of PF resin
Tablica 2. Svojstva fenol-formaldehidne (PF) smole

Properties / *Svojstva*	**PF**
Color / *boja*	Dark / *tamna*
Solid content / *sadržaj čvrste tvari*, 105 °C, 3 H, %	62.00
Density / *gustoća*, g/cm^3	1.13
PH 25 °C	7.25
Viscosity / *viskoznost*, 20 °C, cPas	320
Gel time / *vrijeme geliranja*, 100 °C, s	300

OSB panels were manufactured using a standardized procedure that simulated industrial production at the laboratory. For the preparation of the panels, strands (120 mm × 30 mm × 0.6 mm) were mixed in a rotary blender equipped with resin spraying. The strands were oriented manually into a forming box and then the strands mats were hot-pressed at pressure of 3.43 N/mm^2 and temperature of 190 °C for 10 minutes. The dimensions of the panels were 460 mm × 460 mm × 16 mm. Target board density was set at 760 kg/m^3. The

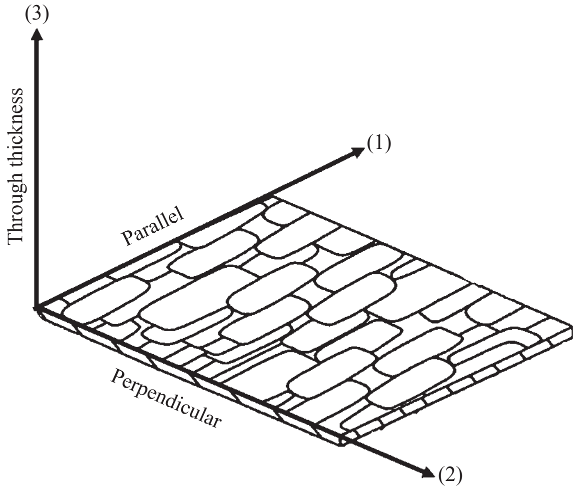

Figure 2 Schematic of principal axes of OSB
Slika 2. Shematski prikaz glavnih osi OSB ploče

manufactured panels were conditioned at relative humidity of (65±5) % and temperature of (20±3) °C. The OSB panels are assumed as an elastic, anisotropic wood composite material with orthotropic symmetry, where the symmetry planes are defined in terms of parallel direction of strand alignment (direction 1), perpendicular direction of strand alignment (direction 2) and thickness of the panel (direction 3) (Figure 2).

3.3. Ultrasonic tests
3.3. Ultrazvučni testovi

Four types of samples with different orientations to the major axis of anisotropy for ultrasonic testing were of cubical shape with 16 mm edge length (Figure 3). For each sample, 6 replications and a total of twenty-four samples were provided. Density of all samples was kept at 0.76 g/cm^3. Prior to testing, all the specimens were conditioned at a temperature of (20±3) °C and a relative humidity (RH) of (65±5) % to ensure uniform moisture content.

In the present study, orthotropic symmetry was assumed for elastic properties of the OSBs. According to Bucur (2006), three longitudinal and three shear wave velocities propagating along the principal axes of anisotropy, and also three quasi-longitudinal or quasi-shear wave velocities, measured at the angle θ of the wave orientation vector, are needed in order to determine all independent components of the stiffness matrix. In this research, three longitudinal waves (*Vii*), six shear waves

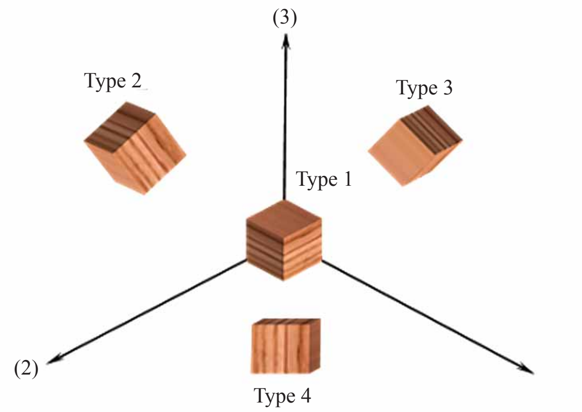

Figure 3 Types of specimens used for ultrasound velocity measurements in different orientations
Slika 3. Vrste uzoraka rabljenih za ultrazvučna mjerenja brzina različitih smjerova

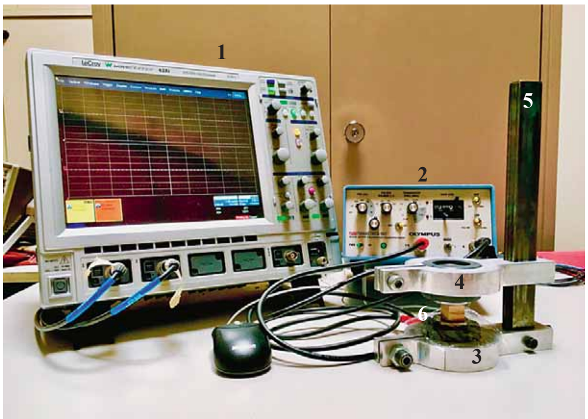

Figure 4 Ultrasonic equipment: 1. oscilloscope, 2. pulser-receiver, 3. transducer sender, 4. transducer receiver, 5. auxiliary testing device, 6. sample
Slika 4. Oprema za ultrazvučna mjerenja: 1. osciloskop, 2. prijamnik impulsa, 3. pretvornik-predajnik, 4. pretvornik-prijamnik, 5. pomoćni uređaj za ispitivanje, 6. uzorak

(*Vij*) and three quasi-shear waves at 45° (*Vij/ij*) were measured. The equipment used for performing ultrasonic measurements consists of a digital oscilloscope (WaveRunner 62Xi, Lecroy Corporation, Chestnut Ridge, NY, USA), a pulser-receiver (5077 PR, Panametrics Inc., Waltham, MA, USA), two pairs of transducers with frequencies of 100 kHz and 250 kHz for longitudinal and transversal waves, respectively, as well as an auxiliary testing device (Figure 4). For better contact between the transducers and the specimens, a thin layer of honey was used. A cellophane film was applied in order to prevent the infiltration of honey into the wood microstructure, and hence influencing its stiffness properties. In this study, through-transmission technique was used to determine the ultrasonic wave velocities. In this technique, two transducers are used, one sending a signal into the specimen and one receiving the sent signal on the opposite side of the specimen (Figure 4).

As reported by continuum (micro) mechanics (Salençon, 2001; Zaoui, 2002), ultrasound-derived elastic properties of micro-heterogeneous materials are defined by a representative volume element (RVE). Thus, the characteristic length of the RVE (L_{RVE}) must be considerably larger than the length of inhomogeneities d inside the RVE ($L_{RVE} \gg d$), and the characteristic length of the RVE (L_{RVE}) need to be smaller than the wavelength λ of the propagation waves ($L_{RVE} \ll \lambda$). Mathematically, this is expressed by means of the separation-of-scales requirement (Kohlhauser and Hellmich, 2013),

$$d \gg L_{RVE} \ll \lambda \tag{8}$$

The wavelength λ is readily accessible from the measured wave speed V and from the chosen signal frequency f as $\lambda = V/f$. The wave speed is equal to the travel distance s of the wave divided by the travel time t of the signal $V= S/t$.

4 RESULTS AND DISCUSSION
4. REZULTATI I RASPRAVA

Homogenized material properties of micro-heterogeneous materials are defined on representative volume elements (RVEs). The inhomogenities within an RVE of OSB result from the strands made from Poplar wood with an average fiber lumen diameter of 15.67 μm (Table 1). Thus, the minimum longitudinal and shear wavelength amounted to 9.3 and 3 mm, respectively, and the length of RVE≈0.76 mm (Table 4). In this study, it is implied that the characteristic length of RVE (L_{RVE}) is considerably larger than the lumen diameter of Poplar strands (*d)* inside the RVE, and L_{RVE} is smaller than both longitudinal and shear wavelength values. Consequently, the separation of scales requirement is fulfilled, and the measured velocities can be used to determine the elastic properties of the OSB.

The mean values and standard deviations of density and ultrasonic wave velocities are given in Table 3, and the corresponding wavelengths are given in Table 4. The maximum and minimum longitudinal wave velocities amounted to V_{11}= 4.2 and V_{33} = 0.93 km/s, respectively (V_{11}>$V_{22} \gg V_{33}$). This means that strands were predominantly oriented in the principal axis of the boards and they behaved as orthotropic materials. The velocities are related to the material elasticity, because the propagation of the wave generates mechanical oscillations (Keunecke *et al*., 2007). As reported in literature (Bucur, 2006; Bucur and Archer, 1984; Gerhards, 1982), the velocities in thickness direction (V_{33}) are significantly lower than in parallel and perpendicular to manufacturing direction, respectively. In thickness direction (V_{33}), there is no continuous medium to make it possible to conduct the wave, so velocity is always lower in this direction.

The values of shear wave velocities with directions of propagation and polarization in the same symmetry plane are unequal. The different values for each shear wave velocities proved the anisotropy of OSBs. Generally, longitudinal wave velocities are higher than shear wave velocities, because the particle oscillations are parallel to the direction of longitudinal wave propagation, while they are perpendicular to each other in shear waves (Wang, 20013; Wang *et al*., 2007; Zhang *et al*., 2011). Wood-based panel anisotropy could be

Table 3 Mean values of density and ultrasonic wave velocities in OSB
Tablica 3. Srednje vrijednosti gustoće i brzina ultrazvučnih valova u OSB ploči

Density *Gustoća* g/cm³	**Longitudinal wave, km/s** *Uzdužni val,* km/s			**Shear wave, km/s** *Poprečni val,* km/s						**Quasi-shear wave, km/s** *Kvazipoprečni val,* km/s		
Mean value *Srednja vrijednost*	V_{11}	V_{22}	V_{33}	V_{12}	V_{21}	V_{13}	V_{31}	V_{23}	V_{32}	$V_{12/12}$	$V_{21/21}$	$V_{13/13}$
0.76 (±0.08)[a]	4.2 (±0.16)	3.39 (±0.11)	0.93 (±0.05)	1.8 (±0.55)	1.67 (±0.36)	1.03 (±0.08)	1.72 (±1.09)	0.75 (±0.21)	0.83 (±0.17)	1.58 (±0.13)	1.00 (±0.08)	0.97 (±0.03)

[a] Values in parenthesis are the standard deviation. / *Vrijednosti u zagradama standardne su devijacije.*

Table 4 Mean values of wavelengths in OSB
Tablica 4. Srednje vrijednosti valnih duljina u OSB ploči

Wavelength / *Valna duljina*, mm											
λ_{11}	λ_{22}	λ_{33}	λ_{12}	λ_{21}	λ_{13}	λ_{31}	λ_{23}	λ_{32}	$\lambda_{12/12}$	$\lambda_{13/13}$	$\lambda_{23/23}$
42	33.9	9.3	7.2	6.68	4.12	6.88	3.00	3.32	6.32	4	3.9

Table 5 Anisotropy of OSB expressed by velocity ratios in principle anisotropic directions and planes
Tablica 5. Anizotropija OSB ploče izražena odnosima brzina u glavnim anizotropnim smjerovima i ravninama

Anisotropy in principal directions *Anizotropija u glavnim smjerovima*		**Anisotropy in symmetry planes** *Anizotropija u simetričnim ravninama*		**Birefringence in the same plane** *Dvostruka refrakcija u istoj ravnini*	
Longitudinal waves velocities *Brzine uzdužnih valova*	Ratios *Omjeri*	Shear waves velocities *Brzine poprečnih valova*	Ratios *Omjeri*	Shear waves velocities *Brzine poprečnih valova*	Ratios *Omjeri*
V_{11}/V_{22}	1.23	V_{12}/V_{13}	1.74	V_{12}/V_{21}	1.07
V_{11}/V_{33}	4.5	V_{13}/V_{23}	2.4	V_{13}/V_{31}	1.7
V_{22}/V_{33}	3.64	V_{13}/V_{23}	1.37	V_{23}/V_{32}	0.9

calculated by the ratios between velocities of longitudinal and shear waves in the three main symmetry directions (Bucur, 2006). The anisotropy of OSB can be deduced from the values noted in Table 5. V_{12}/V_{21}= 1.07 shows a low anisotropy in 1-2 plane. The highest anisotropy expressed by birefringence is in 1-3 plane. Bucur *et al.* (1998) argued that the anisotropy is much higher in planes containing the axis 3, and that it is related to the type and size of the particles.

Calculated stiffness properties are summarized in Table 6. The stiffness tensor components are arranged as follows:

$$C_{11}>C_{22}\gg C_{33},\ C_{66}>C_{55}>C_{44},\ \text{and}\ C_{12}\gg C_{13}>C_{23} \quad (9)$$

The order of the stiffness coefficients is related to the theoretical acoustic behavior and mechanical properties of wood and its composites (Goncalves *et al*., 2011). The shear stiffness in the plane of the board C_{66} (2.31 GPa) is greater than the shear stiffnesses in the out-of-plane directions, where C_{44} (0.47 GPa) is smaller than C_{55} (1.44 GPa). The stiffness tensor components derived from ultrasonic tests are in the same order of magnitude as the values reported by Bucur *et al.* (1998), who worked on elastic constants of OSB, MDF and chipboard using ultrasonic velocity method (Table 6). Kazemi Najafi *et al.* (2005) also determined elastic constants of two types of commercial particleboards by means of ultrasonic technique, and they obtained a similar trend for stiffness coefficients. The values of stiffness components in this study are greater (13-44 %) than the stiffness values obtained by Bucur *et al.* (1998) (Table 6).

The values of engineering elastic constants of OSB are given in Table 7. The modulus of elasticity in parallel direction (refer to Figure 2) (E_1) is 7.14 GPa, which is 29 % greater than the modulus of elasticity in perpendicular direction (E_2) (5 GPa). Bucur *et al.* (1998) reported that the E_1 in OSB is 20 % higher than E_2, and Kazemi Najafi *et al.* (2005) also obtained the E_1 17 % higher than E_2 in particleboard. The minimum modulus of elasticity amounted to 0.5 GPa in thickness direction (E_3).

The literature, there are few references about modulus of elasticity in the perpendicular and thickness directions, shear modulus and Poisson's ratio. Mostly, the modulus of elasticity in the direction of strand alignment was measured in static tests on OSBs. Furthermore, the comparability between the measurement results obtained in this study with other results is generally complicated and unreliable since different manufacturing processes, glues, densities, specimen dimensions, frequencies and measurement techniques are used in the majority of cases.

In this study, shear modulus obtained from ultrasonic results, in parallel, perpendicular and thickness

Table 6 Mean values and standard deviation of stiffness tensor components derived from ultrasonic testing according to Equations 4, 5 and 6
Tablica 6. Srednje vrijednosti i stadardne devijacije krutosti komponente tenzora derivirane iz ultrazvučnih ispitivanja prema jednadžbama 4, 5 i 6

Diagonal stiffness tensor components *Komponente tenzora dijagonalne krutosti*	**Mean value, GPa** *Srednja vrijednost,* GPa	**Mean value[#], GPa** *Srednja vrijednost[#],* GPa	**Off-diagonal stiffness tensor components** *Komponente tenzora izvandijagonalne krutosti*	**Mean value[#], GPa** *Srednja vrijednost[#],* GPa
C_{11}	13.4 (±0.86)[a]	9.6	C_{12}	7.02 (±0.34)
C_{22}	8.8 (±0.41)	6.5	C_{13}	1.34 (±0.14)
C_{33}	0.66 (±0.08)	0.33	C_{23}	1.06 (±0.11)
C_{44}	0.47 (±0.07)	0.31		
C_{55}	1.44 (±0.09)	0.8		
C_{66}	2.31 (±0.12)	2.00		

[a] Values in parenthesis are the standard deviation. / *Vrijednosti u zagradama standardne su devijacije.*
[#] Bucur and Archer (1984)

Table 7 Elastic engineering parameters determined from ultrasonic measurements
Tablica 7. Parametri elastičnosti određeni iz ultrazvučnih mjerenja

Young's modulus, GPa *Youngov modul,* GPa				**Shear modulus, GPa** *Modul smicanja,* GPa				**Poisson's ratios** *Poissonovi omjeri*					
E_1	E_2	E_3		G_{12}	G_{13}	G_{23}		ν_{12}	ν_{21}	ν_{13}	ν_{31}	ν_{23}	ν_{32}
7.14	5	0.5		2.32	1.43	0.47		0.66	0.46	0.93	0.06	0.7	0.07

direction, are about *E1*/3, *E1*/5 and *E1*/15, respectively. The values of Poisson's ratios were obtained from the literature, i.e. 0.23 in bending test in 1-3 plane (Ting and Chen, 2005), and Bucur (1992) measured the value of Poisson's ratio from 0.068 to 1.52 in flakboard. For validation of the obtained Poisson's ratios in this study, Poisson's ratio can be estimated as (Kazemi Najafi *et al.*, 2005; Bucur, 1992):

$$(1-\nu_{12}\cdot\nu_{21}) > 0$$
$$(1-\nu_{13}\cdot\nu_{31}) > 0 \qquad (10)$$
$$(1-\nu_{23}\cdot\nu_{32}) > 0$$

And the

$$(1-\nu_{12}\cdot\nu_{21}-\nu_{13}\cdot\nu_{31}-\nu_{23}\cdot\nu_{32}-2\cdot\nu_{21}\cdot\nu_{32}\cdot\nu_{31}) > 0 \qquad (11)$$

As a result, these conditions are satisfied and it can be deduced that the coefficients are valid in ultrasonic range of measurement. Theoretically, Poisson's ratios for anisotropic materials with orthotropic symmetry can have no bounds (Ting and Chen, 2005). In the present study, there are no values exceeding 1.00 for Poisson's ratios, while Ozyhar *et al.* (2013) and Bucur (1992) obtained Poisson's ratios with values exceeding 1.00. They stated that Poisson's ratios with values higher than one are assumed to be unusual for wood and wood composites, and they have not been reported in static tests. Kohlhauser and Hellmich (2012) and Bader *et al.* (2016) argued that the ultrasonic characterization of off-diagonal stiffness components is very sensitive to inaccuracies regarding the wave velocity measurements and, to solve this problem, they proposed a combined ultrasonic-mechanical method to obtain the Poisson's ratios.

5 CONCLUSION
5. ZAKLJUČAK

Engineering elastic parameters of OSB made from Poplar were studied using ultrasonic contact pulse transmission. The ultrasonic contact pulse transmission shows great potential to determine the characterization of elastic wave velocity, stiffness and engineering elastic parameters and also study the anisotropic behavior of OSB, as an easy, fast, reliable and economic method, since few information can be found in the literature about elastic constants (stiffness, shear modulus and Poisson's ratios) of OSB. Based on the findings of this study, the measured velocity V_{11} was 19 and 78 percent higher than V_{22} and V_{33}, respectively. Generally, the highest velocity was measured in the direction of strands alignment, and on the other hand, the lowest velocity was that of shear waves, observed in the transverse plane. The normal stiffness in thickness direction, C_{33}, was considerably lower than the normal stiffness in the plane of the board. The obtained order of stiffness tensor components was $C_{11}>C_{22}\gg C_{33}$, $C_{66}>C_{55}>C_{44}$. The ratio of longitudinal and shear velocities showed the highest anisotropy in 1-3 plane. The highest values of Young's modulus and shear modulus were calculated for E_1 and G_{12}. The value of Poisson's ratio ranged between 0.06 and 0.93.

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Adhesivity of Bio-Based Anhydrous Citric Acid, Tannin-Citric Acid and Ricinoleic Acid in the Properties of Formaldehyde-Free Medium Density Particleboard (MDP)

Mogućnost primjene ekološki prihvatljivoga anhidrida limunske kiseline, taninsko-limunske kiseline i ricinoleinske kiseline kao ljepila za proizvodnju iverica srednje gustoće (MDP) bez formaldehida

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ABSTRACT • *Particles of flooded gum (Eucalyptus grandis) were bonded using three bio-based adhesives - anhydrous citric acid (CA), tannin-citric acid (TCA) and ricinoleic acid (RA) - from renewable sources and hot pressed to produce medium density particleboard (MDP). The bonding capacity of such adhesives and properties of the MDP were evaluated and compared to the requirements of seven grades of particleboards, according to the EN 312 (2010) standard. The RA did not create adhesion reaction with the wood particles. Adhesives formulated with CA and TCA presented capacity to bond eucalyptus particles into MDP confirmed by esterification reactions of the FTIRS analysis. MDP bonded with CA met requirements as high as grade P5 of the EN 312 (2010) standard for static modulus of elasticity (MOE) and internal bond (IB) and P2 for modulus of rupture (MOR). Panels bonded with TCA met requirements up to grade P3 for MOE, however, did not withstand water absorption.*

Keywords: *Eucalyptus grandis; bio-based adhesives; particleboards; bonding capacity; FTIR analysis; EN requirements*

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SAŽETAK • *Za izradu iverice srednje gustoće (MDP) upotrijebljeno je iverje drva eukalipta (Eucalyptus grandis) lijepljeno trima ekološki prihvatljivim ljepilima dobivenim iz obnovljivih izvora na bazi anhidrida limunske kiseline (CA), taninsko-limunske kiseline (TCA) i ricinoleinske kiseline (RA) te prešano u vrućoj preši. Kvaliteta lijepljenja tim ljepilima i svojstva iverice ocijenjeni su usporedbom sa sedam klasa uporabe prema normi EN 312 (2010). Ljepilo RA nije uspjelo povezati drvno iverje. Ljepila CA i TCA pokazala su sposobnost lijepljenja eukaliptova iverja pri izradi MDP ploče, što je potvrđeno reakcijom esterifikacije u FTIR analizi. MDP ploča izrađena primjenom CA ljepila udovoljava visokim zahtjevima klase uporabe P5 prema EN 312 (2010) za modul elastičnosti (MOE) i čvrstoću na raslojavanje (IB) te klase P2 za modul loma (MOR). Ploče izrađene uporabom TCA ljepila ispunile su zahtjeve klase uporabe P3 za modul elastičnosti (MOE), ali nisu zadovoljile zahtjeve o upijanju vode.*

Ključne riječi: *Eucalyptus grandis; ekološki prihvatljiva ljepila; iverice; sposobnost lijepljenja, FTIR analiza, EN zahtjevi*

1 INTRODUCTION
1. UVOD

Medium Density Fiberboard (MDF), Hardboard or fiberboard (HB) and High Density Fiberboard (HDF) are reconstituted wood-based panels composed of wood fibers, while Medium Density Particleboard (MDP) is produced with wood particles and adhesive, pressed under high pressure and temperature. MDF and HDF are produced with the addition of a synthetic adhesive using a dry process and their density ranges from 600 to 900 kg/m³, and HB results from hot pressing that uses a wet process without the addition of adhesives that reactivates the natural binders of wood, such as lignin.

MDP is a popular composite with density ranging from 551 to 750 kg/m³, which presents high use of wood raw material, mainly from planted forests, at affordable price, with broad application in the furniture industry, construction/remodeling and handmade articles in replacement of solid wood (FAO, 2017).

MDP and MDF are currently the most consumed wood-based reconstituted panels worldwide (FAO, 2017). The Brazilian production of reconstituted wood-based panels in 2018 was 8.2 million m³, 40 % MDP and 60 % MDF/HDF. The production of MDF/HDF and HB dropped 2.5 % and 0.4 %, respectively; MDP increased 3.4 % (IBÁ, 2019).

The Brazilian wood-based panel sector ranked 8th place in 2018 in the global market of largest producers, the same position as the previous year (IBÁ, 2019).

Formaldehyde-based synthetic resins are the most used adhesives in the production of reconstituted wood-based panels, especially urea-, phenol- and melamine-formaldehyde, and the combination of these resins. The formaldehyde acts as the catalyst of the resin setting.

According to Silva *et al*. (2013), the urea-formaldehyde adhesive is the most significant input to environmental impacts of reconstituted panels, such as abiotic resources depletion, eutrophication, ozone photochemical formation, acidification and global warming. Furthermore, chemical compounds based on formaldehyde are classified by the International Agency for Research on Cancer (IARC) as carcinogenic, tumorigenic and teratogenic. According to IARC (2006), historically, the major source of formaldehyde gas release in dwellings is urea-formaldehyde derived from insulation panels. That is why the replacement of formaldehyde-based adhesives is currently in demand and requires research into developing new and sustainable adhesives, especially bio-based ones that should be biodegradable, non-polluting, derived from renewable sources and economically feasible.

In this context, previous publications on the use of citric acid as a bio-based adhesive in MDP have presented promising results (Umemura *et al.,* 2012a, b, 2013; Liao *et al.,* 2016; Kusumah *et al.,* 2016). Although the adhesion mechanism with citric acid is yet not well known, acts as a cross-linking agent, forming ester bonds with wood biopolymers (Yang *et al.,* 1996; Zagar and Grdadolnik 2003; Umemura *et al.,* 2013, 2015; Widyorini *et al.,* 2016; Kusumah *et al.,* 2016).

Tannins are also an alternative for formaldehyde-based resins, due to the large number of phenolic rings in its structure (Santana and Teixeira, 1996; Chupin *et al.,* 2013). Zhao *et al*. (2015) investigated the effects of citric acid on the curing properties of tannin-sucrose adhesives and concluded that the addition of citric acid promotes the reaction between tannin and sucrose at lower temperatures. Ricinoleic acid is also from a renewable source, derived from castor bean oil, which could be used to form polyesters (Péres *et al.,* 2014) and, probably, be used as a natural adhesive in particleboards.

Environmental and human health benefits are the main advantage of these three compounds, as they are formaldehyde-free, non-toxic and non-polluting substances. They are also derived from renewable resources and can generate biodegradable materials. Consequently, the application of such materials in the industry can reduce the environmental impact and minimize the demand for petroleum products.

Considering the above, the present work aims at evaluating the properties of MDP made with eucalyptus particles bonded with three bio-based adhesives based on ricinoleic acid, anhydrous citric acid and tannin-citric acid.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Particles processing
2.1. Proizvodnja iverja

Eucalyptus grandis flakes were hammer-milled and classified into particles after passing through a set of screen sieves. Then, particles were classified in a vibrating sieve by a set of sieves of 20, 40 and 60 mesh. Particles retained in the 40 mesh sieve were used in the panels production.

In order to evaluate if the proposed pressing temperature of MDPs was adequate, thermal analysis of the particles was performed using a thermogravimetric analyzer Shimadzu, model DTG-60H at a heating rate of 10 °C/min from 25 °C to 800 °C with nitrogen flow of 30 mL/min.

2.2 Preparation of adhesive solutions
2.2. Priprema ljepila

For the manufacture of the medium density particleboard, three formulations of adhesives were used: anhydrous citric acid (CA), tannin-citric acid (TCA) and ricinoleic acid (RA).

Anhydrous Citric Acid (CA) at 99.5 % purity level was purchased from food suppliers. The CA adhesive formulation was prepared by mixing water and CA at a ratio of 1:1 (mass:mass). The viscosity of the solution was measured in a rotational Brookfield DV-I-Prime viscometer for small samples using #18 spindle, at the speed of 100 RPM and room temperature of (27±2) °C. A pH indicator tape was used to measure the solution pH. The CA formulation presented pH of 1 and viscosity of 74 cP.

For the preparation of the ricinoleic acid (RA), castor bean oil was saponified with NaOH solution, followed by acidification with HCl, according to the methodology used by Péres *et al*. (2014).

The tannin-citric acid adhesive (TCA) was prepared as an aqueous solution by dissolving citric acid and tannin in water. Initially, the tannin was diluted in water at a ratio 1:1 (mass:mass) at 50°C until complete solubilization, and then the citric acid was added at the same ratio.

2.3 Manufacture of MDPs
2.3. Izrada MDP ploča

The adhesive solutions were sprayed onto selected particles (-40 mesh +60 mesh) in a rotatory drum mixer, and the furnish was subsequently dried at 60 °C, for 6 hours, to 9 % moisture content (determined in a moisture meter thermobalance model BEL). The mat was hand formed and hot pressed at (180 ± 3) °C for 10 minutes under the pressure of 4 MPa. Single-layer flat boards were produced with dimensions of 30 cm (length) × 30 cm (width) × 1 (thickness) cm. The three adhesive solutions (CA, TCA and RA), as described above, were tested at a concentration of 18 % based on the dry mass of particles (Table 1).

For each treatment, three panels were produced, from which five specimens were cut for each test. The panels were conditioned in a climate room with controlled conditions of relative humidity (60±2) % and temperature (20±1) °C to reach equilibrium moisture content.

2.4 MDP characterization
2.4. Karakterizacija MDP ploča

The physical properties evaluated were density (EN 323:1993), water absorption (*WA*) and thickness swelling (*TS*) after 24 hours immersion in water (EN 317:1993). For the evaluation of mechanical properties, the internal bonding (*IB*) (EN 319:1993), modulus of elasticity (*MOE*) and modulus of rupture (*MOR*) in static bending (EN 310:1993) were determined. The panels were classified according to the requirements of EN 312:2010 standard, which establishes seven grades of particleboards.

The experiment was carried out in a completely randomized design (CRD). Statistical analysis was conducted using the t-student test at 5 % significance level.

2.5 Scanning Electron Microscopy (SEM)
2.5. Pretražni elektronski mikroskop (SEM)

Samples of particles and particles detached from panels were analyzed by Scanning Electron Microscopy (SEM), using a Field Emission Electron Microscope (JEOL, JSM-7001 F) operating at 15 kV. For SEM analysis, particles were pre-treated by sputter coating with gold.

2.6 Carbon-Hydrogen-Nitrogen analysis
2.6. Ugljik-vodik-dušik analiza

The Carbon-Hydrogen-Nitrogen (CHN) analyses were carried out in an Elemental Analyzer Perkin Elmer, model EA 2400 Series II, aiming to evaluate the carbon gain (*CG*) that was calculated by equation 1, and expressed as mean values of three measurements:

$$\%CG = \frac{(\%CAP - \%CBP)}{\%CBP} \text{ x } 100 \quad (1)$$

Where:
$\%CG$ – carbon gain after pressing;
$\%CAP$ – carbon content in eucalyptus particles after pressing;
$\%CBP$ – carbon content in eucalyptus particles before pressing.

2.7 FTIR analysis
2.7. FTIR analiza

Samples from non-treated particles and from particleboards were ground in a hammer mill and then pelleted in Potassium bromide (KBr). The KBr disks were analyzed by Fourier Transform Infrared (FTIR) spec-

Table 1 Description of MDP manufacturing parameters
Tablica 1. Parametri izrade MDP ploča

Adhesive / *Ljepilo*	**Pressing conditions** *Uvjeti prešanja*	**Adhesive** *Ljepilo*, %	ρ^*, g/cm³
Anhydrous citric acid (CA) / *anhidrid limunske kiseline (CA)*	180 °C/10 min	18	0.80
Ricinoleic acid (RA) / *taninsko-limunska kiselina (TCA)*	180 °C/10 min	18	0.80
Tannin-citric acid (TCA) / *ricinoleinska kiselina (RA)*	180 °C/10 min	9 (CA)/9 (TAN)	0.80

*ρ – target apparent density (at 12 % moisture content) / *ρ – ciljana prividna gustoća (pri 12 % sadržaja vode)*; TAN – tannin / *TAN – tanin*

troscopy in the mid-infrared spectrum (4000 – 400 cm^{-1}) using a Shimadzu spectrometer, model IR Prestige-21.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 DTG analysis
3.1. DTG analiza

The TG and DTG curves of eucalyptus particles indicated three bands of thermal degradation (Figure 1), the first (from 25 °C to 89 °C) corresponding to approximately 7.13 % of mass loss, was attributed to moisture loss. The two others were attributed to the degradation of hemicellulose and cellulose (from 230 °C to 362 °C) and lignin deterioration (364 °C to 510 °C), as lignin is the most resistant biopolymer of lignocellulosic materials (Seye *et al.,* 2010).

In the temperature range of 100-220 °C, the mass loss was about 0.82 %. According to Randriamanantena *et al*. (2009), this range corresponds to the zone of thermal stability, which is limited by the initial thermal degradation temperature of the main components of wood. This indicates that the ideal temperature for pressing eucalyptus particleboards should be in between this range.

3.2 SEM analysis
3.2. SEM analiza

Non-treated particles presented apparent pores, which is typical of lignocellulosic materials (Figure 2a), while particles from panels with ricinoleic acid, anhydrous citric acid and tannin-citric acid were covered by the adhesives and presented more heterogeneous surfaces (Figure 2b, c, d). Comparing to other treatments, particles covered by RA (Figure 2b) presented more loose fibril bundles. This analysis is import to understand the ability of the particles to be bonded to the adhesives and how the pores are filled up.

3.3 MDP properties
3.3. Svojstva MDP ploča

Particleboards bonded with RA did not present sufficient adhesion even after being pressed at 180 °C for 10 minutes. As a result, it was not possible to characterize RA bonded particleboards. Compared to CA panels, TCA particleboards presented visibly lower adhesion and particles were easily detached and presented rougher surface.

After the water immersion test, the specimens of TCA bonded panels disintegrated into loose particles indicating that the adhesive was not resistant to water. Thus, it was impossible to measure *TS* and *WA*. However, CA particleboards maintained their integrity after immersion in water but they did not achieve the minimum requirements of the EN 312:2010 for *TS*. The resistance of CA particleboards against water can be explained by Vukusic *et al*. (2006), who described the chemical reaction between CA and wood cellulose, in which hydrophobic esters groups replaced some hydrophilic groups of wood biopolymer, reducing the absorption of water by wood particles.

According to Table 2, there is no significant difference in apparent density of CA and TCA treatments. The moisture content of both treatments met the requirements specified by the EN 312:2010 standard.

All mechanical properties (*MOR*, *MOE* and *IB*) of panels bonded with CA were higher than those of panels bonded with TCA, indicating that this treatment presented better adhesion. Taking into account the requirements of EN 312:2010 standard, in general MDPs produced with anhydrous citric acid are graded as panels to be used in dry conditions (P2 boards). Neverthe-

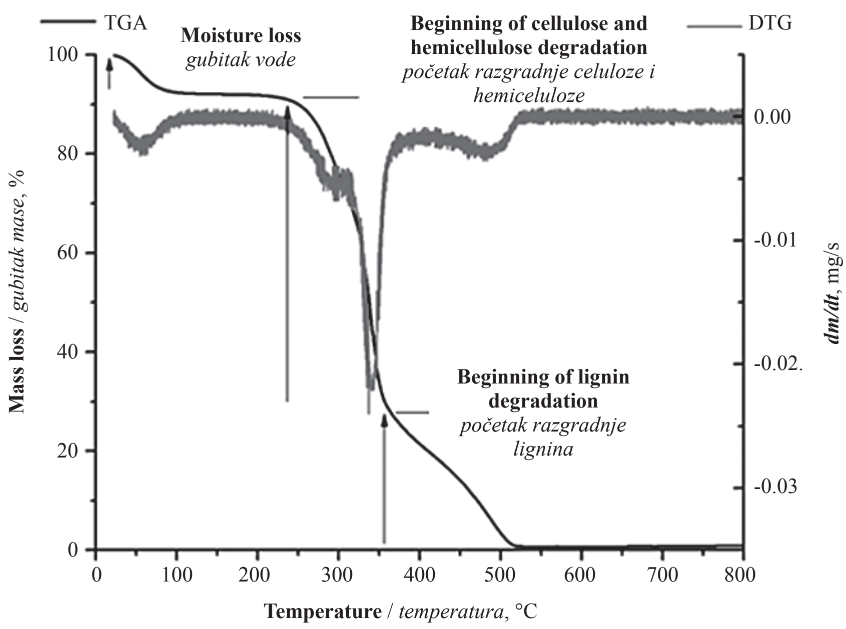

Figure 1 Thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG) curve of eucalyptus particles "in natura"
Slika 1. Termogravimetrijska analiza (TGA) i derivirana termogravimetrijska (DTG) krivulja iverja prirodnog drva eukalipta

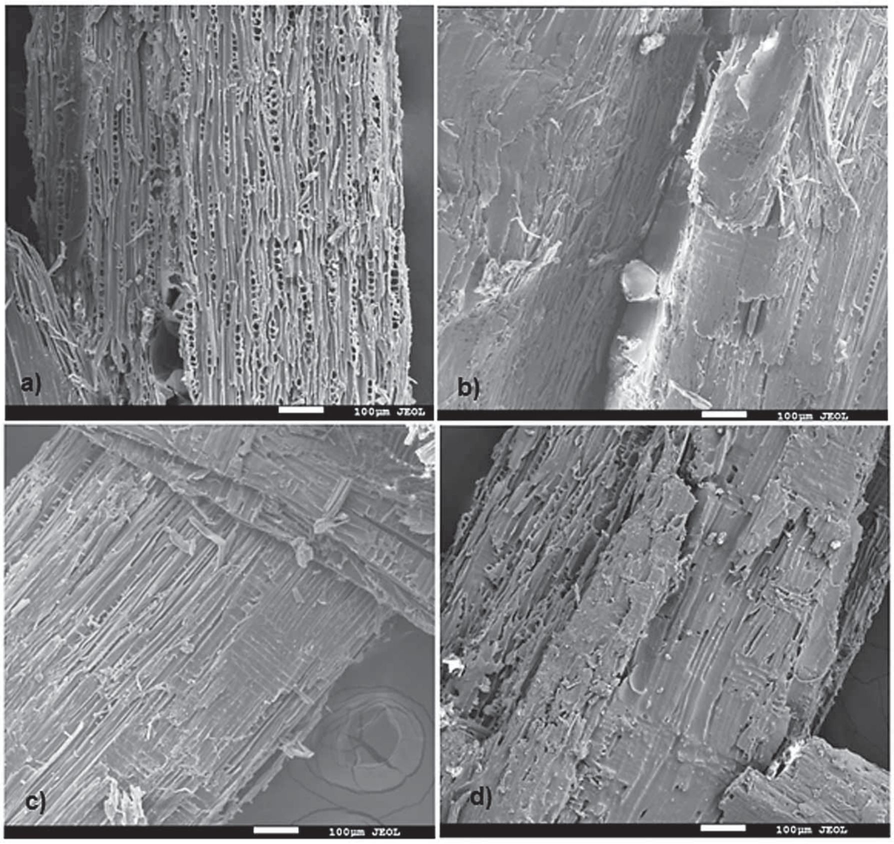

Figure 2 Micrographs of particles detached from panels after pressing. a) eucalyptus particle ("in natura"); b) eucalyptus particle with ricinoleic acid resin; c) eucalyptus particle with anhydrous citric acid resin; d) eucalyptus particle with tannin-citric acid resin
Slika 2. Mikrofotografije iverja odvojenoga iz ploča nakon prešanja: a) iverje drva eukalipta (prirodno); b) iverje drva eukalipta sa smolom ricinoleinske kiseline; c) iverje drva eukalipta sa smolom anhidrida limunske kiseline; d) iverje drva eukalipta sa smolom taninsko-limunske kiseline

less, considering only mechanical properties (*MOR*, *MOE* and *IB*), they were graded as load bearing boards to be used in humid conditions (P5 boards). As for the panels bonded with tannin-citric acid they did not meet the minimum requirements for *IB* and *MOR*, while the requirements of non-load bearing boards were met for *MOE*.

The temperature and pressure applied in CA particleboards were sufficient to promote polymerization reactions between the citric acid molecules and wood molecules. It is likely that, due to polyesterification reactions, the adhesiveness was between carboxylic groups of citric acid and the hydroxyl groups of wood biopolymers (lignin, cellulose and hemicellulose) (Figure 3). According to Mano and Mendes (1999), molecules with functional groups that are prone to reactions by three or more points, which is the case of citric acid, may create cross-linked polymers with thermosetting characteristics.

Table 2 Means and coefficient of variation of physical and mechanical properties of MDPs
Tablica 2. Srednje vrijednosti i koeficijenti varijacije fizičkih i mehaničkih svojstava MDP ploča

Adhesive *Ljepilo*	**ρ, g/cm³**	**Modulus of rupture *MOR*** *Modul loma MOR* MPa	**Modulus of elasticity *MOE*** *Modul elastičnosti MOE* MPa	**Internal bonding *IB*** *Čvrstoća na raslojavanje IB* MPa	**Moisture content *MC*** *Sadržaj vode MC* %	**Thickness swelling *TS24h*** *Debljinsko bubrenje TS24h* %	**Water absorption *WA24h*** *Upojnost vode WA24h* %
Ricinoleic acid (RA) *ricinolenska kiselina (RA)*	NA*	NA	NA	NA	NA	NA	NA
Anhydrous citric acid (CA) *anhidrid limunske kiseline (CA)*	0.80 ^{a**} (5.6)***	12.04 ^{b} (10.7)	2,823.8 ^{b} (7.5)	0.49 ^{b} (16.6)	10.17 ^{b} (4.1)	22.04 (4.7)	52.8 (8.9)
Tannin-citric acid (TCA) *taninsko-limunska kiselina (TCA)*	0.80 ^{a} (6.8)	9.37 ^{a} (24.0)	2,201.0 ^{a} (24.7)	0.24 ^{a} (32.0)	9.27 ^{a} (2.5)	NA	NA

*NA – not available / *NA – nije dostupno*
**Mean values followed by the same letter in the same column are not significantly different by the *t*-student test at 5 % significance level. / *Ako se iza srednjih vrijednosti u istom stupcu nalazi isto slovo, tada se one ne razlikuju značajno uz razinu značajnosti od 5 % prema t-testu.*
***Numbers in parenthesis are coefficients of variation, %. / *Brojevi u zagradama koeficijenti su varijacije,* %.

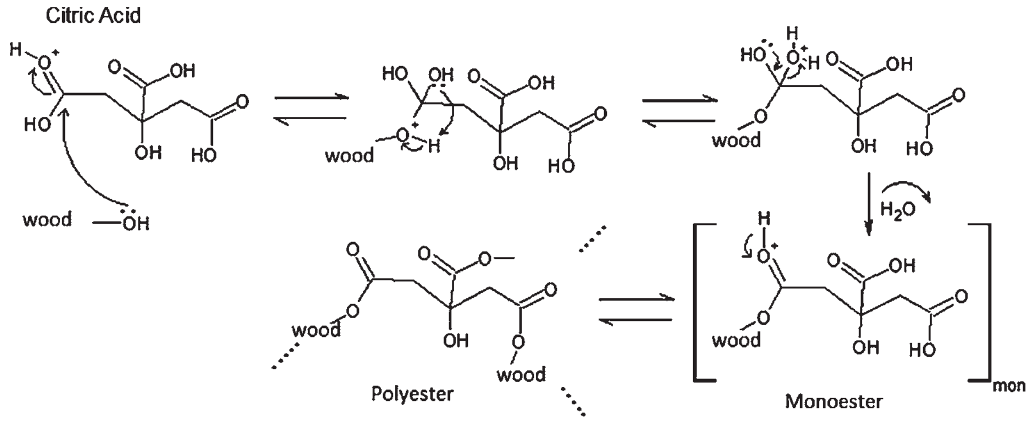

Figure 3 Proposed scheme of polyesterification reaction in anhydrous citric acid bonded particleboards
Slika 3. Predložena shema reakcije poliesterifikacije u ivericama izrađenima primjenom ljepila na bazi anhidrida limunske kiseline

In particleboards bonded with tannin-citric acid, the most probable adhesion mechanism is also polyesterification between citric acid, tannin and the hydroxyl groups of wood biopolymers. However, it is more likely that reactions between tannin and citric acid molecules took place, since the tannin is more accessible than wood biopolymers. This can explain why samples disintegrated into loose particles after water immersion.

The particles of panels bonded with ricinoleic acid did not create adhesion reaction, even in the presence of two functional groups (carboxyl and hydroxyl) prone to esterification reaction with the hydroxyl sites of wood biopolymers. It may be stated that pressing conditions were not sufficient to promote such esterification reaction. Furthermore, Péres *et al*. (2014) obtained a biopolyester of ricinoleic acid, without catalysts, only after six hours of reaction in a reactor at 190 °C. Additionally, the molecule of ricinoleic acid is larger than that of citric acid, which may hinder the linking process with wood hydroxyls.

3.4 CHN elemental analysis
3.4. Elementarna analiza CHN

The carbon gain (*CG*) after pressing the particleboard was 0.4 % with CA and 3.91 % with TCA (Table 3). These results are an indicator that esterification reaction took place in the pressed glued particles.

Table 3 Carbon-Hydrogen-Nitrogen analysis of eucalyptus particles
Tablica 3. Ugljik-vodik-dušik analiza iverja drva eukalipta

Particle / *Iverje**	**%C**	**%H**	**%N**	**%*CG*****
E	45.80	6.05	0.14	-
CA	46.00	5.92	0.11	0.44
TCA	47.59	6.14	0.18	3.91

*E – untreated eucalyptus particles (“in natura”); CA – eucalyptus particles bonded with anhydrous citric acid; TCA – eucalyptus particles bonded with tannin-citricacid / *E – prirodno iverje drva eukalipta; CA – iverje drva eukalipta lijepljeno anhidridom limunske kiseline; TCA – iverje drva eukalipta lijepljeno taninsko-limunskom kiselinom*
** CG – carbon gain / *dobitak ugljika*

3.5 FTIR analysis
3.5. FTIR analiza

The IR spectra of eucalyptus particles “in natura” presented a larger band in the region of 3400 cm^{-1} (Figure 4a), which indicates the presence of O-H stretch.

The fingerprint region between 1725-1740 cm^{-1} presented a peak, which is related to axial stretching of carbonyl groups (C=O) in carboxylic acid groups. The 1050 cm^{-1} band corresponds to stretches of the C-O group of celluloses, hemicelluloses and lignin or to the C-O-C groups of hemicellulose (Brum *et al.,* 2008).

The bands of IR spectra at 1508 cm^{-1} and 1430 cm^{-1} are related to the aromatic ring vibrations of the guaiacyl present in lignin (Hergert, 1971). The bands observed below 1000 cm^{-1} correspond to hydroxyl groups of cellulose (Castro *et al.,* 2004).

Regarding CA bonded particleboards (Figure 4b), peaks of IR spectra were observed in four characteristic bands indicating esterification reactions. The first was a strong and prominent peak in band 1737 cm^{-1}, corresponding to the carbonyl stretching (C=O) of ester. The second was a peak in the band at 1374 cm^{-1}, corresponding to CH bonds of CH_3 groups. The third was a peak in between 1200-1350 cm^{-1}, indicating stretching the C-O bond of -O-(C=O)-. The last peak was in the bands between 1010-1150 cm^{-1}, corresponding to stretches of C-O bonds (Pavia *et al.,* 2008.). There was also a broad band in the region between 3200-3600 cm^{-1}, corresponding to the axial deformation of O-H groups. This can be attributed to the presence of water or to the hydroxyls of wood that were not chemically bonded with the citric acid.

Particleboards bonded with TCA adhesive (Figure 4c) have also shown IR spectra with a broad peak in the band between 3200-3600 cm^{-1}. TCA particleboards presented peaks between bands 1010-1150 cm^{-1} and in between 1200-1350 cm^{-1}. However, when compared to CA bonded particleboards, there was no evidence of a strong peak at the band 1737 cm^{-1}, indicating less esterification reactions between particles and TCA adhesive.

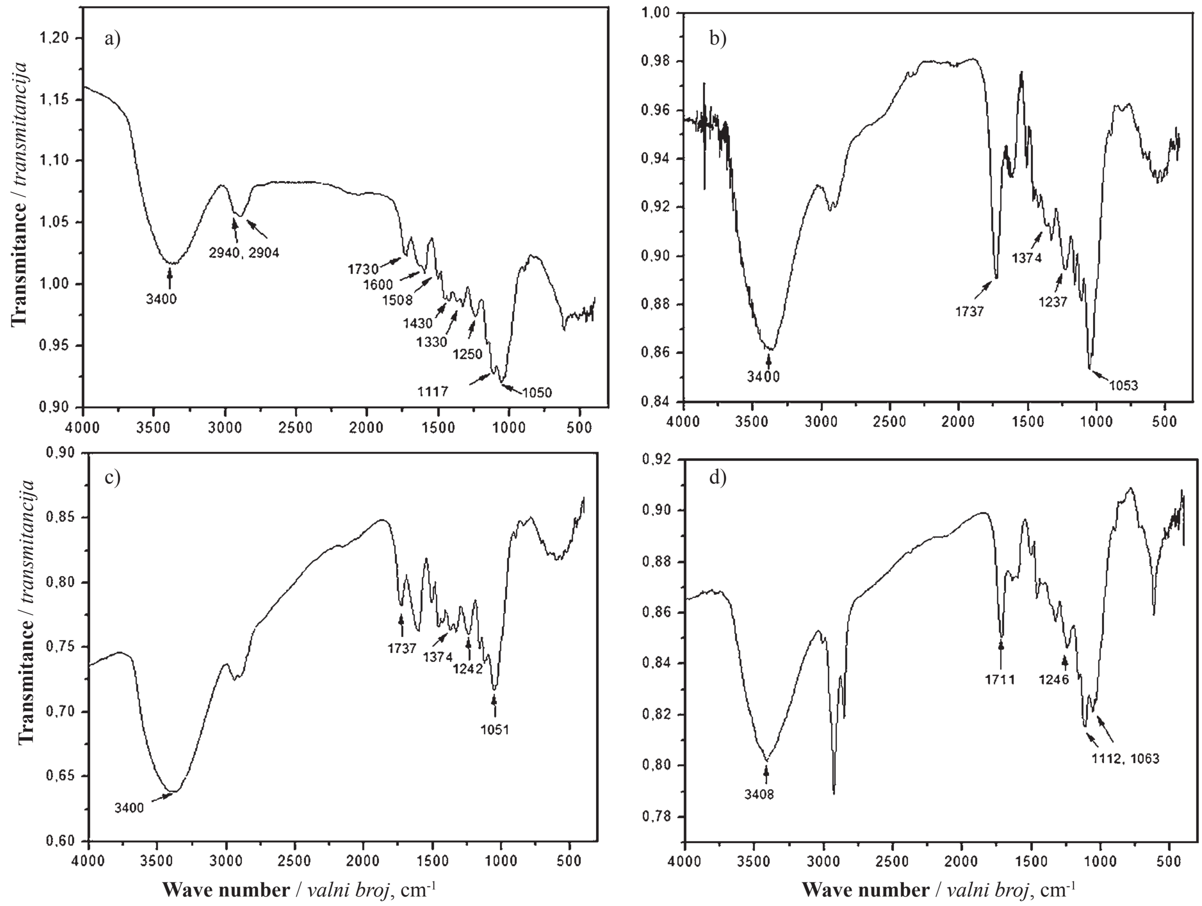

Figure 4 FTIR spectra: a) eucalyptus particles "in natura"; b) CA particleboards; c) TCA particleboards; d) RA particleboards
Slika 4. FTIR spektri: a) prirodno iverje drva eukalipta; b) CA iverice; c) TCA iverice; d) RA iverice

Finally, RA bonded particleboards (Figure 4d) presented a prominent peak in 1711 cm^{-1} band, which is typical of C=O groups of carboxylic acids. When compared to CA particleboards, RA bonded panels also presented a lower peak in the band 1737 cm^{-1}. These results indicate a little or no esterification reaction that is related to the lack of adhesiveness in RA particleboards.

4 CONCLUSIONS
4. ZAKLJUČAK

The bio-based adhesives formulated with anhydrous citric acid and tannin-citric acid presented the capacity to bond eucalyptus particles into MDPs. Yet, ricinoleic acid cannot be used as an adhesive for particleboards based on the parameters used in this study.

The particleboards with anhydrous citric acid as adhesive presented the best physical and mechanical properties. For *MOR*, the MDPs met the requirements for the use in interior fitments, in dry conditions. For *MOE* and *IB*, it met the requirements for the use of load bearing boards in humid conditions (EN 312, 2010).

The FTIRS analysis confirmed esterification reactions in tannin-citric acid and anhydrous citric acid bonded particles, which is related to the adhesives polymerization, and MDP that met the requirements as high as P3 grade for *MOE*.

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Durability and Mechanical Performance of Differently Treated Glulam Beams during Two Years of Outdoor Exposure

Trajnost i mehanička svojstva različito obrađenih lameliranih nosača tijekom dvije godina izlaganja u eksterijeru

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ABSTRACT • *The performance of the composites is influenced by the service life of input raw wood material and used adhesives. The aim of the study was to assess the durability and mechanical performance of glulam beams treated in a different way (thermally modified and/or treated with copper-based wood preservative) and exposed in an outdoor application. Glulam beams (83 mm × 68 mm × 1100 mm), made of three layers of Norway spruce (Picea abies) with PUR adhesives used have been exposed in use class 3.2 in a horizontal position since 4th November 2016. Part of the specimens was equipped with MC sensors. Every year, the degradation was evaluated visually. The dynamic modulus of elasticity was determined by longitudinal vibration, and the static modulus of elasticity using a 4-point bending test. On the smaller specimens, cut from glulams, compressive strength, delamination, and shear strength of adhesive bonds were determined. After two years of exposure, the results indicate that the performance of glulams is determined by the wood modification and applied wood preservative.*

Keywords: *degradation; glulam; mechanical testing; performance; service life; wood*

SAŽETAK • *Na svojstva kompozita utječu trajnost sirovine i svojstva primijenjenih ljepila. Cilj ovog istraživanja bio je procijeniti trajnost i mehanička svojstva različito obrađenih lameliranih nosača (toplinski modificiranih i/ili impregniranih bakrom) izloženih u eksterijeru. Lamelirani nosači (83 mm × 68 mm × 1100 mm) izrađeni su od tri sloja smrekovine (Picea abies) koji su slijepljeni PUR ljepilom. Nosači su prema klasi uporabe 3.2 izloženi u vodoravnom položaju od 4. studenoga 2016. u trajanju od dvije godine. Na dio uzoraka postavljeni su senzori za mjerenje sadržaja vode u njima. Svake je godine vizualno ocjenjivano propadanje uzoraka. Dinamički modul elastičnosti određen je longitudinalnom vibracijom, a statički modul elastičnosti savijanjem u četiri točke. Na manjim uzorcima ispiljenima od nosača određena je tlačna čvrstoća, delaminacija i čvrstoća lijepljenog spoja na smicanje. Nakon dvije godine rezultati izlaganja pokazali su da svojstva lameliranih nosača ovise o toplinskoj modifikaciji drva i sredstvu za impregniranje.*

Ključne riječi: *razgradnja; glulam; mehanička ispitivanja; svojstva; vijek trajanja; drvo*

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1 INTRODUCTION
1. UVOD

Wood is one of the earliest construction materials, and the structural use of wood and wood-based composites continues to steadily increase. In fact, new wood-based materials continue to be developed and successfully introduced into the engineering and construction marketplace. The primary driving force behind the increased use of wood-based composites is the ever-increasing need to provide economical housing. Supporting this demand, however, has been an evolution of our understanding of wood as a structural material and our ability to analyse and design safe and functionally efficient wood and wood-based composites (Kržišnik *et al*., 2018). Modern building and construction practice would not be possible without the use of wood composites. They have the potential to replace other construction materials, such as steel, in many building applications (Ansell, 2015). Wood composites include a range of derivative wood products, which are produced by binding the fibres, strands, particles, veneers or boards of wood with adhesives, or other methods of fixation. All of these components form composite materials. This approach enables the use of wood of lower quality for the production of materials with engineered properties for specific, target applications. At the beginning, composites were predominately used in indoor applications, however, nowadays they are more and more frequently used in outdoor applications, as well (Ansell, 2015). Some of the composites, like glulams, are used in rather exposed conditions, like bridges (Niklewski *et al*., 2018). Wood, as well as wood composites in outdoor applications, are exposed to biological degradation and weathering (Humar *et al*., 2019). The positive aspect of biological decomposability of waste wood can turn into the opposite when the wood is used in moist conditions and exposed to various discolouring and degrading organisms (Despot, 1998). Protective measures are therefore unavoidable for many outdoor applications where wood is exposed to a condensing environment, to the weather or is in contact with the ground (Preston, 2000). In order to increase the potential of wood composites, their performance in outdoor applications has to be determined.

The service life of wooden objects and building components is one of the most important data, which enables the safe and environmentally acceptable selection of the materials. Service life is defined as the time during which a particular wooden structure or component will perform its task (Isaksson and Thelandersson, 2013). The technical service life of the wood is predominately affected by wood-decaying fungi (brown and white rot fungi) in outdoor applications (van den Bulcke *et al*., 2011). In addition to a material-inherent durability, the moisture conditions and temperature are the most important factors influencing the ability of fungi to degrade wood (Brischke *et al*., 2008). These two factors are influenced by the design of the construction, exposure conditions and local climatic conditions that can be referred to as microclimate. If moisture content (*MC*) and temperature (*T*) are monitored, the severity of a particular location can be evaluated (Welzbacher *et al*., 2009). Based on the location conditions, additional protection can be applied with design or other measures if necessary (Kutnik *et al*., 2014).

Usually, composites are manufactured from the wood used to manufacture lumber. Therefore, some properties of the composites reflect the properties of the source material. Hence, composites are, similarly as most of the European wood species, prone to degradation that can be caused by various abiotic and biotic factors (CEN, 2013). The service life of the composites is influenced by the service life of wood and adhesives, therefore both parameters need to be considered. Studies about the long term performance of wood composites in outdoor applications are rather rare. Therefore, we believe that this kind of study is necessary as they will enable safer constructions. The aim of the present study was to elucidate the overall performance of the composites exposed to outdoor conditions, namely to determine the development of decay, do determine the changes of the glue-line after weathering and to assess the moisture performance of glulam.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The running experiment started on 4th November 2016 and is based on the model glulam beams (83 mm × 68 mm × 1100 mm), exposed in use class 3.2 conditions, 500 mm above ground in a horizontal position on the test field of the University of Ljubljana, Biotechnical faculty (Figure 1) (46°02'55.7" N 14°28'47.3" E, elevation above sea level 293 m). The average temperature in Ljubljana is 10.4 °C, the annual precipitation is 1290 mm and the Scheffer Climate Index is 55.3 (Scheffer, 1971). The hazard potential of different climates was estimated by empirically determined decay intensity. Scheffer focused on the parameters temperature and distribution on rainfall as follows in Eq. 1:

$$Climate\ index = \frac{\sum_{\mathrm{Jan}}^{\mathrm{Dec}}\left[(T-35)(D-3)\right]}{30} \qquad (1)$$

Where T is the mean day temperature of the month (°F), and D is the mean number of days with more than 0.001 inch of rain per month (-).

Three-layer glulam beams (Table 1) were made of Norway spruce (*Picea abies*), and thermally modified spruce according to Silvapro® process (Silvaprodukt, Slovenia). A Polyurethane (PUR) adhesive was used. Thickness of lamella was between 24 mm and 22 mm. Outer lamellas were thinner than inner ones, as the beams were planed to the final dimension before the exposure. Final dimensions of the beams were comparable. One set of specimens was shell treated with a copper-ethanolamine based (CuEA) wood preservative (Silvanolin®) (Silvaprodukt, Slovenia). Beams were immersed into copper-based preservative solution for 24 h. We did not want to use vacuum-pressure regime, as this might affect the quality of the glue-line. As a control, untreated solid Norway spruce sam-

Figure 1 Glulams at the beginning of the experiment on the test field of the University of Ljubljana, Biotechnical faculty
Slika 1. Lamelirani nosači na početku izlaganja na izlagalištu Biotehničkog fakulteta Sveučilišta u Ljubljani

Table 1 List of presented Norway spruce glulam materials (1-4) and control solid Norway spruce sample (5). Silvanolin® is copper-based wood preservative and Silvapro® is process of thermal modification.
Tablica 1. Popis materijala za nosače od smrekovine (1 – 4) i kontrolni uzorak smrekovine (5); Silvanolin® je drvo impregnirano bakrom, a Silvapro® je proces toplinske modifikacije

Number *Broj*	**Treatment** *Postupak*	**Adhesive** *Ljepilo*
1	-	1K-PUR Type I
2	Silvanolin®	1K-PUR Type I
3	Silvapro®	1K-PUR Type I
4	Silvapro® and Silvacera®	1K-PUR Type I
5	-	-

ple with the same cross-section was used with the purpose of determining the influence of the glue lines as a water barrier in glulam beams.

Part of the specimens is equipped with moisture content sensors as shown in Figure 2. For moisture content (MC) measurements, resistance sensors were applied at 32 positions and linked to a signal amplifier (Gigamodule, Scanntronik) that enabled wood MC measurements between 6 % and 60 %. Sensors were positioned in every lamella of three-layered glulam beams. In the top lamella, sensors were positioned approximately 10 mm bellow surface to avoid surface water-related phenomena. Similarly, in the two lower ones, approximately 10 mm from the glue line, the

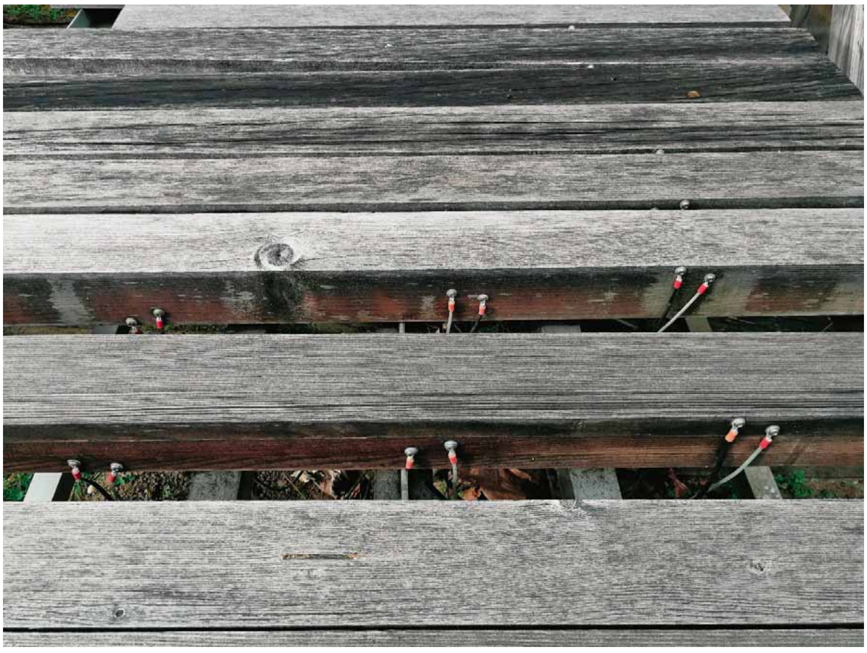

Figure 2 Distribution of moisture content sensors in each layer of tested samples
Slika 2. Raspored senzora za mjerenje sadržaja vode u svakom sloju ispitivanih uzoraka

electrical resistance of the wood was measured every twelve hours and these data were used for calculating the wood MC. Resistance characteristics for each material were determined as reported by (Brischke and Lampen, 2014) using the methodology described by (CEN, 2015).

Selected beams were sampled annually. Three beams per treatment were selected and analysed. The degradation was evaluated visually according to the methodology suggested by Rapp and Augusta (2004) using the grading system according to EN 252 (CEN, 2015) to assess the extent of the decay. For bigger sized specimens, the rating scheme was adapted to the respective dimensions.

In addition, the dynamic modulus of elasticity (E_f) was determined by longitudinal and transversal non-destructive testing techniques, and the static modulus of elasticity (E_s) with a 4-point bending using a Zwick Roell Z100 testing machine (CEN, 2010). According to the cutting scheme (Figure 4), glulams were cut to smaller pieces, and decay on the cross-sections was determined. On the smaller specimens' compressive strength (CEN, 2013), total delamination according to method B (CEN, 2013), and shear strength (CEN, 2013) of the glue lines were determined.

Non-destructive methods for testing wood are usually based on determining the speed of sound and damping sound oscillation. With the acoustic method, we can determine the mechanical properties and some anomalies of the wood (Bucur, 2006). The dynamic modulus of elasticity of the glulam specimens was determined from the frequency response of free-lying specimen vibration. The supports were placed at 0.224 lengths from each end of glulam specimens (Figure 3). With microphone (PCB-130D20) and the measuring card (NI-9234), we determined the frequency response to transverse and longitudinal excitation of each glulam sample in the first vibration mode. In LabView 8.1 we determined, according to Bernoulli theory, the modulus of elasticity from the frequency response (Eq. 2) (Gorišek *et al*., 2014).

$$E_f = \frac{4 \cdot \pi^2 \cdot L^4 \cdot \rho \cdot f_n^2 \cdot A}{I \cdot k_n^4} \quad (2)$$

Where, E_f – modulus of elasticity determined by the frequency response (GPa), L – length of specimen (m), ρ – density of specimen (kg/m³), f – natural frequency of specimen in the first vibration mode (s^{-1}), A – area of cross section (m²), I – moment of inertia (m⁴) and k – Bernoulli constant (k = 4.73).

Acoustic determination of modulus of elasticity enabled the comparative evaluation of visual classification with results of acoustic measurements.

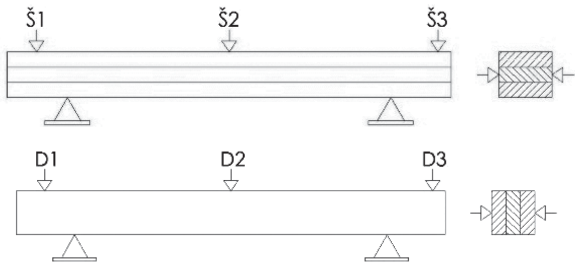

Figure 3 Measuring the frequency response of glulams. Transverse vibration ‖ to the lamellas (top picture) and transverse vibration ⊥ to the lamellas (bottom picture). Š1-Š3 and D1-D2 mark the locations of measurements
Slika 3. Mjerenje frekvencije odziva lameliranih nosača. Poprečna vibracija ‖ na lamele (gornja slika) i poprečna vibracija ⊥ na lamele (donja slika); Š1 – Š3 i D1 – D2 oznake su mjesta mjerenja

Table 2 Grading system for decay according to EN 252 (CEN, 2015)
Tablica 2. Ocjene propadanja prema EN 252 (CEN, 2015.)

Rating *Ocjena*	**Description** *Opis*	**Definition** / *Definicija*
0	Sound *bez znakova propadanja*	No evidence of decay. Any change of colour without softening has to be rated as 0. *Nema dokaza propadanja. Svaka promjena boje bez omekšanja uzorka treba se ocijeniti kao 0.*
1	Slight attack *blago propadanje*	Visible signs of decay, but of very limited intensity or distribution: - changes which only reveal themselves externally by very superficial degradation, softening of the wood being the most common symptom, to an apparent depth in the order of one millimetre. *Vidljivi znakovi propadanja, ali vrlo ograničenog intenziteta ili distribucije: - promjene koje su vidljive samo na površini kao posljedica površinske razgradnje; najčešće je vidljivo omekšanje drva do dubine 1 mm.*
2	Moderate attack *umjereno propadanje*	Clear changes to a moderate extent according to apparent symptoms: changes reveal themselves by softening of the wood to a depth of approximately 1 to 3 millimetres over more than 1 cm² per stake. *Jasne promjene umjerenog intenziteta: promjene koje su uzrokovane omekšanjem drva do dubine 1 – 3 mm na više od 1 cm² površine.*
3	Severe attack *izraženo propadanje*	Severe attack: - marked decay in the wood to a depth of more than 3 millimetres over a wide surface (more than 20 cm²) or by softening deeper than 10 mm over more than 1 cm² per stake. *Izraženo propadanje: - značajno propadanje drva do dubine veće od 3 mm na znatnijoj površini (većoj od 20 cm²) ili omekšanje površine dublje od 10 mm na više od 1 cm² površine.*
4	Failure *propali uzorak*	Impact failure of the stake. *Izraženo propadanje površine.*

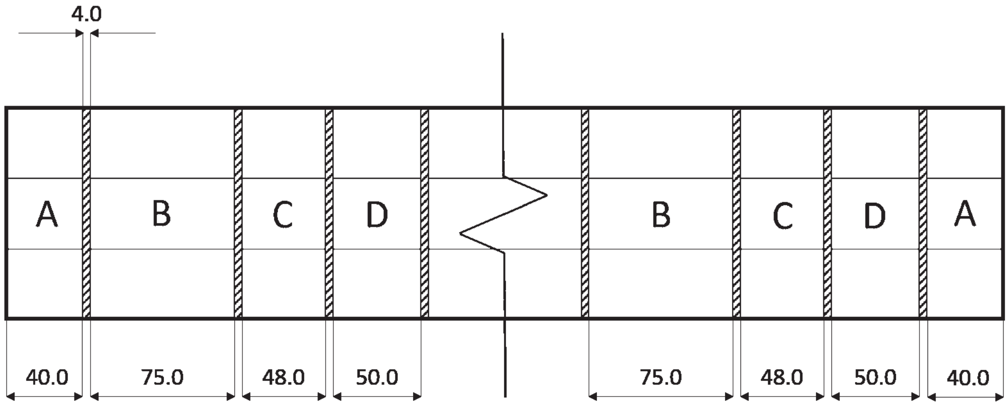

Figure 4 Cutting scheme of three-layer glulams. A was cut off and saved, B sample was used for delamination test according to EN 14080, C samples were used for testing shear strength of glue lines, and D sample for compressive strength. The rest of glulams was stored. Prior to delamination test, mass and dimensions of B specimens in the oven-dried condition were determined and used in density (ρ_0) calculation

Slika 4. Shema piljenja troslojnoga lameliranog nosača (uzorak A ispiljen je i sačuvan, uzorak B upotrijebljen je za ispitivanje delaminacije prema EN 14080, uzorak C rabljen je za ispitivanje čvrstoće lijepljenih spojeva na smicanje, uzorak D služio je za ispitivanje čvrstoće na tlak, a ostatak lameliranog nosača je spremljen; prije ispitivanja delaminacije određene su masa i dimenzije uzoraka B u apsolutno suhom stanju i te su vrijednosti iskorištene za izračun gustoće (ρ_0).

The glulam samples were also tested on the 4-point bending test of the universal testing machine Zwick/Roel Z100. The distance between the lower supports of the specimen was 938 mm and between upper supports 335 mm. The test pieces were tested according to standard EN 408. The load was applied on the specimen at a displacement rate of 1 mm/min. The static modulus of elasticity (E_s) was determined from the slope of the stress-strain curve in the range between 10 % and 40 % of maximum force (Eq. 3). Please replace Eq. 3 with the following one and with the text provided here.

$$E_{m,g} = \frac{3 \cdot a \cdot l^2 - 4 \cdot a^3}{2 \cdot b \cdot h^3 \left(2 \cdot \frac{w_2 - w_1}{F_2 - F_1} - \frac{6 \cdot a}{5 \cdot G \cdot b \cdot h} \right)} \quad (3)$$

Where $E_{m,g}$ is the global modulus of elasticity in bending (N/mm^2), $F_2 - F_1$ is an increment of load on the regression line with a correlation coefficient (N), $w_2 - w_1$ is the increment of deformation corresponding to $F_2 - F_1$ (mm), a is distance between a loading position and the nearest support (mm), l is span in bending (mm), b is the width of cross-section (mm), h is the depth of cross-section (mm), and G is shear modulus (N/mm^2). Because unknown, G was taken as infinite.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Visual assessment of degradation
3.1. Vizualna ocjena propadanja

A visual assessment can provide many details, predominately information about cracking, blue staining and ongoing decay. It has to be considered that initial stages of decay are difficult to assess because there is no visible evidence of damage to the wood by incipient brown-rot decay shortly after brown-rot fungi initiate colonization and release enzymes (Clausen and Kartal, 2003). Besides, by definition, visual inspection is neither objective nor sure (Schmidt, 2006).

Figure 5 gives the crosscuts of samples. Scanned crosscuts before outdoor exposure are presented in the top row; the second and third row show images after one and two years of weathering in 3.2 use class. From the pictures in the second row, it can be observed that the samples in columns 1, 2, and 5 show some signs of discolouration due to the presence of blue-stain fungi on the surface and in the vicinity of cracks and crack formation in different layers of glulam beams. Thermally modified samples (columns 3 and 4) look intact. This observation indicates that the higher dimensional stability and durability of TMT is reflected in less cracked glulam. Higher dimensional stability of thermally modified wood can be ascribed to lower equilibrium moisture content (EMC) associated to the chemical modification of organic functional end-groups (Willems *et al*., 2015), and additionally to the fungal durability (Altgen *et al*., 2014). This is also in line with previous observations of the performance of thermally modified wood in outdoor applications (Esteves and Pereira, 2009; Humar *et al*., 2015).

3.2 Density
3.2. Gustoća

The density and porosity of wood affect the moisture gain, which is proportional to the pore volume of wood: the pore volume, as well as the water capacity of decayed wood, is higher than that of undecayed, sound wood (Viitanen, 1997). Consequently, the same amount of water absorbed will cause larger gain in moisture content in a light specimen than in a heavy one. The density of the thermally modified (440.2 kg/m^3) wood was slightly lower than that of unmodified wood (469.4 kg/m^3). This is expectable, as wood mass is lost during the modification process. However, no mass loss was recorded in the material tested due to the outdoor exposure. Even if the exposed specimens did lose some of the mass, due to leaching of extractives, etc., this small reduction was hindered

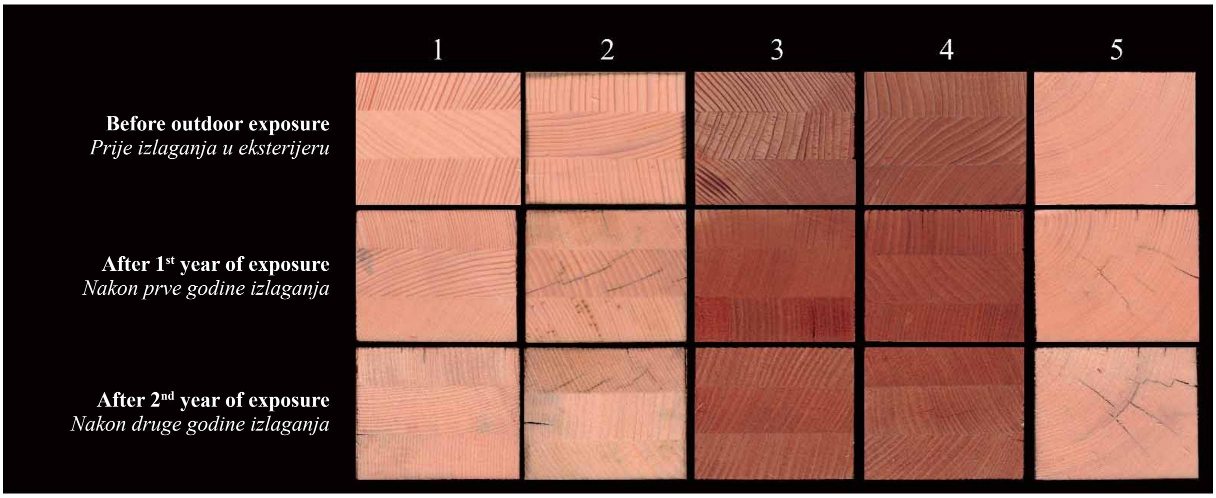

Figure 5 Crosscuts of glulam beams before outdoor exposure and after the first and the second year of outdoor exposure
Slika 5. Presjeci lameliranih nosača prije izlaganja u eksterijeru i nakon prve i druge godine izlaganja na otvorenom prostoru

by the natural variability of the material investigated. However, it should be considered that incipient decay is hardly visible, and usually does not result in mass loss (Highley, 1999).

3.3 Bonding strength of glue lines
3.3. Čvrstoća lijepljenog spoja

Performance requirements of glued laminated timber were evaluated according to EN 14080 (CEN, 2013). The bonding strength of glue lines can be either evaluated by the delamination test or shear test. The shear strength of the glue lines depends on properties of the bulk adhesive, properties of the wood-adhesive interphase region, and properties of wood adherents. After one year of exposure, fungal degradation was not noted, yet. After the second year, first signs of decay appeared on some of the untreated spruce specimens. Samples were evaluated according to the modified EN 252 rating scheme. Untreated spruce wood samples were rated as 1, corresponding to a slight attack, which

Table 3 Results of different performed tests and measurements before outdoor exposure and for each year of exposure in use class 3.2
Tablica 3. Rezultati testova i mjerenja provedenih prije izlaganja u eksterijeru i za svaku godinu izlaganja u klasi uporabe 3.2

No. *Broj*	**Visual assessment of degradation** *Vizualna ocjena propadanja*			**Oven dry density, kg/m³** *Gustoća u apsolutno suhom stanju*, kg/m³			**Delamination test Total delamination, %** *Test delaminacije Ukupna delaminacija, %*			**Shear test** / *Smično ispitivanje* **Shear strength, N/mm² / Wood failure, %** *Čvrstoća na smicanje*, N/mm² / *Lom po drvu*, %					
	Year of outdoor exposure *Godina izlaganja u eksterijeru*			**Year of outdoor exposure** *Godina izlaganja u eksterijeru*			**Year of outdoor exposure** *Godina izlaganja u eksterijeru*			**Year of outdoor exposure** *Godina izlaganja u eksterijeru*					
	0	1	2	0	1	2	0	1	2	0		1		2	
1	/	0	1	450	457	465	0.0	1.6	9.5	7.9	100 %	8.7	84 %	6.1	100 %
2	/	0	0	461	448	475	0.4	1.0	1.0	8.8	94 %	7.1	97 %	9.3	98 %
3	/	0	0	464	433	429	0.0	5.8	7.3	9.1	97 %	7.5	93 %	8.0	99 %
4	/	0	0	454	424	437	0.0	0.0	2.3	7.3	99 %	7.7	86 %	9.6	96 %
5	/	0	1	506	493	477				8.5	100 %	8.0	100 %	9.2	100 %

No. *Broj*	**Compressive strength, N/mm²** *Čvrstoća na tlak*, N/mm²			**Static E_s - 4-point bending test, GPa** *Statički E_s – ispitivanje u 4 točke*, GPa			**Dynamic E_f - longitudinal vibration, GPa** *Dinamički E_f - longitudinalna vibracija*, GPa			**Dynamic E_f – transverse vibration ⊥, GPa** *Dinamički E_f – poprečna vibracija ⊥*, GPa			**Dynamic E_f - transverse vibration ∥, GPa** *Dinamički E_f – poprečna vibracija ∥*, GPa		
	Year of outdoor exposure *Godina izlaganja u eksterijeru*			**Year of outdoor exposure** *Godina izlaganja u eksterijeru*			**Year of outdoor exposure** *Godina izlaganja u eksterijeru*			**Year of outdoor exposure** *Godina izlaganja u eksterijeru*			**Year of outdoor exposure** *Godina izlaganja u eksterijeru*		
	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
1	43.5	42.5	51.2	12.0	11.4	9.1	13.6	13.2	14.6	11.6	11.8	13.3	12.7	12.1	-
2	40.7	41.1	47.4	10.2	11.8	11.7	13.0	13.7	14.2	11.4	12.1	13.2	10.7	12.9	-
3	53.4	48.9	47.3	12.1	10.6	10.9	14.0	12.9	12.0	12.2	10.9	10.6	12.7	11.0	-
4	48.6	49.3	50.2	11.8	12.5	12.1	14.5	13.8	14.1	12.4	11.7	12.5	12.4	13.0	-
5	43.0	46.5	50.1	11.3	9.6	9.5	16.0	13.5	12.3	12.9	11.6	11.2	13.0	11.9	-

is of very limited intensity or distribution. Changes on the surface are indicated as superficial degradation, softening of the wood, to an apparent depth in the order of one millimetre. This is reflected in the loss of the analysed mechanical properties (Table 3).

The type of material, surface coating applied, and type of adhesive used affect the adsorption and desorption properties and moisture content of glulam beams. Predominately, crack development and potential delamination has a considerable effect on the moisture content of individual lamellas and the number of days when MC exceeds the fibre saturation point. According to the requirements of EN 14080 standard (CEN, 2013), the shear strength of the glue lines of all groups of beams is still adequate after two years of exposure. On the other hand, the total delamination of glue layers in glulams without the surface treatment is too high. A more pronounced strength loss of glue layers was only observed in glulams made of unmodified Norway spruce without surface coating (after two years of exposure, the shear strength was 6.1 N/mm^2). For glulams without surface protection (both unmodified and thermally modified Norway spruce), an increased degree of delamination was noticed. For unmodified and modified glulams, the total delamination increased to 7.3 % and 9.5 %, respectively.

Table 3 gives indications of what happens with the overall performance of glulam. Past observations indicate that the bending test is in general a much better indicator than the compressive test (Humar and Thaler, 2017). From the respective data, it can be seen that the compressive strength remained rather constant through the exposure. Variation can be ascribed to natural variation of wood. On the other hand, much more prominent variation was noticed at 4-points static modulus of elasticity. A decrease in static modulus of elasticity was noticed in the untreated beam (material 5) and untreated spruce glulam (material 1). Static modulus of elasticity decreased from 12.0 GPa at the beginning to 11.4 GPa after one year and 9.1 GPa after two years of exposure. This reduction of modulus of elasticity can be ascribed to incipient decay, and changes in the adhesive.

3.4 Monitoring of moisture content in glulams
3.4. Praćenje sadržaja vode u lameliranim nosačima

Products like glued laminated timber (glulam) and other structural composite lumber all have different moisture dynamics to solid timber (Jones and Brischke, 2017). The main reasons for this originate in the possible surface treatment and the presence of glue lines. Glue lines act like barriers that considerably slow down water flows through different layers. Additionally, high daily variations of moisture, at high levels of relative humidity, can cause large moisture gradient close to external surfaces with the development of so-called moisture-induced stress (MIS) and possible increase of crack risk, because the MIS perpendicular to grain may exceed the tensile and compressive strength also in the absence of external mechanical loads (Angst and Malo, 2012; Fragiacomo *et al*., 2011). Figure 6 illustrates the moisture content variations for all three lamellas in the glulam made from Norway spruce. From the beginning of monitoring in February 2017 until approximately July 2018, the differences between the lamellas can be seen (e.g. the upper lamella had higher MC than the other two, middle and bottom one). After July 2018, MCs in all three lamellas become much more similar due to the occurrence of deep cracks throughout the cross-section of the glulam. As can be seen from the respective plot, differences are more prominent in the wet part of the year. During summer months, MCs of respective lamellas are more uniform. In general, the upper lamella has the highest MC, with the exception of the period when the snow covered the samples (Dec 2017 – Jan 2018). The slow melting of the snow resulted in a slow diffusion of water into the samples. Snow coverage prevented drying, so water accumulated in the interior of the glulam. A similar effect was ob-

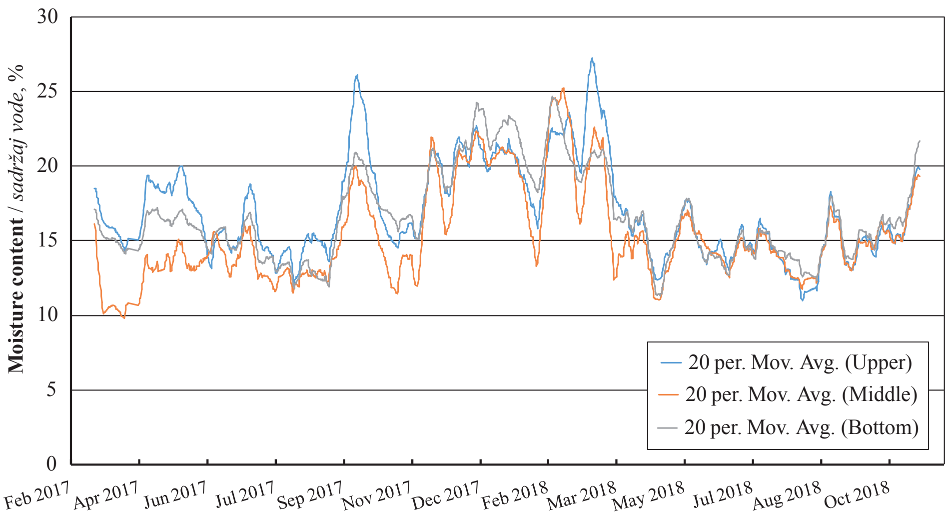

Figure 6 Moisture content in three lamellas of Norway spruce glulam. The MCs of upper (blue line), middle (orange line), and bottom (grey line) lamella are displayed as twenty measurements moving average
Slika 6. Sadržaj vode u tri lamele lameliranog nosača od smrekovine; sadržaj vode gornje lamele (plava linija), srednje lamele (narančasta linija) i donje lamele (siva linija) prikazan je kao srednja vrijednost 20 mjerenja

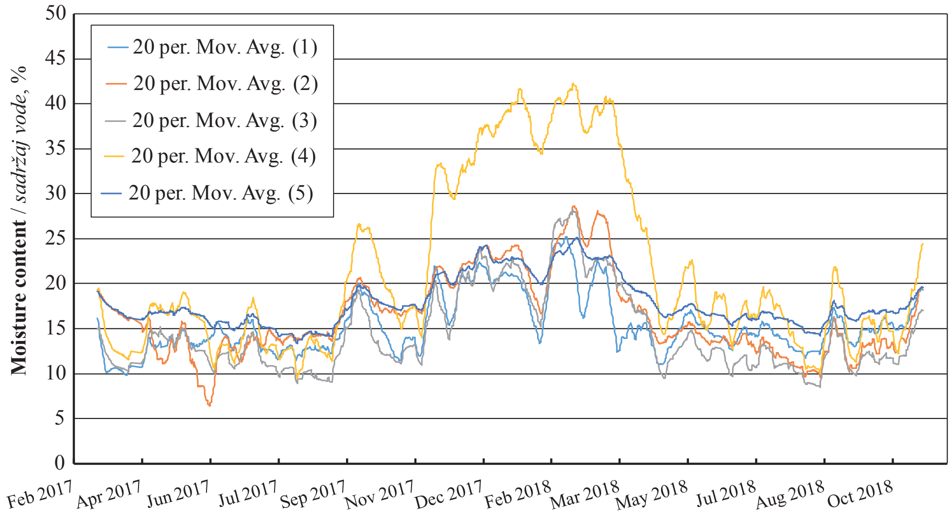

Figure 7 Moisture contents of middle lamellas of all five presented glulams. Measured MCs are presented using twenty measurements moving average values. In brackets are numbers of test materials
Slika 7. Sadržaj vode u srednjoj lameli svih pet lameliranih nosača (izmjereni sadržaj vode prezentiran je kao srednja vrijednost 20 mjerenja; u zagradama su brojevi ispitivanog materijala)

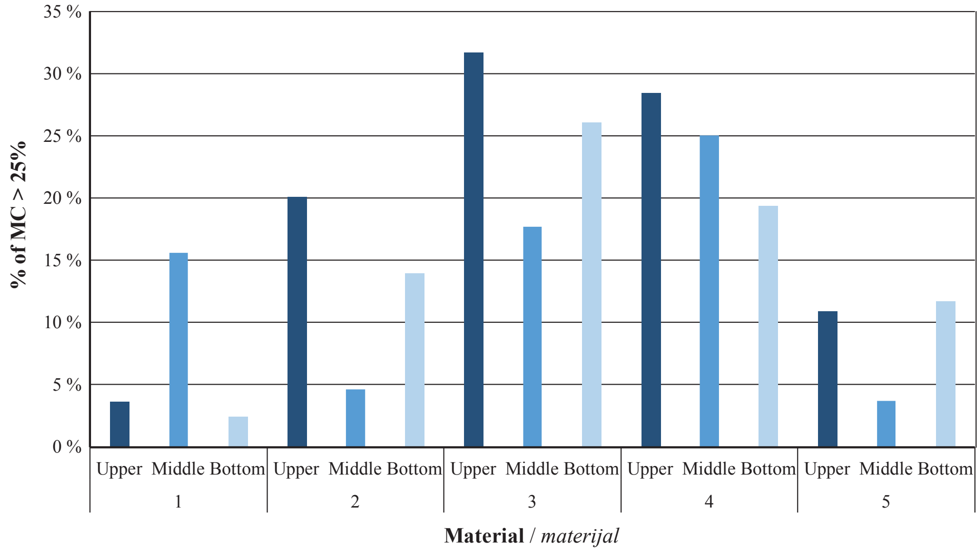

Figure 8 Percentage of measurements (N = 1216) when MC was equal or higher than 25 %. Results are presented for each lamella individually
Slika 8. Postotak mjerenja (N = 1216) kada je sadržaj vode bio 25 % ili veći (prikazani su rezultati za svaku lamelu pojedinačno)

served in other glulams. Similarly, MCs of the five samples are plotted in Figure 7. The poor moisture performance of thermally modified spruce is well known and it has been already reported. Reduced moisture performance is associated with degraded pit membranes during thermal modification and micro-cracks formed on the surface acting as capillaries that take up water (van Acker *et al*., 2015; Žlahtič and Humar, 2016). Variations in MC dynamics are higher in all the glulams compared to the massive timber presented with dark blue line. On average, the highest MC was measured in thermally modified and wax treated glulam, while the lowest MCs were measured in thermally modified glulam. Despite the variety in the nature of different modification techniques, efficacy in improving decay resistance has often been linked with reduced amounts of moisture in the wood (Hill, 2002; Ibach and Rowell, 2000; Thybring *et al*., 2018). Fungal attack can occur on wood, if the substrate can be metabolised by the fungi and if the substrate moisture content is above a certain threshold level. Figure 8 presents the percentage of measurements exceeding the threshold level of 25 % for all glulams in all three lamellas (Meyer and Brischke, 2015). Commonly, this threshold can be reached for 15 % of measurements in at least one lamella with the exception of solid Norway spruce timber. The respective graph indicates that there were two general patterns. At glulam made of untreated spruce, the highest MC content was determined at the middle lamella. The prime reason for this is the development of cracks on the upper lamella, which opens voids for water through the glue line. As thermally modified wood is considerably more resistant to cracking, there were no cracks formed through the glue line, hence water stayed in the upper lamella. A similar effect was also determined in copper treated lamellas (material 2).

4 CONCLUSIONS
4. ZAKLJUČAK

The preliminary test of the model glulam beams indicates that the performance of the respective material is determined by wood modification, adhesive used and surface coatings applied. In the first period of exposure, the adhesive line served as a barrier that limits the penetration of moisture to lower lamellas. Later on, deep cracks developed, opening voids for water penetration. No prominent degradation developed in the glulams after the first two years of exposure. Incipient decay developed on untreated spruce wood, only. Surface treatment reduced decay development, however it can be expected that decay will proceed after the first damages of the surface coating. Exposure of the glulams is reflected in the slight loss of the mechanical properties of adhesives. The test is about to continue to obtain more reliable results.

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Strength Investigation of an Upholstered Furniture Frame with Side Plates of PB, OSB and PLY by Finite Element Method

Ispitivanje čvrstoće okvira ojastučenog namještaja s bočnim stranicama od drvnih ploča metodom konačnih elemenata

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ABSTRACT • *Comparative analysis of the strength characteristics of one-seat upholstered furniture frame with rails of Pinus Sylvestris L. and side plates of PB, OSB and PLY boards was carried out. 3D geometric model of the upholstered furniture frame was created by Autodesk Inventor Pro®. Linear static analyses were carried out by the method of finite elements (FEM) simulating light-service loading. The orthotropic material characteristics of the used materials were considered in the analyses. Two variants of corner joints in the frame (model A – staples and PVAc; model B - staples, PVAc and strengthening elements under the rail of the seat) were considered. The laboratory established coefficients of rotational stiffness of used staple corner joints in the skeleton were considered in finite element analysis (FEA). As result, the distribution of the maximum and minimum principal stresses in the 3D model of upholstered furniture frame side plates were derived and analysed. The worst failure indexes according to Tsai-Wu failure criteria were calculated at heavy-service load. The study provided database of strength values that can help in the engineering of upholstered furniture frames with side plates of PB, OSB and PLY.*

Key words: *strength; upholstered furniture frame; particleboard; oriented strand board; plywood; CAE/FEM.*

SAŽETAK • *Provedena je usporedba svojstava čvrstoće okvira ojastučenog naslonjača s poveznicima od borovine (Pinus Sylvestris L.) i s bočnim stranicama od drvnih ploča (iverice, OSB ploče i furnirske ploče). Za potrebe ispitivanja uz pomoć programa Autodesk Inventor Pro® izrađen je 3D geometrijski model okvira ojastučenog namještaja. Linearne statičke analize provedene su metodom konačnih elemenata (FEM) uz simuliranje malog opterećenja. U analizama su uzeta u obzir svojstva ortotropnog materijala. Promatrane su dvije varijante kutnih spojeva okvira (model A – sponke i PVAc; model B – sponke, PVAc i pojačanja poveznika ispod sjedala). Analizom konačnih elemenata (FEA) razmatrani su laboratorijski utvrđeni koeficijenti rotacijske krutosti sponki upotrijebljenih za kutne spojeve okvira. Time je dobivena i analizirana raspodjela najvećih i najmanjih glavnih naprezanja u 3D modelu bočnih stranica potkonstrukcije ojastučenog namještaja. Najlošiji indeksi loma prema Tsai-Wu kriterijima loma izračunani su pri velikim opterećenjima. Kao rezultat istraživanja dobivena je baza podataka o vrijednostima čvrstoće koja može pomoći u projektiranju okvira ojastučenog namještaja s bočnim stranicama od iverica, OSB ploča i furnirskih ploča.*

Ključne riječi: *čvrstoća; okvir ojastučenog namještaja; iverica; OSB ploča; furnirska ploča; CAE/FEM*

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1 INTRODUCTION
1. UVOD

The frame of upholstered furniture is usually made of wood and/or wood-based products. The choice of the materials from which the structure elements in the furniture frame construction are made and their thickness is essential both for the economy of the structure and for the strength behaviour during operation. Strength characteristics of upholstered furniture frames are very important to ensure optimal design of upholstered furniture.

There is a limited number of references concerning the strength behaviour of upholstered furniture frames, especially of frames with side plates of particleboard (PB), oriented strand board (OSB) and plywood (PLY).

Smardzewski (2001) found an optimal solution for the construction of a supporting structure in a single-seat armchair made of wood and chipboard joined with staples using Algor® computer program. Material optimization of construction was performed assuring optimal strength parameters, but the materials were considered as isotropic. He recommended the sides of the construction should be produced of a 19 mm thick chipboard in order to comply with safety requirements. Lately Smardzewski *et al.* (2009) have carried out laboratory and numerical investigations of two-person sofa frame with side elements of PB and beam elements of pine and beech wood (joints with staples and PVAc glue) taking account of orthotropic nature of used materials in the finite element analysis (FEA) with Algor®. They have proposed smaller cross section dimensions and side thickness of the construction elements that would result in consumption reduction of beech wood by 36 % and that of PB by 25 % without significant change of the operational safety, rigidity and strength.

Wang (2007) investigated a three-seat sofa frame made of 18 mm thick OSB plates. She created 3D models by beam finite elements with software SAP 2000 of three constructions of a sofa frame with rigid and semi-rigid connections and two types of connectors: screws and metal plates; staples and metal plates. Nonlinear static analysis was performed simulating light-, medium- and heavy-service loads. Wang has established the most appropriate configuration of the sofa frame of OSB and concluded that the type of connectors does not change the strength remarkably.

Kasal (2006) investigated the strength properties of glued dowel joined armchair frame constructed of solid wood or wood based composite materials, 18 mm thick (PLY, MDF and OSB) using the finite beam elements by CAE. Considering wood materials as isotropic, he established that significant differences were not found in mechanical behaviour properties, but that the OSB had the lowest load bearing capacity. He has established that the failure of OSB sofa frame is the pull-out of dowels from the member with some core wood particles attached to the dowel, while some splits occur at the edge of the butt members in the sofa frames. In the frame constructed of pine wood (PW), delamination occurs in the layers of the plywood but such a construction has close strength values to the construction of beech and can be preferred to the solid beech and solid pine due to its many technical and economic advantages.

Using the simplified methods of structural analysis, Erdil *et al.* (2008) investigated the behaviour of 3-seat upholstered furniture frames constructed of 3/4 inch thick OSB, PLY (Douglas-fir and sweet gum), and yellow birch dowels joining elements and aliphatic resin glue (PVA). They have concluded that these materials may be used in construction of upholstered furniture frames to meet specific design loads.

Staneva *et al*. (2018a, b, c) made preliminary investigations of upholstered frame with side plates of PB (2018a), OSB (2018b) and PLY (2018c) at light-service load by FEM and have established the distribution of the principal stresses.

The object of this study is to carry out a comparative FEA of static strength of an upholstered furniture frame with side plates of PB, OSB and PLY furniture boards and joints with staple and PVAc glue with a CAE system.

2 METHODS – 3D FEM MODELLING AND ANALISYS
2. METODE – 3D FEM MODELIRANJE I ANALIZA

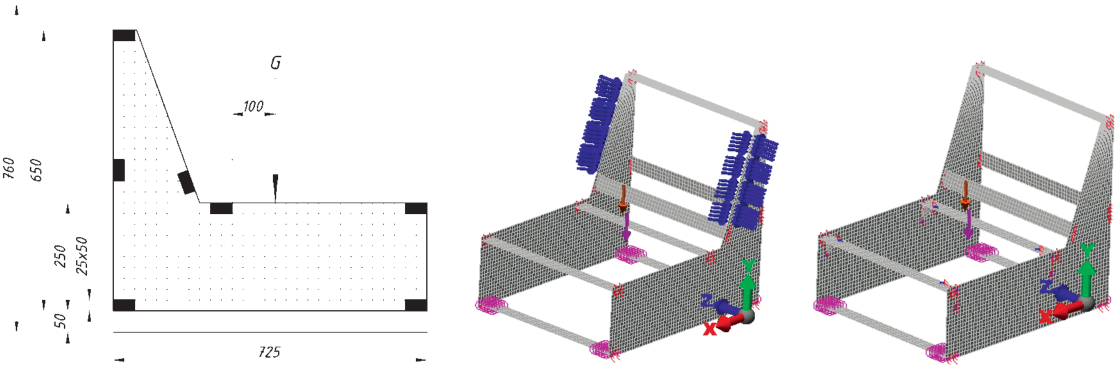
3D discrete model of one-seat upholstered furniture side frame with length 600 mm, width 725 mm and height 650 mm (Figure 1a) was developed with Autodesk Inventor Pro® and marked *model A* – Figure 1b. The cross section of used rails was 25×50 mm. Besides the *model A,* strengthening details under the rails of the seat of the frame with the shape of a triangular prism were modelled and this discrete model was marked as *model B* – Figure 1c. The generated midplane meshes with plate orthotropic finite elements have 5130 finite elements and 33616 DOF's for *model A* and 5230 finite elements and 34096 DOF's for *model B*.

Linear static analyses by the Finite Elements Method (FEM) of the upholstered furniture frame models were carried out with CAE system Autodesk Simulation Mechanical®.

Orthotropic materials for construction elements of the side frame for both *models A* and *B* were considered in the analyses:

Scots pine (*Pinus sylvestris* L.) for rails and strengthening details with measured density of 431 kg/m^3 according to BDS EN 323:2001 and the following characteristics: $E_z=E_l=9000\times10^6$ N/m^2, $E_x=E_t=593\times10^6$ N/m^2; $G_{lt}=554.5\times10^6$ N/m^2; $\nu_{lr}=0.03$, $\nu_{lt}=0.027$, $\nu_{tl}=0.41$, $\nu_{rl}=0.49$; bending strength 100×10^6 N/m^2; compression strength $\sigma_{c//}=46\times10^6$ N/m^2 and $\sigma_{c\perp}=7.5\times10^6$ N/m^2; tension strength $\sigma_{t//}=109\times10^6$ N/m^2 and $\sigma_{t\perp}=5.4\times10^6$ N/m^2; shear stress 7.4×10^6 N/m^2.

Particleboards (PB) for side plates with thickness of 16 mm, measured density of 678 kg/m^3 and the following characteristics: modulus of elasticity in bend-



a) b) c)

Figure 1 FEM models A and B of upholstered furniture side frame and loading
Slika 1. A i B modeli bočne stranice ojastučenog namještaja za FEM

ing E_y=$E_\perp$=2700×10⁶ N/m² and E_x = $E_{//}$=1600×10⁶ N/m²; ν_{yx} =0.30, ν_{xy} =0.18 (Bodig *et al*., 1982), bending strength 11×10⁶ N/m²; compression strength $\sigma_{c//}$=13.4×10⁶ N/m² and $\sigma_{c\perp}$=80×10⁶ N/m²; tension strength $\sigma_{t//}$=7.9×10⁶ N/m² and $\sigma_{t\perp}$=0.8×10⁶ N/m²; shear stress 6.1×10⁶ N/m².

Oriented strandboard, type EGGER OSB2 with thickness of 16 mm (BDS EN 13986:2004) and the following mechanical characteristics: density 596 kg/m³; modulus of elasticity in bending E_x=$E_{//}$=3800×10⁶ N/m²; modulus of elasticity in bending E_y=$E_\perp$=3000×10⁶ N/m²; bending strength $\sigma_{m//}$=16.4×10⁶ N/m² and $\sigma_{m\perp}$=8.2×10⁶ N/m²; compression strength $\sigma_{c//}$=15.4×10⁶ N/m² and $\sigma_{c\perp}$=12.7×10⁶ N/m²; tension strength $\sigma_{t//}$=9.4×10⁶ N/m² and $\sigma_{t\perp}$=7×10⁶ N/m²; shear stress 6.8×10⁶ N/m²; ν_{xy}=0.30 (Thomas, 2003) and ν_{yx}=0.24, calculated by the equation (Bodig *et al*., 1982):

$$\frac{\nu_{xy}}{E_x} = \frac{\nu_{yx}}{E_y}, \quad (1)$$

Plywood (PLY) boards from birch *(Betula)* with thickness of 15 mm and 11 layers (BDS EN 14279:2004) and the following characteristics: density of 629 kg/m³; modulus of elasticity in bending E_x=$E_{//}$=7224×10⁶ N/m²; E_y=$E_\perp$=5709×10⁶ N/m²; bending strength $\sigma_{m//}$=61×10⁶ N/m² and $\sigma_{m\perp}$=57×10⁶ N/m²; compression strength $\sigma_{c//}$=52.2×10⁶ N/m² and $\sigma_{c\perp}$=52×10⁶ N/m²; tension strength $\sigma_{t//}$=93×10⁶ N/m² and $\sigma_{t\perp}$=54×10⁶ N/m²; shear stress 6×10⁶ N/m²; ν_{xy}=0.30 (Bodig *et.al*., 1982) and ν_{yx}=0.237 (equation 1).

Support boundary conditions were set: bottom front rail – no translation on y direction, and bottom rear rail no translation on *x*, *y* and *z* direction – Figure 1 b.

In order to simulate semi-rigid connections between rails and side plates of the frame, the following actions were performed: *First* – in the place of joints in the discrete frame model, narrow zones were created with established via tests by FEM lower modules of elasticity of the used materials; *Second* - the coefficients of rotational stiffness of the corner joints with 2 staples and PVAc glue, loading under compression were laboratory established by Hristodorova (2019) according to the method described in Jivkov *et al.* (2006): case butt joints (for pine-PB *c* = 1018 Nm/rad; for pine-OSB *c* = 767 Nm/rad; for pine-PLY *c* = 1788 Nm/rad) and end to face butt joints (for pine-PB *c* = 823 Nm/rad; for pine-OSB *c* = 510 Nm/rad; for pine-PLY *c* = 1433 Nm/rad). These coefficients of rotational stiffness were introduced in the nodes of the respective corner joints in the frame models as nodal 3D spring supports - Figure 1, b and c.

Both discrete frame models *A* and *B* were loaded with a total load of 800 N, distributed as follows (Figure 1b): *Seat*: 80 % was set as a remote force, distributed between rails of the seat with application point of 100 mm in front of the rear rail; *Backrest*: 16 % set as equal nodal forces, distributed on the edges of the two sides of the backrest.

The validity of this approach was proven and described in Staneva *et al.* (2018a).

Additionally, both *models A* and *B* with side plates of PB, OSB and PLY, were loaded with a heavy-service load of 2400 N, distributed only on the seat (Figure 1c) in order to calculate the failure indexes according to Tsai-Wu failure criteria:

$$F = \left(\frac{1}{X_t} - \frac{1}{X_c}\right)\sigma_1 + \left(\frac{1}{Y_t} - \frac{1}{Y_c}\right)\sigma_2 + \frac{\sigma_1^2}{X_t X_c} + + \frac{\sigma_2^2}{Y_t Y_c} + 2F_{12}\sigma_1\sigma_2 + \frac{\tau_{12}^2}{S^2}, \quad (2)$$

Where

σ_1, σ_2, σ_{12} and τ_{12} are the calculated normal and shear stresses;

X_t and X_c - longitudinal strength in both tension and compression;

Y_t and Y_c – transverse strength in both tension and compression;

S – in-plane shear strength;

F_{12} – interaction term.

Failure is predicted to occur when $F \geq 1$.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The main criteria for assessing the strength of the upholstered furniture frame, modelled with plate finite elements, are the extreme stresses (maximum principal stresses σ_{maxPR} and minimum principal stresses σ_{minPR}) calculated for each structural element. The signs of the extreme stresses plus (+) and minus (-) are tension and compression stress, respectively.

The results of the static analysis for *model A* and *model B* of the upholstered furniture frame are shown in Table 1, Figure 2 to 10. The previewing of deformed model in the figures is with a scale factor of 3 % of model size for the whole model and 5 % for side plates.

The maximum value of maximum principal stress σ_{maxPR} (tension stress) 7.79×10^6 N/m^2 for the frame *model A* with side plates of PB and 7.47×10^6 N/m^2 for model with side plates of OSB is localized in the middle of the rear rail of the seat, on the bottom, while for the frame with side plates of PLY, it is localized in the side plate, in the area of attachment of rear rail of the seat (7.63×10^6 N/m^2), Table 1. In the middle of the rear rail of the seat, on the bottom, the value of the tension stress (σ_{maxPR}) of the model with side plates of PLY is 6.94×10^6 N/m^2.

The maximum value (absolute) of the minimum principal stress σ_{minPR} (compression stress) of -8.01×10^6 N/m^2 for *model A* with side plates of PB is localized in the middle on the top of the rear rail of the seat (Figure 2), while for the frame with side plates of OSB and PLY, it is localized in the side plate, in the area of attachment of rear rail of the seat (-11.78×10^6 N/m^2 for OSB and -12.88×10^6 N/m^2 for PLY) – Table 1. In the middle of the rear rail of the seat, on the top, for *model A* with side plates of OSB and PLY, the maximum value of the compression stress (σ_{minPR}) is -7.78×10^6 N/m^2 for OSB and -7.24×10^6 N/m^2 for PLY – Table 1.

In *model B,* the localization of the maximum stress values is in the reinforcing details of rear rail of the seat for all materials of side plates (Figure 2 and 3, Table 1), due to the arising significant bending moments in the joints with higher stiffness in the model. Due to the redistribution of the stresses, the reinforcement of the frame leads to decreasing of the maximum value of tension stress in the middle of the rear rail of the seat although insignificantly depending on the type of furniture boards: 1.2 times for the frame with PB side plates and 1.3 times for OSB and PLY side plates (Table 1), while the maximum value of compression stress decreases 1.2 times for all materials of the side plates (Figure 4, Table 1).

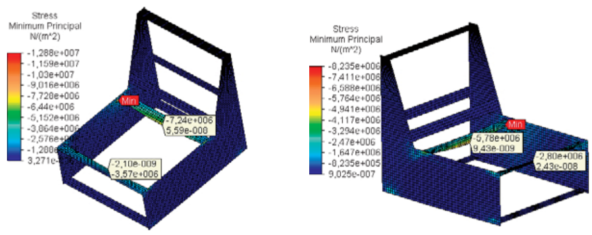


Figure 2 Distribution of σ_{minPR} for *model A* and *model B* with side plates of PLY
Slika 2. Raspodjela σ_{minPR} za model A i model B sa stranicama od furnirske ploče

The reinforcement of the frame results in increasing of σ_{maxPR} in the joints of rear rail of the seat with the side plates 3 times for the frame with PB side plates and 1.1 time for the OSB side plates, while for PLY side plates it decreases 1.2 times (Table 1). The minimum principal stress in the joints of rear rail of the seat with the side plates increases 1.3 times for PB side plates, while it decreases for OSB side plates 1.4 times and for PLY side plates 1.6 times.

In the side plates for *model A,* the maximum value of tension stress (σ_{maxPR}) is localized at the front of

Table 1 Values of principal stresses in the model with side plates of PB, OSB and PLY
Tablica 1. Vrijednosti glavnih naprezanja u modelu s bočnim stranicama od iverice, OSB ploča i furnirskih ploča

Parameter *Parametar*	**Location** / *Lokacija*	**PB** *Ploča iverica*		**OSB** *OSB ploča*		**PLY** *Furnirska ploča*	
		model *A*	model *B*	model *A*	model *B*	model *A*	model *B*
σ_{maxPR} ×10^6 N/m^2 (*F*=800 N)	front rail of the seat / *prednji poveznik sjedala*	3.66	3.12	3.57	3.07	3.38	2.80
	rear rail of the seat / *stražnji poveznik sjedala*	7.79	6.39	7.47	5.86	6.94	5.21
	rear rail – joint / *stražnji poveznik – spoj*	4.63	4.16	5.39	4.53	6.19	5.04
	side plate – joint rear rail *bočna stranica – spoj sa stražnjim poveznikom*	2.21	1.96	6.25	2.85	7.63	3.35
	strength. detail rear rail *pojačanje stražnjeg poveznika*	-	7.11	-	6.76	-	6.36
σ_{minPR} ×10^6 N/m^2 (*F*=800 N)	front rail of the seat / *prednji poveznik sjedala*	-3.79	-3.10	-3.75	-3.03	-3.57	-2.80
	rear rail of the seat / *stražnji poveznik sjedala*	-8.01	-6.72	-7.78	-6.36	-7.24	-5.78
	rear rail – joint / *stražnji poveznik – spoj*	-4.15	-3.95	-4.94	-4.32	-5.95	-4.71
	side plate – joint rear rail *bočna stranica – spoj sa stražnjim poveznikom*	-6.23	-2.53	-11.52	-3.72	-12.88	-4.76
	strength. detail rear rail *pojačanje stražnjeg poveznika*	-	-8.29	-	-8.27	-	-8.24
σ_{maxPR} ×10^6 N/m^2 (*F*=2400 N)	side plate - front rail *bočna stranica – prednji poveznik*	11.48	8.30	-	10.69	-	12.40
	side plate – rear rail *bočna stranica – stražnji poveznik*	-	-	22.05	-	28.47	-
σ_{minPR} ×10^6 N/m^2 (*F*=2400 N)	side plate – rear rail *bočna stranica – stražnji poveznik*	23.47	-9.46	-37.21	-14.10	-48.40	-12.87

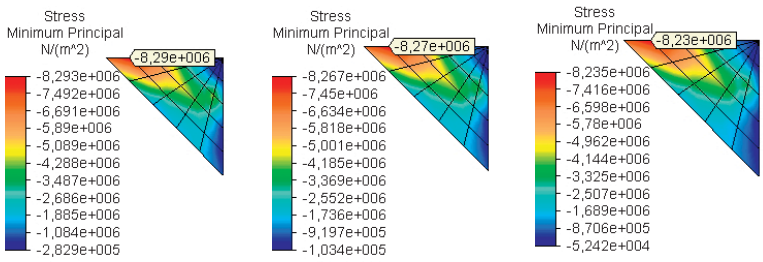


Figure 3 Distribution of σ_{minPR} in reinforcing details (*model B*; PB, OSB and PLY side plates)
Slika 3. Raspodjela σ_{minPR} za pojačane detalje (model B: iverica, OSB ploča, furnirska ploča)

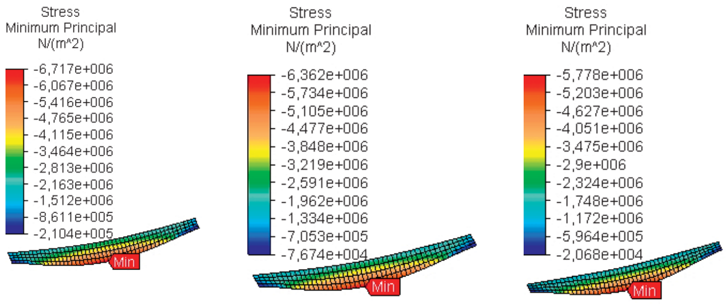


Figure 4 Distribution of σ_{minPR} in rear rail of the seat (*model B*; PB, OSB and PLY side plates)
Slika 4. Raspodjela σ_{minPR} za stražnji element sjedala (model B: iverica, OSB ploča, furnirska ploča)

the side plate, in the field of front rail of the seat for PB side plate, whereas for OSB and PLY side plate it is localized in the area of attachment of the rear rail of the seat – Figure 5. For the strengthened *model B* for all materials, the maximum value of σ_{maxPR} in the side plate is localized at the front of the side plate, in the field of front rail of the seat due to the reinforcement of the seat rails – Figure 6.

For *model A*, the tension stress for PW side plate (7.63×10^6 N/m^2) is 2.5 times greater than that for PB (3.05×10^6 N/m^2) and 1.2 times than that for OSB (6.25×10^6 N/m^2) – Figure 5. The tension stress for OSB side plate is 2 times greater than that for PB.

In *model B*, the tension stress for PW side plate (3.55×10^6 N/m^2) is 1.6 times greater than that for PB (2.22×10^6 N/m^2) and 1.2 times than that for OSB (2.85×10^6 N/m^2) – Figure 6. The tension stress for OSB side plate is 1.3 greater than that for PB.

The maximum value of the compression stress in the side plate is localized in the area of the rear seat rail attachment for all materials in *model A* - Figure 7. For *model B*, for all materials, the maximum value of the compression stress in the side plate is also localized in the area of the rear seat rail attachment - for PB it is in the area of the reinforcing element, whereas for OSB and PLY it is at the top edging of the side plate – Figure

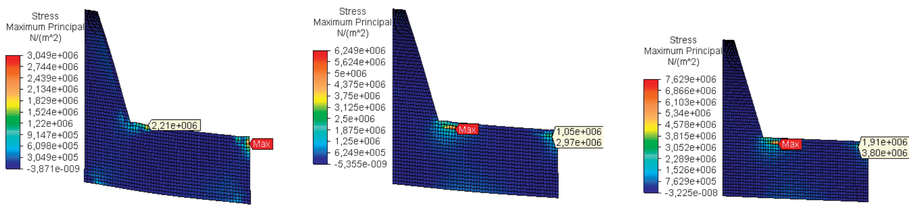


Figure 5 Distribution of max principal stress in side plates of PB, OSB and PLY for *model A*
Slika 5. Raspodjela najvećih naprezanja u stranicama od iverice, OSB ploče i furnirske ploče za model A

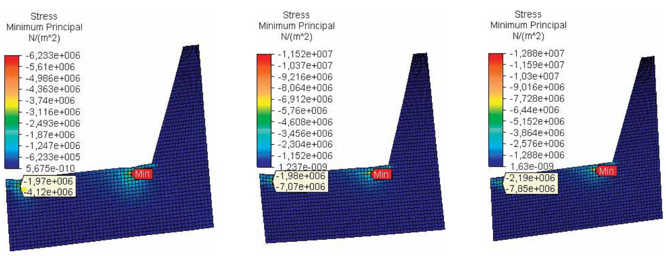


Figure 6 Distribution of min principal stress in side plates of PB, OSB and PLY for *model A*
Slika 6. Raspodjela najmanjih naprezanja u stranicama iverice, OSB ploče i furnirske ploče za model A

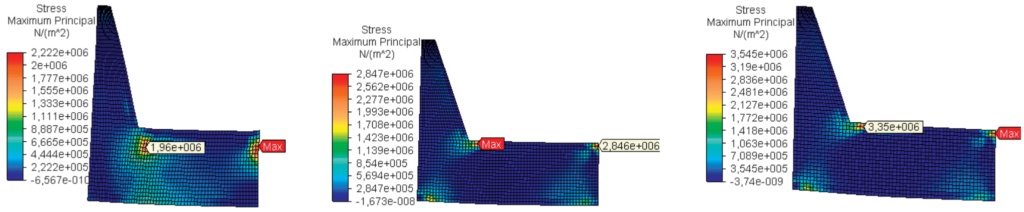


Figure 7 Distribution of max principal stress in side plates of PB, OSB and PLY for *model B*
Slika 7. Raspodjela najvećih naprezanja u stranicama od iverice, OSB ploče i furnirske ploče za model B

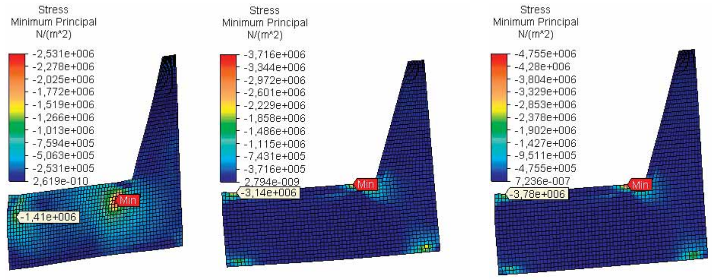


Figure 8 Distribution of min principal stress in side plates of PB, OSB and PLY for *model B*
Slika 8. Raspodjela najmanjih naprezanja u stranicama od iverice, OSB ploče i furnirske ploče za model B

8. The same phenomenon was found in the real tests of corner joints from Scots pine-OSB and Scots pine-PLY with two staples and glue (also established by Kasal (2006).

For *model A*, the absolute maximum value of the compression stress for PLY (-12.88×10^6 N/m^2) is 2.1 time greater than that for PB and 1.1 time than that for OSB – Figure 6. The compression stress for OSB (-11.52×10^6 N/m^2) is 1.85 times greater than that for PB. In *model B*, the compression stress for PLY (-4.76×10^6 N/m^2) is 1.9 times greater than that for PB and 1.3 times than that for OSB – Figure 8. The compression stress for OSB (-3.72×10^6 N/m^2) side plate is 1.5 times greater than that for PB.

The results for the principal stresses in heavy-service load (F=2400 N) indicate that the maximum values stresses, especially the minimum principal stresses in the side plates, have exceeded the strength of PB and OSB boards (Table 1).

In both models, the values of the in-plane failure index in the side plates in heavy-service load (F=2400 N**)** only on the seat are greatest for side plates of PB, especially for *model A* (Figure 9 and 10). The maximum value of the failure index is established in the field of the front rail joining to the side plate of PB for *model A* and in the field of joining of strengthening details of rear rail for *model B*. Obviously, PB side plates have a high risk of damage in heavy-service load, even for the strengthened *model B*.

The failure index in side plates of OSB is also critical - F>1 for both *models A* and *B* and it is approximately 2 times lower than that for PB side plates.

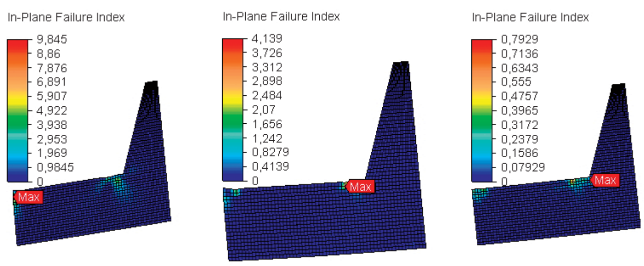


Figure 9 Failure index for PB, OSB and PLY side plates in *model A* (F=2400 N)
Slika 9. Indeks loma stranica od iverice, OSB ploče i furnirske ploče za model A (F=2400 N)

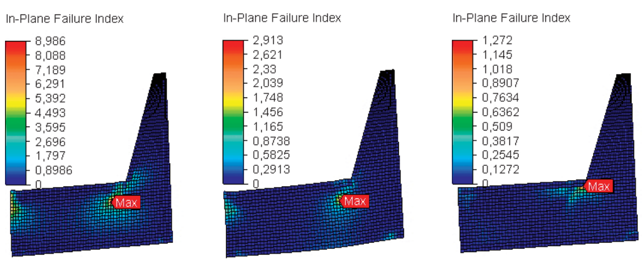


Figure 10 Failure index for PB, OSB and PLY side plates in *model B* (F=2400 N)
Slika 10. Indeks loma stranica od iverice, OSB ploče i furnirske ploče za model B (F=2400 N)

For side plates of PLY, the failure index $F<1$ for *model A* and approximately equal to 1 (1.27) for *model B* (Figure 9 and 10).

4 CONCLUSIONS
4. ZAKLJUČAK

From the results of this study by FEM with CAE program Autodesk Simulation Mechanical® on the strength of the one-seat upholstered furniture frame with side plates of PB, OSB and PLY, rails of Scots pine and staples with glue corner joints under light-service load, several conclusions can be derived:

1. Due to the redistribution of the stresses, the reinforcement of the seat rails improves the strength of the upholstered furniture frame: the maximum values of the tension stresses decrease by about 8.7 % for the frame with side plates of PB, 9.5 % for OSB and 17 % for PLY; compression stresses decrease by about 28 % for the frame with side plates of OSB and 36 % for PLY, while for PB side plates, they increase by 3 % - almost negligible.

2. The most critical joints in the investigated upholstered furniture frame are the joints of rear rail of the seat with the side plates for all side plate materials. The reinforcement of the frame results in increasing the compression stress in these joints by 33 % for PB side plates and decreasing by 28 % for OSB and 36 % for PLY side plates.

3. The strength behaviour of the side plates of PB, OSB and PLY is considerably improved after strengthening of the rails to the side plate joints of the seat: the tension stresses in the side plates are reduced by approximately 27 % for PB, 54 % for OSB and PLY. The compression stresses are reduced by approximately 59 % for PB, 68 % for OSB and 63 % for PLY.

4. The type of furniture plate affects the strength of the side plates in the upholstered furniture frame: in the reinforced frame the tension stress decreases by approximately 38 % for side plates of PB and 20 % for side plates of OSB and PLY; the compression stress decreases by approximately 47 % for side plates of PB and 22 % for side plates of OSB and PLY.

5. All results for stresses and failure indexes determine PLY side plates as the most appropriate and PB side plates as the most inappropriate furniture boards for upholstered side frame constructions concerning their strength. In order to observe safety requirements in designing, frames with side plates of PB and OSB in case of joints with staples and glue have to be produced of boards with thickness of 18 mm or to be further strengthened.

6. The values obtained for the maximum and minimum principal stresses allow the prediction of strength behaviour of upholstered furniture frame made of Scots pine rails and side plates of PB, OSP and PLY and corner joints with staples and glue.

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The Effect of Sapwood and Heartwood Differences on Mechanical Properties of Fast-Growing Tree Species

Utjecaj razlika između bjeljike i srži na mehanička svojstva drva brzorastućih vrsta

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ABSTRACT • *In most uses where wood material needs impregnation or dimensional stability is essential, the properties of sapwood and heartwood should be taken into account. Also, due to the structural differences between heartwood and sapwood, differences in the strength of wood materials should be predicted. Therefore, the aim of this study was to reveal the differences between the mechanical properties of sapwood and heartwood of some important fast-growing forest trees. For this purpose, two softwoods (Pinus sylvestris) and (Pinus brutia) and two hardwoods (Populus usbekistanica) and (Eucalyptus grandis) were selected as test trees. Compression strength parallel to grain (CS ∥), static quality value (IS), bending strength (MOR), modulus of elasticity (MOE), tensile strength perpendicular to grain (TS⊥), shearing strength parallel to grain (SS ∥), impact bending strength (IBS), dynamic quality value (ID) and Janka hardness values (JH) of sapwood and heartwood of test trees were determined in laboratory studies. The results of the t-test analysis showed that all mentioned mechanical properties of sapwood and heartwood of test trees were separated from each other as significant, except the shear strength of Eucalyptus, dynamic quality values of red pine and Scots pine and Janka hardness value of red pine. Finally, the results of the study revealed that the differences between sapwood and heartwood strength should be taken into account when wood species are used in constructions and other sensitive areas.*

Key words: *mechanical properties; sapwood; heartwood; softwoods; hardwoods*

SAŽETAK • *U većini primjera uporabe drva u kojima je potrebna impregnacija ili je postojanost dimenzija iznimno važna treba uzeti u obzir različita svojstva drva bjeljike i srži. Usto, zbog strukturnih razlika između srži i bjeljike treba predvidjeti i razlike u njihovoj čvrstoći. Cilj je ovog istraživanja bio utvrditi razlike između mehaničkih svojstava srži i bjeljike nekih važnih brzorastućih šumskih vrsta drva. Stoga su za izradu uzoraka odabrane dvije vrste četinjača (Pinus sylvestris i Pinus brutia) i dvije vrste listača (Populus usbekistanica i Eucalyptus grandis). U laboratorijskim su uvjetima za uzorke drva četinjača i drva listača određena ova svojstva: tlačna čvrstoća paralelno s vlakancima (CS ∥), vrijednost statičke kvalitete (IS), čvrstoća na savijanje (MOR), modul elastičnosti (MOE), vlačna čvrstoća okomito na vlakanca (TS⊥), smična čvrstoća paralelno s vlakancima (SS ∥), čvrstoća drva na udarce (IBS), vrijednost dinamičke kvalitete (ID) i tvrdoća po Janki (JH). Rezultati usporedbe uz pomoć t-testa pokazali su da se istraživana mehanička svojstva drva bjeljike i srži znatno razlikuju, osim smične čvrstoće drva eukalipta, dinamičkih vrijednosti kvalitete drva crvenog bora i običnog bora te tvrdoće drva crvenog bora po Janki. Zaključno, rezultati studije pokazali su da je pri upotrebi drva brzorastućih*

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vrsta u graditeljstvu i drugim osjetljivim područjima nužno uzeti u obzir razlike među mehaničkim svojstvima drva bjeljike i srži.

Ključne riječi: *mehanička svojstva; bjeljika; srž; drvo četinjača; drvo listača*

1 INTRODUCTION
1. UVOD

Wood is composed of sapwood and heartwood resulting from its anatomical structure. The above mentioned wood species differ in appearance and anatomical structure. The sapwood is generally light colored, alive and located between the heartwood and the bark. In fact, the heartwood is formed as a result of sapwood aging. Besides, the formation period of heartwood can be affected by soil, climate and habitat conditions. Tree age, place of growth and tree stand have an important impact on the width of sapwood (Bosshard, 1968; Doğu, 2002). When compared with sapwood, the heartwood consisting of extractives is drier, heavier, harder and with lower fiber saturation point and lower hygroscopicity. In addition, the difference between sapwood and heartwood is entirely due to the change in chemical structure (Bozkurt and Erdin, 1997). Generally, heartwood contains more lignin and less cellulose than sapwood (Fengel and Wegener, 1989). Bertaud and Holmbom (2004) reported that heartwood has less cellulose and more lignin than sapwood and almost the same hemicellulose content.

As a result, there are differences between the sapwood and heartwood in terms of physical and mechanical properties. Therefore, physical and mechanical properties of wood should absolutely be taken into consideration when using wood. In some use areas, it is important to know the mechanical properties of sapwood and heartwood.

Cherelli *et al.* (2016) studied density measurements between sapwood and heartwood in three different trees, including eucalyptus grandis, and concluded that there was no significant difference between sapwood and heartwood densities.

In literature, there are few studies on the mechanical properties of sapwood and heartwood of trees in the world and especially in Turkey. Bal and Bektas (2013) determined some mechanical properties of heartwood and sapwood of E. Grandis and found that the sapwood samples provided better mechanical properties than the heartwood samples. However, Merela and Čufar (2013) stated that there was no statistically significant difference between the mechanical properties of the sapwood and heartwood.

In a study on Japanese persimmon performed by Noda *et al*. (2002), the specific gravity, equilibrium moisture content, modulus of rupture, and modulus of elasticity of the blackened heartwood were higher than those of sapwood. Besides, Noack (1963) mentioned that there are no significant differences between the most important physical and technological properties of European oak heartwood and sapwood. The stiffness and strength of the young acacia sapwood were found to be higher than those of heartwood (Hai *et al*. 2010).

Ozalp and Hafizoglu (2008) examined the time-dependent changes in the main components of non-impregnated Scots pine (*P. sylvestris*) and red pine (*P. brutia*) sapwood and heartwood used in water cooling towers.

Moreover, Gültekin (2014) investigated the relationship between the sapwood and heartwood in terms of morphological, anatomical and physical characteristics of some conifers and broadleaf trees. The results obtained in the same study showed that there are statistically significant differences between sapwood and heartwood of most of the properties mentioned above.

In light of the above, the subject of this study is the "comparison of mechanical properties of sapwood and heartwood of Scots pine, spruce, poplar, and eucalyptus, which are Turkey's industrial forest trees and fast-growing species".

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The fast-growing tree species yield a minimum of ten cubic meters of wood per hectare per year at the end of the management period (Dwivedi, 1993). The species reaching a diameter value of native or indigenous species at the end of the management period, which is considered 1/3 of the management period applied for native species, are yet defined as fast-growing species (LIS, 1996).

In this study, two softwoods (Scots pine (*Pinus sylvestris* L.) and Turkish red pine (*Pinus brutia* Ten.)) and two broadleaf trees (Asian poplar wood (*Populus usbekistanica* "Afganica") and eucalyptus (*Eucalyptus grandis*)), accepted as fast-growing species, were selected as test trees according to TS 4176. The average age of experimental trees was as follows: Scots pine - 46, Red pine - 53, Eucalyptus - 20 and poplar - 27. The altitude and slopes of wood samples were as follows: Scots pine - 1900 m and 315, Red pine - 1025 m and 64 %, Eucalyptus - 5 m and 8 % and poplar - 1250 m and 67 %.

1 m-length test specimens were taken between 2 and 4 m from the base in accordance with TS 4176 (1984). Then, the cross-sections of the specimens taken from the logs were sanded in order to identify sapwood and heartwood. In cases where the limit was not very clear, the test samples were taken at a certain distance (approximately 1 cm) from the common boundary between heartwood and sapwood, because knowing the precise boundary between sapwood and heartwood is not necessary for this study. Specimens of sapwood and heartwood were prepared separately for tests according to relevant standards and conditioned at the temperature of 20 ± 2 °C and at the relative humidity of 65 ± 5 %. Then, the mechanical tests, such as compres-

sion strength parallel to grain (including static and specific quality values), elasticity modulus, static bending strength, tensile strength perpendicular to grain, shear strength, dynamic bending strength (including dynamic quality value) and Janka hardness were performed according to TS 2595, TS 2474, TS 2478, TS 2476, TS 3459,TS 2477 and TS 2479, respectively.

As explained in TS 2595, the static and specific quality values are calculated as follows: static quality value = compression strength/(100×D_{12}); specific quality value = compression strength/(100×D^2_{12}) (where: D_{12} is air dry density (g/cm^3)). Also, the dynamic quality value is determined in TS 2477 as follows: dynamic quality value = dynamic bending strength/(100×D^2_0) (where: D_0 is oven dry density (g/cm^3).

SPSS 17.0 Independent Samples T-Test was used to determine the differences between sapwood and heartwood.

3 RESULTS AND DISCUSSIONS
3. REZULTATI I RASPRAVA

Table 1 shows the values of the compression strength parallel to grain of sapwood (SW) and heartwood (HW) of the above wood species and the results of Independent Samples *T*-Test analysis. As can be understood from Table 1, in all wood species, the compression strength values of sapwood and heartwood (p<0.05) differed significantly from each other. When the data are evaluated on the average, it can be seen that the HW values of eucalyptus (39.5 N/mm^2) and red pine (65 N/mm^2) are higher than SW values and lower in other wood species (26.1 and 29.7 N/mm^2). On the other hand, compression strength parallel to fibers of sapwood and heartwood of *Quercus robur* and *Quercus cerris* was researched by Merela and Čufar (2013). According to the results obtained, compression strength of *Quercus robur* sapwood (41.6 N/mm^2) is lower than that of heartwood (45.4 N/mm^2). This result also applies to *Quercus cerris* (SW: 54.8 and HW: 51.6 N/mm^2).

While the increase in density increases the compression strength, the increases in temperature, knots field, amount of resin, and humidity decrease the compression strength (Bektaş, 1997). It can be concluded that the high compression strength measured in the red pine is especially due to the high resin content in this species. Table 2 contains the data of the static quality value, which is accepted as one of the criteria for the quality related to the compression properties of the wood material (Bektaş, 1997; Bozkurt and Göker, 1996). The static quality values of sapwood of wood species shown in Table 2 were statistically (p<0.001) separated from their heartwood.

Static quality values are considered to be of "medium quality" for softwoods when ranging between

Table 1 Compression strength values (∥) of sapwood and heartwood of wood species
Tablica 1. Vrijednosti tlačne čvrstoće bjeljike i srži ispitivanih vrsta drva paralelno s vlakancima

Wood species *Vrsta drva*	**Wood type** *Tip drva*	***N***	**Mean** *Srednja vrijednost* N/mm^2	***SD***	***SE***	***COV*** **%**	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	48	37.8	2.295	0.331	6.07	-2.961	0.041
	HW	47	39.5	5.641	0.823	14.26		
Poplar wood / *drvo topole*	SW	48	27.4	1.212	0.175	4.42	4.099	0.049
	HW	48	26.1	1.848	0.267	7.08		
Red pine / *drvo crvenog bora*	SW	48	45.1	2.335	0.337	5.18	-18.255	0.000
	HW	48	65.0	7.209	1.040	11.09		
Scot pine / *drvo običnog bora*	SW	53	39.3	7.541	1.036	19.19	7.055	0.000
	HW	44	29.7	5.382	0.811	18.10		

N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

Table 2 Static quality values of sapwood and heartwood of wood species
Tablica 2. Vrijednosti statičke kvalitete bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	***N***	**Mean** *Srednja vrijednost* km*	***SD***	***SE***	***COV*** **%**	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	48	0.6	0.055	0.008	9.37	-36.567	0.000
	HW	47	1.1	0.072	0.011	6.79		
Poplar wood / *drvo topole*	SW	48	1.1	0.037	0.005	3.37	41.549	0.005
	HW	48	0.8	0.031	0.005	3.91		
Red pine / *drvo crvenog bora*	SW	48	0.8	0.047	0.007	5.56	-9.772	0.035
	HW	48	1.0	0.103	0.015	10.24		
Scot pine / *drvo običnog bora*	SW	53	0.9	0.046	0.007	5.13	12.870	0.048
	HW	44	0.7	0.087	0.013	12.39		

*The unit of static quality value is km (Bozkurt and Göker, 1996). / *Jedinica vrijednosti statičke kvalitete je* km *(Bozkurt i Göker, 1996.)*. *N* – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

Table 3 Specific quality values of sapwood and heartwood of wood species
Tablica 3. Vrijednosti specifične kvalitete bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	***N***	**Mean** *Srednja vrijednost* km*	***SD***	***SE***	***COV* %**	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	48	0.9	0.147	0.021	16.28	-25.904	0.000
	HW	47	1.8	0.173	0.025	9.88		
Poplar wood / *drvo topole*	SW	48	2.2	0.100	0.014	4.52	2.846	0.053
	HW	48	2.1	0.144	0.021	6.77		
Red pine / *drvo crvenog bora*	SW	48	1.6	0.125	0.018	7.86	0.900	0.370
	HW	48	1.6	0.182	0.026	11.70		
Scot pine / *drvo običnog bora*	SW	48	2.0	0.111	0.016	5.65	6.644	0.000
	HW	43	1.7	0.245	0.037	14.40		

*The unit of specific quality value is km (Bozkurt and Göker, 1996). / *Jedinica vrijednosti specifične kvalitete je* km *(Bozkurt i Göker, 1996.).*
N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

0.80-0.95, of "low quality" below these limits and of "good quality" above these values. Besides, it is accepted that static quality values for hardwoods are of "medium quality" in the range of 0.60-070, of "low quality" below these values and of "good quality" above these limits (Bozkurt and Göker, 1996; Bozkurt and Erdin 1997). According to these classifications, eucalyptus heartwood (1.1), poplar sapwood (1.1) and red pine heartwood (1.0) have "good quality" properties in terms of their compression characteristics. At the same time, except for Scots pine heartwood, the sapwood and heartwood of other wood species are considered to be of "medium quality". Also, Scots pine heartwood (0.6) has a "low quality".

Another "quality indicator" for wood is the specific quality value that is calculated from the relationship between compression strength and density, given in Table 3 (Bozkurt and Göker, 1996). The specific quality values calculated for each tree species and statistical analysis results are presented in Table 3.

Statistically significant differences were found in the other two species, while there was no significant difference between the specific quality values of poplar and red pine wood. In addition, as can be seen from the averages calculated in Table 3, sapwood and heartwood specific quality values showed a mixed composition in term of size and smallness.

When the bending strength values of the test specimens are evaluated according to the data given in Table 4, it can be seen that there is a significant difference between sapwood and heartwood values at p <0.001 significance level. In addition, the bending strength values (94.1 and 74.9 N/mm^2) of eucalyptus and Scots pine sapwood were higher than those of heartwood (61.3 and 65.8 N/mm^2). The bending strength values (48.2 and 68.5 N/mm^2) of poplar and red pine sapwood were also measured as lower than those of heartwood (56.4 and 80.9 N/mm^2). These results are consistent with the bending strength values of acacia wood (SW: 150.3 and HW: 132.1 N/mm^2) determined by Hai *et al*. (2010).

Again, Junior and Moreschi (2003) determined the oven dry density of 0.54 g/cm^3 and bending strength of 73.4 N/mm^2 in Loblolly pine (*Pinus taeda*) mature wood. As is known, the mature wood of a tree largely corresponds to its heartwood (Bozkurt and Erdin, 1997).

Table 5 shows the results of t-test analysis of elasticity modulus values of sapwood and heartwood of the wood species. According to t-test results, it is understood that there is a significant difference (at the level of p<0.001) between the elasticity modulus values of sapwood and heartwood in all of the test specimens. On the other hand, the mutual size distribution of the elastic modulus values of sapwood and heartwood showed similarity to those of bending strength values. To be specific, the elasticity modulus of eucalyptus and Scots pine sapwood taken from the test specimens (7280.9 and 6539.3 N/mm^2) was higher

Table 4 Static bending strength (*MOR*) values of sapwood and heartwood of wood species
Tablica 4. Vrijednosti čvrstoće na savijanje bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	***N***	**Mean** *Srednja vrijednost* N/mm^2	***SD***	***SE***	***COV* %**	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	35	94.1	9.234	1.561	9.81	12.948	0.000
	HW	33	61.3	11.594	2.018	18.92		
Poplar wood / *drvo topole*	SW	42	48.2	3.211	0.496	6.67	-9.489	0.000
	HW	39	56.4	4.574	0.732	8.10		
Red pine / *drvo crvenog bora*	SW	42	68.5	10.467	1.615	15.27	-4.165	0.000
	HW	34	80.9	15.259	2.617	18.87		
Scot pine / *drvo običnog bora*	SW	32	74.9	5.541	0.980	7.40	4.944	0.000
	HW	36	65.8	8.940	1.490	13.58		

N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

Table 5 Modulus of elasticity (*MOE*) values of sapwood and heartwood of wood species
Tablica 5. Vrijednosti modula elastičnosti bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	*N*	**Mean** *Srednja vrijednost* N/mm²	*SD*	*SE*	*COV* %	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	35	7280.9	580.35	98.10	7.97	13.219	0.000
	HW	33	5264.5	676.19	117.71	12.84		
Poplar wood / *drvo topole*	SW	42	4179.1	293.55	45.30	7.02	-5.046	0.000
	HW	39	4551.2	368.10	58.94	8.09		
Red pine / *drvo crvenog bora*	SW	42	6118.0	1189.85	183.60	19.45	-4.671	0.000
	HW	34	7496.8	1382.97	237.18	18.45		
Scot pine / *drvo običnog bora*	SW	32	6539.3	425.63	75.24	6.51	10.851	0.000
	HW	36	5193.8	575.12	95.85	11.07		

N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

than that of heartwood, while the elasticity modulus of poplar and red pine heartwood (4551.2 and 7496.8 N/mm²) was higher than that of sapwood. The elasticity modulus values of Acacia sapwood and heartwood were found to be 20690 and 18800 N/mm², respectively (Hai *et al*. 2010). Another study on the subject (Junior and Moreschi, 2003) reported that the modulus of elasticity of *Pinus taeda* mature wood is 10020 N/mm².

The data in Table 6 shows no difference in the shear strength of sapwood and heartwood of the test specimens prepared from eucalyptus wood. However, the shear strengths of sapwood and heartwood of poplar wood, red pine and Scots pine wood were statistically separated from each other.

Likewise, as shown in Table 6, the shear strength values (eucalyptus 9.1 N/mm², poplar 4 N/mm², Scots pine 6.3 N/mm²) of the sapwood, except those of red pine, were found to be higher than those of the heartwood (eucalyptus 8.5 N/mm², poplar 3.2 N/mm², Scots pine 4.2 N/mm²). The shear strength values of the red pine sapwood and heartwood were calculated as 4.5 N/mm² and 7.9 N/mm², respectively. This difference in red pine is likely due to factors (resin, etc.) related to anatomical structures of the specimens, especially those that increase the density of the heartwood. In a study, Bao *et al*. (2001) found that the shear strength values of the heartwood were lower than those of the sapwood. These results are consistent with the present study, except for red pine species. The shear strength of red pine sapwood and heartwood was determined by Özkaya (2013) as 2.3 N/mm² and 2.5 N/mm², respectively. In another study, Cherelli *et al*. (2016) reported that the density results showed no statistical difference between heartwood and sapwood of *eucalyptus grandis*. Here, the absence (ρ>0.372) of a statistically significant difference between heartwood and sapwood of eucalyptus can be explained by this determination.

According to the results of the t-test performed on the tensile strength perpendicular to fiber of sapwood and heartwood of the wood species shown in Table 7, it can be concluded that the SW and HW of the species have statistically significant differences in the confidence level p<0.001.

When the values of tensile strength perpendicular to fibers are evaluated in terms of sapwood and heartwood height, the above mentioned strength values also apply here. Unlike other species, the calculated tensile strength perpendicular to fibers of red pine sapwood (3.4 N/mm²) is higher than that of heartwood (2.1 N/mm²). While the highest difference between the tensile strength of sapwood and heartwood was obtained for eucalyptus samples (1.4 N/mm²), the lowest difference was obtained for red pine (-1.3 N/mm²). The tensile strength perpendicular to fibers of the eucalyptus sapwood and heartwood were determined by Bal and Bektas (2013) as 5.0 and 3.7 N/mm², respectively. The cellulose content of sapwood is about 1-3 % higher than that of heartwood (Bektas, 1997; Bektas *et al*., 2017). As is known, this increase in cellulose content increases the tensile strength of wood material.

Table 6 Shear strength values of sapwood and heartwood of wood species
Tablica 6. Vrijednosti smične čvrstoće bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	*N*	**Mean** *Srednja vrijednost* N/mm²	*SD*	*SE*	*COV* %	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	33	9.1	2.322	0.404	25.46	0.901	0.372
	HW	22	8.5	2.360	0.503	27.64		
Poplar wood / *drvo topole*	SW	24	4.0	0.905	0.185	22.41	3.680	0.001
	HW	24	3.2	0.592	0.121	18.34		
Red pine / *drvo crvenog bora*	SW	32	4.5	2.145	0.379	47.77	-5.995	0.000
	HW	25	7.9	2.154	0.431	27.16		
Scot pine / *drvo običnog bora*	SW	25	6.3	3.017	0.603	47.73	3.533	0.001
	HW	37	4.2	1.645	0.270	38.96		

N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

Table 7 Tensile strength values of sapwood and heartwood of wood species
Tablica 7. Vrijednosti vlačne čvrstoće bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	***N***	**Mean** *Srednja vrijednost* N/mm²	***SD***	***SE***	***COV*** **%**	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	38	4.4	0.322	0.052	7.35	16.820	0.000
	HW	43	3.0	0.419	0.064	14.09		
Poplar wood / *drvo topole*	SW	38	2.2	0.506	0.082	23.11	6.154	0.000
	HW	37	1.6	0.299	0.049	18.74		
Red pine / *drvo crvenog bora*	SW	46	2.1	0.559	0.082	27.51	-8.361	0.000
	HW	41	3.4	0.921	0.144	27.23		
Scot pine / *drvo običnog bora*	SW	34	2.5	0.682	0.117	27.81	6.179	0.000
	HW	44	1.7	0.433	0.065	25.99		

N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

Table 8 shows the findings obtained as a result of experiments and analyses performed to determine the dynamic bending strength differences in sapwood and heartwood of test trees. Based on the data in the table, resulting from the t-test, it can be seen that there are significant differences between the dynamic bending strengths of sapwood and heartwood of all wood species.

The dynamic bending strengths (eucalyptus 0.085 Nm/mm², poplar wood 0.035 Nm/mm², Scots pine 0.047 Nm/mm²) of the wood species sapwood, except for red pine, were calculated as higher than those of heartwood (eucalyptus 0.042 Nm/mm², poplar wood 0.027 Nm/mm², Scots pine 0.029 Nm/mm²). In contrast to other wood species, the dynamic bending strength value (0.041 Nm/mm²) of the red pine heartwood was measured higher than that of sapwood (0.027 Nm/mm²). The dynamic bending strength of sapwood and heartwood of eucalyptus was determined as 0.095 Nm/mm² and 0.057 Nm/mm², respectively (Bal and Bektaş 2013). These results are consistent with the dynamic bending strength values calculated for the wood specimens other than red pine. Some studies have reported that the dynamic bending strengths of *E. camedulensis* (Awan *et al.,* 2012), *E. Grandis* (Bektaş *et al*., 2008), *P. brutia* (Bektaş *et al*., 2008) and *P. sylvestris* (Dündar, 2005) were found to be 0.06, 0.05, 0.04 and 0.05 Nm/mm², respectively. According to these results, it can be said that the average values (eucalyptus 0.06 Nm/mm², poplar 0.03 Nm/mm², red pine 0.03 Nm/mm² and Scots pine 0.04 Nm/mm²) of dynamic bending strength of

Table 8 Dynamic (impact) bending strength values of sapwood and heartwood of wood species
Tablica 8. Vrijednosti čvrstoće na udarce bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	***N***	**Mean** *Srednja vrijednost* Nm/mm²	***SD***	***SE***	***COV*** **%**	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	34	0.085	0.017	0.003	19.28	12.781	0.000
	HW	32	0.042	0.010	0.002	23.46		
Poplar wood / *drvo topole*	SW	42	0.035	0.007	0.001	20.88	5.367	0.000
	HW	39	0.027	0.005	0.001	18.74		
Red pine / *drvo crvenog bora*	SW	43	0.027	0.009	0.001	32.07	-4.057	0.000
	HW	34	0.041	0.020	0.004	49.31		
Scot pine / *drvo običnog bora*	SW	32	0.047	0.008	0.002	17.65	8.116	0.000
	HW	33	0.029	0.009	0.002	31.60		

N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

Table 9 Dynamic quality values of sapwood and heartwood of wood species
Tablica 9. Vrijednosti dinamičke kvalitete bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	***N***	**Mean** *Srednja vrijednost*	***SD***	**Quality class** *Klasa kvalitete*	***COV*** **%**	t_{value}	**Sig. (2-tailed)**
Eucalyptus / *drvo eukalipta*	SW	34	2.9	0.601	"good"	20.48	8.207	0.000
	HW	32	1.7	0.592	"fair"	34.29		
Poplar wood / *drvo topole*	SW	42	2.8	0.586	"good"	21.15	8.866	0.000
	HW	39	1.1	0.643	"low"	57.56		
Red pine / *drvo crvenog bora*	SW	43	0.9	0.414	"low"	47.72	-1.675	0.093
	HW	34	1.1	0.573	"fair"	54.28		
Scot pine / *drvo običnog bora*	SW	32	2.1	0.418	"fair"	19.82	0.380	0.705
	HW	33	2.1	0.625	"fair"	30.36		

N – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

Table 10 Janka hardness value* of sapwood and heartwood of wood species
Tablica 10. Vrijednosti tvrdoće po Janki* bjeljike i srži ispitivanih vrsta drva

Wood species *Vrsta drva*	**Wood type** *Tip drva*	**MD**	***N***	**Mean** *Srednja vrijednost* N/mm²	***SD***	***SE***	***COV*** **%**	t_{value}	**Sig. (2-tailed)**
Eucalyptus *drvo eukalipta*	SW	R	24	47.1	2.960	-	6.28	13.393	0.000
		T	24	53.6	5.275	-	9.84		
		L	24	63.9	3.654	-	5.72		
		AVE.	24	54.9	2.673	0.546	4.78		
	HW	R	35	27.6	6.246	-	22.61		
		T	35	35.7	6.195	-	17.37		
		L	35	52.0	7.506	-	14.44		
		AVE.	35	38.4	5.585	0.944	14.54		
Poplar wood *drvo topole*	SW	R	48	14.0	1.393	-	9.93	24.448	0.000
		T	48	11.4	1.789	-	15.68		
		L	48	24.5	1.367	-	5.57		
		AVE.	48	16.7	1.128	0.163	6.77		
	HW	R	40	9.8	1.365	-	13.98		
		T	40	9.5	1.511	-	15.94		
		L	40	14.2	1.567	-	11.05		
		AVE.	40	11.1	0.955	0.151	8.57		
Red pine *drvo crvenog bora*	SW	R	47	30.1	1.778	-	5.91	0.229	0.819
		T	47	29.7	1.507	-	5.08		
		L	47	48.5	4.650	-	9.58		
		AVE.	47	36.1	1.957	0.285	36.1		
	HW	R	42	32.0	7.262	-	22.72		
		T	42	35.2	4.795	-	13.63		
		L	42	40.6	6.006	-	14.79		
		AVE.	42	35.9	5.140	0.793	35.9		
Scots pine *drvo običnog bora*	SW	R	39	26.1	8.186	-	31.38	15.933	0.000
		T	39	23.2	3.677	-	15.85		
		L	39	39.2	3.120	-	7.96		
		AVE.	39	29.5	3.616	0.579	12.26		
	HW	R	38	16.5	3.789	-	22.95		
		T	38	14.4	2.707	-	18.75		
		L	38	24.3	3.926	-	16.15		
		AVE.	38	18.4	2.323	0.377	12.61		

* *t*-test analyses were based on average values / *t-test temeljen je na srednjim vrijednostima*, MD – Measurement directions / *smjer mjerenja*, *N* – Number of samples / *broj uzoraka*, SW – Sapwood / *bjeljika*, HW – Heartwood / *srž*, *SD* – Standard deviation / *standardna devijacija*, *SE* – Standard error / *standardna pogreška*, *COV* – Coefficient of variation / *koeficijent varijacije*

sapwood and heartwood given in Table 8 are consistent with the literature. The criteria and analysis results related to the dynamic quality value, which is one of the indicators of the impact quality of wood material, are given in Table 9.

In the column “quality class” given in Table 9, the dynamic quality groups based on the evaluation of wood species are as follows; eucalyptus: $ID<1$ is “low quality”, $1<ID<2$ is “fair quality”, $2<ID$ is “good quality”; poplar: $ID<1.5$ is “low quality”, $1.5<ID<2.5$ is “fair quality”, $2.5<ID$ is “good quality”; red pine and Scots pine: $ID<1.0$ is “low quality”, $1.0<ID<2.5$ is “fair quality”, $2.5<ID$ is “good quality”(Bozkurt and Göker 1996).

When the dynamic quality values of heartwood and sapwood were compared statistically, there were significant differences in eucalyptus and poplar specimens, but no meaningful difference was found between red pine and Scots pine. According to the classification of the dynamic quality values in Table 9, eucalyptus and poplar sapwood was evaluated as “good quality”, eucalyptus, red pine and Scots pine heartwood as “fair quality” and poplar HW and red pine SW as “low quality”. Some studies by Kollmann and Cote (1968), Korkut and Güller, (2008) stated that European Hop-hornbeam has good shock quality according to dynamic quality value.

Table 10 shows the results of the statistical analysis of the hardness values calculated separately for radial (R), tangential (T), and longitudinal (L) sections in sapwood and heartwood of test trees. Considering the t-test results in the same table, it can easily be seen that there is a significant difference in $p<0.001$ confidence level between sapwood and heartwood of other species except for red pine.

When Janka hardness values are taken into consideration, it will be understood that the sapwood hardness is higher than heartwood hardness, except for red pine wood. Here, it can be said that the obtained hardness values were well correlated with the density of the wood species. It was determined by Gültekin (2014) that sapwood densities of Scots pine, eucalyptus and poplar were higher than those of heartwood densities, while there is an opposite relationship for red pine wood. Also, Bal and Bektaş (2013) studied the Janka hardness values of eucalyptus sapwood and heartwood on the basis of directions, in the cross section and tangential directions, and they found that the hardness of heartwood was higher than that of sapwood. In the radial direction, the hardness of sapwood was found higher.

Bektaş (1997) stated that the thickness of the cell walls, besides the density effect, increased wood hardness. Gültekin (2014) determined that the cell wall thicknesses of Scots pine, red pine and eucalyptus wood were found to be the maximum. Besides, the annual ring width is one of the factors that affects wood hardness. So, the hardness value increases as the annual ring expands in the pine trees (Örs and Keskin, 2008). Naidoo *et al*. (2010) reported that "many eucalypt species do not show distinct growth rings because cambial activity does not show a strong response to seasonal variation in climate". Also, the same research confirmed that "*Eucalyptus grandis*, one of the most important commercial hardwood species in South Africa, is a species that does not have well-defined growth rings".

4 CONCLUSION
4. ZAKLJUČAK

In this study, differences between the mechanical properties of sapwood and heartwood of some fast-growing forest trees (Eucalyptus, poplar, red pine and Scots pine) were investigated and the main findings are given below:

- According to t-tests analyses, it was found that the difference between the mechanical properties of sapwood and heartwood of experimental wood species was statistically significant.

- According to the results of this study, the mechanical properties of the wood species, with statistically significant differences between sapwood and heartwood, can be listed as follows: compression strength (for all trees), static quality value (for all trees), specific quality value (for all trees except for Scots pine), static bending strength (for all trees), modulus of elasticity (for all trees), shear strength (for all trees except for Eucalyptus), tensile strength (for all trees), dynamic bending strength (for all trees), dynamic quality value (for all trees except for Scots pine and red pine) and Janka hardness (for all trees except for red pine).

- Also, when comparing sapwood and heartwood, no significant difference could be determined in the shear strength of eucalyptus, dynamic quality values of red pine and Scots pine, and Janka hardness values of red pine.

- The mechanical properties of sapwood were higher than those of heartwood, except for red pine wood. It is thought that this situation with red pine is related to the resin contained in the samples.

- These differences between the mechanical properties of sapwood and heartwood should be taken into account in the use areas that require attention, especially in wooden structures in seismic regions. However, differences in natural durability between sapwood and heartwood should also be taken into account. As known, the natural durability of sapwood is higher than that of heartwood due to its extractive content (Bozkurt and Göker, 1996).

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LABORATORY
FOR HYDROTHERMAL PROCESSING
OF WOOD AND WOODEN MATERIALS

Testing of hydrothermal processes of wood and wooden materials

Thermography measurement in hydrothermal processes

Standard and nonstandard determination of moisture content in wood

Determination of climate and microclimate conditions in air drying and storage of wood, organization of lumber storage

Project and development of conventional and unconventional drying systems

Steaming chamber projects

Establishing and modification of kiln drying schedules

Consulting in selection of kiln drying technology

Introduction of drying quality standards

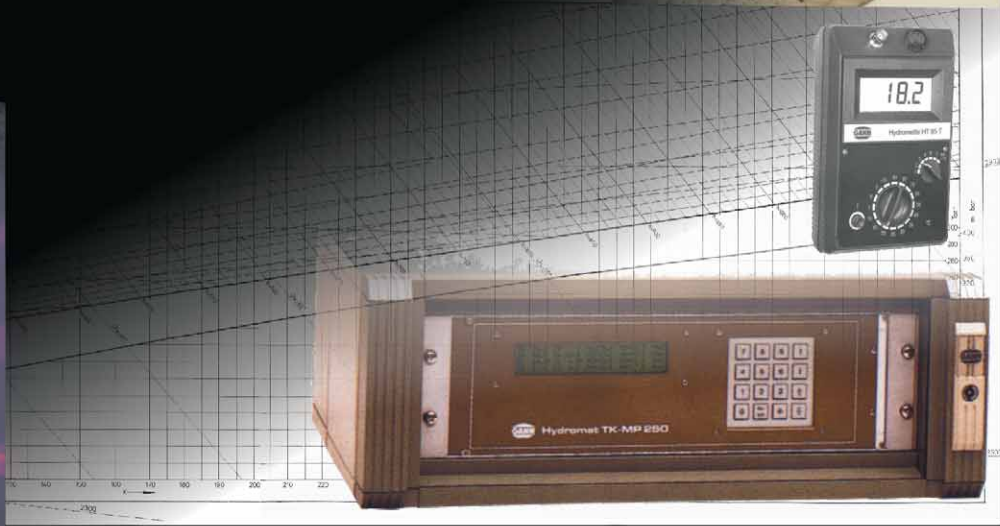
Determination of wood bending parameters

Detection and reducing of hydrothermal processes wood defects

Reducing of kiln drying time

Drying costs calculation

Kiln dryer capacity calculation



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Wood Surface Finishing of Selected Invasive Tree Species

Površinska obrada nekih invazivnih vrsta drva

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ABSTRACT • *Due to their strong renewal power, the invasive tree species are spreading rapidly, especially in abandoned agricultural and forest areas and along traffic routes and water courses. One way of their restriction is the promotion of their use. In our research, we investigated surface finishing of wood of five selected invasive species in Slovenia, Box elder (Acer negundo L.), Black locust (Robinia pseudoacacia L.), Horse-chestnut (Aesculus hippocastanum L.), Honey locust (Gleditsia triacanthos L.) and Chinese sumac (Ailanthus altissima (Mill.) Swingle), and compared it with the finishing of the European beech (Fagus sylvatica L.) wood. For coatings, we selected one-component waterborne finish on acrylate-polyurethane basis, one-component solventborne finish on polyurethane basis and tung oil as a natural finish. Several surface properties were investigated. We proved that surface hardness, resistance to impact and adhesion were very much related to interactions between the coating and the substrate, while resistance to cold liquids was only dependant on the type of the finish. It was also shown that, in general, finishing of woods of selected invasive tree species was not problematic. The only exception was Black locust wood on which tung oil cured very slowly.*

Keywords: *coating, finishing; invasive tree species; oil; wood*

SAŽETAK • *Invazivne vrste drva brzo se šire zbog izrazito jakog svojstva obnavljanja, posebice na zapuštenim poljoprivrednim i šumskim površinama te uz prometnice i vodotokove. Jedan od načina ograničavanja njihova širenja jest poticanje uporabe njihova drva. U ovom smo istraživanju proučavali površinsku obradu pet invazivnih vrsta drva u Sloveniji: negundovca (Acer negundo L.), bagrema (Robinia pseudoacacia L.), divljeg kestena (Aesculus hippocastanum L.), gledičije (Gleditsia triacanthos L.) i pajasena (Ailanthus altissima (Mill.) Swingle), u usporedbi s površinskom obradom bukovine (Fagus sylvatica L.). Kao premazni materijali upotrijebljeni su jednokomponentni vodeni lak na bazi poliakrilata i poliuretana, jednokomponentni otapajući poliuretanski lak i tungovo ulje kao prirodni premazni materijal. Pritom je ispitivano nekoliko svojstava površine. Dokazano je da tvrdoća površine, otpornost na udarce i adhezija izrazito ovise o međudjelovanju premaza i podloge, a otpornost na hladne tekućine ovisi samo o vrsti premaza. Također je dokazano da površinska obrada promatranih invazivnih vrsta drva nije problematična. Izuzetak je drvo bagrema, na kojemu se tungovo ulje vrlo sporo suši.*

Ključne riječi: *premaz; površinska obrada; invazivne vrste drva; ulje; drvo*

1 INTRODUCTION
1. UVOD

According to the definition of the International Union for Conservation of Nature (IUCN), invasive alien species (IAS) is an alien species that has stabilized and is causing environmental change, threatening human health, the economy and/or native biotic variety (Bačič and Strgulc Krajšek, 2013). Due to their strong renewal power, the invasive tree species are spreading rapidly, especially in abandoned agricultural and forest

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areas and along traffic routes and water courses. One way of their restriction is the promotion of their use.

The optimal processing of wood species for high added value products is only possible with a thorough knowledge of the basic properties of the raw materials. Some properties also restrict the use of certain wood species. In our previous research, 17 Slovenian wood IAS were identified as suitable for processing into wood products. Several species grow as ornamental shrubs and as such are not interesting for technological exploitation. Therefore, the research was more focused on species from which a sufficient quantity of wood could be obtained for carrying out the tests. Those were Box elder (*Acer negundo* L.), Black locust (*Robinia pseudoacacia* L.), Horse-chestnut (*Aesculus hippocastanum* L.), Honey locust (*Gleditsia triacanthos* L.) and Chinese sumac (*Ailanthus altissima* (Mill.) Swingle). The following properties were investigated: physical-mechanical properties, basic chemical composition with specificities, machinability, gluing properties, durability and impregnability (Merela *et al.*, 2019). However, no research has been made about the wood surface finishing yet. Also, in the literature, only few investigations can be found.

Nemeth *et al.* (2014) performed an evaluation of Black locust strip parquet flooring panels after long-term, in-service exposure. By controlled steam treatment prior to oiling, they further increased the utilization potential of this material. After 5 years of in-service and laboratory tests, they concluded that oil treatment of wood did not contribute significantly to a higher performance of the parquet compared to the untreated one. According to Pánek and Reinprecht (2014), the Black locust was usually shown as better wood substance for transparent paints in comparison to the Norway spruce (*Picea abies* (L.) Karst) wood, evaluating colour stability and rate of surface destruction at natural weathering. Later on, Pánek and Reinprecht (2016) investigated the impact of the number of coats on the colour stability and the surface defects of painted Black locust and Norway spruce woods after up to three years of natural weathering. The colour stability of the surfaces and their resistance to defects was better when the coating system was applied to Black locust wood compared with Norway spruce wood. Smoother surfaces of wood before painting resulted in a higher resistance against cracking and other defects caused by natural weathering; however, the effect of the initial wood roughness on the colour stability of painted woods during natural weathering was negligible. On the same woods, Pánek and Reinprecht (2019) also showed some possibilities for predicting changes in the colour of painted wood in the exterior by its accelerated weathering in Xenotest, using suitable correlation analyses.

Kúdela *et al.* (2016) focused on the influence of accelerated ageing on surface-treated Chinese sumac wood veneers. The observed coating system had a high resistance against photo-degradation under the dry mode, while under the wet mode (UV radiation with rainfall simulation) some colour changes were present. They established that bigger amounts of dark pigments in the coatings resulted in better protection of the Chinese sumac wood surface against UV-induced degradation. Further on, Kúdela *et al.* (2017) evaluated accelerated ageing effects on quality of Chinese sumac wood surface finished with a water-based coating system applied in several colour hues, and concluded that the colour variability of the coating system had no effects on roughness, wetting performance and surface free energy values.

The red stain common in Box elder wood appears to be created by the tree as a response to wounding. Wood displaying this pigment is commonly used in decorative woodturning. Unfortunately, when the pigment is exposed to UV light, it is degraded regardless of the used coating (Robinson *et al.*, 2013).

In the case of wood surface finishing with usually thin coating films, the properties of the finished surface depend not only on the final coat but also on the layers just below the top and definitely on the substrate itself. There is a synergy between the coating system (consisting of one or more layers of the same or different coating materials) and wood substrate. All this forms the so-called surface system, which determines the quality of all constituents (Pavlič *et al.*, 2003). Therefore, protection or resistance of the wooden structure against physical and chemical influences can be obtained by surface treatment, which depends on the selected coating and the type of substrate (Keskin and Tekin, 2011; Veigel *et al.*, 2014). Substrate properties, such as structure, density, surface roughness, chemical composition and colour may influence the effect of the coating. In indoor applications, the mechanical coating properties, like surface hardness, deformability as well as resistance to impact, friction, scratch and abrasion, are of prime importance (Brischke *et al.*, 2019).

In our research, we investigated the surface finishing of wood of five above mentioned invasive species in Slovenia, Box elder, Black locust, Horse-chestnut, Honey locust and Chinese sumac, and compared it with the finishing of the European beech wood. For coatings, we selected one-component waterborne finish on acrylate-polyurethane basis, one-component solventborne finish on polyurethane basis and tung oil, as a natural finish. We presumed that interactions between wood substrates and selected finishes are suitable to achieve quality surface systems that will be investigated by the determination of several properties.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Sample preparations
2.1. Priprema uzoraka

We prepared three boards with radial orientation of the growth rings and dimensions of (800 × 120 × 20) mm from dry wood for each wood species (Table 1). After machining, the boards were kept for one week at a temperature of (23 ± 2) °C and a relative humidity of (50 ± 5) %. Before application of finishes, the boards were sanded with a P180 grit size sand paper and sawn into three equal parts. In this way, for each wood species, we prepared three sets of three sequential sam-

Table 1 Used wood species and their abbreviations
Tablica 1. Ispitivane vrste drva i njihove kratice

Wood species *Vrsta drva*	**Abbreviation** *Kratica*
European beech *Obična bukva (Fagus sylvatica L.)*	FaSy
Box elder *Negundovac (Acer negundo L.)*	AcNe
Black locust *Bagrem (Robinia pseudoacacia L.)*	RoPs
Horse-chestnut *Divlji kesten (Aesculus hippocastanum L.)*	AeHi
Honey locust *Gledičija (Gleditsia triacanthos L.)*	GlTr
Chinese sumac *Pajasen (Ailanthus altissima (Mill.)* Swingle)	AiAl

ples, one for each finish. Prior to finishing, the colour of the wood surface was determined.

For finishing, we selected unpigmented semi-gloss one-component waterborne coating on acrylate-polyurethane basis (WPU), unpigmented glossy one-component solventborne finish on polyurethane basis (SPU) and tung oil (TO). The coatings were applied with manual quadruple film applicator (Model 360, ERICHSEN GmbH & Co. KG, Hemer, Germany) at an application gap height of 180 μm and a speed of (3 ± 0.5) cm/s. The tung oil was hand-rubbed by a cotton cloth and after 10 minutes wiped off with a dry one. All finishes were applied two times, without intermediate sanding. The drying time between the first and second application was 24 h.

After the finishing, samples were conditioned at a temperature of (23 ± 2) °C and a relative humidity of (50 ± 5) % for 21 days, and the following properties were investigated: colour, gloss, dry coating film thickness, coating adhesion, finished surface resistance to cold liquids, coated surface hardness and resistance to impact. The drying stage of the oiled surfaces was monitored already after 24 h from the last application.

In addition, special samples were prepared for the measurement of coating material sorption, coating hardness and attenuated total reflection Fourier transform infrared (ATR FT-IR) spectroscopy.

2.2 Sorption measurements
2.2. Mjerenje sorpcije

For the measurement of the coating material sorption, for each substrate, we prepared 15 (5 for each finish) sequential samples with a radial ring orientation, of a normal growth rate, and cross section of (15 × 15) mm and longitudinal dimension of 30 mm. Samples were mounted into the tensiometer (K100MK2, KRÜSS GmbH, Hamburg, Germany), where the cross section was immersed into the coating material for 1 mm. The mass gain was monitored for further 200 s, without changing the position of the sample.

2.3 Determination of the drying stage
2.3. Određivanje stupnja osušenosti uljem premazane površine

Determination of the drying stage of oiled surfaces was monitored according to DIN 53 150 (2002) on the first set of sequential coated samples of each substrate. A paper disc with a diameter of 26 mm and grammage of 80 g/m² was placed on the surface and loaded with a mass of 20 g for 60 s. Later on, the surface was examined for any changes. If the surface was not damaged, the procedure was repeated and a paper disc was loaded with the higher mass, until the final, 7th drying stage was reached (drying stage 2 - 20 g, 3 - 200 g, 5 - 2 kg, 7 - 20 kg).

2.4 Determination of coating hardness
2.4. Određivanje tvrdoće premaza

Coating hardness of WPU and SPU was determined by the pendulum damped oscillations test method with the use of König pendulum tester (Model 299/300, Erichsen GmbH & Co. KG, Hemer, Germany; EN ISO 1522, 2007). The coatings were applied on a glass plates with manual quadruple film applicator (Model 360, ERICHSEN GmbH & Co. KG, Hemer, Germany) at an application gap height of 360 μm and a speed of (3 ± 0.5) cm/s. After drying and conditioning at (23 ± 2) °C and a relative humidity of (50 ± 5) % for 21 days, the coating hardness was measured (3 samples per coating, 5 measurements per sample). The hardness value corresponded to the damping time of the pendulum oscillating on the coating surface from 6° to 3°, in respect to normal axis, measured with an electronic counter.

2.5 Colour measurements
2.5. Mjerenje boje

The colour of wood surfaces before and after finishing was determined according to CIELAB system (SIST EN ISO 11664-4, 2011) using a spectrophotometer (SP 62, X-Rite Pantone, Grand Rapids, MI USA) with diffuse/8° sphere optical geometry, fixed 14 mm aperture, specular component included, illuminant D65 and a 10° standard observer. For each sample (3 samples per wood species for each finish), ten measurements were performed and the average values were recorded. The colour differences (ΔE^*) between untreated wood and 21 days after the finishing were calculated as follows:

$$\Delta L^* = \Delta L^*_1 - \Delta L^*_0 \quad (1)$$

$$\Delta a^* = \Delta a^*_1 - \Delta a^*_0 \quad (2)$$

$$\Delta b^* = \Delta b^*_1 - \Delta b^*_0 \quad (3)$$

$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \quad (4)$$

where ΔE^* represents the total colour difference, L^* is the lightness and darkness of colour, a^* is the redness and greenness of colour, b^* is the yellowness and blueness of colour, and ΔL^*, Δa^*, and Δb^* are the differences of the finished ($_1$) and untreated wood surface ($_0$) of L^*, a^*, and b^*, respectively (Wang *et al.*, 2017). During colour measurements, any anomalies on the surface, like brown to red stain spots on Box elder wood, were avoided. We must also point out that, in case of coloured heartwood species (Black locust and Honey locust), only heartwood was used in our research.

2.6 Gloss measurements
2.6. Mjerenje sjaja

The specular gloss of coated surfaces 21 days after the finishing was determined with gloss meter (AcuGloss TRI, X-Rite Pantone, Grand Rapids, MI USA) according to the method described in EN ISO 2813 (2015). Ten measurements of each sample (3 samples per wood species for each finish) were made and the average value was reported.

2.7 Dry film thickness
2.7. Debljina filma osušenog premaza

Dry coating film thickness of WPU and SPU was measured using the microscopic method according to SIST EN ISO 2808:2007. We prepared cross sections of the coated systems, which were observed under the Olympus SZH stereomicroscope with additional illumination and 120x magnification. As a result, the representative (average) value was reported (3 cross sections per coating, 5 measurements per sample).

2.8 Coating adhesion
2.8. Adhezija premaza

Coating adhesion of WPU and SPU was determined using a pull-off test described in SIST EN ISO 4624 (2016). For this, we used the first set of sequential coated samples of each substrate. On each coated surface, ten dollies were glued, using an epoxy adhesive (UHU plus endfest 300, UHU, Bühl, Germany). After 24 hours, the cured epoxy adhesive and the coating were cut to the substrate around the circumference of the dolly and the test was conducted using a PosiTest AT adhesion tester (DeFelsco Corporation, Ogdensburg, NY, USA). A tensile stress was applied at an increasing speed not greater than 1 MPa/s until the dolly was pulled-off. The breaking strength (in MPa) and the nature of the fracture were recorded.

2.9 Assessment of surface resistance to cold liquids
2.9. Procjena otpornosti površine na hladne tekućine

Assessment of finished wood surface resistance to cold liquids was performed using the method described in SIST EN 12720 (2009). For this, we used the second set of sequential finished samples of each substrate. Paper discs (diameter of 25 mm and a grammage of 450 g/m²) saturated with the test liquids (water, coffee, red vine and alcohol – 45 % ethanol; immersed for 30 s) were placed on the test surface and covered by a specified glass Petri dish. After a 1 h test period, the discs were removed and the test surface was left for 20 h. Thereafter, the test surface was cleaned and after 30 min examined for damages, such as discolouration, change in gloss, change in colour, blistering and swelling. The examination was performed in the laboratory light environment and in the standardised viewing cabinet. The test result was stated in a numerical rating code from 5 (no change) to 1 (strong change).

2.10 Surface hardness – Scratch test
2.10. Tvrdoća površine – ispitivanje grebanjem

The hardness of the coated surfaces was measured indirectly by the SIST EN ISO 1518:2001 scratch test. For this, we used the third set of sequential finished samples of each substrate. We used the so-called spring test pencil (Model 318, Erichsen GmbH & Co. KG, Hemer, Germany). A needle is inserted in it with a tip of a half-shaped sphere of 1 mm in diameter. The load on the tip can vary (from 1 N to 20 N), which is adjusted by moving the slip ring, pressing inside the inserted spring. With this spring pencil, we scratched the surface in a length of at least 60 mm. The scratch speed was between 30 mm/s and 40 mm/s and the scratch was performed perpendicular to the grain direction. We increased the load to the tip to the extent that cracks in the coating film appeared or the width of the trace (plastic deformation) was greater than 0.5 mm. The greater the load (force) is, the more the coated surface is resistant to scratching and consequently is harder.

2.11 Resistance to impact
2.11. Otpornost na udarce

To determine the resistance to impact of a coated surface (WPU and SPU), the method SIST ISO 4211-4:1995 was used by descending the weight of (500 ± 5) g from different heights (10 mm, 25 mm, 50 mm, 100 mm, and 200 mm) on a steel ball with a diameter of 14 mm. For this, we also used the second set of sequential coated samples of each substrate, on which resistance to cold liquids was also measured. After the impacts, the surface was carefully examined, also with a magnifier (10x magnification). The resistance of the surface to impacts (average value) from different heights was evaluated with numerical grades from 5 (no change) to 1 (strong change). From each height, 5 impacts were performed and the nearest whole number to the mean was reported. The dropping height was increased until the first cracks in coating film occurred (grade 3).

2.12 Attenuated total reflection Fourier transform infrared (ATR FT-IR) spectroscopy
2.12. Infracrvena spektroskopija uz prigušenu totalnu refleksiju (ATR FT-IR)

ATR FT-IR spectroscopic measurements of the dry coating film were performed using a Perkin Elmer Spectrum Two spectrometer (PerkinElmer Inc., Waltham, Massachusetts, USA), with a $LiTaO_3$ detector in the absorbance mode. The spectra were measured on 3 different spots (16 scans per spot) of each sample, at a wavelength range from 600 cm^{-1} to 4000 cm^{-1} and at a resolution of 0.5 cm^{-1}.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Oil sorption and drying stage of oiled surfaces
3.1. Sorpcija ulja i stupanj osušenosti površine premazane uljem

Drying stage of the oiled surfaces was monitored already 24 h after the last application. Yang *et al.* (2015) reported that tung oil usually requires more than 5 days to dry. This correlates with our findings, in which tung oil reached the final drying stage after

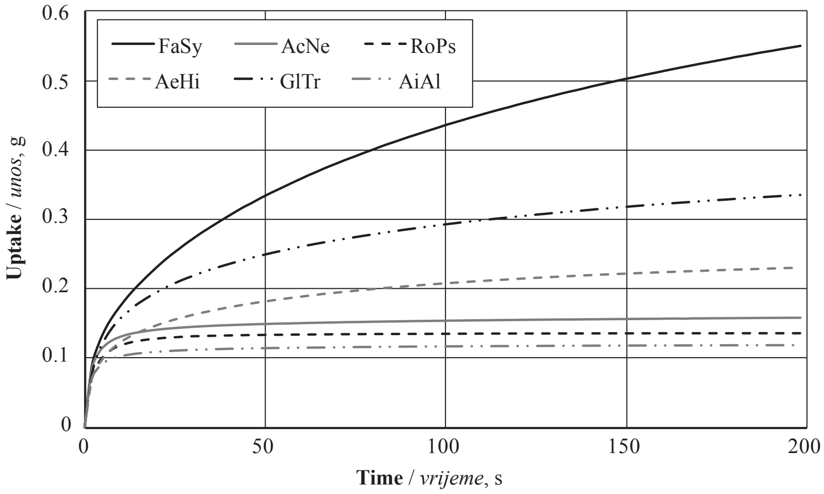

Figure 1 Sorption of tung oil
Slika 1. Sorpcija tungova ulja

Table 2 Drying time of oiled surfaces
Tablica 2. Vrijeme sušenja površina premazanih uljem

Substrate *Podloga*	**Drying stage** / *Faza sušenja*			
	2	3	5	7
FaSy	1 day *1 dan*	1 day *1 dan*	2 days *2 dana*	7 days *7 dana*
AcNe	1 day *1 dan*	1 day *1 dan*	2 days *2 dana*	7 days *7 dana*
RoPs	7 days *7 dana*	13 days *13 dana*	17 days *17 dana*	25 days *25 dana*
AeHi	2 days *2 dana*	2 days *2 dana*	5 days *5 dana*	10 days *10 dana*
GlTr	1 day *1 dan*	1 day *1 dan*	2 days *2 dana*	7 days *7 dana*
AiAl	2 days *2 dana*	2 days *2 dana*	5 days *5 dana*	10 days *10 dana*

7 days of drying on beech, box elder and honey locust wood, but it dried a bit more slowly on horse chestnut and Chinese sumac wood (10 days for d. s. 7), and very slowly on black locust wood, where the final stage was reached only after 25 days (Table 2).

We presumed that these results must have been connected with the interactions of the fresh oil with a substrate. The sorption test (Figure 1) showed that the highest uptake into the substrate was indeed in the case of beech and honey locust wood, but the uptake of oil into box elder wood, on which oil dried normally, was quite low and the sorption dynamic was similar to the ones in case of Chinese sumac and black locust wood.

Nevertheless, black locust wood, on which tung oil dried abnormally slowly, has among the observed species one of the lowest uptake of tung oil, the highest density and the highest value of total extractives (Merela *et al*., 2019). From this, we can conclude that interactions between the substrate and the finish did have an effect on the drying speed of tung oil.

3.2 Coating sorption and dry film thickness
3.2. Sorpcija i debljina osušenog premaza

Thickness of the dry coating film depends on properties of wet coating and substrate. Nevertheless, from the results (Table 3), we can see that, with the same application parameters on the same substrate,

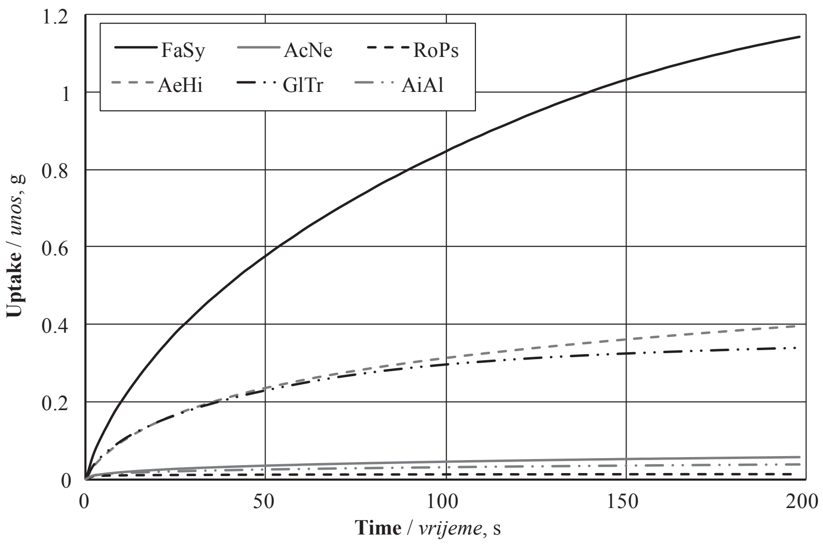

Figure 2 Sorption of one-component solventborne finish on polyurethane basis (SPU)
Slika 2. Sorpcija jednokomponentnoga otapajućeg poliuretanskog premaza (SPU)

Table 3 Dry coating film thickness
Tablica 3. Debljina suhog filma premaza

Substrate *Podloga*	**Thickness** / *Debeljina,* μm			
	WPU		SPU	
	$\bar{x}$	σ	$\bar{x}$	σ
FaSy	65	4.9	42	3.9
AcNe	75	4.3	60	3.8
RoPs	91	6.8	75	4.2
AeHi	83	5.3	58	4.0
GlTr	54	5.4	50	4.1
AiAl	90	5.1	73	4.3

higher thickness of the dry coating film of WPU was always achieved compared to SPU. This relation is pretty much correlated with the results of coating sorption test. The uptake of SPU on all substrates (Figure 2) was higher than the uptake of WPU (Figure 3). This higher uptake of SPU contributed to a lower thickness of the SPU coating films compared to WPU ones.

In our previous research, we investigated the wood anatomy, chemical, physical and mechanical properties (Merela *et al.*, 2019) of the used IAS. If we correlate this data with our sorption results, we can conclude that the average wood density in oven dry state (ρ_0) (FaSy – 680 g/m^3, AcNe – 520 g/m^3, RoPs – 678 g/m^3, AeHi – 479 g/m^3, GlTr – 702 g/m^3, AiAl – 602 g/m^3) correlates the best with the sorption results (Figure 1, 2 and 3). In general, investigated IAS with higher density have lower uptake of coating material.

3.3 Colour and gloss of finished surfaces
3.3. Boja i sjaj površinski obrađenog drva

Colour changes calculated from measurements made 21 days before and after the finishing are shown in Table 4. In general, the coated surfaces with solventborne coating changed the colour the most. The two exceptions are the coated surfaces of black locust and honey locust wood, which changed the colour the most after coating with the waterborne coating. Surfaces became more yellow than the others (RoPs: Δ*b** = 15.27; GlTr: Δ*b** = 8.6). This yellowing occurred later on, during the measurements of coating adhesion connected with the yellowing of the coating film due to possible migration of the extractives, as discussed after ATR FT-IR measurements.

Finishing with oil resulted in less colour variability between surfaces and all surfaces became a bit yellowish, as expected (Yang *et al.*, 2015).

The oiled surfaces had the lowest gloss (from 2.18 to 4.55). The gloss of coated surfaces with semi-gloss waterborne coating was from 18.97 to 25.29. The highest gloss was achieved in the case of finishing with glossy solventborne coating (from 77.44 to 94.12) (Table 5).

Table 4 Changes of colour components (Δ*L**, Δ*a**, Δ*b**) and total colour difference (Δ*E**) after finishing
Tablica 4. Promjene komponenti boje (Δ*L**, Δ*a**, Δ*b**) i ukupne promjene boje (Δ*E**) nakon površinske obrade

Substrate *Podloga*	**WPU**				**SPU**				**TO**			
	Δ*L**	Δ*a**	Δ*b**	Δ*E**	Δ*L**	Δ*a**	Δ*b**	Δ*E**	Δ*L**	Δ*a**	Δ*b**	Δ*E**
FaSy	4.66	-0.59	2.24	5.20	2.35	-0.01	10.20	10.47	-0.85	2.29	9.64	9.94
AcNe	0.10	0.33	1.76	1.80	-4.01	1.31	11.07	11.84	-1.78	1.18	9.21	9.46
RoPs	-2.40	-2.73	15.27	15.69	-5.86	3.62	11.10	13.06	-6.75	4.38	9.82	12.69
AeHi	-0.38	0.71	3.87	3.95	-4.12	1.87	12.94	13.71	-7.46	4.74	9.96	13.32
GlTr	-1.86	0.54	8.60	8.82	-0.18	-1.26	3.36	3.60	-3.75	2.19	8.62	9.65
AiAl	-1.50	-2.48	6.56	7.18	-2.66	-1.77	12.72	13.11	-2.84	-1.82	10.76	11.28

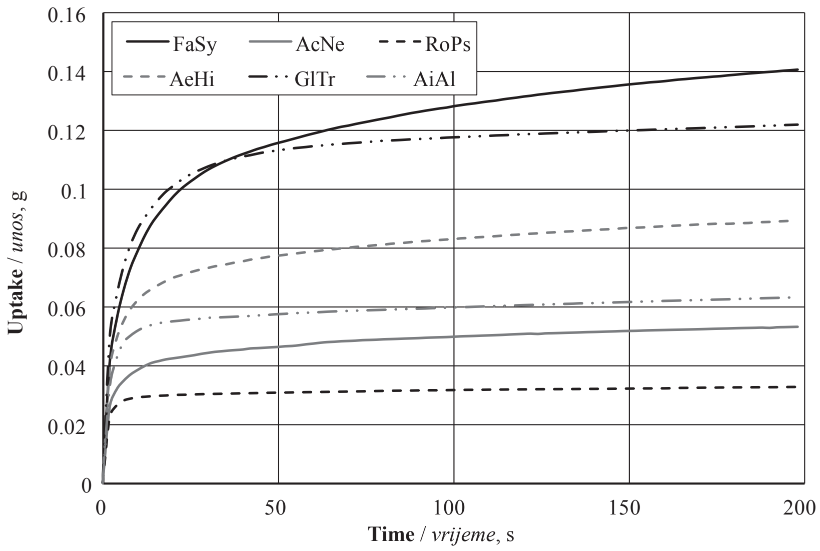

Figure 3 Sorption of one-component waterborne coating on acrylate-polyurethane basis (WPU)
Slika 3. Sorpcija jednokomponentnoga vodenog premaza na bazi poliakrilata i poliuretana (WPU)

Table 5 Gloss of finished surfaces
Tablica 5. Sjaj površinski obrađenih uzoraka

Finish *Premaz*	**FaSy**		**AcNe**		**RoPs**		**AeHi**		**GlTr**		**AiAl**	
	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
WPU	20.84	0.96	22.97	1.27	24.73	0.36	25.29	0.44	18.97	0.82	24.34	1.08
SPU	82.46	6.16	94.12	2.58	88.86	1.23	83.04	3.97	77.44	3.14	84.74	3.72
TO	4.27	0.18	4.55	0.39	2.18	0.30	3.49	0.16	3.13	0.16	3.43	0.13

3.4 Coating adhesion
3.4. Adhezija premaza

According to experiences of our Laboratory for wood finishing, the value of coating adhesion of 2 MPa represents the minimum value for a sufficient coating performance in practice (Pavlič *et al.*, 2003). In our research, the coating adhesion was way above this value in all cases (Table 6). The results also show that, on the same substrate, SPU always had better adhesion than WPU. This is nicely correlated with the increased sorption of SPU compared to WPU (Figure 2 and 3).

In the case of diffuse-porous wood species (Table 6, FaSy, AcNe, AeHi), we can observe also the presence of the cohesive fracture of the substrate (K). Obviously, the coatings penetrated into those substrates more evenly and in this way more substrate was anchored with a coating, but of course, the appearance of the cohesive fracture also depends on physical and mechanical properties of wood (Kúdela and Liptáková, 2006). If the cohesive fracture of the substrate appears during the pull-off test, then it means that the coating adhesion is not clear but for sure is above the measured value.

While observing the pulled off coating films, we noticed that the coating film of WPU removed from the RoPs was yellowish, while the substrate underneath preserved its natural colour. Similar, but less intense yellow colouring was also noticed in the case of WPU on GlTr. That was the reason why we decided to record ATR-FTIR spectra of WPU on glass (samples from measurements of coating hardness), GlTr and RoPs.

3.5 Coating and coated surface hardness
3.5. Tvrdoća premaza i premazane površine

The pendulum hardness test is based on the principle that the harder the measured surface, the greater the oscillation time of the pendulum is. The amplitude of the pendulum oscillation decreases gradually because of the damping during the pendulum hardness test. The pendulum hardness of the coating is greatly related to its dry film thickness (Ma *et al.*, 2013). The coating film of SPU applied on a glass plate (thickness film about 55 μm) had a very low oscillation time of 28.39 s in average, meaning high damping of the pendulum due to the elastic deformations of the film. The coating film of WPU on glass, despite of a bit higher thickness (60 μm), exhibited higher oscillation time (65.54 s), meaning that it had much greater hardness.

It is known that coating hardness greatly depends on the thickness of coating; it gradually decreases with the increasing thickness of coating (Sönmez *et al.*, 2011; Ma *et al.*, 2013; Gurleyen *et al.*, 2017). However, in our research, this was not evident since the coating hardness and type of the substrate had much higher influence on coated surface hardness, determined by the scratch test (Table 7). We can see that surfaces coated with SPU had marks wider than 0.5 mm at lower forces (FaSy, AcNe) and at the same or higher forces no cracks in the coating film appeared during the scratch test (RoPs, AeHi, GlTr, AiAl), meaning that the surfaces coated with SPU are more flexible than the ones coated with WPU.

The influence of the substrate on coated surface hardness was especially evident in the case of substrates coated with WPU (Table 7). The coating film on the ring-porous wood species (RoPs, GlTr, AiAl) cracked, even at lower scratch forces. This is most often the case of the surface systems with ring-porous substrates when the scratch tip passes the coating on non-totally even filled open wood cell lumens (Pavlič *et al.*, 2003).

3.6 Impact resistance
3.6. Otpornost na udarce

As a result of the impact resistance of the coated surfaces, the minimum dropping height at which the coating cracked (grade 3 or less) is stated to differ the impact marks at the same height, if relevant (Table 8).

Table 6 Coating adhesion (σ) and type of fracture (A – adhesive fracture between coating and substrate, K – cohesive fracture of substrate)
Tablica 6. Adhezija premaza (σ) i vrste loma (A – adhezijski lom između premaza i podloge, K – kohezijski lom u podlozi)

Substrate *Podloga*	**Adhesion** / *Adhezija,* MPa					
	WPU			**SPU**		
	$\bar{x}$	σ	Fracture / *Lom*	$\bar{x}$	σ	Fracture / *Lom*
FaSy	4.95	0.36	70 % A, 30 % K	5.45	0.33	80 % A, 20 % K
AcNe	4.09	0.29	20 % A, 80 % K	4.11	0.30	85 % A, 15 % K
RoPs	4.47	0.48	100 % A	4.58	0.41	100 % A
AeHi	3.98	0.33	25 % A, 75 % K	4.01	0.29	20 % A, 80 % K
GlTr	4.56	0.45	100 % A	4.89	0.44	100 % A
AiAl	4.05	0.43	100 % A	5.12	0.42	100 % A

Table 7 Coated surface resistance to scratching with the type of scratch mark (w – wider than 0.5 mm, c – the presence of cracks in coating film) and dry coating film thickness
Tablica 7. Otpornost površine na ogrebotine s oznakom tipa ogrebotine (w – širina veća od 0,5 mm, c – pukotina vidljiva na premazu) i debljina suhog filma premaza

Substrate *Podloga*	**WPU**		**SPU**	
	Resist. to scratching *Otpornost na ogrebotine*	**Thickness, μm** *Debljina,* μm	**Resist. to scratching** *Otpornost na ogrebotine*	**Thickness, μm** *Debljina,* μm
FaSy	11 N, w	65	10 N, w	42
AcNe	11 N, w	75	10 N, w	60
RoPs	4 N, c	91	9 N, w	75
AeHi	10 N, c	83	10 N, w	58
GlTr	8 N, c	54	10 N, w	50
AiAl	8 N, c	90	9 N, w	73

Table 8 Impact resistance of coated surfaces
Tablica 8. Otpornost premazane površine na udarce

Substrate *Podloga*	**WPU**		**SPU**	
	Dropping height *Visina udara*	**Grade*** *Ocjena*	**Dropping height** *Visina udara*	**Grade*** *Ocjena*
FaSy	10 mm	2	100 mm	3
AcNe	10 mm	2	100 mm	1
RoPs	10 mm	3	100 mm	3
AeHi	10 mm	2	100 mm	1
GlTr	10 mm	3	200 mm	3
AiAl	10 mm	3	200 mm	1

*5 – no visible changes (no damage) / *nema vidljivih promjena (nema oštećenja)*
4 – no cracks in the surface but the impact mark is visible when light from the source is reflected from the surface at or very near the test point / *nema pukotina na površini, ali je pri reflektiranju svjetlosti s površine vidljivo mjesto udara*
3 – slight cracking at the surface, usually one or two circular cracks within the impact mark / *vide se male pukotine na površini, obično jedna ili dvije kružne unutar mjesta udara*
2 – moderate to heavy cracking limited to the impact mark / *umjereno do intenzivno pucanje ograničeno na mjesto udara*
1 – cracks that extend outside the impact mark and/or flaking of the surface finish / *pukotine koje se protežu izvan mjesta udara i/ili se ljušti premaz*

It is interesting that there were such big differences between surfaces coated with WPU and SPU. With WPU coated surfaces, the film cracked at much lower dropping height (10 mm) than it was the case with SPU, where the first cracks appeared not before the dropping height of 100 mm. This result is directly connected with the established higher hardness of WPU film and with higher WPU coated surface hardness.

From the results, we can also see the influence of the substrate. In the case of finishing with WPU, we can see that all these substrates cracked at a dropping height of 10 mm, but the amount of cracks was different (grade 3 and 2). Even much higher differences occurred in the case of SPU coated surfaces. There, we had a different minimum dropping height at which the coating cracked and also the grades were different. It is interesting that, in the case of this property this time RoPs systems (WPU and SPU) proved to be the most resistant to impact. This result could be connected to the highest density of RoPa wood (Merela *et al.*, 2019).

3.7 Finished surface resistance to cold liquids
3.7. Otpornost površine na hladne tekućine

Assessment of finished wood surface resistance to cold liquids was performed by selection of the most common liquids and test periods that are usually used in the laboratories for such quick evaluation. In the case of 1-h exposure to water, coffee and alcohol (48 % ethanol), all surfaces proved to be totally resistant to these liquids (grade 5). However, in the case of 1-h exposure to red wine, only surfaces finished with SPU and TO had no problems (grade 5), since the surfaces finished with WPU were drastically coloured (grade 1). This proves that, in our case, the resistance to selected liquids was only dependent on the type of finish used.

3.8 ATR FT-IR spectra
3.8. ATR FT-IR spektri

Infrared spectroscopy is a sensitive and reliable technique that permits to detect the chemical changes of the chemical structure of polymer materials. Figure 4 shows the infrared spectra of WPU, applied on glass, GlTr and RoPs.

The marked bands are discriminative in showing the difference between WPU on glass and WPU on GlTR and RoPs. This proves that the chemical structure of the last two coating films is different. This different chemical structure, which resulted in the yellowish coating film on GlTr and RoPs, can be connected with the extractives from the wood substrates. It is known that wood extractives can migrate into the coating and cause undesired changes in the dry coating film colour (Kúdela and Liptáková, 2006). Among the investigated IAS, the RoPs has the highest value of total content of extractives, determined by speed extraction (9.26 % *w*/*w*), followed by GlTr (6.35 % *w*/*w*), while the value of other wood species is significantly much lower (Merela *et al.*, 2019). However, to undoubtedly confirm the presence of extractives in the dry coating film, a more detailed analysis of the discriminative peaks should be made.

4 CONCLUSION
4. ZAKLJUČAK

The woods of selected invasive alien tree species (IAS) were successfully finished with one-component waterborne finish on acrylate-polyurethane basis

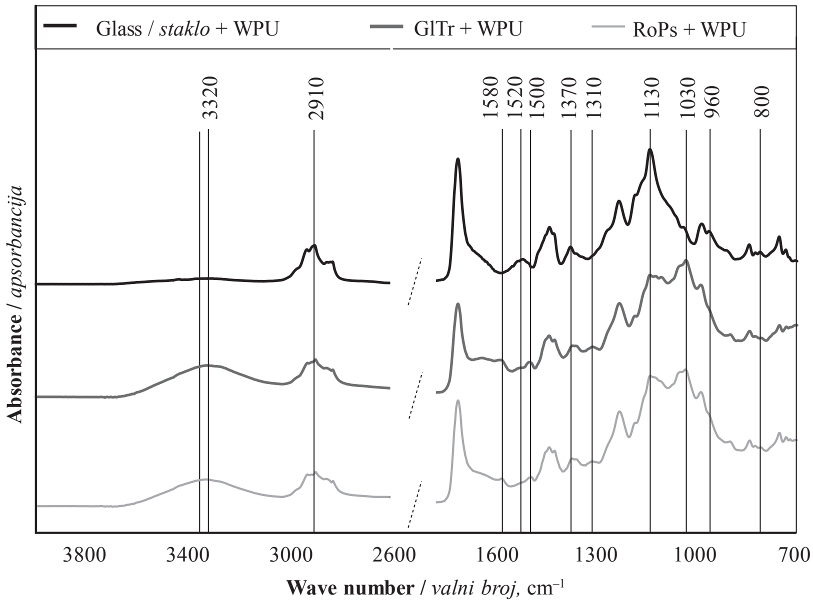

Figure 4 ATR-FTIR spectra of WPU on glass, GlTr and RoPs
Slika 4. ATR-FTIR spektri WPU premaza na staklu, GlTr and RoPs

(WPU), one-component solventborne finish on polyurethane basis (SPU) and tung oil (TO). The quality of the surface finishing was evaluated by investigation of various important properties and compared with finishing of most commonly used beech wood.

Interactions between the substrate and finish did have an effect on the drying speed of TO and dry coating film thickness (WPU and SPU). Wood species with higher density had lower oil uptake and consequently oil on those surfaces had longer drying time. Wood species with higher density also had lower uptake of used coatings, which contributed to a higher thickness of the coating films.

The final appearance evaluated by colour and gloss measurements very much depended on the type of the substrate and finish being used. On the black locust (RoPs) and honey locust wood (GlTr), the yellowing of the coating film due to most possible migration of wood extractives was noticed.

Lower coating hardness of SPU compared to WPU resulted in a higher flexibility and higher resistance to impact of SPU systems. It was also shown that surface hardness (determined by scratch test), resistance to impact and coating adhesion are very much related to interactions between the coating and the substrate, while resistance to cold liquids was only dependant on the type of the finish.

In general, woods of the selected IAS are not problematic for finishing. However, it is reasonable to take into account the findings of our study, which also showed that TO cured very slowly on RoPs wood and that the coating film may turn yellow on RoPs and GlTr wood.

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Competitiveness of Selected South-Eastern European Countries in European Union Wood Flooring Market

Konkurentnost odabranih zemalja jugoistočne Europe na tržištu drvenih podova Europske unije

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ABSTRACT • *Selected South-Eastern European countries (SEEC - Albania, Bosnia and Herzegovina, Croatia, Montenegro, North Macedonia, Serbia and Slovenia) represent significant producers and exporters of wood flooring in Europe. In 2018, 9.4 % of Europe's wood flooring production originated from this region. The region is a net exporter of wood flooring since it exports over 50 % of total production. The most important market for the export of wood flooring is the European Union with a share of over 60 % in total exports. Trends in this market are important for manufacturers and exporters from the region. Therefore, the analysis of the impact of the European Union imports on wood flooring production in the SEEC was conducted by application of econometric modelling. The parameters of the obtained model show that the increase of approximately 0.75 % could be expected in the production of wood flooring in selected South-Eastern European countries for each precentral increase in the European Union imports. In addition to these results, the paper presents the analysis of the competitiveness of wood flooring export from the region measured by the Competitiveness Growth Index (RCA1). The aim of this analysis was to quantify the level of their price and non-price competitiveness in the European Union market. Conducted analyses show that the Competitiveness Growth Index (RCA1) had positive values (higher than one) for most significant countries from the SEEC for most of the observed period.*

Key words: *competitiveness; flooring; market; models; wood*

SAŽETAK • *Odabrane zemlje jugoistočne Europe (SEEC – Albanija, Bosna i Hercegovina, Hrvatska, Crna Gora, Sjeverna Makedonija, Srbija i Slovenija) značajni su proizvođači i izvoznici drvenih podova u Europi. U 2018. godini 9,4 % europske ponude drvenih podova proizvedeno je upravo u toj regiji. Regija je neto izvoznik drvenih podova jer izvozi više od 50 % ukupne proizvodnje. Najvažnije je tržište za izvoz drvenih podova Europska unija,*

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na koju otpada više od 60 % ukupnog izvoza. Trendovi na tržištu Europske unije vrlo su važni za proizvođače i izvoznike iz promatranih zemalja SEEC-a. Stoga je primjenom ekonometrijskog modeliranja analiziran utjecaj uvoza Europske unije na proizvodnju drvenih podova u SEEC regiji. Parametri dobivenog modela pokazuju da se sa svakim postotkom povećanja uvoza u Europsku uniju može očekivati rast proizvodnje drvenih podova u odabranim zemljama jugoistočne Europe za oko 0,75 %. Osim rezultata provedene analize, u radu su izneseni i rezultati analize konkurentnosti izvoza drvenih podova iz zemalja SEEC-a mjereni indeksom rasta konkurentnosti (RCA1). Cilj analize bio je kvantificiranje razine njihove cjenovne i necjenovne konkurentnosti na tržištu Europske unije. Provedene analize pokazuju da je indeks rasta konkurentnosti (RCA1) za najznačajnije zemlje SEEC-a u većini godina promatranog razdoblja imao pozitivne vrijednosti (veće od 1).

Ključne riječi: *konkurentnost; podovi; tržište; modeli; drvo*

1 INTRODUCTION
1. UVOD

Analysis of the market situation, trends and competitiveness are the subjects of interest to scientists and professionals dealing with wood industry. This is due to the stochastic character of the market development, whose intensity of changing is largely determined by the market positions of companies and countries on the regional and world markets. Therefore, the results of market research are a subject of interest to business sector, strategy makers and decision makers in companies and institutions. Research linkages and cause-effect relationships between different phenomena on the market are among the key elements of the market research in the field of wood industry.

According to Dzian *et al.* (2018), modelling of the market was researched on many different scientific platforms. In their papers, Gravelsins *et al*. (2017) used the system of dynamics modelling to determine the added value for different wood products. Within their econometric market analysis, Toppinen *et al*. (2010) studied the following elements: 1) modelling of product demand and supply, 2) price analysis and testing of market integration, 3) market demand and price forecasting, 4) modelling industry location and 5) production technology and factor demand for wood based products.

Appropriate indices are generally used for the analysis of competitiveness in the wood processing industry. In such a way, Paluš *et al.* (2015) analysed the trade performance and competitiveness of the Slovak wood processing industry and compared them with the Visegrad group countries. They used a set of trade performance and competitiveness indicators for analysing the position and changes in competitiveness of the respective countries, as followed: Trade Specialisation Index, Export/Import Ratio, Standard Grubel-Lloyd Index, Revealed Comparative Advantage and Vollrath's Revealed Competitive Advantage Indices.

For analysing the competitiveness of wood and semi-finished wood products of Slovakia, Parobek *et al.* (2016) used the Revealed Comparative Advantage (*RCA*) index and the Comparative Price Level (*CPL*) index.

Most of the above-mentioned examples were confirmed by Hetemäki *et al.* (2016), who stated in their work that comprehensive market analyses related to the trends in the global forest products industry came in surprisingly short supply. The forest products market long-term outlook studies are rarely published in scientific journals. They tend to be published regularly by consulting companies and international organizations or commissioned by governments. Otherwise, research on the forest industry market outlook takes place less systematically and typically focuses on one particular product category or region.

When it comes to the competitiveness of wood products produced in the SEEC (South-Eastern European countries, alphabetically: Albania, Bosnia and Herzegovina, Croatia, Montenegro, North Macedonia, Serbia and Slovenia), there are not many published papers. Based on the analysis of the competitiveness of the Serbian wood and furniture industry, Glavonjić *et al.* (2016) concluded that the value of the current wood products exported from Serbia to certain markets was symbolic compared to the overall turnover of these products at specific markets. In order to change that, one of the conditions is to increase the degree of finalisation of wood raw material available in Serbia.

Considering the above-mentioned, there is a need to use relevant scientific and statistical tools to obtain reliable answers to various market questions important to decision-makers. This paper presents the impact of the EU imports on the production of wood flooring in the SEEC. Wood flooring is one of the hallmark wood products by which the SEEC are recognised in Europe and beyond.

The main aim of the research is to examine the relationships and draw conclusions about the cause and effect relationships between the import of wood flooring in the EU countries and their production in the SEEC. In addition, the specific goal of the research is to analyse the price and non-price competitiveness of the wooden flooring that is exported from this region.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The material required for the analysis in this paper comprehends data and outputs from relevant primary and secondary sources related to the competitiveness of products, industries and countries, as well as data obtained from relevant statistical databases. The most important primary data sources were the wood flooring companies, while the secondary sources were statistical databases on trade of wood products from countries in the region as well as international data-

Table 1 Set of variables used in models
Tablica 1. Varijable primijenjene u modelu

ID	**Variable** / *Varijabla*	**Unit** *Mjera*	**Source** / *Izvor*
PRD	Production / *proizvodnja*	m^2	EUROSTAT; Statistical offices of selected countries (SEEC); University of Belgrade-Faculty of Forestry
IMP	Import / *uvoz*	m^2	EUROSTAT

bases (EUROSTAT, FAO, and UNECE). Available scientific papers, studies and analyses were used as additional secondary data sources.

Analytical-synthetic methods were used for the purpose of data collection, systematization and processing. Statistica 7.0 software package was used for econometric modelling, in which correlation and regression are combined into a single methodological tool. Evaluation of parameters in econometric models was performed on the basis of the methodological guidance developed by Ranković (1996) and Jovičić (2018). Out of the general scientific methods, the hypothetical-deductive method was chosen and applied. Table 1 shows the name of the variables chosen for the econometric modelling, their symbols and measuring units.

The Competitiveness Growth Index (*RCA1*) was used to analyse the competitiveness of export of wooden flooring. The choice of this indicator is a result of the fact that the competitiveness of only one product group (wood flooring) is considered, and not the competitiveness of the industry. Therefore, the analysis based on the value of this selected index is sufficient to assess the competitiveness of this product group. The following indexes: Revealed comparative advantage – *RCA*; Index of net business performance – *RCA2*; Index of contribution to the trade balance – *CTB*; Grubel-Lloyd index – *GLI*, Michaely index – *MI* are usually used to measure the competitiveness of industries and countries.

In that sense, Index of Competitiveness Growth (*RCA1*) is calculated as follows (Milićević *et al*. 2017):

$$RCA1 = \frac{\frac{X_{ij}}{X_j}}{\frac{X_i}{X}}$$

Where:
X_{ij} – export value of commodity group „*i*“ within industry „*i*“ in country „*j*“
X_j – value of total export from country „*j*“
X_i – world export of commodity group „*i*“
X – total world export

If *RCA1* > 1, there is comparative advantage of industry in the worldwide market. If *RCA1* < 1 a, commodity group has no competitive ability in the relevant market.

The fact is that there is not only one indicator that can comprehensively measure competitiveness. Some indicators are only applicable to the level of the overall economy. Others are applicable at the industry level, and some of them can be used to measure competitiveness at lower levels of economic structure (Bobáková and Hečková, 2007). Considering the fact that the paper investigates the competitiveness of only one product group as well as the complexity of indicators that measure competitiveness at higher levels of economy, it can be concluded that the choice of Index of Competitiveness Growth (*RCA1*) is a sufficiently reliable and comprehensive indicator for that product group, able to fulfil the aim of the research.

3 RESULTS
3. REZULTATI

The results contain the following segments: Wood flooring market in Europe including the SEEC; Impact of the EU imports on development of wood flooring production in the South-Eastern European countries: the econometric model; and Assessment of the competitiveness of exports of wood flooring from the SEEC.

3.1 Wood flooring market in Europe
3.1. Tržište drvenih podova u Europi

The analysis of data on wood flooring production and consumption in Europe shows that the market has not yet recovered after the global economic crisis. Production and consumption in 2018 are still below the 2007 values. In terms of consumption, it reached the level of 93.5 million m^2 in 2018, which is 3.9 million m^2 less than the maximum level reached in 2009. Norway (about one million m^2) and FEP (European Federation of the Parquet Industry) members (about 7.2 million m^2) have recorded the largest drop in consumption in the last ten years. On the other hand, consumption growth of 0.42 million m^2 and 1.26 million m^2, respectively, has been recorded in Switzerland and the SEEC. Despite the fall in consumption, the European Union remains the largest market for the consumption of wood flooring in Europe (without Russian Federation), with a share of 86 % in 2018 (Figure 1, sources: University of Belgrade Faculty of Forestry, Timber Trade Centre database (internal); FEP, 2019). Observed by countries, the largest consumers of wood flooring in Europe are Germany, Italy, France, Sweden, Austria and Switzerland (FEP – European Federation of the Parquet Industry, 2019).

The SEEC increased their consumption of wood flooring from 2.82 million m^2 in 2009 to 4.08 million m^2 in 2018 (source: University of Belgrade Faculty of Forestry, Timber Trade Centre database (internal)). Consequently, their share in the total European consumption of wood flooring has increased from 2.9 % in 2009 to 4 % in 2018. The highest consumption growth was recorded in Croatia, Bosnia and Herzegovina and Serbia.

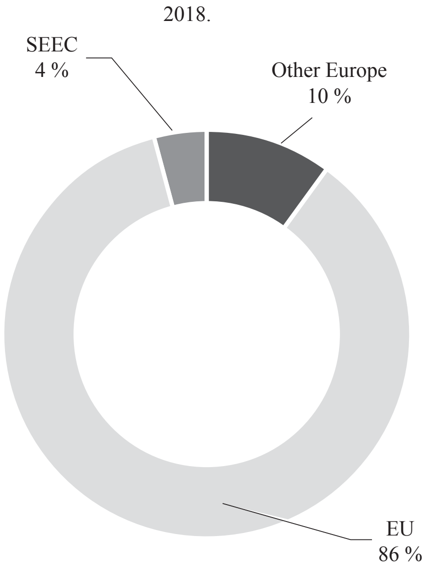

Figure 1 Share of selected regional groups in total consumption of wood flooring in Europe
Slika 1. Udio pojedinih regionalnih grupacija u ukupnoj potrošnji drvenih podova u Europi

The total production of wood flooring in the SEEC in 2018 amounted to 8.48 million m^2, representing 9.4 % of production in Europe. In the structure of production and consequently consumption, multilayer floors come in the first place, followed by classic and mosaic parquet. This structure of production is very similar to the structure of production in Europe. According to the FEP report for 2018 (source: FEP, 2019), multilayer flooring accounted for 82 % of the total production of this association, while classic and mosaic parquet accounted for 17 % and 1 %, respectively. In Serbia in 2018, the share of multilayer flooring was 78 %, classic parquet 20 %, and solid flooring 2 % (source: University of Belgrade Faculty of Forestry, Timber Trade Centre database (internal)).

The dominant share of multilayer flooring in the structure of total production has greatly influenced its value. In 2018, the total value of wood flooring production in Europe was approximately € 1.9 billion or 21.1 €/m^2. Finland and Italy were the two leading countries in Europe in terms of output value per 1m^2, with 55.8 €/m^2 and 47.2 €/m^2, respectively. Poland and Slovakia had the lowest value of this indicator and it was below 10 €/m^2 (source: Eurostat, 2019). In terms of the SEEC, Croatia had the highest value amounting to 18 €/m^2, followed by Slovenia with 17.8 €/m^2 and Serbia with 17.4 €/m^2. Compared to the average value of this indicator for Europe, all three countries were below the European average. Northern Macedonia (9.7 €/m^2) and Albania (10.6 €/m^2) had the lowest values of this indicator (sources: Croatian Bureau of Statistics, 2019; Statistical office of the Republic of Serbia, 2019; Statistical office of the Republic of Slovenia, 2019; Monstat, 2019; State Statistical office of the Republic of North Macedonia, 2019; Institute of Statistics of Albania, 2019; The Agency for statistics of Bosnia and Herzegovina, 2019).

Oak has been the most popular wood species in the consumption of wood flooring in Europe for several decades. According to the FEP report for 2018, the share of oak in the total consumption of wood flooring in this association was 80.3 %, while all other wood species shared the remaining 19.7 %. Ash accounted for 6.8 %, tropical species 3.7 %, beech 2.2 % and walnuts 1.3 %, while the share of other species was about or below 1 % (source: FEP, 2019).

Compared to the production, the consumption of wood flooring in Europe in 2018 was higher by approximately 3.4 million m^2, which means that the missing amount was settled from imports. Europe is a major exporter but also a major importer of wood flooring and is, therefore, an important market for many countries. This is especially true for the European Union, which is the main market for the export of wood flooring from the SEEC.

Imports of wood flooring in the European Union have been growing over the last ten years at the average annual rate of 3.6 %. In quantitative terms, imports of wood flooring in the EU increased from 56.9 million m^2 in 2009 to 78.7 million m^2 in 2018, or about 21.8 million m^2, which confirms the previous finding on the size of this market.

The analysis of foreign trade flows for 2018 showed that 64 % of total exports of wood flooring from the SEEC were placed in the European Union market. Among other regions, the Russian Federation was significant with a share of 19 %, while the share of all other countries was only 17 % (Figure 2, sources: Croatian Bureau of Statistics, 2019; Statistical office of the Republic of Serbia, 2019; Statistical office of the Republic of Slovenia, 2019; Monstat, 2019; State Statistical office of the Republic of North Macedonia, 2019; Institute of Statistics of Albania, 2019; The Agency for statistics of Bosnia and Herzegovina, 2019).

Having in mind the importance of the EU market for the export of wood flooring from the SEEC, the results of econometric modelling of the impact of the EU imports on the development of production of wood

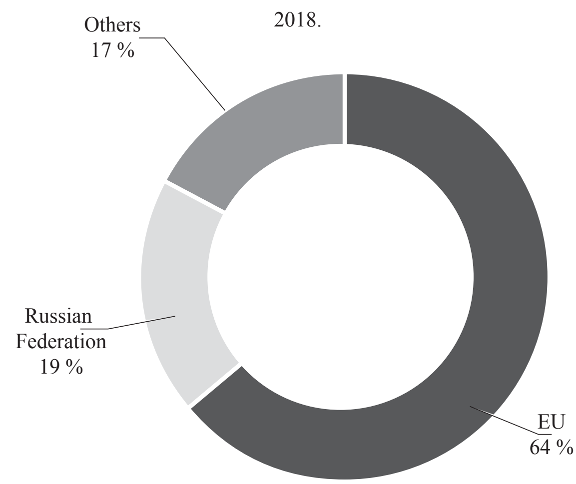

Figure 2 The main export destinations of wooden flooring from selected South-Eastern European countries
Slika 2. Glavna odredišta izvoza drvenih podova iz promatranih zemalja jugoistočne Europe

flooring in the SEEC are presented below in order to consider the cause and effect relationships between these two economic variables.

3.2 Impact of EU imports on development of wood flooring production in selected South-Eastern European countries - econometric model
3.2. Utjecaj uvoza EU-a na razvoj proizvodnje drvenih podova u promatranim zemljama jugoistočne Europe – ekonometrijski model

The impact of the EU imports on production of wood flooring in the SEEC is best illustrated by its degree of form in the simple regression model. The basic parameters of this regression model are presented in Table 2.

The coefficient of determination shows that 71 % of variations in wood flooring production in the SEEC are explained by the model. The high correlation coefficient, its significance at a given level of significance as well as the precisely estimated parameter *b* (t-test) show the strong impact of the EU imports on the production of wood flooring in the SEEC. In this case, it can be expected that for each percentage increase of the EU imports, the production of wood flooring in the SEEC could increase by approximately 0.75 %.

Table 2 Model results
Tablica 2. Rezultati modela

Model *Model*	**Constant** *Konstanta*	**Import** *Uvoz*
PRD (y)	2.3666	0.74774
St. error	3.06859	0.1705
t-test	0.77123	4.3838
|*t*-test|	$\| t_a \| < t_{005}$	$\| t_b \| > t_{005}$
Statistical characteristic *Statističke karakteristike*		
R	R^2	R^2 cor
0.84	0.71	0.67
F(1,8)	S_e	*DW* (+)
19.218	0.05323	1.71467

PRD – production / *proizvodnja*, *R* – correlation coefficient / *koeficijent korelacije,* R^2 – coefficient of determination / *koeficijent determinacije*, St. error – standard error / *standardna pogreška*, DW – *Durbin-Watsonova statistika*, *F* – *F-test*, *p* – level (0,05) / *razina značajnosti*

3.3 Assessment of competitiveness of wood flooring export from selected South-Eastern European countries
3.3. Ocjena konkurentnosti izvoza drvenih podova iz promatranih zemalja jugoistočne Europe

The competitiveness of exporting a product from a country can be assessed in several ways. One of the more accurate ways of assessing competitiveness is to measure competitiveness by using appropriate indexes. For the purpose of this paper, the Competitiveness Growth Index (*RCA1*) was selected as an indicator whose values best represent the state of the competitiveness of the selected product in the selected time period.

Based on the formula given in the "Materials and methods" chapter, the Competitiveness Growth Index (*RCA1*) for the four SEEC countries was calculated and shown in Table 3 (sources: Croatian Bureau of Statistics, 2019; Statistical office of the Republic of Serbia, 2019; Statistical office of the Republic of Slovenia, 2019; The Agency for statistics of Bosnia and Herzegovina, 2019). In the remaining three countries (Albania, Montenegro and Northern Macedonia), the share of wood flooring export is symbolic, with their exports being mostly directed to the surrounding countries.

The Competitiveness Growth Index (*RCA1*) has positive values (higher than one) for all selected countries from SEEC region for most of the observed period. This shows the high competitiveness of wood

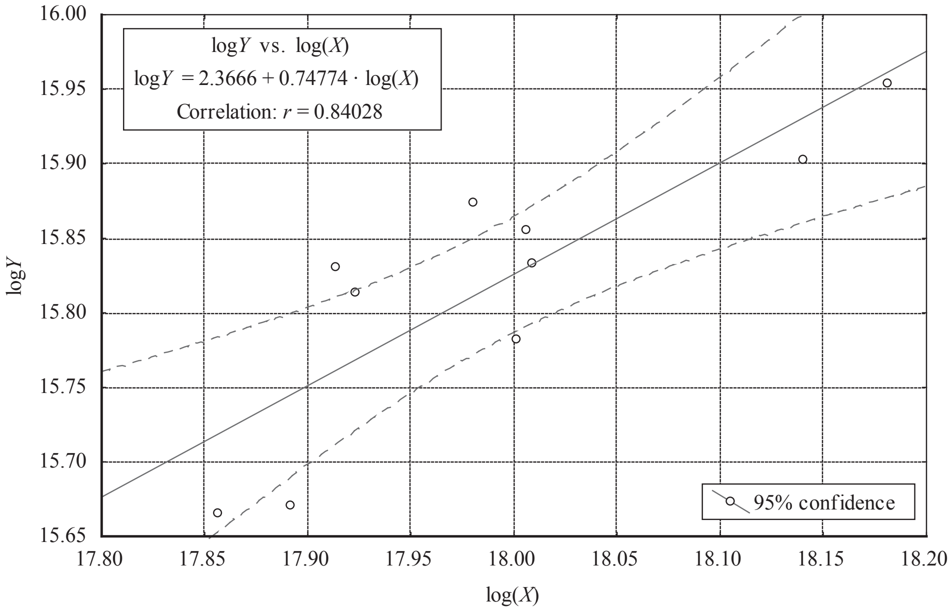

Figure 3 Impact of EU imports on wood flooring production in selected South-Eastern European countries: econometric model
Slika 3. Utjecaj uvoza EU-a na proizvodnju drvenih podova u promatranim zemljama jugoistočne Europe – ekonometrijski model

Table 3 Competitiveness Growth Index (*RCA1*) values for the export of wood flooring from four most significant SEEC countries
Tablica 3. Vrijednosti indeksa rasta konkurentnosti izvoza drvenih podova za četiri najznačajnije zemlje iz SEEC regije

	2009	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Bosnia and Herzegovina *Bosna i Hercegovina*	0.40	1.35	6.67	8.93	8.74	10.53	10.05	10.87	9.98	7.91
Croatia / *Hrvatska*	15.96	14.37	18.54	18.72	20.31	16.29	12.40	11.32	12.47	18.53
Serbia / *Srbija*	29.88	35.31	40.34	40.55	30.25	25.13	14.81	10.67	13.10	12.98
Slovenia / *Slovenija*	1.45	1.01	0.98	1.40	1.10	2.52	1.88	1.54	1.67	1.37

Note: Author's calculations based on statistical data. / *Izračunano na temelju statističkih podataka.*

flooring exported from these countries to the international market, including the EU. Serbia is the leader in the region, in terms of the *RCA1* index value, whose average value in the observed period was 25.30, followed by Croatia with 15.89. The other two countries, Bosnia and Herzegovina and Slovenia, had significantly lower average values of this index of 7.54 and 1.49, respectively. Bosnia and Herzegovina had an *RCA1* value of less than 1 in 2009, and Slovenia in 2011, but after those years its value increased rapidly. The largest fluctuation in the value of the *RCA1* index was recorded by Serbia due to the large drop in exports in 2015 and 2016. Although exports increased during 2017 and 2018, this growth could not mitigate the fluctuations of *RCA1* index.

4 DISCUSSION
4. RASPRAVA

The high value of the *RCA1* index for Serbia and Croatia shows that the export of wood flooring is a significant item in the total exports of these countries. The average share of wood flooring exports in the total export of Serbia, in the observed period, was 0.32 %, and in the total export of Croatia 0.21 %.

The price competitiveness of wood flooring export from the SEEC to the EU market was analysed in this paper using the indicator of export value per square meter (€/m^2). The total value of exported wood flooring from Croatia in 2018 amounted to € 34.8 million or 17.2 €/m^2, and from Serbia to € 27.4 million or 14.6 €/m^2. Slovenia had the highest export value per unit of this product amounting to 20.2 €/m^2, despite the fact that its export of wood flooring was significantly lower (€ 6.7 million) compared to Serbia and Croatia. Bosnia and Herzegovina had the lowest export value per unit of this product, amounting to 11.1 €/m^2 (sources: Croatian Bureau of Statistics, 2019; Statistical office of the Republic of Serbia, 2019; Statistical office of the Republic of Slovenia, 2019; The Agency for statistics of Bosnia and Herzegovina, 2019).

The average import (€/m^2) of wood flooring in first four most important EU countries for Croatian wood flooring export in 2018, was: Italy (22.3 €/m^2), Lithuania (18.0 €/m^2), Germany (18.0 €/m^2), Austria (17.4 €/m^2). For Serbia, the average import (€/m^2) of wood flooring in the first two most important EU countries in 2018, was: Romania (14.7 €/m^2), Bulgaria (15.6 €/m^2) (sources: Croatian Bureau of Statistics, 2019; Statistical office of the Republic of Serbia, 2019).

Comparative analysis of the average value of exports per unit of product from the selected countries and of the average value of imports per unit of product for the EU countries, their most significant markets, clearly shows that the average value of exports of wood flooring from the SEEC was below the average value of imports of selected EU countries. It can be concluded that the raw material used in the production of wood flooring has not yet reached the level of added value that would be desirable in its export to the EU market. Therefore, the main competitive advantages of the SEEC continue to be in the area of lower operating costs for businesses. A similar conclusion was drawn by Milićević *et al.* (2017) in analysing the competitiveness of the Serbian wood processing industry. They state that the establishment of long-term competitiveness in the domain of wood processing industry cannot depend on the exploitation of natural resources only, but has to be increasingly based on production and implementation of technologically complex products and services with higher value added, on the basis of intensive exploitation of natural resources (various types of wood assortment).

Export prices for solid flooring from Serbia have increased slightly over the last few years compared to the domestic sales prices. In the higher quality classes such as *select* and *nature*, there was an increase of about 10 %, while in the lower *rustic* class this increase was about 5 %. This was influenced by several factors, the most significant being the increase of prices of logs, especially in the purchase from private forests. In addition, on several occasions, there has been an increase of salaries and price of electricity. For example, in 2019, the price of electricity for industrial consumers in Serbia increased by about 25 %, which also resulted in an increase in production costs.

Considering that the current competitive advantages of producers from the SEEC cannot be the main pillars of competitiveness in the long run, innovations are needed in the production of new types of flooring with significantly greater added value in the short term.

When it comes to non-price competitive factors, wooden flooring produced and exported from the SEEC meet the market requirements in terms of quality of raw materials, precision of manufacturing, ecological components of the surface treatment, humidity, packaging, delivery time and other requirements. Most manufacturers in the region have the technology and the skills of the workforce to meet almost all market requirements related to non-price elements of the competitiveness. The main problems in their business in the last few years have been the growth of exports of the highest quality wood raw material from the region (especially logs and elements of oak, ash, maple, walnut). Therefore, the supply of raw materials for flooring has been reduced year by year. The decrease in supply has led to the increase in the prices of wood raw materials and, consequently, to the increase in the cost of production.

If this trend continues in the following years, it will have a severe negative impact on the profitability of the wood flooring production. The manufacturer's response to this situation can be in the form of innovation and production of new types of flooring, combined with government measures to discourage the export of wood raw material and to build supply chains between small producers of raw material and high-value-added producers. This would contribute to strengthening the competitiveness of the wood flooring exporters.

5 CONCLUSION
5. ZAKLJUČAK

The research conducted and the results of the analyses in this paper have shown that the SEEC have a significant role in the production of wood flooring in Europe and their import into the EU. In 2018, 8.48 million m^2 of wood flooring was produced in the SEEC, representing 9.4 % of total production in Europe. 2.6 million m^2 or 64 % of total exports of wood flooring from this region were exported to the EU market. The share of exports from the region in the total EU imports of wood flooring in 2018 was 3.3 %, indicating that this market is important for exports and, therefore, for the production of wood flooring in the SEEC. This is confirmed by the results of econometric modelling, which shows that with every percentage increase in the EU imports, the production of wood flooring in the SEEC could be expected to increase by 0.75 %.

Concerning the competitiveness of the wood flooring exported from the region to the EU and other markets in the world, the conducted analyses and obtained values of the Competitiveness Growth Index (*RCA1*) have shown that the competitiveness of wood flooring in the region is satisfactory, especially in the segment of non-price elements of competitiveness. However, the analysis of price competitiveness has shown that the average values of wood flooring exports from the countries of the region are still lower than the average values of wood flooring imports of the selected EU countries. Therefore, it can be concluded that the raw material used in the production of wood flooring in the countries of the region has not yet reached the level of the added value that would be desirable in their export to the EU market. Therefore, the main competitive advantages of the SEEC continue to be in the area of lower export prices and lower operating costs of enterprises. For this reason, innovations are needed in the production of new types of flooring with significantly higher added value, in the short term.

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Contribution to the Evaluation of Thermal Insulation Properties of a Simple and a Double Window in a Log building

Doprinos procjeni svojstava toplinske izolacije jednostrukoga i dvostrukog prozora na drvenoj kući

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ABSTRACT • *The paper describes the method for the determination and evaluation of thermal insulation properties of various types of windows made from pine wood. The method has been used for a simple and a double window that are parts of a log house in the Czech Republic. Both windows are located in one room. The method for the evaluation of thermal insulation properties consists in determining the boundary conditions of the frame and sash temperature from the interior and exterior. Additionally, the temperature of the window surroundings was measured, at the building envelope. The boundary conditions were measured by different sensors to ensure an accurate setting of the thermographic camera. Based on the values determined, the method calculates the heat transfer coefficient and the temperature factor of the internal surface. Then, the thermal insulation properties of integrated windows can be determined and compared. The priority of this measurement was a basic comparison of thermal insulation properties of two different types of windows located in a log house. This measurement will serve as the basis for a comparison of thermal insulation properties of the same types of windows in different log houses located in regions with different weather conditions. After a comprehensive comparison, based on the results, the right type of window can be recommended with respect to the location of the log house in question.*

Keywords: *simple window; double window; thermal insulation properties; heat transfer*

SAŽETAK • *U radu je opisana metoda određivanja i procjene svojstava toplinske izolacije različitih tipova prozora od borovine. Metoda je primijenjena za ispitivanje svojstava jednostrukoga i dvostrukog prozora postavljenih na drvenoj kući u Češkoj Republici. Oba se prozora nalaze na istoj prostoriji. Metoda procjene svojstava toplinske izolacije sastoji se od određivanje graničnih uvjeta prozora i doprozornika s unutarnje i vanjske strane. Usto, izmjerena je temperatura oko prozora u ovojnici kuće. Granični su uvjeti izmjereni različitim senzorima kako bi se osigurala točna postavka termografske kamere. Na temelju utvrđenih vrijednosti uz pomoć spomenute metode izračuna se koeficijent prolaska topline i toplinski faktor unutarnje površine. Nakon toga se mogu odrediti i usporediti svojstva toplinske izolacije ugrađenih prozora. Prioritet ovog mjerenja bila je usporedba svojstava toplinske izolacije dvaju različitih tipova prozora na drvenoj kući. Provedeno će mjerenje poslužiti kao osnova*

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za usporedbu svojstava toplinske izolacije istih tipova prozora na različitim drvenim kućama koje se nalaze na lokacijama s različitim vremenskim uvjetima. Nakon složene usporedbe na temelju rezultata može se preporučiti odgovarajući tip prozora s obzirom na lokaciju drvene kuće.

Ključne riječi: *jednostruki prozor; dvostruki prozor; svojstva toplinske izolacije; prolazak topline*

1 INTRODUCTION
1. UVOD

A window is an important part of the building external envelope, primarily providing daylight and natural ventilation for the interiors and thus meeting basic health requirements for living spaces (Motyková, 2008). Given the current energy cost increase, house owners wish to improve the energy performance of their houses. This improvement can be continually made throughout the house life. As early as when designing the house and its technical facilities, the climatic conditions of the house location should be taken into account. Disregarding this aspect may lead to significantly increased costs of the house operation. Heat loss of a house can occur through floors, roof, the perimeter wall, doors, and windows. Heat loss through windows is among the largest ones; windows usually represent approximately 30 to 50 percent of the heat loss through the building envelope (Gustavsen, 2011). Therefore, the greatest attention should be paid to window selection, not just from the aesthetic perspective, but mainly with respect to its thermal insulation properties.

When selecting windows, it is especially important to focus on the material of the window frame, as an improved thermal resistance of the frame contributes to the overall energy efficiency of the window. The materials used for the production of window frames include aluminium, metal, composite, fibreglass, vinyl, and wood. Each of these materials has its advantages and disadvantages. Windows in the Czech Republic are typically opened vertically, and they can be simple or double. By a double window, we mean a window of the traditional style with reveal and space in between the panes (Schneck, 2001).

Thermography generally means taking images in wavelengths, which is allowed by the scenographic radiation of the objects measured, in the range from 230 to 310 K (Hollan, 2005). In contact with the surface measured, the radiation can be absorbed, reflected, or go through the material measured. These ratios are called the absorbance, reflectance, and transmittance (permeability) (Anon, n.d.b). FLIR E60 thermographic camera is intended to be used in civil engineering, offering a higher thermal sensitivity (0.045 °C), and in addition to the common measuring functions (temperature point, area with the minimum, maximum and isotherm localized), it has special measurement functions designed for the building industry. FLIR E60 thermographic camera is suitable for all applications in civil engineering (Anon, n.d.c):

– Localization and extent determination of thermal bridges;
– Checking air tightness of the perimeter envelope;
– Checking the systems of technical installations in buildings;
– Humidity and moisture content issues (ČSN EN ISO 13788:2002).

The aim of this measurement is to be able to recommend the best type of windows for log houses located in different regions with different weather conditions.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The measurements were carried out in a log house, located in the village of Nasavrky u Chocně, Czech Republic, at an altitude of 345 m. The log building was completed in 2009. Pine timber, 200 mm thick, was used for its construction. Two types of building windows were measured: a simple window and a double window (Figure 1), pine being the wood species used. Dimensions and parameters of both types of windows were: window size $w \times h$ – 1040 mm × 1300 mm, frame profile 65 mm × 60 mm, sash profile 50 mm × 50 mm, insulating glass panes 24 mm thick (4 mm × 16 mm × 4 mm). Sealing in a groove was present along the entire perimeter between the sash and frame. The simple window was double glazed. The double window also had double glazing of both parts - internal and external. The depth of the double window reveal was 100 mm. The windows were installed in the living room, with ground plan proportions of 7.6 m × 3.5 m and a height of 2.9 m. The mean outside and inside temperatures during the entire measurement were 4.6 ºC and 20 ºC, respectively. The room is heated by hot air brought into the room through two ceiling vents.

2.1 Methodology used for thermographic camera measuring
2.1. Metodologija primijenjena za mjerenje termografskom kamerom

Prior to the measurement done by the thermographic camera, boundary conditions were determined in order to obtain the most precise settings of the camera and avoid inaccuracies of the measurement:

1) Measuring the surface temperature of the measured materials (window frame and the surrounding wall), the measurement was carried out by a predetermined diagram;
2) Measuring the distance of the thermographic camera from the measured materials;
3) Measuring the relative humidity of the measured environment.

2.2 Methodology for ALMEMO 710 measuring
2.2. Metodologija mjerenja uređajem ALMEMO 710

The ALMEMO 710 datalogger is a device with 10 inputs for measuring and recording physical quanti-

Figure 1 A view of simple and double windows from the exterior
Slika 1. Pogled na jednostruki i dvostruki prozor s vanjske strane

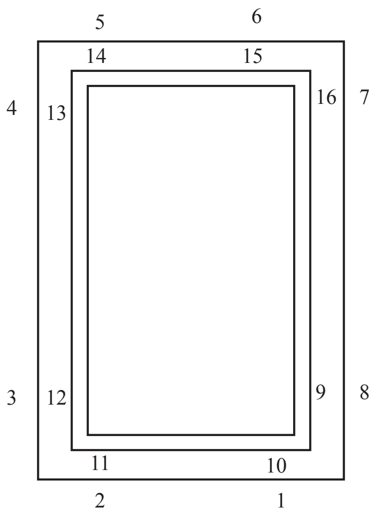

Figure 2 Marks for temperature measurement of windows in the interior
Slika 2. Oznake mjesta mjerenja temperature na prozoru s unutarnje strane

ties that can be displayed on the colour display in numerical form, in line and column charts with a record in the internal memory with an output to PC (Anon, n.d.d). The measurements were conducted for a week for each window individually. To make the measurement as precise as possible, 2005 individual values were recorded in 10-minute intervals. Before the measuring of the windows by ALMEMO 710, it was necessary to determine appropriate locations and locate the device and its sensors:

– A sensor measuring relative humidity and air temperature (type: FHAD 46-2) - A sensor measuring relative humidity and air temperature located in the window interior;
– A sensor measuring relative humidity and air temperature (type: FHA646-1) - A sensor measuring relative humidity and air temperature located in the window exterior;
– Temperature sensor (type: FPA686) - A foil sensor measuring the surface temperature located on the window sash in the interior;
– Temperature sensor (type: FPA686) - A foil sensor measuring the surface temperature located on the window frame in the exterior.

2.3 Calculation of heat transfer coefficient, *U*
2.3. Izračunavanje koeficijenta prolaska topline, *U*

The measurement of heat transfer coefficient through windows integrated in buildings is not exactly described and established in any regulation. The only measurement method based on specified regulations is the measurement in a laboratory under set conditions of the surrounding environment, which mainly serves for the determination of standards for window manufacturers (Černíková, 2012). An alternative way for the calculation of thermal efficiency of window frames is to use 2D numerical simulations, which can be used for a comparison with the values measured in integrated windows (Bossche, 2015; Baldinelli, 2014).

The calculation of thermal efficiency of window frames can be done by 2D numerical simulations (Bossche *et al.*, 2015). The basic calculation of heat transfer coefficient, U, was conducted based on (ČSN EN ISO 10077-1:2007). As a complex transfer coefficient of the entire window had to be measured, we chose the method based on the calculation of the heat transfer coefficient, U, on the frame and sash of each evaluated window and the following comparison of the thermal insulation properties of the windows, using the formula:

$$U = \alpha_i \frac{\Delta T_1}{\Delta T_2} \tag{1}$$

$$\Delta T_1 = T_i - T_{WK,WR} \tag{2}$$

$$\Delta T_2 = T_i - T_e \tag{3}$$

Where
T_i – interior air temperature (ºC)

T_e – exterior air temperature (ºC)
T_{WK} – surface temperature of internal window sash (ºC)
T_{WR} – surface temperature of internal window frame (ºC)
α_i – a constant 7.69 W/m²K

The method is based on the parallel measuring of the interior air temperature T_i by a measuring device, measuring of the temperature of the internal surface of the structure by T_W probes and measuring of the exterior air temperature T_e by a radio probe. The three temperatures are used together with constant α_i = 7.69 W/m²K (Anon, n.d.e 2011) to calculate the heat transfer coefficient, U, by the following formula:

$$\alpha_i = \frac{q}{T_W - T_i} \qquad (4)$$

2.4 Calculation of internal surface temperature factor, f_{Rsi}
2.4. Izračunavanje toplinskog faktora unutarnje površine, f_{Rsi}

It is important to determine in winter the internal surface temperature factor, f_{Rsi}, especially at joints and places with an uneven insulation of the structure, as moisture can be condensed and mould can occur. The internal surface temperature factor, f_{Rsi}, which is the ratio of the difference of the internal surface temperature to the external air temperature and the difference of the internal air temperature to the external air temperature, can be calculated using two equations (ČSN 73 0540-2:2002):

$$f_{Rsi} = \frac{\theta_{si} - \theta_e}{\theta_{ai} - \theta_e} = 1 - \frac{\theta_{ai} - \theta_{si}}{\theta_{ai} - \theta_e} \qquad (5)$$

$$f_{Rsi} = 1 - U_x \cdot R_{si} \qquad (6)$$

Where
θ_{si} – internal surface temperature of the structure (ºC)
θ_e – external air temperature (ºC)
θ_{ai} – internal air temperature (ºC)
θ_x – local heat transfer coefficient at place x of internal surface (W/m²K)
θ_{si} – resistance during heat transfer on internal side of the structure and, in compliance with ČSN EN ISO 13788, it has a value of 0.25 m²K/W (Slanina, 2012).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The results of the measuring with the thermographic camera are presented in Table 1 and 2 and in Figure 3 and 4.

The measured values show that the double window has significantly better thermal insulation properties than the simple window. The values presented in Table 1 and 2 indicate that the mean temperature difference between these windows is 1.5 ºC, which can cause a significant heat loss in the log building given its total number of windows.

The images show the largest heat losses in the simple window in the space between the window frame and its sash (black spectrum). The heat loss is not so apparent in the double window, which is indicated by the light spectrum of the image. This is caused by the sufficient air insulation between the internal and exter-

Table 1 Temperatures measured in a simple window interior
Tablica 1. Temperature izmjerene na jednostrukom prozoru s unutarnje strane

Measuring no. *Broj mjerenja*	**Wall temperature, ºC** *Temperatura zida, °C*	**Frame temperature, ºC** *Temperatura okvira, °C*	**Difference in temperatures, ºC** *Razlika u temperaturama, °C*
1 - 10	18.7	17.1	1.6
2 - 11	19.0	17.0	2.0
3 - 12	18.8	17.4	1.4
4 - 13	19.2	17.8	1.4
5 - 14	20.4	19.2	1.2
6 - 15	21.2	19.6	1.6
7 - 16	22.0	19.0	3.0
8 - 9	19.4	17.3	2.1
Arith. mean *Srednja vrijednost*	19.8	18.5	1.8

Table 2 Temperatures measured in a double window interior
Tablica 2. Temperature izmjerene na dvostrukom prozoru s unutarnje strane

Measuring no. *Broj mjerenja*	**Wall temperature, ºC** *Temperatura zida, °C*	**Frame temperature, ºC** *Temperatura okvira, °C*	**Difference in temperatures, ºC** *Razlika u temperaturama, °C*
1 - 10	20.0	19.6	0.4
2 - 11	19.9	19.6	0.3
3 - 12	20.2	19.9	0.3
4 - 13	22.1	21.8	0.3
5 - 14	22.8	22.5	0.3
6 - 15	22.4	22.2	0.2
7 - 16	22.2	22.1	0.1
8 - 9	20.6	20.3	0.3
Arith. mean *Srednja vrijednost*	21.3	21.0	0.3

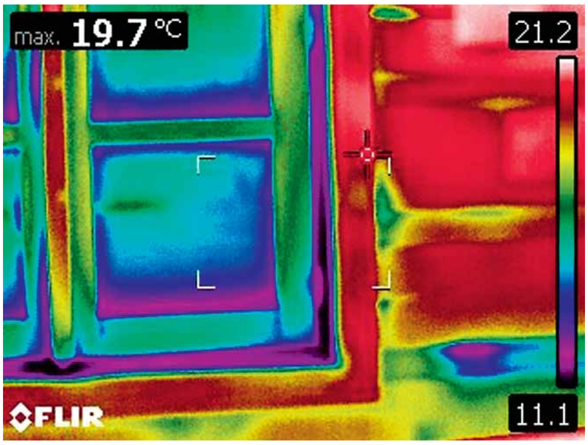

Figure 3 Image of a simple window
Slika 3. Termografska slika jednostrukog prozora

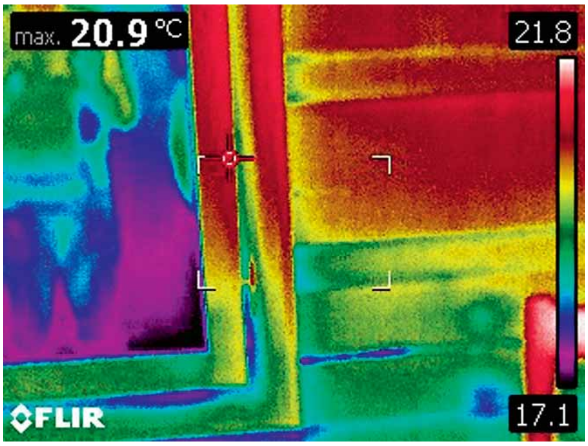

Figure 4 Image of a double window
Slika 4. Termografska slika dvostrukog prozora

Table 3 Heat transfer coefficient, U_N
Tablica 3. Koeficijent prolaska topline, U_N

Day *Dan*	***U* – Simple-sash** *U – jednostruki doprozornik*	***U* – Simple-frame** *U – jednostruki okvir*	***U* – double-sash** *U – dvostruki doprozornik*	***U* – double-frame** *U – dvostruki okvir*
1	2.8	1.4	0.3	0.3
2	2.4	1.2	0.6	0.6
3	1.9	0.8	0.6	0.6
4	1.8	0.8	0.7	0.7
5	1.5	0.8	0.8	0.6
6	1.6	0.7	0.8	0.6
7	2.6	1.3	0.7	0.7
Arith. mean *Srednja vrijednost*	2.2	1.0	0.7	0.7

nal window panes. The values of heat transfer coefficient calculated, U_N, are presented in Table 3.

The surrounding factors have a significant effect on the different values of the heat transfer coefficient:
– Temperature of external environment;
– Intensity of sunlight;
– Air velocity in exterior and interior;
– Relative air humidity in exterior and interior.

The values measured were compared with the values demanded related to the standard applicable in the Czech Republic - ČSN 730540-2, which establishes the standard values of the heat transfer coefficient, U_N (W/m²K).

– Values required U_{N20} 1.50 (W/(m²K)
– Values recommended U_{N20} 1.20 (W/m²K)
– Values recommended for passive buildings U_{N20} 0.80 (W/m²K).

The heat loss in the simple window is considerable and the window efficiency is so low that, from the economic point of view, the simple window should be replaced with a double one. The calculated values of the internal surface temperature factor, f_{Rsi}, are presented in Table 4.

After calculating the internal surface temperature factors of the frames and sashes and comparison with the table of temperatures corresponding to the critical factor of the internal surface, the frames of both windows, simple and double, comply with ČSN 730540-2

Table 4 Critical factor for internal surface temperature, f_{Rsi}
Tablica 4. Kritični toplinski faktor unutarnje površine, f_{Rsi}

Day *Dan*	**Critical factor for internal surface temperature, f_{Rsi}** *Kritični toplinski faktor unutarnje površine, f_{Rsi}*			
	Simple window sash *Jednostruki doprozornik*	**Simple window frame** *Jednostavni okvir*	**Double window sash** *Dvostruki doprozornik*	**Double window frame** *Dvostruki okvir*
1	0.30	0.65	0.93	0.93
2	0.40	0.70	0.85	0.85
3	0.53	0.80	0.85	0.85
4	0.56	0.80	0.83	0.83
5	0.63	0.80	0.80	0.85
6	0.60	0.83	0.80	0.85
7	0.35	0.68	0.83	0.83
Arith. mean *Srednja vrijednost*	0.48	0.75	0.84	0.86

requirements. The mentioned standard, ČSN 730540-2, was used for experimental measuring at the time when this study was processed, so it would be recommendable to use it again for the measurements of other log buildings in order to obtain comparable results. The temperature of the internal surface critical factor of the double window sash is compliant; in contrast, the simple window sash does not meet the requirements.

4 CONCLUSIONS
4. ZAKLJUČAK

Windows are the weakest spot of each building envelope from the perspective of thermal insulation properties and thus the economic performance of log houses. The aim of this study was to obtain values that will allow for a basic comparison of thermal insulation properties of two different types of windows located in the same log building. This measurement will serve as a basis for a more complex comparison of thermal insulation properties of the same types of windows in other log buildings located in regions with different weather conditions. The advantages of the method used are mainly the exact recording of measured values in exact sequences, possible recording of window opening and closing during the measurement process, and the consequent exclusion of these data from the evaluation in order to eliminate errors. Another advantage is that the method is simple and cheap. A drawback was the necessity to measure each window separately because we do not have a sufficient amount of measuring devices to measure them at the same time. According to ČSN 730540-2 the frame of the simple window with a measured mean of 0.80 W/m^{2}K meets even the value recommended for passive buildings; the sash of the simple window with a measured mean of 2.20 W/m^{2}K does not meet any of the required or recommended values. Generally, the simple window does not meet the thermal transmission coefficient requirements of ČSN 730540-2. In contrast, the frame and sash of the double window with a mean of 0.70 W/m^{2}K meet the values recommended for passive buildings, based on ČSN 730540-2. Generally, the double window meets the thermal transmission coefficient requirements of ČSN 730540-2. The measured values show that the greatest heat loss occurs in the sash of the simple window. The measurement of thermal insulation properties of windows indicates that, in order to improve the energy performance of a building, it is necessary to consider boundary conditions of the building environment before selecting the specific type of windows.

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Preliminary Qualitative Analysis and Implications of Wood Products Perception on Social Media

Preliminarna kvalitativna analiza i posljedice percepcije drvnih proizvoda u društvenim medijima

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ABSTRACT • *The article presents the results of the qualitative research of social media, managed by the Institute of the Civil Society, University of Ss. Cyril and Methodius in Trnava, in cooperation with the Slovak University of Technology in Bratislava. The research aimed to analyse different areas of the current management challenges and their perception of the selected social networks. The study concentrates on the presentation of the chosen manufacturers of the automotive industry and furniture industry on social media. The content analysis was based on the VADER (Valence Aware Dictionary and Entiment Reasoner) lexicon that was explicitly tuned to sentiments expressed in social media and QDA software.*

Key words: *automotive industry; qualitative analysis; sentiment analysis; social media; furniture industry*

SAŽETAK • *U članku su prikazani rezultati kvalitativnog istraživanja društvenih medija koje je proveo Zavod za civilno društvo Sveučilišta Svetog Ćirila i Metoda u Trnavi u suradnji sa znanstvenicima Slovačkoga tehnološkog sveučilišta u Bratislavi. Cilj istraživanja bio je analizirati različita područja aktualnih menadžerskih izazova i njihovu percepciju na odabranim društvenim mrežama. Studija je koncentrirana na prezentaciju proizvoda izabranih iz automobilske industrije i industrije namještaja u društvenim medijima. Analiza sadržaja temeljila se na leksikonu VADER (Valence Aware Dictionary and Entiment Reasoner), koji je eksplicitno utemeljen na dojmovima izraženim u društvenim medijima i na QDA softveru.*

Ključne riječi: *automobilska industrija; kvalitativna analiza; analiza dojmova; društveni mediji; industrija namještaja*

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1 INTRODUCTION
1. UVOD

Social networking through online media can be understood as a variety of digital sources of information that are created, initiated, circulated, and consumed by Internet users as a way to educate one another about products, brands, services, personalities and issues (Chauhan and Pillai, 2013). As stated in the research of Enginkaya and Yılmaz (2014), social media integrates consumers with their own voice, not as passive respondents in their relationships with brands as in the past, rather as active members of brand communities (Miller and Lammas 2010). These attributes enable brands to reach the right people, in the right place and at the right time (Schivinski and Dabrowski, 2016). According to Karlíček and Král (2011) cited in Čeněk *et al*. (2016), the most notable positive qualities of online marketing are the possibility of precise consumer targeting, personalisation, interactivity, multimedia content, simple efficiency measurement, and relatively low costs. Marketing the brands through social media is becoming precise, personal, interesting, interactive and social (Sri *et al*., 2011). During the last five years, social media in marketing has become a subject of many studies and interests (see Figure 1 representing the worldwide search interest on Google).

This study demonstrates partial results from the research conducted by the Institute of Civil Society, University of Ss. Cyril and Methodius in Trnava. The research is oriented to the qualitative analysis of social media and their utilisation by different industries. Firstly the qualitative analysis was applied for the automotive industry (Slovakia is the leading car producer per 1000 habitants in the world). The results of the qualitative analysis have been published in Babčanová *et al.* (2019) and Šujanová *et al.* (2019). This qualitative analysis has been extended to the comparative analysis between the automotive industry and selected producers of the consumer durables like furniture or electronics.

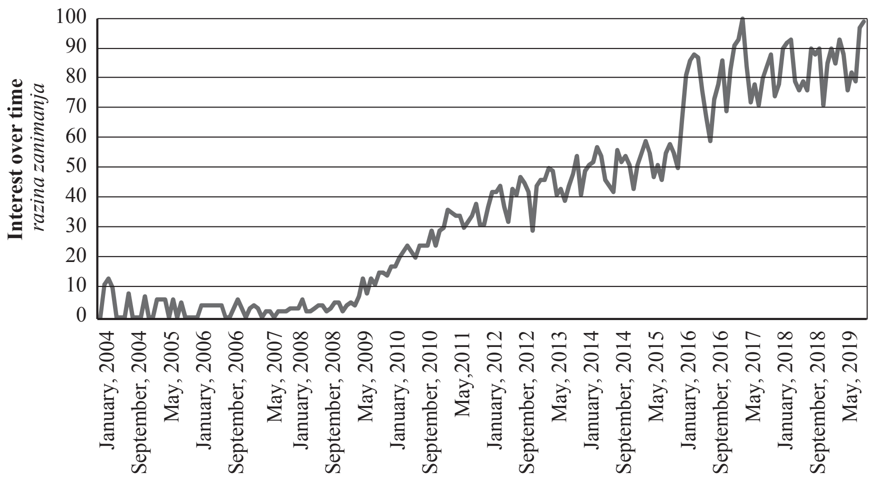
Presented results of the text content analysis of the selected social media for the furniture industry are based on one-week data collection (tweets) and customer comments published on YouTube for selected manufacturers. The content analysis was based on the VADER (Valence Aware Dictionary and Entiment Reasoner) lexicon that was explicitly attuned to sentiments expressed in social media (Hutto and Gilbert, 2014) and QDA software (MAXQDA).

This paper is divided into the following sections: The first part presents a literature review supporting the conceptual framework of the study. The second part is dedicated to the description of the research methodology as well as applied tools and data sources. The third part contains the results of the quantitative analysis of the social media content and comparison of the two selected industries. The final section provides the author’s conclusion about the research results.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The goal of the research was to analyse the content of the selected social media and compare the results for two different industries. Data collection was made using:

- Social media: YouTube and Twitter. The used QDA software influenced the selection of the media.
- Industries: Automotive and furniture industry. Previously conducted studies influenced the selection of these industries.



Note: Numbers represent search interest relative to the highest point on the chart for the given region and time. A value of 100 is the peak popularity for the term. A value of 50 means that the term is half as popular. A score of 0 means there was not enough data for this term. / *Napomena: Brojevi predstavljaju interes za pretraživanje u odnosu na najvišu točku na grafikonu za datu regiju i vrijeme. Vrijednost 100 je najveća popularnost pojma. Vrijednost 50 znači da je pojam upola manje popularan. Ocjena 0 znači da nije bilo dovoljno podataka za taj pojam.*

Figure 1 Worldwide interest over time in the term of “Social Media in Marketing”
Source: Google Trends
Slika 1. Globalno zanimanje za pojam *društveni mediji u marketingu* tijekom vremena
(izvor: Google Trends)

Content analysis:
– Data sources: YouTube and Twitter
– Data collection:
  • Seven days of tweets collection filtered according to the selected automotive and furniture manufacturers in Europe.
  • Visitors' comments on YouTube presentations of the selected automotive and wood furniture manufacturers in Europe.
– Data analysis tools: MAXQDA software
– Content analysis methodology: Sentiment analysis with the lexicon-based approach (dictionary-based approach) (Pawar *et al.*, 2015).

Analysed manufacturers:
– Car manufacturers: Lexus, Renault, SEAT, Peugeot, BMW.
– Furniture manufacturers: Calligaris, Nobia, HSL, Howdens, Molteni&C.

The selection of the automotive and furniture manufacturers was made according to the available analysis and reports. For the automotive industry, we used statistics for the year 2018 (Bekker, 2019). From the top best-selling car manufacturers in Europe in 2018, we have randomly selected five manufacturers. The same principle of randomness was applied for the selection of furniture manufacturers in Europe where the list of firms, analysed in the Centre for Industrial Studies report (CSIL, 2019), was used.

3 RESULTS
3. REZULTATI

To use the official channels of YouTube and Twitter media, authors have created a list of representation of the selected manufacturers on social media (see Table 1). The list was based on the information obtained from the official web sites of the companies (Calligaris, Nobia, HSL, Howdens, Molteni&C, Lexus, Renault, SEAT, Peugeot, BMW).

As we can see, Facebook, YouTube and Instagram are the most used social media, while LinkedIn and Pinterest are not so popular.

3.1 YouTube

For the content analysis of YouTube, we have used official channels obtained from the manufacturer's official web sites. Each channel was analysed according to the number of subscribers and videos (see Table 2).

There is a significant difference between the car and furniture manufacturers, whereas the number of subscribers for car manufacturers varies between 24 400 and 975 000, it is from 9 to 1520 for furniture manufacturers.

Table 1 Social media representation of the selected manufacturers (the X mark is for the social media officially used by the manufacturer)
Tablica 1. Zastupljenost odabranih proizvođača u društvenim medijima (oznaka X odnosi se na društvene medije kojima se proizvođač službeno koristi)

Manufacturer *Proizvođač*	**Social Media** / *Društveni mediji*					
	Facebook	Twitter	YouTube	Instagram	LinkedIn	Pinterest
Calligaris	X	X	X	X		
Nobia		X			X	
HSL	X		X	X		X
Howdens	X		X	X		X
Molteni&C	X	X	X	X	X	X
Lexus	X	X	X	X		X
Renault	X	X	X	X	X	
SEAT	X	X	X	X	X	
Peugeot	X	X	X	X		
BMW	X	X	X	X		

Table 2 Official YouTube channels data
Tablica 2. Službeni podatci kanala YouTube

Manufacturer *Proizvođač*	**YouTube Channel** / *Kanal YouTube*	**Subscribers, *n*** *Broj pretplatnika, n*	**Videos, *n*** *Broj videa, n*
Calligaris	https://www.youtube.com/user/Calligaris1923	1350	64
Nobia	https://www.youtube.com/user/NobiaGroup	9	3
HSL	https://www.youtube.com/user/hslchairs	116	42
Howdens	https://www.youtube.com/howdens	3780	92
Molteni&C	https://www.youtube.com/user/OfficialMolteniDada	1520	164
Lexus	https://www.youtube.com/user/LexusVehicles	143000	501
Renault	https://www.youtube.com/user/renault	61400	1381
SEAT	https://www.youtube.com/seat	24400	590
Peugeot	https://www.youtube.com/peugeot	68100	484
BMW	https://www.youtube.com/user/BMW	975000	911

Subscribers represent the number of subscribers of the manufacturer official YouTube channel and Videos represent the number of the videos published on the manufacturer official YouTube channel. / *Pod pretplatnicima se razumijeva broj pretplatnika službenog kanala YouTube, a „video" označava broj objavljenih videozapisa na službenom YouTube kanalu proizvođača.*

Table 3 Most popular manufacturers' videos on YouTube data
Tablica 3. Videozapisi najpopularnijih proizvođača prema podatcima YouTubea

Manufacturer *Proizvođač*	**Views, *n*** *Pregledi, n*	**Like, *n*** *Sviđa mi se, n*	**Dislike, *n*** *Ne sviđa mi se, n*	**Comments, *n*** *Komentari, n*
Calligaris	114687	166	12	2
Nobia	1325	1	0	0
HSL	517	3	2	1
Howdens	277	191	13	3
Molteni&C	451	37	1	0
Lexus	19 907 096	17 000	8 500	1 352
Renault	3 724 574	170	55	13
SEAT	746 013	64	2	2
Peugeot	10 593 293	6 700	173	704
BMW	16 921 631	64 000	1 600	1 397

Views represent the number of views of the most popular videos on the manufacturer official YouTube channel, Comments are a count of visitors' comments on the manufacturer official YouTube channel / *Pregledi predočuju broj pregleda najpopularnijeg videozapisa na službenom kanalu YouTubea, a komentari označavaju broj komentara posjetitelja na proizvođačevu službenom YouTube kanalu*

The data used for the analysis was obtained from the most popular video of the channel. Again, authors analyse data according to the number of views, likes, dislikes and comments for each video (see Table 3).

Comparing the absolute values (number of views) of the car and furniture manufacturers' most popular video, we can conclude that there is again a significant difference. A closer look on the percentage of those that like or dislike the video gives us a different result, whereas for Howden the number of views was 451, around 69 % gave the "Like to this video". The highest percentage of "Likes" for the car producers was given to BMW, and it was just 0.37 %.

3.2 Twitter

The use of QDA software limited twitter analysis of one batch to:

- Maximum 10000 tweets
- Maximum 7 day period.

Table 4 Number of tweets with the selected keyword during the 7 days
Tablica 4. Broj tvitova s odabranom ključnom riječi tijekom 7 dana

Manufacturer / *Proizvođač*	**Tweets, *n*** / *Broj tvitova, n*
Calligaris	28
Nobia	0
HSL	0
Howdens	37
Molteni&C	4
Lexus	more than 10 000 više od 10 000
Renault	more than 10 000 više od 10 000
SEAT	more than 10 000 više od 10 000
Peugeot	4381
BMW	more than 10 000 više od 10 000

Tweets represents the activity of the users on the manufacturer official Tweeter account – number of published tweets during the monitored period. / *Broj tvitova predočuje aktivnost korisnika na službenom Tweeter-računu proizvođača, tj. broj objavljenih tvitova tijekom promatranog razdoblja.*

Table 5 Number of tweets from the manufacturers´ address during the 7 days
Tablica 5. Broj tvitova s adrese proizvođača tijekom 7 dana

Manufacturer / *Proizvođač*	**Tweets, n** / *Broj tvitova, n*
Calligaris	0
Nobia	0
HSL	Not applicable *nije primjenjivo*
Howdens	Not applicable *nije primjenjivo*
Molteni&C	0
Lexus	13
Renault	52
SEAT	5
Peugeot	12
BMW	58

Tweets represents the number of tweets published by the manufacturer on the manufacturer official Tweeter account during the monitored period. / *Broj tvitova obuhvaća broj onih koje je proizvođač objavio na službenom Tweeter-računu tijekom praćenog razdoblja.*

As VADER lexicon was used, another limitation was related to tweets in English.

We have collected two data sets:

– Using the name of the manufacturer as a keyword (see Table 4)
– Using the name of the Twitter account (see Table 5).

The data was collected from February 9th 2019 to August 8th 2019.

As well as for YouTube, Twitter results are very different between the industries. Twitter activities on the car manufacturer's official accounts are hardly comparable to the activities of the furniture manufacturers.

We can see that the furniture manufacturer does not use Twitter as a channel for sharing the information with the customers.

3.3 Twitter sentiment analysis with the lexicon-based approach
3.3. Tweeterova analiza dojmova s leksikonskim pristupom

For the lexicon-based sentiment analysis, the text was extracted from tweets. After removing the tweets

Table 6 Tweets word frequencies
Tablica 6. Učestalost riječi u tvitovima

Manufacturer *Proizvođač*	**Word frequency, *n*** *frekvencija riječi, n*	**Go list word frequency, *n*** *Frekvencija riječi popisa Go, n*	**Ratio Go/Total, *n*** *Omjer Go/ukupno, n*
Lexus	136	48	0.28
Renault	873	182	0.21
SEAT	65	27	0.41
Peugeot	121	27	0.22
BMW	651	194	0.3

Word frequency represents summary of frequencies of words used in the published tweets on the manufacturer official Twitter account during the monitored period. Go list word frequency is the summary of frequencies of words from the VADER lexicon used in the published tweets, Ratio - compares a frequency of words from the VADER lexicon to the total frequency of the used words. / *Frekvencija riječi predstavlja zbroj frekvencija riječi koje se upotrebljavaju u tvitovima objavljenim na službenom Twitter-računu proizvođača tijekom promatranog razdoblja. Frekvencija riječi popisa Go predstavlja zbroj frekvencija riječi iz leksikona VADER koje se navode u objavljenim tvitovima; omjer daje usporedbu frekvencije riječi iz leksikona VADER s ukupnom frekvencijom upotrijebljenih riječi.*

that did not fulfil the criteria (keyword or address) and freeing the text of non-applicable graphics, we counted word frequencies in tweets using the Go list dictionary function of the MAXQDA software. VADER lexicon was used as a dictionary. The same operation, word count, was also applied without the VADER lexicon. The results of the word frequencies are presented in Table 6.

For car manufacturers, there is a significant difference between the SEAT and other manufacturers. The tweets on the SEAT official account contained significantly more sentiment words than those of the rest of analysed car manufacturers.

Lexus

Lexus tweets contained 20 words from the VADER lexicon, where 19 had a positive average value, and one word (limited) had a negative average value.

The five words and emoticons with the highest average positive value were: best, greatest, love, amazing, win.

Renault

Renault tweets contained 73 words from the VADER lexicon, where 68 had a positive average value and 5 words (demand, limited, no, accidents, mistakes) had a negative average value.

The five words and emoticons with the highest average positive value were: best, love, excellence, great, amazing.

SEAT

SEAT tweets contained 15 words from the VADER lexicon, all of them with the positive average value.

The five words and emoticons with the highest average positive value were: best, :*, kind, care and :).

Peugeot

Peugeot tweets contained 13 words from the VADER lexicon, where 12 had a positive average value, and one word (broken) had a negative average value.

The five words and emoticons with the highest average positive value were: exciting, glad, *:, easy, sparkle.

BMW

BMW tweets contained 48 words from the VADER lexicon, where 43 had a positive average value and 5 words (cutting, limited, no, difficult, problems) had a negative average value.

The five words and emoticons with the highest average positive value were best, excellence, great, happy, pleasure.

4 CONCLUSIONS
4. ZAKLJUČAK

From the very beginning, we have to acknowledge that to compare two very different industries (automotive and furniture) applying just quantitative data brought the expected result: automotive industry representation on social media is incomparable with the representation of furniture industry. Where, for example, the number of subscribers to the official channels on YouTube for the automotive industry ranges between tens of thousands and hundreds of thousands, in the case of furniture industry the number ranges from tens to thousands of subscribers.

Differences can also be observed in the range of supported social media. For the automotive industry, all manufacturers have a Twitter account, for the furniture industry, just three of those selected. A different situation is seen with Pinterest, where most of the furniture producers have an account, while among the car producers, just Lexus has such an account.

Twitter analysis brought similar results. Selected representatives of furniture manufacturers have been mentioned in the tweets during the analysed period from 0 to 37 times. In contrast, in automotive industry, this number ranged from 4381 to more than ten thousand.

Differences have also been observed in activities on the official Twitter accounts, where there was no activity during the analysed period for furniture manufacturers. Therefore, there is no comparison between the content of the tweets applying the sentiment analysis with the lexicon-based approach. It can just be concluded that, for the automotive industry, the content of the tweets on the official tweet accounts contained mostly positive words from the VADER lexicon. The word with the highest positive average value was best (four manufacturers), followed by excellence, kind, and care (two manufacturers).

Authors have not expected such significant differences in the use of social media between the selected car and furniture manufacturers considering the fact that selected manufacturers are listed between the top best-selling producers for the year 2018. It is evident that the automotive industry is widely exploiting social media and customers' opinion data for the innovation aimed to fulfil customers' needs and expectations. As for the furniture industry, the potential of the social media influence on consumer behaviour, according to the preliminary research results, was not sufficiently recognised.

The present research will continue with the detailed sentiment analysis using Twitter and YouTube data for a larger group of manufacturers during at least ten discrete periods.

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Bio-based Methods with Potentials for Application in Wooden Furniture Industry

Biološke metode s potencijalom za primjenu u proizvodnji namještaja od drva

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ABSTRACT • *Furniture market is shifting towards green and innovative products. The use of bio-based methods in wooden furniture industry presents a big potential for the development of materials with new characteristics, of unique furniture items, and can reduce the environmental impact. Bio-based methods can be used for wood protection and decoration, fibre board production, and development of new wooden materials, such as wood hybrids and functionalised wood. The bio-based methods, investigated for their potentials in wood industry, include the use of living organisms, natural products, and biomimicry. Despite ongoing developments there are still major drawbacks associated with many of these technologies: unreliability and inadequate efficiency of the methods, inadequate mechanical properties or dimensional stability of the final products, and high costs. Thus, further developments are needed. In this review, we present the existing and arising bio-based methods with potential in wooden furniture production. Furthermore, we shortly present their marketing potential.*

Key words: *biotechnology; natural products; wood; furniture; wood protection; wood colouring; natural adhesives; wood functionalisation; biomimicry*

SAŽETAK • *Tržište namještaja sve se više pomiče prema zelenim i inovativnim proizvodima. Primjena bioloških metoda u proizvodnji namještaja od drva znači velik potencijal za razvoj materijala novih svojstava te za proizvodnju jedinstvenih predmeta namještaja. Osim toga, uvođenje bioloških metoda u industriju namještaja može pridonijeti i smanjenju štetnog utjecaja na okoliš. Biološke se metode mogu primijeniti u zaštiti i dekoraciji drva, u proizvodnji ploča vlaknatica i u razvoju novih drvnih materijala kao što su drvni hibridi i funkcionalizirano drvo. Spomenute metode, čiji se potencijal primjene u proizvodnji namještaja istražuje, uključuju biotehnologiju, uporabu prirodnih proizvoda i biomimikriju. Unatoč stalnom razvoju, još postoje znatni nedostatci povezani s primjenom tih tehnologija. To su složenost ili nepouzdanost metoda, neadekvatna mehanička svojstva ili dimenzijska stabilnost konačnih proizvoda te visoki proizvodni troškovi. Stoga je potrebno i dalje razvijati te metode radi njihove primjene u proizvodnji namještaja. U ovom su radu predstavljene razvijene biološke metode i one koje su u fazi razvoja a imaju potencijala za primjenu u proizvodnji namještaja od drva. Usto je ukratko opisan i njihov marketinški potencijal.*

Ključne riječi: *biotehnologija; prirodni proizvodi; drvo; namještaj; zaštita drva; bojenje drva; prirodna ljepila; funkcionalizacija drva; biomimikrija*

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1 INTRODUCTION
1. UVOD

Furniture production represents a big market (International Wooden Furniture Markets: A review, 2004; Wang *et al*., 2016), which requires design of original products to move up the value chain. This, among others, includes upgrades of the manufacturing processes and of the final product (International..., 2004). Such original products can be designed with the use of innovative bio-based technologies.

Wood biotechnology and the use of natural products in wooden furniture industry have long history and are still being developed. They have potential for development of materials with new characteristics, unique furniture items, and can help to reduce the environmental impact (Burgert *et al*., 2015; Mai *et al*., 2004; Robinson *et al*., 2012). Applications based on organisms and their products with potential in wood industry can be classified into three categories: 1) biotechnological use of live organisms or their enzymes for production of new substance or for catalytic purposes (Mai *et al*., 2004; Smith, 2009), 2) use of extracts or other non-catalytic products of organisms (Yang, 2009), and 3) biomimicry (Chen *et al*., 2017; Umorina, 2017).

There are quite a few reviews describing specialised topics of wood biotechnology or the use of natural products in the wood industry. For example, wood protection and fibre board production has been previously described in Mai *et al*. (2004) and surface functionalisation in Petrič *et al*. (2013). Furthermore, advanced breeding methods for creation of new tree and wood varieties are gaining importance (Bhalerao *et al*., 2003). However, the latter is out of the scope of this review as we focus on the processing of wood for production of furniture. Moreover, we failed to find a general overview of methods based on live organisms or their products used in wood processing. Thus, we review developed and arising methods based on live organisms or their products with potential in wooden furniture industry. Our main focus is on the methods that have not yet been widely applied in the industry. We also briefly discuss the marketing potential of these technologies.

2 ADHESIVES AND WOODEN BOARDS
2. LJEPILA I DRVNE PLOČE

Normally, production of board materials requires the use of high pressure and temperatures as well as toxic chemicals. This is associated with higher costs and adverse environmental effects (Liu *et al*., 2010; Mai *et al*., 2004). Thus, more environmentally-friendly techniques are being developed, as described by Ferdosian *et al*. (2017). This includes both natural adhesives, such as lignin and plant proteins (Ferdosian *et al*., 2017), and the use of oxidative enzymes or live organisms to increase adhesive properties of wood and catalyse covalent bond formation between adhesives (Mai *et al*., 2004). Enzymatic systems can be single-component, utilising only oxidative enzymes such as peroxidases or laccases, which are most commonly used enzyme, or two-component with addition of lignin and similar phenolic substances as adhesives. (Mai *et al*., 2004; Widsten and Kandelbauer, 2008).

Enzymes can be used in pre-treatment of wooden fibres or to aid in the gluing processes. This can reduce the heat and glue content needed to produce medium-density fibre boards. The use of enzymes may also contribute to the mechanical properties of the boards (Fackler *et al*., 2008; Mai *et al*., 2004). Pre-treatment of fibre particles with laccases increases the self-bonding properties of the fibres surface (Gabrič and Pohleven, 2014). Furthermore, adhesive surface properties can be improved by enzymatic functionalisation. Laccase-catalysed covalent binding of urea to fibres was shown to increase the adhesion. However, this effects was smaller than the effects of board density and glue content (Fackler *et al*., 2008). Laccase was also tested at the pilot level for catalysis of bonds between lignin molecules already present in the fibre particles. The process is claimed to have a potential, but it is limited by poor dimensional stability of the product and the need for the use of higher temperatures in the processing of boards (Felby *et al*., 2002). Cost effective production of laccases is also being studied. Laccase producing fungi can be grown on medium where main nutrients are waste materials (Zhou *et al*., 2014).

The use of lignin as an adhesive has been thoroughly investigated. Lignin can be used to partially substitute phenolic components in synthetic adhesives. Products created with such an adhesive have only slightly reduced strength retention and only slightly higher water uptake (Jin *et al*., 1990). Lignin can be produced either with wood degradation by brown rot fungi, which is a time consuming process with difficult extraction steps and requires further enzymatic processing of lignin, or from the industrial waste, which contains lignin with reduced adhesive properties (Gabrič and Pohleven, 2014; Jin *et al*., 1990; Mai *et al*., 2004). An alternative to lignin adhesives is the use of proteins. A combination of soy proteins and $CaCO_3$ resulted in a glue with good adhesive properties and water resistance (Liu *et al*., 2010).

3 WOOD PROTECTION
3. ZAŠTITA DRVA

Wood must be protected against biological and abiotic factors in all stages of furniture production (Yang, 2009). Selection of preservatives depends on the intended use of the wooden material, e.g. indoor or outdoor. Some outdoor protectants can be harmful to human health, leading to respiratory problems and allergies or even serious medical complications. They can also have negative effects on environment, especially at the time of the disposal (Pánek *et al*., 2014). Examples of traditional preservatives with negative effects on the health are those containing compounds of arsenic, zinc, copper, and creosotic oil. Due to their adverse effects they are often prohibited from the use in furniture industry (Pánek *et al*., 2014; Schubert *et al*., 2012). Therefore, new wood protection technologies are being developed. Biological protectants can have more targeted mode of action against wood pathogens and are biodegradable. However, they are also more sensitive to degradation and hence require special care (Mai *et al*., 2004). Another option for protection against pathogens is modification of wood properties, leading to more hydrophobic nature and reduced water content of wood (Burgert *et al*., 2015; Humar and Lesar, 2013).

3.1 Protection with microorganisms
3.1. Zaštita mikroorganizmima

Pathogenic organisms cause wood degradation and loss of mechanical properties, unwanted colouring, and production of harmful toxins (Yang, 2009). Due to high humidity in some living spaces, it is necessary to protect wood against pathogenic microorganisms. This can be done with the inoculation of wood with protective non-pathogenic organisms (Bruce & King, 1991; Mai *et al*., 2004), as further described by Mai *et al*. (2004) and Susi *et al*. (2011). Bio-controlling organisms compete with the pathogens or produce compounds that prevent the growth of pathogens (Mai *et al*., 2004; Susi *et al*., 2011). However, protection with microorganisms is not long-lasting, retaining effectiveness only for a few years (Bruce & King, 1991; Mai *et al*., 2004). It also has varying results against different fungi and in different environments (Mai *et al*., 2004). Microbial extracts may improve the reliability of protection under varying conditions (Yang, 2009). However, bio-control fungi only provide preventive protection against the invasive fungi. Thus, it is important to apply the protective organism already during the production of furniture (Bruce & King, 1991; Mai *et al*., 2004). On the other hand, application of bacterial and fungal spores on wood already infected by insects has some potential (Mai *et al*., 2004). Bio-finishes based on black mould and oil are already used in practice (van Nieuwenhuijzen *et al*., 2016). On the other hand, some bio-controlling organisms will require further research before becoming commercially applicable. These include *Streptomyces* isolates (Jung *et al*., 2018) and *Bacillus subtilis* that can be combined with the application of essential oils (Sajitha *et al*., 2018; Wang *et al*., 2012).

Fungi can also be used for increasing the permeability of the outdoors wood to commercial preservatives. However, the technology is still not regarded as economically feasible (Schwarze & Schubert, 2017; Thaler *et al*., 2012).

3.2 Protection with natural products
3.2. Zaštita prirodnim proizvodima

Natural protectants have a long tradition. Many protectants like resins, extractives, essential oils, and lignin are still being further tested (Fernández-Costas *et al*., 2017) and some have also been patented (Yang, 2009). Examples include capsaicin containing extract from chilli, extracts from durable wood species containing tannins, flavonoids, and terpenoids, and essential oils containing phenols (Pánek *et al*., 2014). The application of different extracts for the protection of wood is more thoroughly described in Yang (2009).

The use of natural protectants has various benefits. They can be applied as a protection against organisms from different kingdoms, can be nontoxic to humans, and are produced from renewable sources – organisms, ranging from plants to fungi and bacteria (Pánek *et al*., 2014; Yang, 2009). Treatment with natural products can change the surface properties of wood and thus reduce the leaching of other protectants (Fernández-Costas *et al*., 2017). Multifunctional protectants that also serve as dyes have been investigated (Colak, 2016; Ozen *et al*., 2014). Furthermore, protectants can be extracted from waste materials. An example is bark, which has protective potential due to high content of tannins, resins, and waxes (Yang, 2009). Similarly, lignin, a waste product from paper industry, has potential as protectant due to its phenolic content (Fernández-Costas *et al*., 2017). Some plant extracts with antifungal properties, such as mimosa and quebracho extracts, are already commercially available (Tascioglu *et al*., 2013).

However, the use of natural protectants still poses a problem. Their activity can be inconsistent and some of them are subjected to microbial or UV degradation, being suitable only for interior use (Pánek *et al*., 2014). Furthermore, they can be subjected to leaching or are insoluble in water, thus requiring the use of organic solvents (Yang, 2009).

3.3 Enzymatic ligation of protectants
3.3. Enzimsko povezivanje zaštitnih sredstava

Preservatives are often subjected to leaching from wood. This can be prevented by chemical ligation or grafting of preservatives into the wood. Enzymes can catalyse the creation of covalent bonds between wood and preservative (Kudanga *et al*., 2008; Petrič, 2013; Schubert *et al*., 2012). In comparison to chemical and physical methods of functionalisation, the use of enzymes is more environmentally friendly due to the reduced use of energy and chemicals (Kudanga *et al*., 2008). Additionally, the use of enzymes removes the need for expensive catalysts (Slagman *et al*., 2018). However, poor penetration of the enzymes into the wood poses a problem for the use of enzymatic grafting (Slagman *et al*., 2018).

Oxidases, including laccases, are used for grafting. Laccases, in contrast to other oxidases, require only oxygen and not hydrogen peroxide for oxidation. Furthermore, the addition of mediators enables oxidation of substances that otherwise do not fit in the active site of laccases (Slagman *et al*., 2018). Grafting often involves the use of phenolic compounds, although other substrates have been tested as well (Slagman *et al*., 2018). One of such examples is the use of iodine, which is cheap and is not associated with microbial resistance. Oxidation of iodide (I^-), which has no antimicrobial activity, to antimicrobial three iodide (I_3^-) with laccases and mediators leads to binding of three iodide to aromatic groups of lignin. This provides protection against bacteria, yeast and higher fungi. The use of laccases prevented leaching of the protectant and led to similar effectiveness as a commercial preservative. Furthermore, the lignin degradation by laccases was reported to be small (Schubert *et al*., 2012). Additional improvements can be achieved by the use of anchoring molecules that are covalently bound to the wood and serve as anchors for protectant binding (Kudanga *et al*., 2008).

3.4 Surface treatments for increased hydrophobicity
3.4. Površinska obrada radi povećanja hidrofobnosti

Wood absorbs water both from vapour and liquid state (Glass and Zelinka, 2010). This can lead to swelling and cracking of wood and enables colonisation by pathogens (Burgert *et al*., 2015; Mai *et al*., 2004). Cell wall moisture content and hence biological degradation of indoor wood is dependent on the environmental humidity, temperature and ventilation (Mai *et al*., 2004; Žlahtič and Humar, 2016). Wood with moisture content below 12 % is usually not affected by biological degradation, moisture level of 12-18 % enables infestation by insect, above 18 % enables mould growth, 28-33 % enables growth of higher fungi, and if moisture increases even further, the wood can be affected by bacterial degradation (Mai *et al*., 2004). Fungal colonisation depends on average moisture over time. Thus applied protectants must prevent both water absorption and allow drying of wood after the exposure to water (Humar and Lesar, 2013).

Many different approaches for reducing the water content of wood have been tested. Lumen of the cells in the wood can be filled up or the surface characteristics of the wood and cell walls may be changed, for example with alkylation of hydrophilic functional groups of lignin, cellulose and hemicellulose (Burgert *et al*., 2015). Water repellents, such as waxes and oils, including linseed and tung oils, are especially useful as they provide protection against water absorption and at the same time do not seal the wood surface, enabling wood drying (Humar & Lesar, 2013). Combinations of both oils and waxes were also shown to be beneficial (Žlahtič and Humar, 2016). Effectiveness of repellents depends on the successful impregnation of wood. This is affected by wood permeability and characteristics of the repellent. Performance of repellents thus varies across wood species (Humar and Lesar, 2013). Traditional agents used for decreased water absorption, such as waxes, resins and oils, are subjected to leaching from wood. Thus, it was proposed that laccases should be used for binding of hydrophobic molecules, such as lauryl gallate, on the surface of wood and subsequent creation of a resistant hydrophobic layer (Fernández-Fernández *et al*., 2015).

Another option is bio-mimicry of super-hydrophobic surfaces that repel water and also have self-cleaning properties. Super hydrophobic surfaces can be created by surface wrinkling, electrospinning, template-based extrusion, photolithography and soft lithography (Chen *et al*., 2017). General information about these methods is available elsewhere (Bhardwaj & Kundu, 2010; Meng *et al*., 2016; Ouyang *et al*., 2015; Qin *et al*., 2010; Raoufi *et al*., 2015). For example, a super-hydrophobic surface pattern imitation of *Colocasia esculenta* leaf was produced on the wood with soft lithography (Chen *et al*., 2017).

4 DECORATION
4. DEKORACIJA

Visual characteristics of wood are highly valued by consumers (Knauf, 2015; Manuel *et al*., 2015). Besides, bio-based decoration methods can be more environmentally friendly and their application can create unique decorative patterns.

4.1 Natural dyes
4.1. Prirodne boje

Consumers are becoming interested in natural dyes as production of synthetic dyes is often environmentally unfriendly and their use can be potentially harmful to health (Colak, 2016; Prabhu & Bhute, 2012; Yeniocak *et al*., 2015). Different natural dyes are still being tested, such as extracts from pomegranate, red beetroot, and fungi (Colak, 2016; Vega Gutierrez *et al*., 2016; Yeniocak *et al*., 2015).

However, there are also downsides of using natural dyes. The final colour can depend on wood composition and may be affected by UV (Yeniocak *et al*., 2015). Some dyes do not penetrate into the wood and thus colour only the surface (Vega Gutierrez *et al*., 2016). Furthermore, natural dyes can have poor affinity for binding to the wooden surfaces. Their resistance to discoloration can be improved by the use of mordants, which form complexes with dyes and thus increase their binding to the surface. Metal-based mordants (e.g. iron, aluminium) and vinegar are among commonly tested mordants for colouring of the wood and other natural products. (Colak, 2016; Goktas *et al*., 2008; Prabhu & Bhute, 2012; Vega Gutierrez *et al*., 2016; Yeniocak *et al*., 2017). However, mordants can lead to colour changes of the dye. Furthermore, some of the mordants, including the metal-based ones, have toxic properties (Prabhu & Bhute, 2012). Therefore, further research is needed to produce resistant natural dyes.

4.2 Spalting
4.2. *Spalting*

Colouring of wood can also be achieved by the use of live organisms, which produce unique patterns and can excrete protective antimicrobial substances. Process of wood colouration based on dye secretion by organisms inhabiting the wood is called spalting. As many consumers desire unique wooden products, spalted wood is highly valued, regardless of the wood species used (Robinson *et al*., 2012). One of the main concerns is the loss of mechanical properties after spalting. Thus, the use of dense hardwood has been advised (Robinson *et al*., 2007; Robinson *et al*., 2012). However, spalted wood does not have importantly reduced mechanical or acoustic properties. Moreover, spalting increases wood permeability, affecting gluing and surface finishing of the products (Robinson *et al*., 2013b). Increased permeability can be beneficial, leading to better impregnation (Schubert *et al*., 2011).

Spalting can result in various patterns and shades, depending on the used microorganism. Zone lines are usually produced by white rot fungi, while ascomycetes produce wood colouring (Robinson *et al*., 2011a). Spalting can be a consequence of excreted dyes with low molecular mass or inoculation of wood with fungi that have pigmented cell walls, leading to zone lines and blue-grey colouring, also known as blue stain (Robinson *et al*., 2012). Zone lines are easy to produce and can be created by the use of various fungi (Robinson *et al*., 2011b). Zone lines are often produced as the result of competition, for example between *Trametes versicolor* and *Bjerkandera adusta* or *Inonotus hispidus* and *Xylaria polymorpha*. *Xylaria polymorpha* can produce zone lines even when individually inoculated and without application of stressful conditions (Robinson, 2012; Robinson *et al*., 2012). Blue stain of sapwood is produced by fungi from *Ophiostoma* genera that are in nature transmitted by bark beetles. However, blue stain wood is less popular among consumers (Robinson *et al*., 2013b). Pink stain is produced by naphthoquinone of *Arthrographis cuboidea* and xylindein of *Scytalidium cuboideum*, also on conifers and bamboo. However, *Scytalidium cuboideum* produces zone lines instead of pink pigmentation when grown together with other fungi. Bright blue-green pigmentation arises due to xylindein produced by *Chlorociboria* genus on poplar wood. Yellow stain is produced by quinones of *Scytalidium ganodermophthorum* (Mai *et al*., 2004; Robinson, 2012; Robinson *et al*., 2013a; Robinson *et al*., 2013b; Vega Gutierrez *et al*., 2016). Furthermore, wood can be inoculated with a mixture of fungi or inoculated more than once with different fungi (Robinson *et al*., 2013b). For example, increased visibility of spalting can be achieved by initial bleaching of wood with white rot fungi, sterilisation and subsequent inoculation with the desired spalting fungi. However, sterilisation can only be used for small wood pieces, as increased volume leads to overly prolonged sterilisation times (Robinson *et al*., 2012). Nevertheless, this method can still be used for production of "furniture jewellery".

Spalting can be adopted at the industrial level (Robinson *et al*., 2011a). It was tested by Robinson *et al*. (2013a), who discovered that specific combinations of *Scytalidium cuboideum, Xylaria polymorpha* and *Trametes versicolor* produce the best zone lines. In order to achieve spalting fungi must be able to penetrate into the wood and grow inside it (Robinson *et al*., 2012; Vega Gutierrez *et al*., 2016). At the industrial level it is important to choose the right inoculation method, depending on the fungi (Robinson *et al*., 2013a). Additionally, prior sterilisation can increase the pigmentation (Robinson *et al*., 2011b). Growth of the fungi is then stopped before the loss of mechanical properties of wood (Robinson *et al*., 2011a). Fungal growth and spalting depend on may parameters (Robinson *et al*., 2011a), including wood species, which must be chosen based on the desired pigmentation. For example, sugar maple can be spalted by a broad range of fungi, while some wood species can be spalted with only certain fungi or none at all (Robinson *et al*., 2011a). Antifungal substances in wood can importantly reduce fungal growth, while some stressors may increase the spalting. Sugar content also affects the spalting (Robinson *et al*., 2011a). However, the success of spalting varies greatly and thus reliable combinations of wood and fungi should be chosen (Robinson, 2012).

5 NEW WOODEN MATERIALS
5. NOVI DRVNI MATERIJALI

Wood has low density, good mechanical properties, and is relatively inexpensive and sustainable. Thus, new approaches for widening the range of applications of wood are being investigated (Burgert *et al*., 2015; Gan *et al*., 2017; Li *et al*., 2018). However, the heterogeneity of wood decreases the reliability of its mechanical properties and reduces the control over the process of wood functionalisation (Frey *et al*., 2018). Functional wood based materials were described in more detail by Burgert *et al*. (2015).

5.1 Wood densification
5.1. Ugušćivanje drva

Density is one of the main factors affecting mechanical properties of wood. Wood densification can increase homogeneity and mechanical properties, while retaining the ordered structure of wood. (Frey *et al*., 2018). It increases hardness and surface abrasion resistance and can lead to colour changes (Cruz *et al*., 2018; Sozbir and Bektas, 2017). Densification can be used to improve mechanical properties of wood of low-density species. Therefore, hardwood species can be replaced by low-density species in applications such as table tops and floors (Sozbir and Bektas, 2017). Process of wood surface densification has been already industrialised (Sandberg *et al*., 2017). On the other hand, lightweight wooden materials reduce economic and ecological burden of furniture transport (Iejavs and Spulle, 2016) and have potential for multifunctional furniture.

Wood densification process is comprised of wood softening by moistening and heat treatment, followed by compression leading to collapse of cell walls, and is finished by locking the wood in compressed state by drying and cooling. Fixation of the compressed state can be further improved by impregnation with adhesives (Sandberg *et al*., 2017; Sozbir & Bektas, 2017). The process is usually applied only to the surface of the wood, leading to greater usage efficiency of the material, easier production and better mechanical properties for certain applications (Sandberg *et al*., 2017). Uneven compression enables production of wood with gradual variation in density and stiffness (Frey *et al*., 2018). Furthermore, chemical composition of wood importantly affects the mechanical properties of densified wood, as was shows on *Pinus radiata* (Cruz *et al*., 2018). Delignification can be used to ease the curving or twisting of wood (Frey *et al*., 2018).

5.2 Wood functionalisation and hybrid materials
5.2. Funkcionalizacija drva i hibridni materijali

Wood can be functionalised to induce changes in its property profile. For example, incorporation of mineral particles into the wood can increase strength, fracture resistance, hardness, and stiffness (Burgert *et al*., 2015). Furthermore, changes in magnetic, conductor and optical properties could be used to extend the range of applications of wood into electrotechnical industry (Burgert *et al*., 2015; Gan *et al*., 2017; Li *et al*., 2018). Transparent wood has already been produced; however, its optical properties are still greatly dependent on thickness and any subsequent compression of the material. It has potential for the use in buildings due to its low density and light transmittance as well as reduced heath conductivity and frailness in comparison to glass (Li *et al*., 2018). Furthermore, transparent wood can be functionalised with luminescent properties (Gan *et al*., 2017; Li *et al*., 2018).

Transparent wood can be manufactured by delignification or removal of chromophores followed by impregnation with polymer with refractive index matching the wood. The polymer fills pores in the wood that would otherwise lead to scattering of the light (Gan *et al*., 2017; Li *et al*., 2018). However, delignification is time consuming and can pose a burden for the environment (Li *et al*., 2018). Furthermore, functionalisation of bulk wood is challenging. This could potentially be improved by separation of wood into fibres, which would be functionalised and then re-aligned into the wooden structure (Frey *et al*., 2018). For example, Gradwell *et al*. (2004) used soluble pullulan as a model for lignin. Pullulan adsorbed to the cellulose surface leads to self-assembly (Gradwell *et al*., 2004).

Wood can also be used to produce hybrids with synthetic or inorganic materials. The main benefit of wood incorporation is its ordered structure (Burgert *et al*., 2015; Croitoru *et al*., 2018). For example, wood can serve as a framework for production of synthetic materials in which it is otherwise challenging to produce an ordered structure. This has potential for optical implications (Burgert *et al*., 2015). Furthermore, it was proposed that wood may be useful for substituting synthetic polymers (Li *et al*., 2018). Wooden fibres incorporated into plastics are already being used in the industry. However, protectants used in such materials often pose health risks (Croitoru *et al*., 2018). Thus, ionic liquids, substances composed entirely from ions with melting point below 100 °C (Lei *et al*., 2017), were proposed as a substitute (Croitoru *et al*., 2018).

6 MARKETING POTENTIAL
6. MARKETINŠKI POTENCIJAL

Innovations in the wood industry promise better visual and mechanical properties as well as reduced burden for the environment. This has potential for marketing, as consumers already associate wood with wellbeing, aesthetics and environmental friendliness (Manuel *et al*., 2015). Uniqueness is highly valued among consumers, especially when purchasing items with hedonistic rather than strictly functional role (Reich *et al*., 2017). Thus, "furniture jewellery" applications may have a good potential. Furthermore, the lifespan of furniture design is shortening (Scholz and Decker, 2007) and thus novel wood processing technologies may bring about innovations desired by consumers.

Environmental friendliness is important decision factor for many consumers, as shown by a Brazilian study, in which consumers were prepared to pay more for environmentally friendly furniture (de Medeiros *et al*., 2016). Environmental friendliness can be achieved by the reduced use of energy and resources, recycling and waste reduction, and by following the principles of sustainable development (Huang *et al*., 2012). However, main attributes in the choice of furniture are still elsewhere, including: comfort, design, (de Medeiros *et al*., 2016; Holopainen *et al*., 2014), brand, price (Caia *et al*., 2017), and durability (Holopainen *et al*., 2014).

Marketing for new technologies can be challenging. The degree of newness in a product must be balanced, as consumers can distrust the usability of the product or are disheartened by their own uncertainty about the proper maintenance of the item (Cojocaru *et al*., 2013). Additionally, it has been shown in a Chinese study that eco-labels are often distrusted and that many consumers are unable to distinguish between ordinary and green furniture (Caia *et al.*, 2017). Thus, not only the development of new technologies, but also research in their marketing must be conducted.

7 CONCLUSION
7. ZAKLJUČAK

The use of biotechnology, natural products or nature-inspired methods has great potential in furniture industry. These methods can lead to production of eco-friendly wood with changed physical properties and unique visual characteristics. Here presented methods may thus inspire the development of new wooden furniture products.

In general, most investigated methods include the use of enzymes, live organisms, and natural products. Additionally, production of functionalised wood and hybrid materials is also gaining importance. Nevertheless, many applications are still not developed at the industrial level. Common drawbacks include complexity or unreliability of the methods, inadequate mechanical properties or dimensional stability of the final products, and high costs. Thus, further research on both laboratory and pilot scale is required.

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Wood Sector Media Budget Allocation: Comparison of Republic of North Macedonia and some South-Eastern European Countries

Izdvajanja za medije iz proračuna tvrtki drvnog sektora: usporedba Republike Sjeverne Makedonije s nekim zemljama jugoistočne Europe

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ABSTRACT • *The aim of this paper is to analyse and compare the official media reports published in the Republic of North (RN) Macedonia and some other South-Eastern European Countries, such as Croatia, Bosnia and Herzegovina, Serbia, and Bulgaria. According to the official results from Nielsen Arianna, IPSOS, and Alma Quattro, Macedonian furniture companies mainly allocate their media budget to television channels with an amount of EUR 4.786.710, which is 6.7 times lower than the amount allocated by Croatian furniture companies to the same media (EUR 32.223.506). The conclusion is that the media budget of Macedonian furniture companies is on a very low level, compared to selected South-Eastern European Countries, mainly because 74 % of the total number of furniture companies are micro enterprises with up to ten employees, which affects the media budget.*

Key words: *advertising; furniture; media budget allocation; promotion; wood industry*

SAŽETAK • *Cilj je ovog rada analiza i usporedba službenih medijskih izvještaja objavljenih u Republici Sjevernoj Makedoniji i u nekoliko drugih zemalja jugoistočne Europe poput Hrvatske, Bosne i Hercegovine, Srbije i Bugarske. Prema službenim rezultatima agencija Nielsen Arianne, IPSOS i Alma Quattro, makedonske tvrtke za proizvodnju i prodaju namještaja za medijske aktivnosti iz proračuna izdvajaju najviše sredstva za oglašavanje na televizijskim kanalima u odnosu na druge načine oglašavanja. Riječ je o 4 786 710 EUR, što je 6,7 puta manje od iznosa što ga izdvajaju hrvatske tvrtke za proizvodnju i prodaju namještaja za isti način oglašavanja (32 223 506 EUR). Iz toga se može zaključiti da je proračun medijskih aktivnosti makedonskih tvrtki za proizvodnju i prodaju*

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namještaja na vrlo niskoj razini u usporedbi s nekim promatranim državama jugoistočne Europe. Razlog tomu je vjerojatno činjenica da su u Sjevernoj Makedoniji u ukupnom broju tvrtki za proizvodnju i prodaju namještaja 74 % njih mikrotvrtke koje imaju do deset zaposlenih, što utječe na izdvajanja iz njihova proračuna za medije.

Ključne riječi: *oglašavanje; namještaj; izdvajanja iz proračuna za medije; promocija; drvna industrija*

1 INTRODUCTION
1. UVOD

The main objective of advertising, as one of the promotional and marketing communications tools, is to communicate and create brand awareness, build brand image and to initiate and support the consumer buying behaviour. Advertising was the most important marketing communications tool in the previous century, but is now evolving towards more interactive marketing communication in the 21st century. Using the traditional media channels i.e. television, print, radio and outdoor, it is now supported with the digital media, such as internet, mobile, social media and two-way communications. As presented in the research by Žujo (2011), who analysed the EFFIE index, USD 400 billion are spent on advertising per year in the world, and this amount increases at least by 5 % each year.

Worldwide, the media buying is constantly growing, especially the digital media. In 2019, for the first time, the budget allocated to digital media was higher than the total media advertising spending on all other media, with a trend for further growth (emarketer.com, 2019). Selected South-Eastern European countries (SEE countries) and the Republic of North Macedonia are following the same trend of media buying, but are still far from the world figures. The integration of traditional and digital media presented by Petrovska *et al.* (2018) presents a relatively even distribution of advertising through both traditional and digital media, and the new media are changing so fast that mobile media are becoming the dominant form of media. However, the digital media buying in general is still lower that the traditional media buying, and the same applies to the furniture industry. Most of the media buying in the South East Europe is on television, radio and print media, although outdoor, flyers and brochures cover a significant share of the market (Žujo, 2011).

The furniture industry in the Republic of North Macedonia and in most of the selected SEE countries is a strategic sector, as this area is rich with forest resources. Therefore, this is one of the first industries in the Republic of Macedonia, and it has survived through years of different crises, reforms and changes (Stefanovska-Petkovska *et al.*, 2019). Glavonjić *et al.* (2009) also stressed the importance of furniture industry in the SEE countries as the forest richest area in Europe with the strategic location for transport to EU, Middle East, and other regions.

The furniture industry in the Republic of North Macedonia is decreasing, as a number of furniture companies have closed their facilities in the last decades. The last State Statistical report presented the share of furniture in the manufacturing industry of just 14 %. Another fact indicating the furniture low share is the average share of 6 % of employees of furniture industry in the manufacture industry (Stanković Šumanska *et al.*, 2017). According to the number of employees, the furniture industry of the Republic of North Macedonia is mostly made of micro companies (74 %), followed by small companies (13.5 %), and middle and large companies (12.5 %).

The same situation is present in other SEE countries. As presented by Jelačić *et al.* (2012), Croatia, Serbia and Slovenia are showing a decrease in the wood processing and furniture manufacturing (Jelačić, 2010) as well as a decrease in the number of employees in all these three countries, even though Slovenia has been an EU member state since 2012. However, the entrance of IKEA is affecting the furniture industry of these countries, as well as the media buying investments, as presented further in this paper.

The aim of this paper is to analyse the official media monitoring report for TV, radio, print, outdoor and internet in the Republic of North Macedonia, compared to several other countries as Serbia, Bulgaria, Bosnia and Herzegovina and Croatia in the period from 2013 to 2018.

2 RESEARCH METHODS
2. METODE ISTRAŽIVANJA

For this paper, we have considered data from official media monitoring agencies for the selected SEE countries. *AGB Nielsen* is the official media monitoring agency in most of the countries in this region, for monitoring the insertions of TV commercials on all national television channels and Gross Rating Point (GRP) index on the same television channels. For the reports, the agencies also use Rating Cost (RC) as media investment monitoring, even though CPP (Cost Per Point) has already been implemented in these countries.

Ipsos Strategic Plus is the official media monitoring agency for radio and print advertising in Croatia, Serbia and Slovenia. As this agency is not an official monitoring house for the Republic of North Macedonia, there are no official reports for this country for print media and radio channels. The data for these media is collected through interviews with media directors from several media agencies. The official media allocation is then analysed using the methodology of RC.

The outdoor media allocation is reported by the agency *Alma Quattro* as the official agency for Serbia. No other country of selected SEE countries is officially monitored for outdoor advertising; therefore, we also use internal, not official data from advertising agencies from the Republic of North Macedonia, as financial investments (RC) for media allocation.

For monitoring television advertising, the insertions of television commercials and Gross Rating Points (GRP) index of television channels are consid-

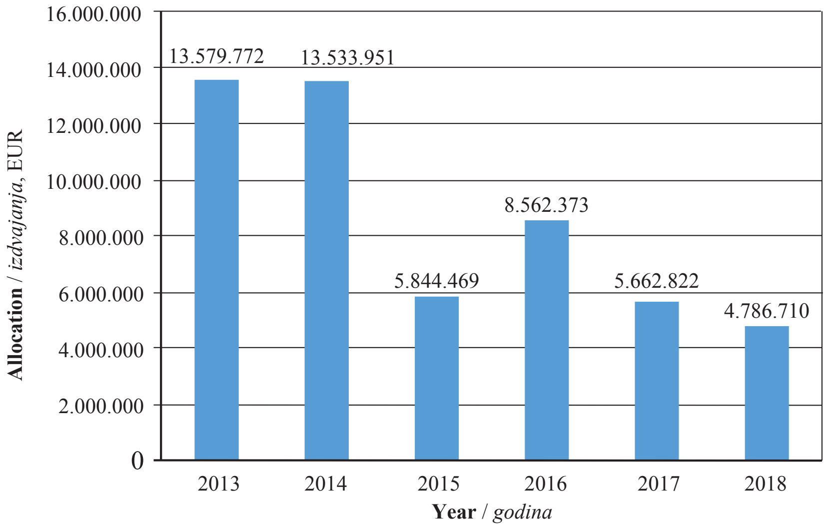

Figure 1 Media buying allocation for furniture in Republic of North Macedonia from 2013 to 2018 in euros
Slika 1. Izdvajanja za kupnju medijskog prostora za oglašavanje namještaja u Republici Sjevernoj Makedoniji od 2013. do 2018. (u eurima)

ered. An insertion is the number of broadcasting of specific television commercials on one television channel. GRP index is a standard measure in advertising, which measures the advertising impact. It is calculated as a percentage of the target market reached, multiplied by the exposure frequency.

$$GRP = reach \times frequency \qquad (1)$$

Reach is the number of individuals or homes that saw an ad at least once in your campaign schedule. Frequency is the average number of times a household or a person saw.

Research period is from 2013 to 2018, which covers the period after recession, and years of growth and new development, with EU integration opportunities. Overall, a descriptive statistical analysis was performed for data processing, analysis and developing research results.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In the first part of the study, the results are presented for the Republic of North Macedonia, followed by the results for some of SEE countries, Serbia, Bulgaria, Bosnia and Herzegovina, and Croatia.

3.1 Media buying allocation in Republic of North Macedonia
3.1. Izdvajanja za kupnju medijskog prostora u Republici Sjevernoj Makedoniji

As there are limited officially published results for media buying only for television in the Republic of North Macedonia, the rest of the data are collected through interviews from advertising agencies. The media buying budget allocated to television (TV) in the Republic of North Macedonia for the period from 2013 to 2018 is presented in Figure 1. The results show a sudden decrease of the total TV media budget allocation in the year 2015, while in 2018 the media budget is 2.8 times lower than that in 2014.

Overall, media budget allocation is in favour of television media buying, as other media budget investments are much lower comparing to television budget, as presented in Figure 2. The outdoor media budget was EUR 120,000, only EUR 15,000 was invested in radio and EUR 25,000 in internet (just for banner advertising), as we could not provide more information for other internet advertising. The data for other media was collected by interviews from advertising agencies, so they are not from an official media monitoring house, as it does not exist in the Republic of North Macedonia.

Analysing the total media budget allocation in 2018 for the furniture industry, it is noticeable that it is in favour of television media buying, as other media budget investments are much lower comparing to television budget, as presented in Figure 2. The outdoor media budget was EUR 120,000, only EUR 15,000 was invested in radio and EUR 25,000 in internet ad-

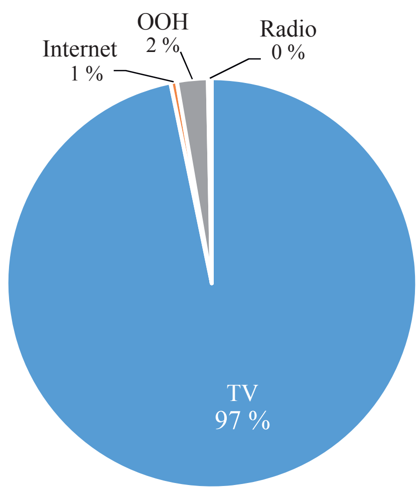

Figure 2 Total media budget allocation for furniture in 2018 in Republic of North Macedonia
Slika 2. Ukupna izdvajanja za medije iz proračuna tvrtki u Republici Sjevernoj Makedoniji za oglašavanje namještaja u 2018.

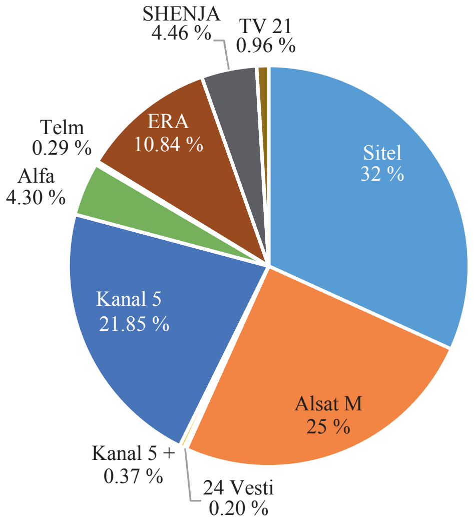

Figure 3 Total TV media budget allocation for furniture companies in 2018 in Republic of North Macedonia
Slika 3. Ukupna izdvajanja za TV medije iz proračuna tvrtki za proizvodnju i prodaju namještaja u Republici Sjevernoj Makedoniji u 2018.

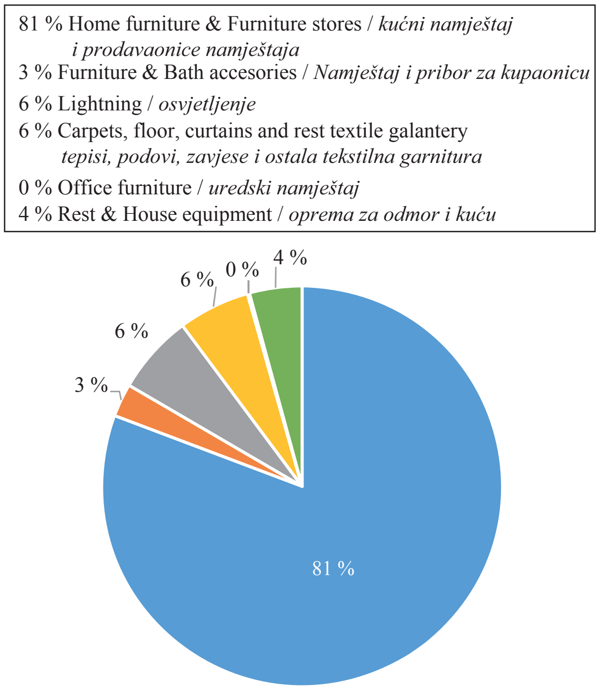

Figure 4 Total TV media budget allocation by furniture companies categories in 2018 in Republic of North Macedonia (in %)
Slika 4. Ukupna izdvajanja za TV medije iz proračuna tvrtki za proizvodnju i prodaju namještaja u Republici Sjevernoj Makedoniji prema kategorijama proizvoda u 2018. (u postotcima)

vertising, just for banner advertising, not including other types of internet advertising.

The analysis of the budget allocation to TV media shows that most TV investments are made in the main national TV stations as presented in Figure 3. *Sitel* TV station has a share of 32 % of the total media budget allocation to TV media for furniture in the Republic of North Macedonia. *Alsat M* TV station, which is an Albanian national TV station, also has a share of 25 %, considering the fact that Albanian population is a minority in this country. Then follows *Kanal 5,* a TV station with a share of 22 % of the TV media budget allocation. These are the three top TV stations, which account for a share of 79 % of the total TV media budget allocation for furniture in the Republic of Macedonia. The rest of the TV stations (*Era, Shenja, Alfa and TV21*) have a smaller share, namely 21 % of the total TV media budget for furniture in the Republic of North Macedonia.

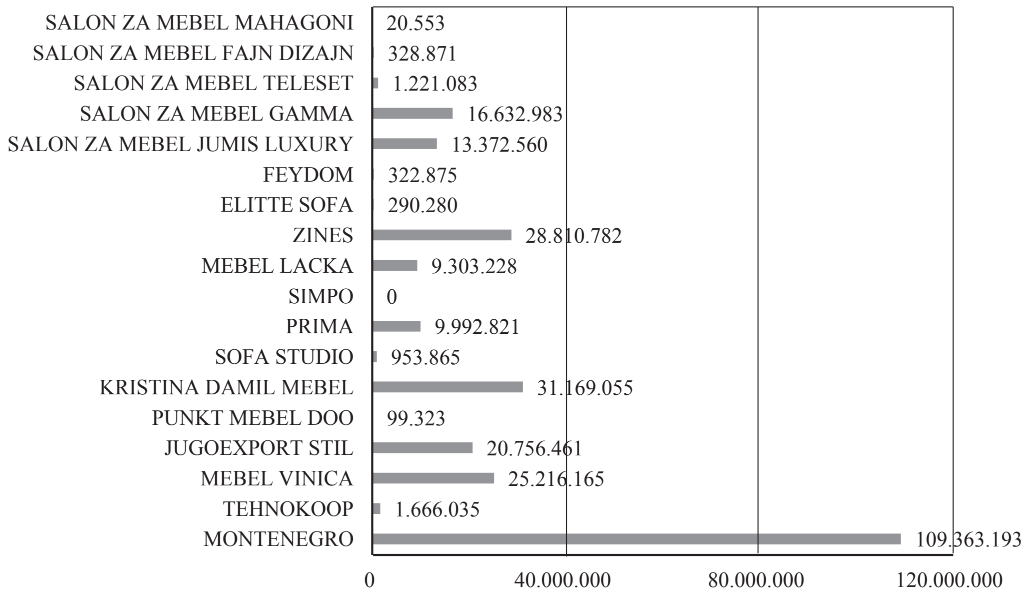

Figure 5 Total TV media budget allocation in euros for category: *Home furniture and furniture stores* in 2018 in Republic of North Macedonia
Slika 5. Ukupna izdvajanja za TV medije iz proračuna u Republici Sjevernoj Makedoniji za kategoriju kućnog namještaja i prodavaonica namještaja u 2018. (u eurima)

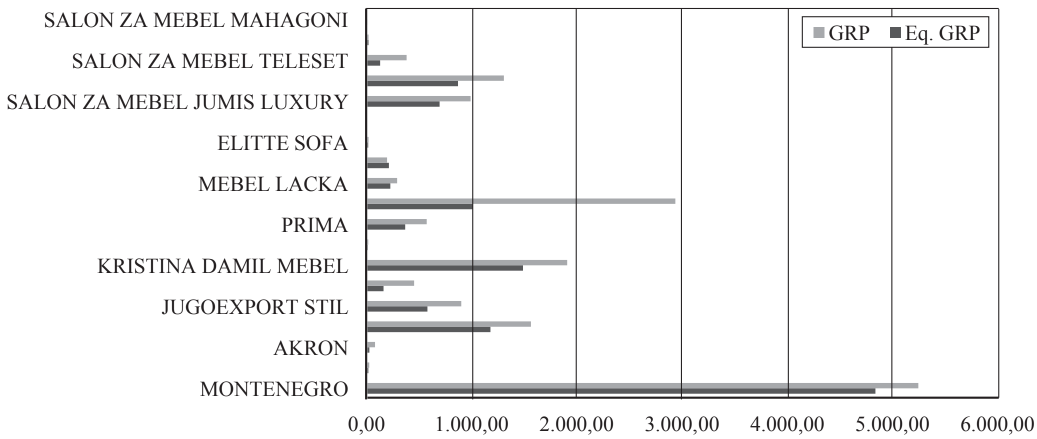

Figure 6 Equal GRP and GRP overview of furniture companies for category *Home furniture and stores* in 2018
Slika 6. Pregled ujednačenoga GRP-a i GRP-a tvrtki za namještaj za kategoriju kućnog namještaja i prodavaonice namještaja u 2018.

Further analysis of the total TV media budget allocation for furniture in the Republic of North Macedonia shows the advertisers on each TV station for every month in 2018. Six different categories of furniture companies invest their media budget in TV, namely the companies: 1. for home furniture and furniture stores, 2. for furniture and bath equipment, 3. for lightning, 4. for carpets, floors, curtains and other textile products, 5. for office furniture and rest, and 6. for kitchen furniture. The biggest advertisers are companies for home furniture and furniture stores with 81 % in the total TV media budget allocation, as presented in Figure 4.

Considering the furniture companies that advertise on TV in the Republic of North Macedonia, we can analyse their TV media budget in order to identify the biggest advertiser. In the category *Home furniture and furniture stores*, the biggest advertiser is the furniture company *Montenegro* with TV media budget 3.5 times higher than that of the second advertiser, *Kristina Damil,* as presented in Figure 5.

Analysing the category *Home furniture and furniture stores* in terms of GRP, the most efficient was *Montenegro* with 5243 GRP, as presented in Figure 6.

Examining the reach of the same category of furniture companies, *Montenegro* and *Simpo* have the biggest reach with 100 % reach1+, meaning that this TV commercial reaches the target group at least once, as presented in Figure 7.

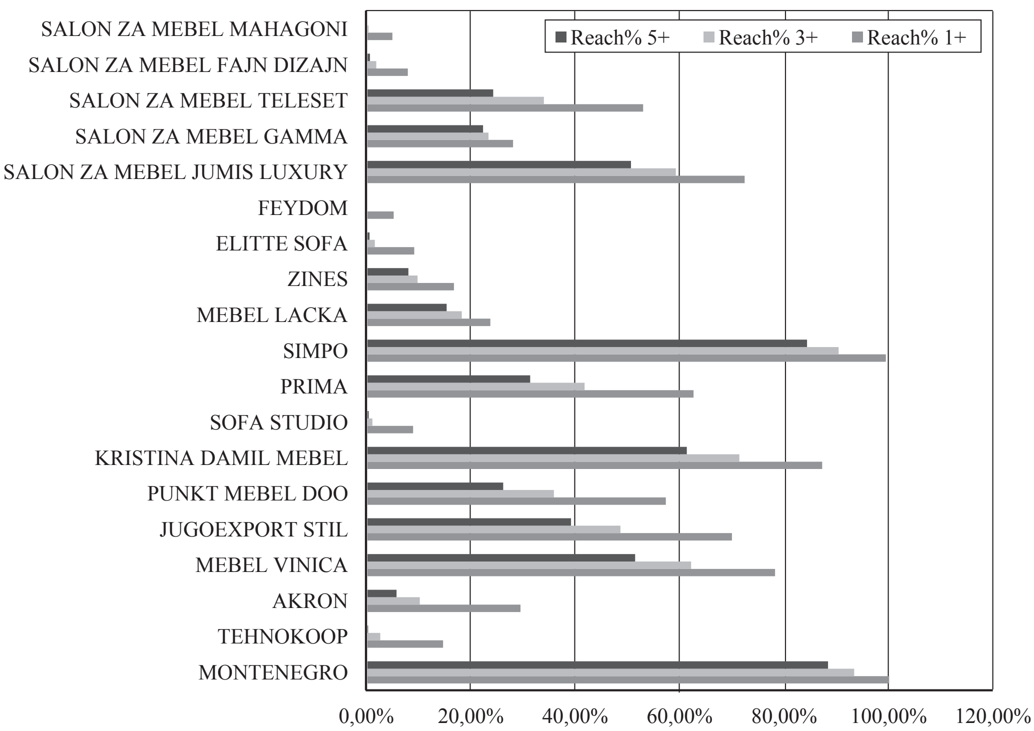

Figure 7 Reach of TV media allocation of furniture companies - category *Home furniture and furniture stores* in Republic of North Macedonia for 2018
Slika 7. Doseg proračunskih izdvajanja za TV medije tvrtki za proizvodnju i prodaju namještaja za kategoriju kućnog namještaja i prodavaonica namještaja u 2018. u Republici Sjevernoj Makedoniji

3.2 Results of media buying allocation for other selected SEE countries
3.2. Rezultati izdvajanja za kupnju medijskog prostora u drugim promatranim SEE zemljama

In the next part, the results of media budget allocation are presented for different SEE countries, in order to make a further comparison analysis with the available data from the region.

The Republic of Serbia, as a neighbouring country of the Republic of North Macedonia, and the bigger furniture market, invests mainly in TV as presented in Figure 8. The biggest increase of the media budget investments is due to the entrance of IKEA in 2017. Television has the dominant investment allocation, followed by print media and out of home (OOH). Unfortunately, internet and radio are not included, as there is no official monitoring agency for internet and radio media.

For Croatia, official monitoring reports are available for all the media. Therefore, we have an overall picture and comparable results for the media allocation of all furniture companies. The results are presented in Figure 9 for the last 6 years for all the media channels such as TV, internet, OOH, radio and print. The biggest media budget was allocated to TV channels as in most of the countries.

Analysing each media budget allocation during the last six years, as presented in Table 1, TV media budget investments show growth from 2013 to 2018. Internet media budget shows a sudden increase in 2018. Internet investment in 2018 is forty times higher than in 2013, showing an increase of 251 % and a positive trend for media allocation in accordance with the use of internet and digital media. The rest of the media budget allocations also present an increase in the media budget, but much lower. We can notice a three times increase in TV, two times increase of the budget in outdoor advertising, very small increase of media budget allocation in radio advertising, and even a decrease in print. All these data are in accordance with the trends of the world media budget allocation presented above.

Bosnia and Herzegovina has official media buying reports only for TV and print media. From Figure 10, it is obvious that TV media budget investments are much higher than the print media investments, which is also common in other countries. In this country, the TV budget decreases, the same as in the Republic of North Macedonia.

For Bulgaria, official monitoring reports are available only for television, radio and print media, as

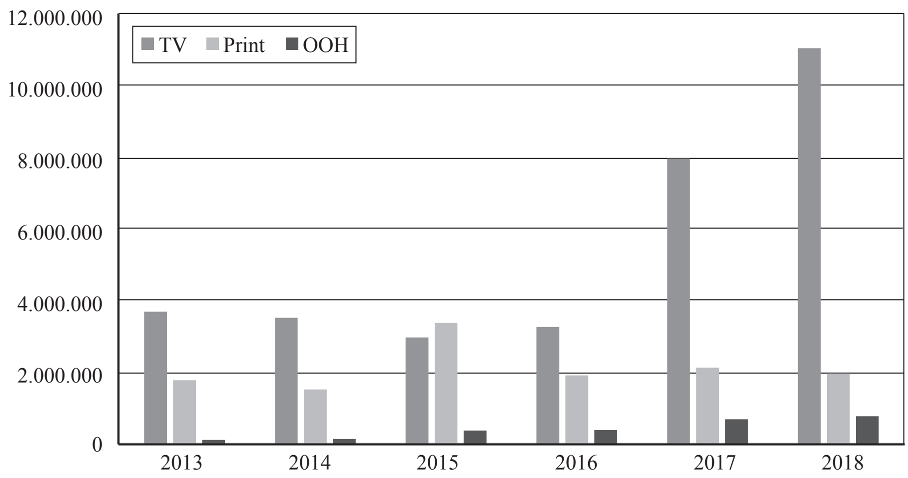

Figure 8 Media budget allocation for furniture companies in Republic of Serbia in euros
Slika 8. Izdvajanja za medije iz proračuna tvrtki za proizvodnju i prodaju namještaja u Republici Srbiji (u eurima)

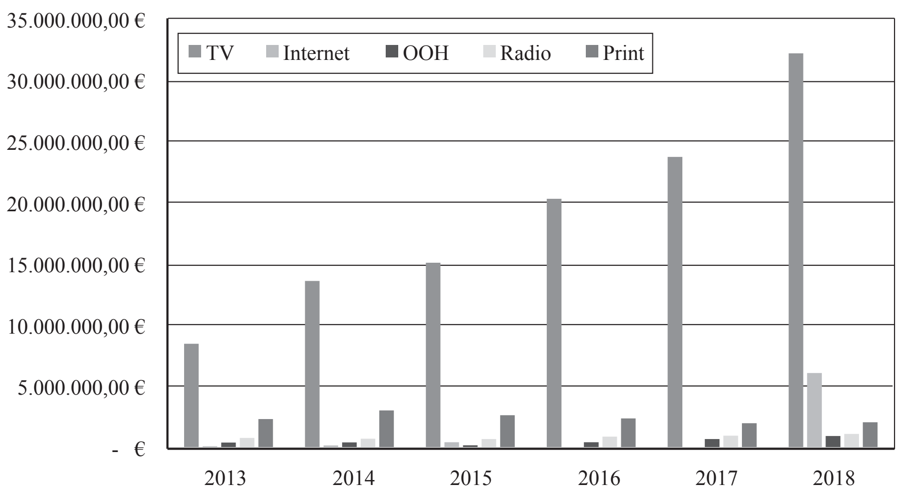

Figure 9 Media budget allocation for furniture companies in Republic of Croatia in euros
Slika 9. Izdvajanja za medije iz proračuna tvrtki za proizvodnju i prodaju namještaja u Republici Hrvatskoj (u eurima)

Table 1 Media budget allocation in Republic of Croatia in euros
Tablica 1. Izdvajanja za medije iz proračuna tvrtki za proizvodnju i prodaju namještaja u Republici Hrvatskoj (u eurima)

	2013	2014	2015	2016	2017	2018
TV	8,515,446.91	13,638,540.26	15,126,280.39	20,357,297.45	23,767,665.61	32,223,506.36
Internet	153,835.39	218,167.60	475.834,43	24,571.07	28,676.11	6,128,253.93
OOH	448,283.85	465,277.74	228,857.36	479,724.31	736,219.79	983,068.11
Radio	833,955.79	762,924.08	742,343.68	938,777.89	1,018.786.71	1,156,569.87
Print	2,369,033.34	3,072,157.12	2,678,766.82	2,428,685.55	2,026,551.96	2,104,427.34

Source: Developed from the authors

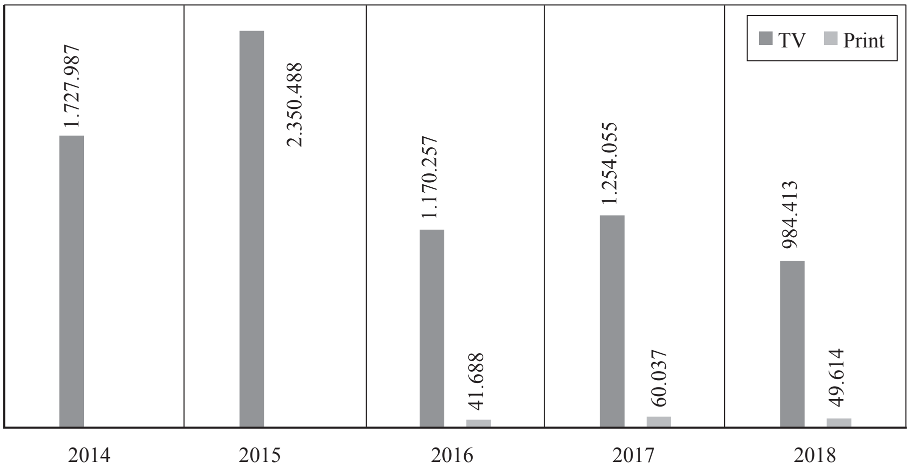

Figure 10 Media budget allocation for furniture companies in Republic of Bosnia and Herzegovina in euros
Slika 10. Izdvajanja za medije iz proračuna tvrtki za proizvodnju i prodaju namještaja u Republici Bosni i Hercegovini (u eurima)

presented in Figure 11. The increase of TV media budget allocation is 2.8 times higher in comparison with 2013. The rest of the monitored media present a decrease in the media budget allocation, both in radio and print media.

3.3 Comparison of media buying allocation of Republic of North Macedonia and some SEE countries for 2018
3.3. Usporedba izdvajanja iz proračuna za kupnju medijskog prostora u Republici Sjevernoj Makedoniji s nekim SEE zemljama u 2018.

We have also made the comparison analysis of the results of media budget allocation of the Republic of North Macedonia and several SEE countries, including Serbia, Bosnia and Herzegovina, Croatia and Bulgaria. For the comparison, we used the results from the official monitoring houses for media monitoring available for each country. Therefore, not all used media are presented, as in some countries there are no official reports of monitoring for all media, such as internet and outdoor.

The Republic of North Macedonia and Bosnia and Herzegovina present the highest investment in television media buying, around 90 % of the total media buying investment, and much smaller investment in outdoor and print media, while the rest of the media have not been covered by official reporting. However, despite the lack of official reports, the media such as internet and radio are much less used by the furniture companies in these two countries.

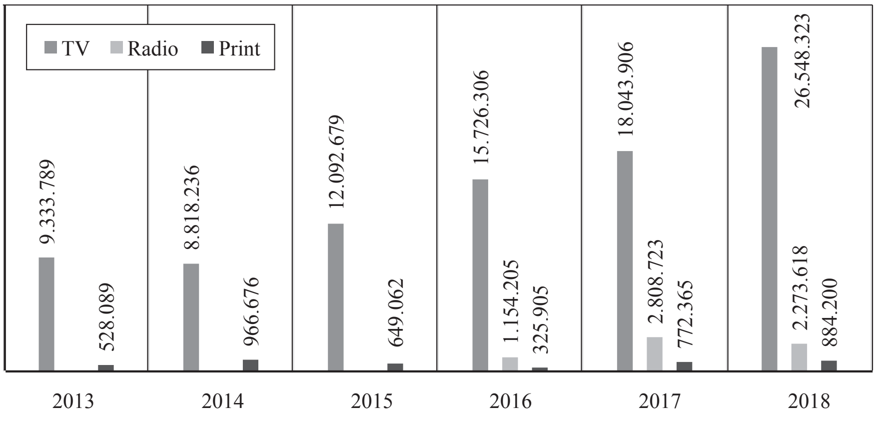

Figure 11 Media budget allocation for furniture companies in Republic of Bulgaria in euros
Slika 11. Izdvajanja za medije iz proračuna tvrtki za proizvodnju i prodaju namještaja u Republici Bugarskoj (u eurima)

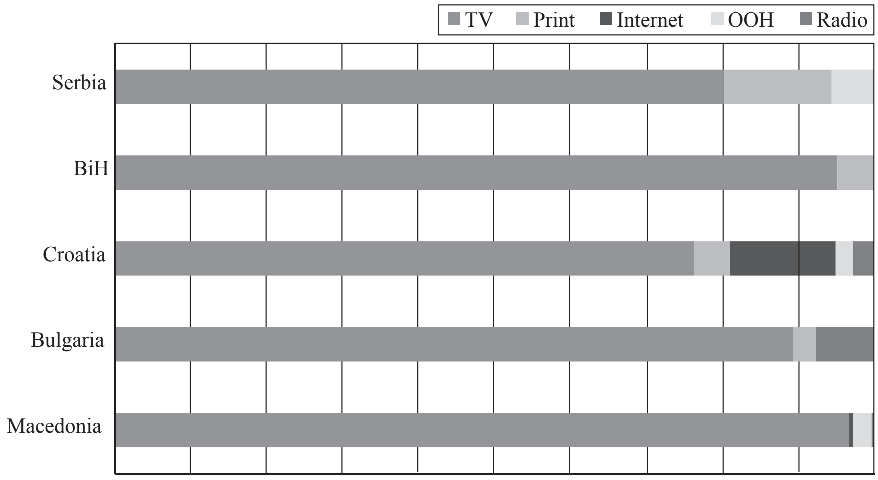

Figure 12 Media budget allocation for furniture companies in selected SEE countries in (%) in 2018
Slika 12. Izdvajanja za medije iz proračuna tvrtki za proizvodnju i prodaju namještaja u promatranim SEE zemljama u 2018. (u postotcima)

Another specific point for these countries, as seen in Figures 1 and 10, is that the budget for television is decreasing in both countries, which is not the case in any other country from the region. The television media budget allocation is increasing in Serbia, Croatia and Bulgaria, as furniture companies invest more in this medium (as shown in Figures, 8, 9 and 11).

The TV media budget in Croatia and Serbia is below 80 % from the total media budget allocation as shown in Figure 12. In Serbia, the rest of the media budget is allocated to print media, while in Croatia the budget is increasingly allocated to internet media, following the world trends.

According to the presented results for media budget allocation in the Republic of North Macedonia and several SEE countries, the media buying in Croatia is the highest with EUR 42.595.823 in 2018, followed by Bulgaria with EUR 29.706.141, Serbia with EUR 13.710.096, Republic of North Macedonia with EUR 4.786.710, and Bosnia and Herzegovina with EUR 1.034.027. The media buying budget of furniture companies in the Republic of North Macedonia is nine times less than that of the Croatian furniture companies.

4 CONCLUSION
4. ZAKLJUČAK

Limitations of this research are that there are no official reports for all the media in all SEE countries, or for monitoring of internet in most of the selected SEE countries, except in Croatia.

The results also show a decrease of media budgets in the Republic of North Macedonia and Bosnia and Herzegovina. Opposite of this, in Croatia, Serbia and Bulgaria media investments are growing, with the increase in internet advertising in Croatia, and decrease in television advertising following the world trends. Both Croatia and Bulgaria are part of EU, and these two countries and Serbia were affected by the appearance of IKEA and its heavy media investments.

As the Macedonian furniture market shows an overall decrease in the number of companies and employees, a decrease is also reflected on the media buying in the country. Internet advertising is growing, but it is still under the world trends. Having in mind that in the Republic of North Macedonia most of the furniture companies are small sized, the television investments are not a priority, and they should be shifted into new and digital media, combining the social media, paid search engine and developing mobile applications, as well as mobile advertising.

The recommendation for further research in this area would be to analyse the effects of promotion on customer purchase decisions and media usage habits, as important preconditions for developing more relevant customer-oriented marketing communications for furniture companies. The customer focus should be a basic point for overall development of the value of furniture companies.

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Drvo amburane (*Amburana cearensis* A. C. Sm.)

NAZIVI I PODRUČJE RASPROSTRANJENOSTI

Amburana cearensis A. C. Sm. vrsta je drva iz porodice *Fabaceae* (*Leguminosae*). Trgovački su nazivi te vrste: cerejira (Njemačka, Francuska, Velika Britanija); amburana (Brazil); cumaru de cheiro (Brazil); cumaru de ceara (Brazil); roble de pais (Argentina); sorioco (Bolivija); ischipingo (Peru). Stabla *Amburana cearensis* A. C. Sm. nalazimo u Južnoj Americi, od Brazila, Bolivije, Perua, Sjeverne Argentine do Paragvaja. Raste u suhim tropskim šumama, često na dubokim, dobro dreniranim tlima te u vlažnim tropskim šumama, na vapnenačkim i kamenitim tlima.

STABLO

Stablo doseže visinu do 30 m. Čisto deblo dugo je od 12 do 15 m, a prsni mu je promjer 50 – 90 cm. Debla su cilindričnog oblika.

DRVO

Makroskopska obilježja

Srž i bjeljika međusobno se vrlo malo razlikuju po boji. Bjeljika je sivkasta, a široka je od 3 do 6 cm. Srž drva je žućkastosmeđa, s vidljivim mrljama, bojom vrlo slična srži. Tekstura drva je gruba, dekorativna, katkad nepravilne žice. Drvo je rastresito porozno. Granica goda je teško uočljiva. Pore drva su krupne i vidljive običnim okom, a drvni su traci uski i vidljivi povećalom.

Mikroskopska obilježja

Traheje su pojedinačno raspoređene i pojavljuju se Drvo je rastresito porozno. Traheje su u malim skupinama, a pojavljuju se i u kratkim radijalnim nizovima (po 2 – 3). Promjer traheja iznosi 145...195...230 mikrometara, a gustoća im je 2...6 na 1 mm^2 poprečnog presjeka. Drvna su vlakanca libriformska. Dugačka su 700...1000 mikrometara, a stijenka im je srednje debela. Apotrahealni je aksijalni parenhim difuzno raspoređen, a paratrahealni je aliforman do konfluentan. Drvni su traci heterocelularni, visoki do 500 mikrometara. Gustoća drvnih trakova je 4...6 na 1 mm tangentnog presjeka.

Fizička svojstva

Gustoća apsolutno suhog drva, ρ_o	oko 570 kg/m^3
Gustoća prosušenog drva, ρ_{12-15}	550...650 kg/m^3
Gustoća sirovog drva, ρ_s	850...900 kg/m^3
Radijalno utezanje, β_r	2,3...3,0 %
Tangentno utezanje, β_t	4,1...5,8 %
Volumno utezanje, β_v	7,6...8,4 %

Mehanička svojstva

Čvrstoća na tlak	oko 50 MPa
Čvrstoća na savijanje	oko 85 MPa
Modul elastičnosti	oko 8,8 GPa

TEHNOLOŠKA SVOJSTVA

Obradivost

Drvo se dobro pili, lijepi, blanja i brusi. Pri piljenju nema posebnih zahtjeva glede alata, a alat se umjereno tupi. Katkad je zbog nepravilne žice teško postići glatku površinu. Drvo dobro drži čavle i vijke. Mokro drvo u dodiru sa željezom mijenja boju.

Sušenje

Drvo se dobro i polako suši. Sklonost promjeni oblika, kolapsu i raspucavanju je malena, ali postoji tendencija da se u debljemu materijalu pojavi skorjelost.

Trajnost i zaštita

Prema normi HRN 350-2, 2005, srž drva amburana srednje je otporna na gljive uzročnice truleži (razred otpornosti 3) i srednje otporna na napad termita (razred otpornosti M). Srž je srednje (teško) permeabilna (razred 2). Po trajnosti pripada razredu 3 te se može upotrebljavati u interijeru.

Uporaba

Drvo se iskorištava za izradu parketa, stepenica, dijelova namještaja, obloga, dekorativnih furnira te vanjskih i unutarnjih konstrukcija.

Sirovina

Drvo na tržište dolazi u obliku trupaca i piljenica različitih dimenzija, kao furnir, furnirske ploče i panel.

Napomena

Drvo *Amburana cearensis* nije na popisu ugroženih vrsta međunarodne organizacije CITES, ali je na popisu ugroženih vrsta međunarodne organizacije IUCN. To je manje poznata i manje istražena vrsta drva. Kora se upotrebljava u medicinske svrhe. Stablo ima jak miris kumarina koji podsjeća na vaniliju. Istoznačnica botaničkog naziva je *Torresia cearensis* Allem. Drvo sličnih svojstava ima vrsta *Amburana acreanna* Ducke. Zbog svoje boje, teksture i svojstava može se upotrebljavati kao zamjena za drvo hrasta, framirea, latija, žutog merantija, iroka, mouvingija, tole, mersawe, bilinga, kota i limbe.

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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 i uz posebno plaćanje), 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, uz plaćanje). 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/node00.html. First published 1997 (pristupljeno 27. siječnja 2010).

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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.

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

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

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

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

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

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

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