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Jozef Krilek, Miroslava Ťavodová, Ján Kováč, Branislav Tichý[1]

Impact of Irregular Tooth Pitch of Circular Saw Blades on Power for Wood Cross-Cutting

Utjecaj promjenjivog koraka zubi kružnih pila na snagu za poprečno rezanje drva

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ABSTRACT • *The article deals with the influence of irregular tooth pitch on energy consumption of cross-cutting wood. In this article, the effect was assessed of feeding velocity and parameters of saw blade on the cutting power Pc of spruce (Picea Abies), pine (Pinus Sylvestris) and beech (Fagus Silvatica) wood during sawing with a guided circular saw. For the research, two types of circular saw blades were used, one of them having irregular tooth pitch. The circular saw blades had sintered carbide inserts with a diameter of D = 350 mm and the same number of teeth. The feed velocities were v_f = 4, 8,12 m·min^{-1} and revolutions n = 3000 min^{-1}. The results showed that the circular saw blades with irregular tooth pitch have higher energy consumption than the circular saw blades with regular tooth pitch. The highest cutting power Pc was shown in the case of beech. It was also shown that energy consumption is increasing linearly with increasing feed velocity.*

Key words*: *energy consumption; cross-cutting wood; circular saw blades; cutting power; irregular tooth pitch

SAŽETAK • *U radu se prikazuje istraživanje utjecaja promjenjivog koraka zubi kružnih pila na potrošnju energije pri poprečnom rezanju drva. Analiziran je utjecaj posmične brzine, parametara lista pile i vrste drva na snagu rezanja (P_c). Eksperiment je proveden piljenjem drva smreke (Picea abies), bora (Pinus sylvestris) i bukve (Fagus silvatica) vođenom kružnom pilom. Za istraživanje su rabljena dva lista kružnih pila, od kojih je jedan imao promjenjivi korak zubi. Oba su lista kružnih pila imala oštrice od sinteriranih karbidnih umetaka, promjer lista D = 350 mm i jednak broj zubi. Primijenjene su tri posmične brzine: 4, 8 i 12 m·min^{-1}, a broj okretaja radnog vratila iznosio je n = 3000 min^{-1}. Rezultati su pokazali da je potrošnja energije kružnih pila s promjenjivim korakom zubi veća od potrošnje energije kružnih pila s jednakim korakom zubi. Najveća snaga rezanja P_c zabilježena je pri piljenju bukve. Uočeno je da se potrošnja energije linearno povećava s povećanjem posmične brzine.*

Ključne riječi*: *energetska potrošnja; poprečno piljenje drva; listovi kružne pile; snaga rezanja; promjenjivi korak zubi

1 INTRODUCTION
1. UVOD

In practice, in the wood cutting process, it is important to keep energy consumption at the lowest possible level. Impacts affecting energy consumption are e.g. cutting conditions (feed per tooth f_z, cutting speed v_c, feed velocity v_f), the choice of material suitable for a cutting tool and geometry of a tool. The cutting pow-

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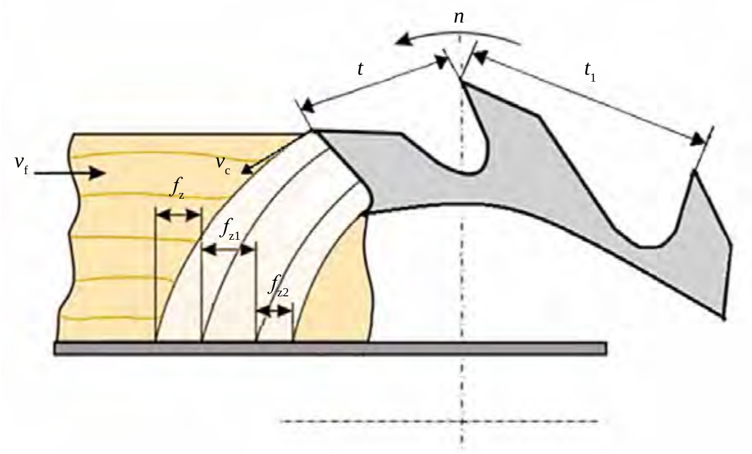

Figure 1 Kinematic scheme of a circular saw blade: f_z – feed per tooth for regular tooth pitch circular saw blades; $f_{z1,2}$ – feed per tooth for irregular tooth pitch of circular saw blades; t – tooth spacing for regular tooth pitch circular saw blades; t_1 – tooth spacing for irregular tooth pitch of circular saw blades; h_z – height of a tooth; v_c – cutting speed; v_f – feed velocity; α – clearance angle; β – cutting edge angle; γ – rake angel; (Siklienka *et al*., 2013)
Slika 1. Kinematička shema lista kružne pile: f_z – posmak po zubu za list kružne pile s jednakim korakom zubi; $f_{z1,2}$ – posmak po zubu za list kružne pile s promjenjivim korakom zubi; t – duljina koraka zubi lista kružne pile s jednakim korakom zubi; t_1 – duljina koraka zubi lista kružne pile s promjenjivim korakom zubi; h_z – visina zubi; v_c – brzina rezanja; v_f – posmična brzina; α – leđni kut; β – kut oštrice; γ – prsni kut (Siklienka *et al*., 2013.)

er is one of the most important factors affecting energy consumption (Atkins, 2009; Barcík *et al*. 2009; Danwé *et al*., 2012).

For the quality of a processed surface, efficiency of machines and tools, and dimensions of a product, it is necessary to provide proper cutting conditions and cutting angles (Argay, 2014; Banski, 2000; Manžos, 1974). Inappropriate cutting angles can result in bad quality of a processed surface, higher possibility of tool wear, lower lifetime of a tool and finally questionable reliability of the whole machine (Goglia, 1994; Mikleš *et al*., 2010; Kminiak *et al*. 2015; Kvietková *et al*., 2015; Lisičan, 1982).

1.1 Cross-cutting wood by circular saws
1.1. Poprečno rezanje drva kružnom pilom

Cutting wood by circular saw blades is a complex process. For getting ideal operating conditions, it is important to know mutual interaction among a tool, a product and influence of technical and technological factors affecting the cutting power and final quality of the product. It is possible to obtain the required quality by setting these factors and parameters. Cutting quality is affected by tool wear.

Circular saw blade cutting is the most widely spread way of wood sawing. Owing to different design and construction of circular saw blades, it is possible to cut in different ways with respect to the wood fibers (Kminiak *et al*., 2016; Strelkov, 2009; Naylor *et al*., 2012).

Using three basic criteria, we can evaluate the impacts on wood cutting and processing, i.e. a machine, a tool and a processed object. The criteria are defined in Tab. 1 (Mikleš *et al*., 2010).

The kinetic equations for cross-cutting are analogous to rip cutting. A cutting speed of 40 - 75 $m \cdot sec^{-1}$ is recommended; if the saw blade temperature drops along its radius, it does not reach its maximum at this speed, in the case of 0 °C (cross-cutting itself in the working cycle is less than 10 %); this means that an increase in temperature in the saw blade is not considered. The selection of a cutting speed also considers the working limits of the saw blade shaft bearings, as well as the noise level, the wear of the cutting edges (v_c < 60 $m \cdot sec^{-1}$) and energy consumed by cutting (v_c = 60 - 80 $m \cdot sec^{-1}$).

Cutting power is an important parameter and it is interesting for every wood processor using machines with respect to energy consumption of the machine

Table 1 Criteria affecting cutting process (Mikleš *et al*. 2010)
Tablica 1. Kriteriji koji utječu na proces rezanja (Mikleš i sur., 2010.)

Criteria *Kriteriji*	**Product** / *Proizvod*	**Machine** / *Stroj*	**Tool** / *Alat*
External *vanjski*	chip shape, cutting depth, cutting quality *oblik strugotine, visina rezanja, kvaliteta rezanja*	feed velocity, cutting forces, material, cutting speed, vibrations, lifetime, cutting power *posmična brzina, sile rezanja, materijal, brzina rezanja, vibracije, vijek trajanja, snaga rezanja*	wear, geometry of the cutting edge *trošenje, geometrija rezne oštrice*
Internal *unutarnji*	wood species, wood strength, direction of fiber cutting, wood moisture, wood density *vrsta drva, čvrstoća drva, smjer rezanja s obzirom na smjer vlakanaca, sadržaj vode, gustoća drva*	material properties, type of material *svojstva materijala, vrsta materijala*	material properties, type of material *svojstva materijala, vrsta materijala*

used (Mikleš *et al*., 2010; Scholz *et al*., 2009). The goal of wood processors should be to achieve the required quality and product parameters at the lowest possible production costs (Kopecký *et al*., 2007; Siklienka *et al*., 2012; Siklienka *et al*., 2005). It is possible to decrease wood cutting costs and increase cutting power and cutting accuracy by a suitable tool, its geometry and cutting conditions (Wasielewski *et al*., 1999; Barcík *et al*., 2008).

Decreasing energy consumption of a machine has a significant impact on the whole value of the final product (Bradbury *et al*., 2000; Schajer *et al*., 2002). Power requirements and performance of the machine are defined according to STN ISO 3002-4. Wood is anisotropic material and its properties vary in different parts of the trunk, and that is the reason why it is difficult to define K (Vladimirovič, 2004; Suchanov, 2015).

Nowadays, the specific cutting resistance k_c is defined according to empirical formulas obtained by long time wood research and experiments. Many parameters are used such as wood species K_d, cutting model K_φ, cutting angle K_δ, cutting speed K_v, wood moisture K_w, tool wear K_ρ and thickness of chips h (Kopecký *et al*., 2014; Kováč *et al*., 2009; Orlowski *et al*., 2006; Svoreň, 2002).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Tested samples
2.1. Ispitni uzorci

The measurement was carried out by using spruce (*Picea Abies*), pine (*Pinus Sylvestris*) and beech (*Fagus Silvatica*). The dimensions of tested samples were 50 mm × 200 mm × 1000 mm. These dimensions were chosen on the basis of technical parameters of the measuring equipment.

The moisture of tested samples was defined by gravimetric analysis in accordance with SS-EN-13183-1. This method belongs to direct methods defining wood moisture. The principle of this method is based on the definition of the wet wood weight followed by drying and repeated weighing (Požgaj *et al*., 1997; Orlowski, 2007). The mean value of moisture of wooden samples was 27 %.

2.2 Circular saw blades
2.2. Listovi kružnih pila

For experimental tests, two circular saw blades were used i.e. circular saw blades with sintered carbide inserts.

The circular saw blades have the same number of teeth and tooth geometry. The first circular saw blade has regular tooth pitch and a full body (Fig. 2). The second circular saw blade has irregular tooth pitch and its body has dilatation gaps for decreasing stress and vibrations in the process of cutting wood (Fig. 3). It is also possible to see in details different shape of teeth (Fig. 3 and 4). Parameters of the circular saw blades are shown in Tab. 2.

The wood cross-cutting process was performed in the testing device shown in Figure 5. This equipment is used for testing wood cutting conditions. It was designed at the Technical University in Zvolen (Slovakia), the Faculty of Environmental and Manufacturing Technology, Department of Environmental and Forest Machinery. The equipment consists of two main parts i.e. feed and cutting parts (Fig. 5).

The transfer of torque on the tested circular saw blade is ensured by the cutting mechanism. Keeping and feeding of the processed material to the place of cutting is ensured by the feed mechanism.

The working desk (Fig. 5) consists of a three-phase asynchronous electric motor of 7.5 kW. The torque is transferred by the belt from the safety clutch GIFLEX GFLL – 28, through the input clutch of a torque sensor, torque sensor HBM T20WN (Fig. 5),

Figure 2 Circular saw blade 1 with regular tooth pitch and full body
Slika 2. List kružne pile 1 s jednakim korakom zubi i punim tijelom

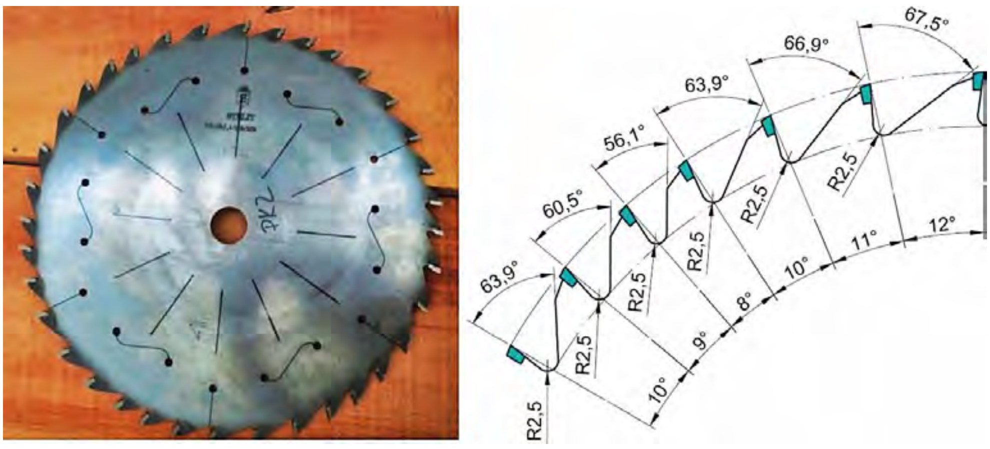

Figure 3 Circular saw blade 2 with irregular tooth pitch and body with dilatation gaps (Svoreň *et al*., 2013)
Slika 3. List kružne pile 2 s promjenjivim korakom zubi i tijelom s dilatacijskim pukotinama (Svoreň i sur., 2013.)

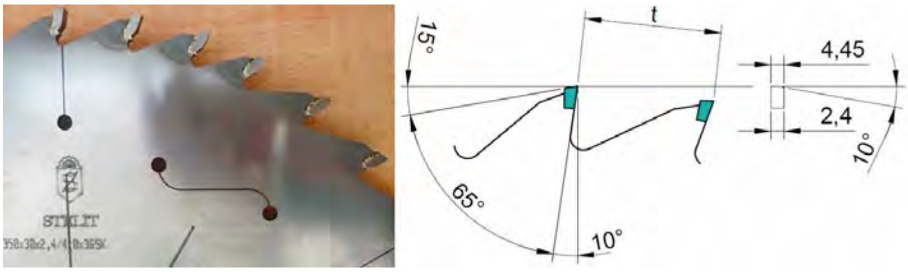

Figure 4 Detail of tooth of circular saw blade 2
Slika 4. Detalj zubi lista kružne pile 2

Table 2 Parameters of circular saw blades
Tablica 2. Parametri listova kružnih pila

Circular saw blade *List kružne pile*	**Geometry** *Kutovi oštrice* (°)	**Basic dimensions** *Osnovne dimenzije* *D* x *b* *s* x *d* mm	**Tooth spacing** *Korak zubi* *t*, mm	**Extension of the cutting edge to the side** *Jednostrano proširenje oštrice* *a*, mm	**No. of teeth** *Broj zubi*
No. 1					
α	15	350 x 4 2.4 x 30	regular *jednak*	0.8	36
β	65				
γ	10				
No. 2					
α	15	350 x 4 2.4 x 30	irregular *promjenjiv*	0.8	36
β	65				
γ	10				

output clutch of a torque sensor, and shaft, to the circular saw blade.

The processed material is caught in the feed part by the lever mechanism, which provides an adequate holding. The feed of the processed object is provided

Figure 5 Measuring equipment for cross-cutting wood
Slika 5. Stroj za eksperimentalno poprečno rezanje drva

by an electric motor of 5.5 kW, a safety clutch GIFLEX GFLL – 28 and feed spring.

The signal from the torque sensor is transferred by the cables to the recording device called SPIDER – 8, which is connected to the PC. Using a torque sensor HBM T20WN, it is possible to record circular saw blade revolutions. Performance and revolutions of electric motors can be regulated by frequency changer with vector controlling (Mikleš *et al*., 2010).

2.3 Measuring equipment
2.3. Mjerna oprema

The measurement was performed by the following equipment (Fig. 6):
- Measuring equipment - SPIDER – 8
- Torque and revolution sensor - HBM T20WN
- Computer with analytic software

Measurement of revolutions and torque of a circular saw blade was performed by the sensor HBM T20WN (Fig. 6). The sensor is self-powered with volt-

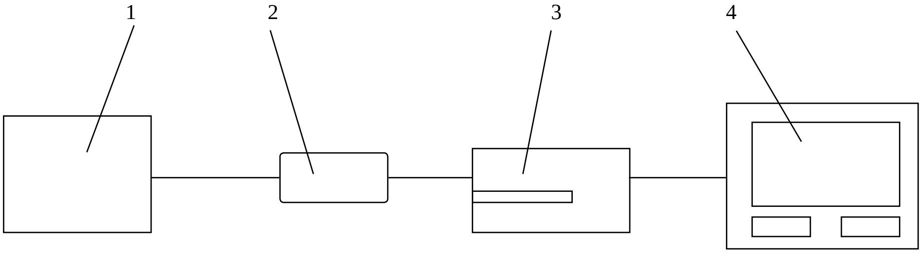

Figure 6 Measuring scheme: 1 – Measuring equipment, 2 – Torque and revolution sensor HBM T20WN, 3 – Measuring equipment SPIDER-8, 4 – PC with analytical software and a recording device
Slika 6. Mjerna shema: 1 – mjerna oprema, 2 – senzor zakretnog momenta i okretaja HBM T20WN, 3 – mjerna oprema SPIDER-8, 4 – PC s analitičkim softverom i uređajem za snimanje

age of 12 V. It has two output signals. It is a tensometric sensor of torque, revolutions and rotation angle. The sensor measures the nominal torque of up to 20 N·m, but it is possible to load it up to 108 N·m. It is protected by flexible clutches, which provide protection of a sensor against the deviations and vibrations caused by shaft defects. They also prevent it to transfer torque over 60 N·m. (www.hbm.com).

The data from a sensor are sent to the measuring equipment SPIDER – 8 (Fig. 6). It is a universal measuring control panel (A/D transmitter), with eight channels, from which data are recorded to the computer hard disc. (www.hbm.com)

3 RESULTS
3. REZULTATI

The goal of the measurement was to search and evaluate energy consumption in the wood cross-cutting process. The measured data of cutting power were analyzed by analytic software STATISICA 12.

The observed factors and results are shown in Tab. 3. The observed factors were: wood species (spruce, pine, beech) with sample dimensions 50 mm x 200 mm x 1000 mm, two types of circular saw blades and three feed velocities (v_f = 4, 8, 12 m·min^{-1}). The test was carried out at nominal revolutions n = 3000 min^{-1}.

First, one-way analysis was performed, where one-dimensional effects were observed. The effect of factors was confirmed in all effects except for wood species where p = 0.247. This means that wood species is not a significant factor. From the statistical point of view, it can be said that the effect of tooth pitch on the power output P_c has a 75 % probability.

Table 4 shows the results of ANOVA for all feed velocities, circular saw blades and wood species. All these factors were statistically very significant. The level of significance p must be lower than 0.05 to ob-

Table 3 Mean values of cutting power P_c for circular saw blade 1 and 2
Tablica 3. Prosječne vrijednosti snage rezanja P_c kružnih pila 1 i 2

Cutting power P_c, kW *Snaga rezanja P_c, kW*			**Cutting power P_c, kW** *Snaga rezanja P_c, kW*			**Cutting power P_c, kW** *Snaga rezanja P_c, kW*		
Wood species *Vrsta drva*	Circular saw blade *List kružne pile*		Wood species *Vrsta drva*	Circular saw blade *List kružne pile*		Wood species *Vrsta drva*	Circular saw blade *List kružne pile*	
	1	2		1	2		1	2
	Feed velocity *Posmična brzina* v_f, m·min^{-1}			Feed velocity *Posmična brzina* v_f, m·min^{-1}			Feed velocity *Posmična brzina* v_f, m·min^{-1}	
	4	4		8	8		12	12
spruce *smreka*	1.47	1.54	spruce *smreka*	2.26	2.35	spruce *smreka*	2.94	3.32
spruce *smreka*	1.55	1.97	spruce *smreka*	1.96	2.39	spruce *smreka*	2.77	3.23
spruce *smreka*	1.54	1.70	spruce *smreka*	1.94	2.37	spruce *smreka*	2.78	3.10
spruce *smreka*	1.51	1.68	spruce *smreka*	1.92	2.42	spruce *smreka*	2.85	3.10
spruce *smreka*	1.54	1.63	spruce *smreka*	2.26	2.40	spruce *smreka*	2.66	3.07
pine *bor*	1.40	1.66	pine *bor*	2.18	2.64	pine *bor*	2.84	3.27
pine *bor*	1.69	1.58	pine *bor*	2.35	2.57	pine *bor*	2.87	3.38
pine *bor*	1.70	1.62	pine *bor*	2.39	2.56	pine *bor*	2.83	3.12
pine *bor*	1.64	1.59	pine *bor*	2.40	2.85	pine *bor*	2.86	3.11
pine *bor*	1.57	1.60	pine *bor*	2.03	2.64	pine *bor*	2.53	3.27
beech *bukva*	1.68	1.68	beech *bukva*	2.45	2.95	beech *bukva*	2.99	3.31
beech *bukva*	1.63	1.89	beech *bukva*	2.68	2.59	beech *bukva*	3.27	3.16
beech *bukva*	1.64	1.99	beech *bukva*	2.64	2.61	beech *bukva*	3.28	3.18
beech *bukva*	1.65	1.93	beech *bukva*	2.59	2.66	beech *bukva*	3.26	3.23
beech *bukva*	1.66	1.80	beech *bukva*	2.54	2.59	beech *bukva*	3.33	3.27

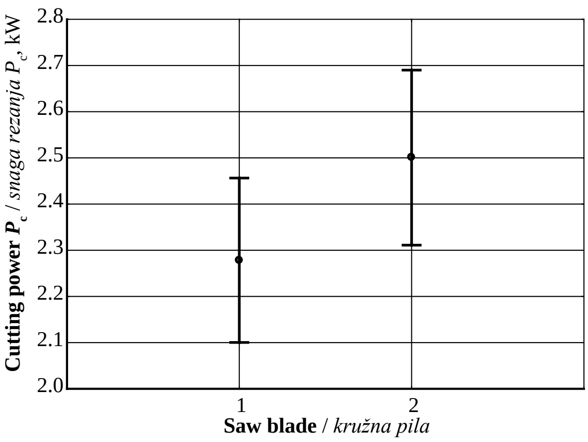

Figure 7 Impact of circular saw blade type on cutting power in sawing researched wood species
Slika 7. Utjecaj vrste kružne pile na snagu rezanja tijekom piljenja ispitivanih vrsta drva

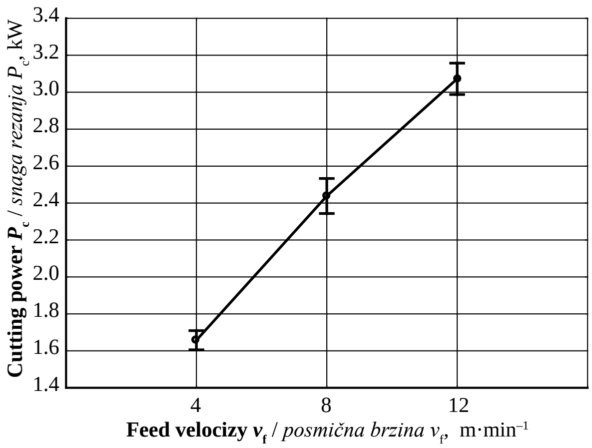

Figure 8 Impact of feed velocity on cutting power during sawing researched wood species
Slika 8. Utjecaj posmične brzine na snagu rezanja tijekom piljenja ispitivanih vrsta drva

tain the results that are statistically significant and valid. The highest interaction with the cutting process was caused by feed velocity v_f, followed by the type of circular saw blade and wood species.

Circular saw blade 1 has regular tooth pitch and a full body. Circular saw blade 2 has the same geometry of tooth made of sintered carbide inserts but it has a different shape of tooth, irregular tooth pitch and dilatation gaps.

Figure 7 it is clear that circular saw blade 2 with the same geometry of angles α, β, γ as circular saw blade 1 but different tooth spacing and dilatation gaps has higher energy consumption than circular saw blade 1. From the statistical point of view, the interaction of circular saw blade 2 is higher that the interaction of circular saw blade 1. It is supported by the level of significance $p<0.0001$ thereby there was confirmed influence of tooth spacing on energy consumption of cross-cutting wood.

Figure 8 shows the dependence between feed velocity ($v_f = 4, 8,12$ m·min^{-1}) and cutting power. The cutting power increases with increasing feed velocity. The curve is significantly linear. The course of cutting power is increasing in the whole range of chosen feed velocities.

The influence of wood species in the process of cross-cutting wood, i.e. cutting power, is shown in Figure 9. Three wood species were compared - spruce,

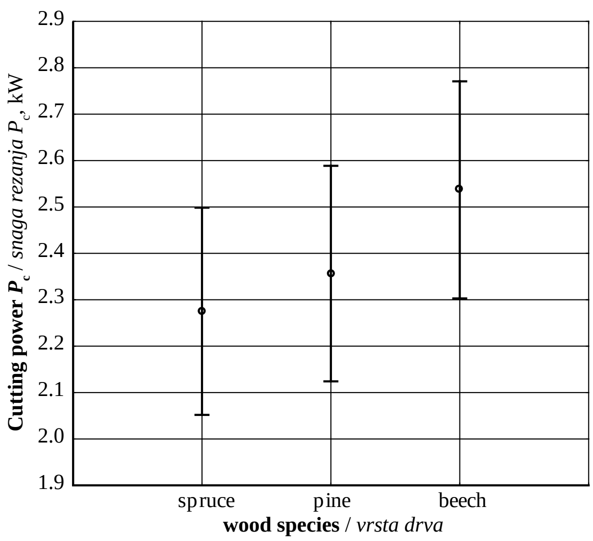

Figure 9 Impact of wood species (spruce, pine, beech) on cutting power for all feed velocities
Slika 9. Utjecaj vrste drva (smrekovina, borovina, bukovina) na snagu rezanja pri različitim posmičnim brzinama

Table 4 Basic analysis of variance of measurement results
Tablica 4. Osnovna analiza varijance mjerenjem dobivenih podataka

Effect / *Utjecajni činitelj*	**Sum of squares** *Zbroj kvadrata*	**Degrees of freedom** *Stupanj slobode*	**Variance** *Varijanca*	**Fisher´s *F*-test**	**Level of significance** *Razina signifikantnosti p*
Circular saw blade / *list kružne pile*	1.11	1	1.11	84	<0.0001
Feed velocity / *posmična brzina,* m·min^{-1}	30.13	2	15.06	1135	<0.0001
Wood species / *vrsta drva*	1.08	2	0.54	41	<0.0001
Circular saw blade * Feed velocity (m·min^{-1}) *list kružne pile * posmična brzina* (m·min^{-1})	0.09	2	0.05	4	0.033
Circular saw blade * Wood species *list kružne pile * vrsta drva*	0.17	2	0.08	6	0.003
Feed velocity v_f (*m·min^{-1}*)* Wood species *posmična brzina* (m·min^{-1}) * *vrsta drva*	0.24	4	0.06	4	0.003
Circular saw blade*Feed velocity (m·min^{1})*Wood species *list kružne pile * posmična brzina* (m·min^{-1})* *vrsta drva*	0.28	4	0.07	5	0.001

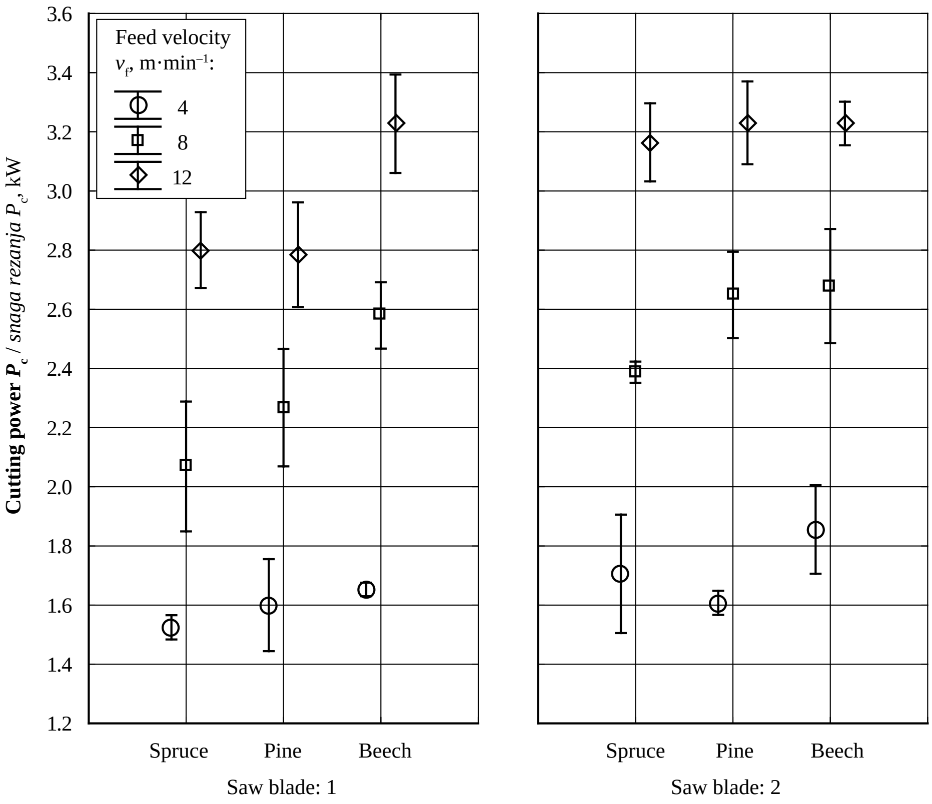

Figure 10 Impact of wood species (spruce, pine, beech), feed velocities (v_f = 4, 8, 12 m·min^{-1}) and type of circular saw blade (type 1 and 2) on wood cross-cutting process
Slika 10. Utjecaj vrste drva (smrekovine, borovine, bukovine), posmične brzine (v_f = 4, 8, 12 m·min^{-1}) i vrste kružne pile (tip 1 i 2) na postupak poprečnog rezanja drva

pine and beech. Beech consumed most energy. The lowest cutting power P_c was shown in the case of spruce.

Figure 10 shows a graph of 95 % confidence of factors affecting wood cross-cutting process i.e. spruce, pine, beech, feed velocity (v_f = 4, 8,12 m·min^{-1}) and type of circular saw blade 1 and 2.

The graph (Fig. 10) clearly shows that circular saw blade 1 with regular tooth pitch and a full body is better for wood cross-cutting process for the chosen factors. Similar values of cutting power to those of circular saw blade 2 with irregular tooth pitch and dilatation gaps were obtained in cutting pine and at the feed velocity v_f = 4 m·min^{-1}. There were also less significant differences in cutting beech and at the feed velocity v_f = 8, 12 m·min^{-1}. The levels of cutting power in cutting beech were the highest for all cutting speeds. From the graph in Figure 10, it is clear that the cutting power increases with increasing feed velocity.

Nearly the same results were obtained for spruce and beech and at the feed velocity v_f = 4 m·min^{-1}. This fact can also be observed at the feed velocity v_f = 12 m·min^{-1}. More significant difference was observed at the feed velocity v_f = 8 m·min^{-1}.

Circular saw blade 1 had the lowest difference in cutting power for all wood species at the feed velocity v_f = 4 m·min^{-1}. Circular saw blade 2 had this feature at a higher feed velocity v_f = 12 m·min^{-1}.

There was almost no difference between circular saw blades during beech cutting. The difference between circular saw blades for spruce and pine cutting was nearly the same.

The measurement showed that circular saw blade 1 had better first contact with processed material. Circular saw blade 2 had higher vibrations, bigger cutting area and cutting power.

Circular saw blade 1 is more suitable for the wood cross-cutting process than circular saw blade 2. Circular saw blade 2 should be used for longitudinal wood cutting, where longer time of cutting is necessary, providing enough time for the stabilization of a circular saw blade, which is important for reducing the effects of its parameters e.g. tension of dilatation gaps and vibrations.

4 DISCUSSION
4. RASPRAVA

In this study, the effect was assessed of feed velocity, saw blade and wood species on the cutting power P_c of spruce (*Picea abies*), pine (*Pinus sylvestris*) and beech (*Fagus silvatica*) wood during sawing with a guided circular saw. The aim of the measurement was to search and evaluate energy consumption in the wood cross-cutting process. The measured data of cutting power were analyzed by analytic software STATISICA 12. The cutting power increases with increasing feed velocity. The curve is significantly linear. Average chip thickness is a critical factor in the sawing process as it greatly affects the cutting power (Nasir *et al.*, 2018).

This is in accordance with what is reported in the literature (Axelsson *et al*., 1993; Vazquez- Cooz *et al*., 2006; Aguilera, 2011; Cristóvão *et al*., 2012). The result confirms previous cross-cutting wood tests of energy consumption (Koljozov *et al*., 2015; Kopecký *et al*., 2014; Krilek *et al*., 2014; Orlowski *et al*., 2006; Kminiak, 2007; Orlicz, 1988). The course of cutting power is increasing in the whole range of chosen feed velocities. The highest energy consumption was measured for beech. To sum up, the specific cutting resistance decreases with the increasing chip thickness (Kopecký *et al*., 2014). The formula for the calculation of the cutting power $P_c = K_c \cdot b \cdot e \cdot v_f$ and Figure 2 confirm this assertion. This phenomenon is known from metal machining, and it was also noticed in wood cutting with circular saw blades (Manžos, 1974; Orlowski, 2010; Orlowski *et al*., 2013; Kopeck *et al*., 2014) and in wood milling (Durkovic *et al*., 2018). The lowest cutting power P_c was observed in the case of spruce. The result confirms previous cross-cutting wood tests of energy consumption (Krilek *et al*., 2014; Kminiak, 2007; Kopecký *et al*., 2014).

5 CONCLUSIONS
5. ZAKLJUČAK

1. The highest cutting power is required for deciduous wood – beech, at all feed velocities (v_f = 4, 8, 12 m·min^{-1}) and circular saw blades used in the research.
2. With increasing feed velocity, energy consumption of the cutting process also increases. Feed velocity has the highest influence on the wood cross-cutting process and cutting power P_c.
3. Circular saw blade 1 with regular tooth pitch had lower energy consumption in the wood cross-cutting process than circular saw blade 2 with irregular tooth pitch for all tested wood species (spruce, pine, beech) and feed velocities (v_f = 4, 8, 12 m·min^{-1}).

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THERMODOMINUS
THERMODUX
THERMOREX
GALEKOVIĆ
Kvaliteta u tradiciji
Tvornica parketa
DUX: Gotovi lakirani masivni klasični parket
DOMINUS: Gotovi lakirani masivni klasični parket - širina 9 cm
REX: Gotovi masivni lakirani podovi - uljeni / lakirani
Termo tretirani podovi: THERMODUX, THERMODOMINUS, THERMOREX
Eksterijeri: fasade, decking
FSC
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Pine Wood Particles Pyrolysis and Radiographic Analysis

Piroliza čestica borovine i radiološka analiza

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ABSTRACT • *The goal of this experiment is to assess the mass and volume loss of medium size pine wood particles undergoing pyrolysis. Wood samples of different sizes and shapes were pyrolysed at 500 ºC with different residence times. A thermogravimetric analysis was carried out for comparison purposes. Finally, the pyrolysed samples were analysed using radiographic methods. A connection between the different analyses was found. For larger particles, the heating rate is lower, and a time gap between hemicellulose and cellulose thermal decomposition was noticed. Research shows that an important part of the analysis of the process is the rate of biomass heating and sample size. As the sample size increases, the pyrolysis time increases; however, the increase is not linear. The publication also shows the great possibilities of radiographic methods in analysing the pyrolysis process.*

Key words: *pyrolysis; biomass; thermogravimetric analysis; radiography; heat transfer*

SAŽETAK • *Cilj istraživanja bio je procijeniti gubitak mase i volumena čestica borovine srednje veličine podvrgnutih pirolizi. Uzorci drva različitih veličina i oblika pirolizirani su pri 500 °C i pri različitim vremenima trajanja pirolize. Za usporedbu je provedena termogravimetrijska analiza borovih čestica. Nakon toga pirolizirani su uzorci analizirani metodom radiografije. Pronađena je veza između različitih analiza. Brzina zagrijavanja većih čestica je niža, a primijećen je i vremenski jaz između toplinskog raspadanja hemiceluloze i celuloze. Istraživanja su pokazala da su važan dio analize procesa pirolize brzina zagrijavanja biomase i veličina uzorka. Kako se veličina uzorka povećava, tako se povećava i vrijeme pirolize, i to nelinearno. Usto, rad upućuje na velike mogućnosti radiografskih metoda u analizi procesa pirolize.*

Ključne riječi*: piroliza; biomasa; termogravimetrijska analiza; radiografija; prijenos topline*

1 INTRODUCTION
1. UVOD

Nowadays, efforts can be seen all around the globe in the direction of gaining autonomy and independence from fossil fuels, pursuing a decrease on greenhouse gas emissions and more sustainable energy future. A possible path is the use of solid biomass, which can be pyrolysed or gasified, either alone or co-processed with coal.

Pyrolysis is the thermal decomposition of organic matter in the absence of oxygen, with temperatures ranging from 200 ºC to 600 ºC. Chemical compounds are decomposed into lighter ones due to several reactions mostly of endothermic nature. The products of pyrolysis are char, bio-oil and gas, the quality and quantity of each product produced being highly influenced by the temperature, residence time, heating rate and size and shape of the particle.

Wood biomass is composed of three main components: lignin, cellulose and hemicellulose. Hemicellulose is the first to be decomposed, between 200 and 250 ºC. Cellulose breaks down in temperatures ranging from 240 to 350 ºC (Czajczyńska *et al*., 2017). Both

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hemicellulose and cellulose are decomposed in mild pyrolysis, also known as torrefaction. Lignin requires higher temperatures, from 280 up to 500 ºC (Demirbas, 2014; Shi and Wang, 2014). Since it does not break down to lighter molecular weight compounds easily, lignin is the main component of char (Lu *et al.*, 2018).

Three main kinds of reactors can be used to perform pyrolysis: fixed bed, fluidised bed and entrained flow. Fixed bed reactors are of simpler design and cheaper production, however they have a limited application. Technical issues, such as bridging and jamming of biomass, make this kind of reactor unsuitable for alternative kinds of biomass and waste (Pham *et al.,* 2018). Pelletizing can be a solution to this constraint (Erlich and Fransson, 2011). Since regular wood biomass does not lead to these inconvenient situations, it can easily be used in fixed bed reactors.

Being pyrolysis one of the first phases in gasification, and the one in which the mass decreases the most and the velocity consequently increases, an empirical understanding of the particles behaviour under such conditions would allow a better design of gasification chambers.

2 MATERIALI AND METHODS
2. MATERIJALI I METODE

Pine wood samples of a different kind were prepared, with different sizes and shapes. Cubes were of 20 mm side, larger cubes of 30 mm side, parallelepipeds of 20×20×5 mm, cylinders with 27 mm of diameter and 35 mm height and finally cylinders with 20 mm of diameter and 5 mm height. When it comes to the parallelepipeds, some of them were cut perpendicular to the grain, whilst the others were cut parallel to the grain.

First, the samples were placed at 500 ºC for different residence times, ranging from 30 s to 960 s, depending on the actual situation. Nitrogen was used to provide an oxygen-free environment to the reaction chamber. A schematic of the experimental setting can be seen in Figure 1.

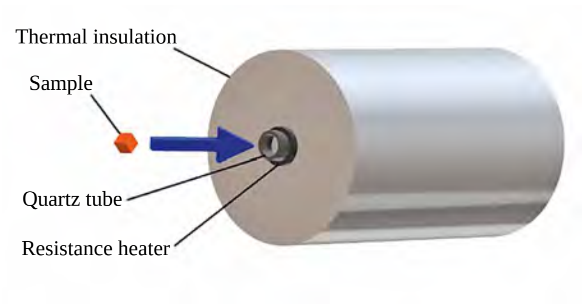

Figure 1 Schematic representation of the pyrolysis chamber used for the experiment
Slika 1. Shematski prikaz komore za pirolizu rabljene u pokusu

The accurate dimensions of each sample were measured and registered before the experiment, as well as their mass. Finally, the samples were weighted and measured again, in order to analyse the pyrolysis effect on them. The final shape of the sample would no longer be a regular one, but it was considered as so, taking the biggest possible measure into consideration. Concerning the cylinders, their base was considered as an ellipse. Mass and volume losses were calculated, as well as the density and its variation.

Lately, a thermogravimetric analysis was performed using an SDT Q600 analyser. The argon flow rate was 100 mL/min and the heating rate 100 K/min, which heated the sample up to 800 ºC.

Finally, the samples were submitted to X-ray, in order to analyse the pyrolysis effect on its inner structure. Radiographic techniques are commonly used in areas like Chemical Analysis, its non-destructive nature being one of its biggest advantages. That being said, this method allows to observe the internal structure of a sample without interfering with it, offering information of the effect of temperature and residence time of pyrolysis in a sample structure. Further ahead, the possibility of analysing the samples via X-ray whilst being pyrolysed inside the chamber could come to life, as a monitoring tool. The use of radiographic techniques is widely spread in science and technology, but the use of these methods to study pyrolysis is not common. It is a technique with large potential in basic research to better understand the pyrolysis process.

3 RESULTS
3. REZULTATI

3.1 Momentary comparison
3.1. Trenutačna usporedba

The mass, volume and density variations after pyrolysis at 500 ºC were compared for different kinds of samples at equal residence times (Figures 2-7). The mass loss was calculated by equation 1, and volume loss in a similar way. It is to be noticed that one single comparison between all kinds of samples was not possible, due to different residence time intervals tested for each shape.

$$mass\,loss\,(\%) = \frac{m_{\text{initial}} - m_{\text{final}}}{m_{\text{initial}}} \times 100\% \qquad (1)$$

It is quite visible that the smaller the sample, the higher will be the mass loss for equal residence times. When it comes to volume, the results are more irregular, but apart from the parallelepipeds cut perpendicular to the grain, the volume decrease is also lower for smaller samples. Finally, a similar situation can be seen for density variations: the smaller the sample, the more it changes.

3.2 Evolutive comparison
3.2. Naknadna usporedba

The ratio between the mass after pyrolysis and the initial one was plotted against residence time. As expected, the bigger the sample the longer it takes for it to be pyrolysed, since the heat transfer is more difficult for these cases.

3.3 Thermogravimetric analysis
3.3. Termogravimetrijska analiza

A thermogravimetric analysis was carried out for a sample weighting 5.1570 mg of pine wood, of the same origin as the tested samples.

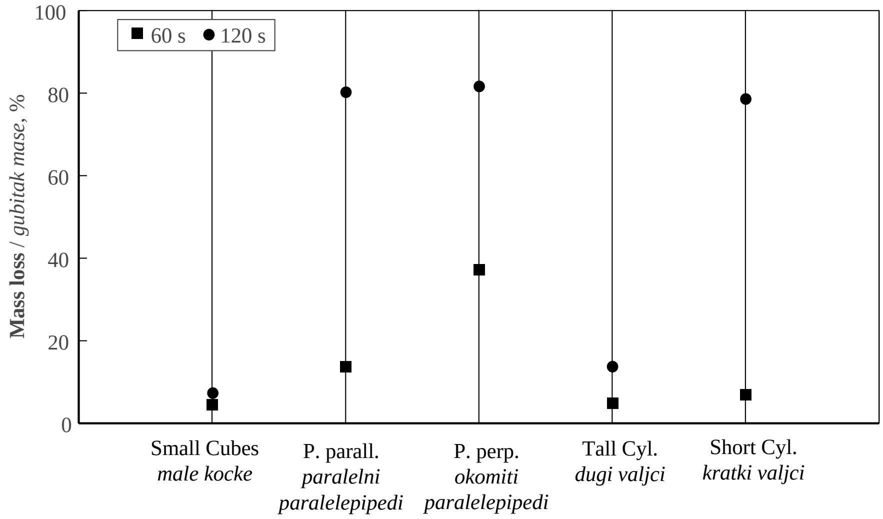

Figure 2 Comparison of mass loss at 60 s and 120 s for different shapes
Slika 2. Usporedba gubitka mase pri pirolizi od 60 i 120 s za čestice različitog oblika

There are three main slopes in the TGA curve (fig. 8). The first one, around 100 ºC, refers to the moisture release, due to water evaporation. The second one, between 300 ºC and 400 ºC, is associated to hemicellulose and cellulose degradation. After 400 ºC the curve's slope is softer since only lignin is decomposed. At 700 ºC, the sample is already completely pyrolysed.

Since the heating rate was 100 K/min, the curves turning point at 400 ºC corresponds to a residence time of 240 s.

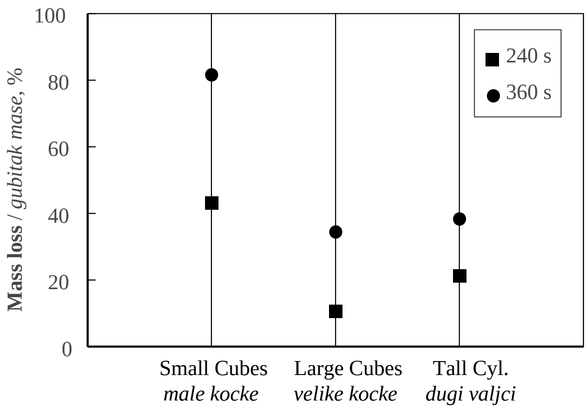

Figure 3 Comparison of mass loss at 240 s and 360 s for different shapes
Slika 3. Usporedba gubitka mase pri pirolizi od 240 i 360 s za čestice različitog oblika

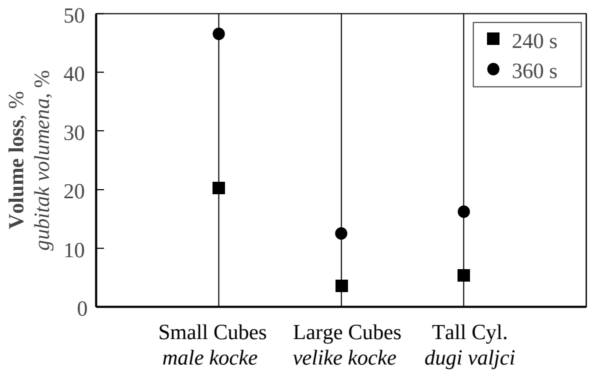

Figure 5 Volume loss at 240 s and 360 s for different shapes
Slika 5. Gubitak volumena pri pirolizi od 240 i 360 s za čestice različitog oblika

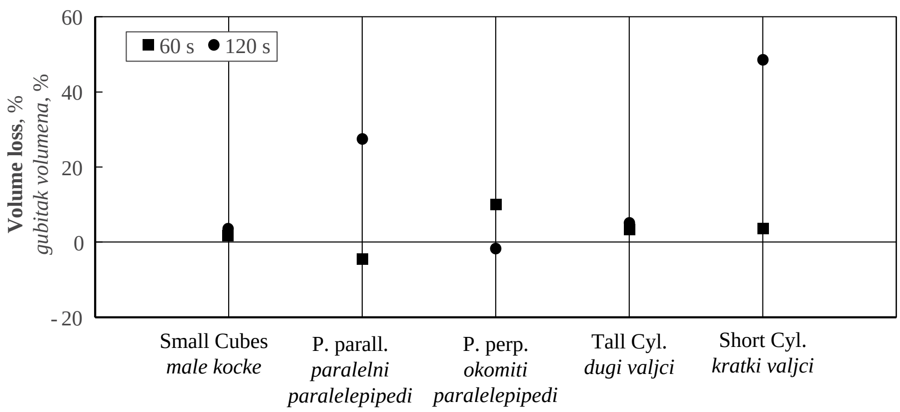

Figure 4 Volume loss at 60 s and 120 s for different samples
Slika 4. Gubitak volumena pri pirolizi od 60 i 120 s za čestice različitog oblika

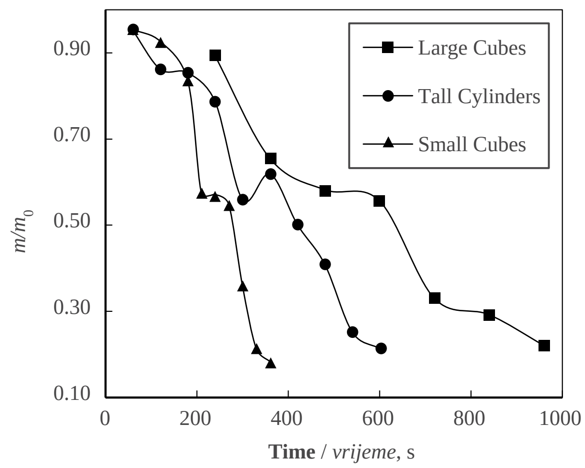

Figure 6 Ratio between final and initial mass versus residence time for larger samples
Slika 6. Odnos konačne i početne mase u ovisnosti o trajanju pirolize za velike uzorke

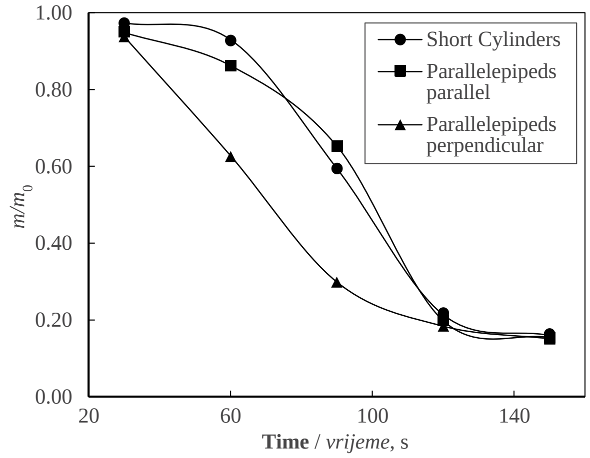

Figure 7 Ratio between final and initial mass versus residence time for smaller samples
Slika 7. Odnos konačne i početne mase u ovisnosti o trajanju pirolize za male uzorke

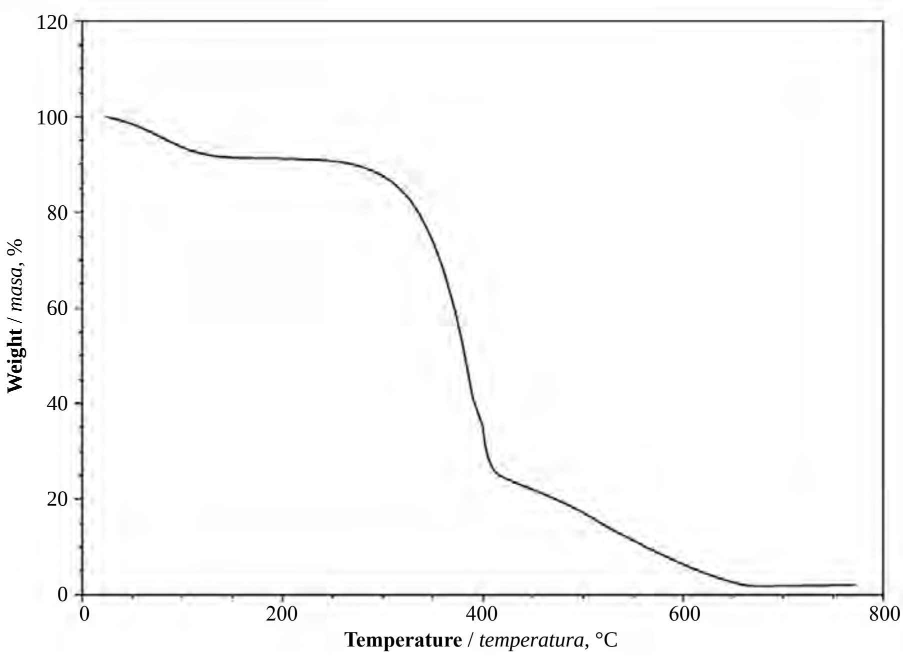

Figure 8 Thermogravimetric analysis of pine wood with an argon flow of 100 mL/min and heating rate of 100 K/min, from 0 to 800 ºC
Slika 8. Termogravimetrijska analiza borovine od 0 do 800 ºC, pri protoku argona od 100 mL/min i pri brzini zagrijavanja od 100 K/min

3.4 Radiographic Analysis
3.4. Radiografska analiza

The pyrolysed samples were exposed to X-ray with the following results:

As expected, the more pyrolysed the sample, the darker it is, since the density is lower. It is worth noticing that, when the samples crack, the crack's direction is perpendicular to the grain, as can be seen in Figure 9. Also, both in Figures 9 and 10, a lighter circle can be seen in the third sample counting from the right. This happens due to the higher exposure of the corners, which leads to their faster thermal degradation.

Figure 9 Radiographic images from larger cubic samples (30 mm side) after pyrolysis at 500 ºC. From left to right: 240 s, 360 s, 480 s, 600 s, 720 s, 840 s and 920 s
Slika 9. Rendgenske snimke uzoraka kocaka većih stranica (30 mm) nakon pirolize pri 500 °C; slijeva nadesno: nakon 240 s, 360 s, 480 s, 600 s, 720 s, 840 s i 920 s

Figure 10 Radiographic images from smaller cubic samples (20 mm side) after pyrolysis at 500 ºC. From left to right: 60 s, 120 s, 180 s, 210 s, 240 s, 270 s, 300 s, 330 s and 360 s
Slika 10. Rendgenske snimke uzoraka kocaka manjih stranica (20 mm) nakon pirolize pri 500 °C; slijeva nadesno: nakon 60 s, 120 s, 180 s, 210 s, 240 s, 270 s, 300 s, 330 s i 360 s

Figure 11 Radiographic images of perpendicular parallelepipeds with approximately 20×20×5 mm, after pyrolysis at 500 ºC. From left to right: 30 s, 60 s, 90 s, 120 s and 150 s
Slika 11. Rendgenske snimke okomitih paralelepipeda (približno 20 × 20 × 5 mm) nakon pirolize pri 500 °C; slijeva nadesno: nakon 30 s, 60 s, 90 s, 120 s i 150 s

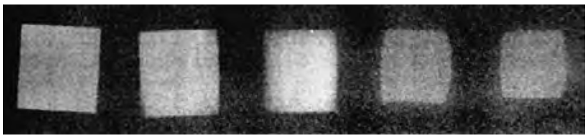

Figure 12 Radiographic images of parallel parallelepipeds with approximately 20×20×5 mm, after pyrolysis at 500 ºC. From left to right: 30 s, 60 s, 90 s, 120 s and 150 s
Slika 12. Rendgenske snimke paralelnih paralelepipeda (približno 20 × 20 × 5 mm) nakon pirolize pri 500 °C; slijeva nadesno: nakon 30 s, 60 s, 90 s, 120 s i 150 s

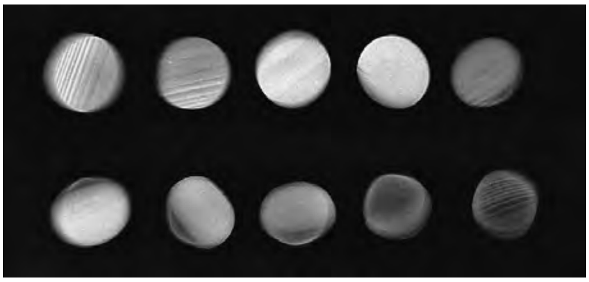

Figure 13 Radiographic images of cylindrical samples with approximately 27 mm of diameter and 35 mm height, after pyrolysis at 500 ºC. From left to right and top to bottom: 60 s, 120 s, 180 s, 240 s, 300 s, 360 s, 420 s, 480 s, 540 s and 600 s
Slika 13. Rendgenske snimke valjkastih uzoraka približnog promjera 27 mm i visine 35 mm nakon pirolize pri 500 °C; slijeva nadesno i odozgo prema dolje: nakon 60 s, 120 s, 180 s, 240 s, 300 s, 360 s, 420 s, 480 s, 540 s i 600 s

Figure 14 Radiographic images for cylindrical samples with approximately 20 mm of diameter and 5 mm height, after pyrolysis at 500 ºC. From left to right: 30 s, 60 s, 90 s, 120 s and 150 s
Slika 14. Rendgenske snimke valjkastih uzoraka približnog promjera 20 mm i visine 5 mm nakon pirolize pri 500 °C; slijeva nadesno: nakon 30 s, 60 s, 90 s, 120 s i 150 s

By analysing Figure 13, it can be noted that the biggest diameter is perpendicular to the heat source, and corresponds to the darkest area in the samples. This happens because the highest volume loss takes place in the direction of the heat transfer, which corresponds to the smallest diameter.

4 DISCUSSION
4. RASPRAVA

The smaller the samples, the bigger was the loss of mass. The mass decrease was also more significant for the samples cut perpendicular to the growth direction, meaning it was easier for the moisture and volatiles to be released in these samples than in the ones cut parallel to the grain. For density variations, a similar situation can be observed, with the exception of the short cylinder sample pyrolysed for 30 s, whose density increased.

When it comes to volume, it would not always decrease. Due to the release of the volatile matter, the samples would shrink, but also stretch in the direction of release, which would sometimes increase their final value. It is worth noticing, however, that this fluctuation is only visible for the samples of smaller size. Once again, this was more noticeable for the perpendicular parallelepipeds, meaning that the gas release and its consequence on the sample's geometry were more intense for them. This situation was also noticed by Ronewicz *et al.* (2016), who considered it a consequence of the pressure of released volatiles. However, this might also be a by-product of incorrect measurements, since once the shape became irregular, the biggest dimension possible would be taken, which might mislead to bigger volumes than is actually true.

It is acceptable to assume that the mass of wood chips will also decrease with the pyrolysis residence time. Since wood chips have a smaller and more irregular form than the samples used, it is likely that the volume will vary in a more uncertain way, leading to possible volume increases, as was the case with parallelepipedal samples, or even to density increases, just as with the first short cylindrical sample.

When analysing the mass variation with time, it is possible to see that the turning point for the smaller cubes is around 240 s, just as in the thermogravimetric analysis. This indicates that the heating rate for these samples was close to 100 K/min. For the larger samples, the turning point happens at higher residence times, as expected. However, it was surprising to notice that it took less time for the smaller samples than for the TGA, meaning that heating rates were higher for the first ones. In fact, since the turning point is around 120 s, it is acceptable to assume that the heating rate should be around 200 K/min for these cases.

The heat transfer is delayed due to the release of volatiles from within the sample. However, the situation changes when it comes to the smaller samples, which have a significantly reduced height in comparison to the base area. These proportions facilitate the release of gases in the height direction, which increases the heat transfer in other directions. This proposal is supported by differences between the perpendicular and parallel parallelepipeds. In the first ones, the gas release is easier, and indeed the mass and density variations have always been more accentuated for perpendicular than for parallel parallelepipeds.

For the large samples, a flat zone between the two main decreases in the mass ratio can be found. The two most accentuated slopes correspond to the degradation of hemicellulose and cellulose, respectively. This flat zone cannot be observed in the smaller samples nor in the TGA, which means that it is a by-product of the more difficult heat transfer due to the sample size and shape.

In the X-ray images of the small and large cubes (Figures 9 and 10), a lighter circle can be seen for 300 s and 720 s, respectively. Once again, this indicates the delayed heat transfer due to the gases released out. It is to be noticed that such density contrast cannot be seen in the parallelepipedal samples, which supports the hypothesis that their structure and increased surface area per mass facilitate the gas release, improving the heating rate.

The subject has not yet been sufficiently explored. Particularly noteworthy is the paper (Dhanarathinam and Kolar, 2013), which also deals with the use of radiography in the analysis of pyrolysis of a single particle. The paper confirms the possibility of using X-rays to analyse the ratio of wood particle decomposition.

5 CONCLUSION
5. ZAKLJUČAK

The mass, volume and shape of the sample have a strong influence on the pyrolysis rate. Overall, the higher the initial mass and volume, the lower is the pyrolysis heating rate, and, therefore, the lower is the mass and volume decrease. Obtaining various products depending on the process parameters is confirmed by the work of other authors (Basu, 2010).

Testing different shapes and sizes gives a diverse range of heating rates, and therefore it can be taken as a good approximation of a real case scenario, in which each particle has its own characteristics.

It is possible to establish a bridge between the X-ray and the thermogravimetric analysis results for larger cubic samples, since the appearance of the circle indicates the turning point after hemicellulose and cellulose decomposition has occurred.

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Synthesis of Bio-Oil-phenol-Formaldehyde Resins under Alkali Conditions: Physical, Chemical and Thermal Properties of Resins and Bonding Performance

Sinteza bioulja s fenolformaldehidnim smolama u alkalnim uvjetima: fizička, kemijska i toplinska svojstva smola i svojstvo lijepljenog spoja

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ABSTRACT • *In the present study, bio-oil produced from vacuum pyrolysis of woody biomass has been investigated as a source of chemical feedstock. Bio-based resins were produced using the bio-oil with phenol substitutions ranging from 10 to 30 wt%. The conventional GC/MS analysis was carried out for the evaluation of the chemical composition of bio-oil. TGA, DSC and FT-IR analyses were used in order to characterize the bio-oil-phenol-formaldehyde (BPF) resins. The bonding quality of wood samples bonded with the BPF resins was investigated under different pre-treatment conditions. The highest shear strength was observed for the control samples bonded with the laboratory PF resin. As the amount of bio-oil was increased up to 30 wt%, the shear strength of the samples decreased from 12.08 to 11.76 N/mm². The bonding performance was not negatively affected by the combination of bio-oil under dry conditions. According to TS EN 12765 standard, the relevant performance requirements for bonded samples under dry conditions must be at least 10 N/mm². Relating to the standard, all samples bonded with BPF resins obtained the requirements for durability class C1. Under wet conditions, the bonding performance was negatively affected by the addition of bio-oil. However, the BPF resins fulfilled the durability requirements for C1, C2, and C3 specified in EN 12765 (2002).*

Keywords*: bio-phenol; bonding performance; phenol formaldehyde resin; shear strength*

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SAŽETAK • *U radu je predstavljeno istraživanje mogućnosti upotrebe bioulja dobivenoga vakuumskom pirolizom drvne biomase kao izvora kemijske sirovine. Biosmole su dobivene zamjenom 10 – 30 % mase (ili težinskog udjela) fenola biouljima. Analiza kemijskog sastava bioulja provedena je GC/MS metodom. Za karakterizaciju biouljnih fenolformaldehidnih smola (BPF) primijenjene su TGA, DSC i FT-IR analiza. Kvaliteta spoja uzoraka drva slijepljenih BPF smolama ispitivana je pri različitim uvjetima predobrade. Najveća čvrstoća na smicanje postignuta je na kontrolnim uzorcima lijepljenim laboratorijskim PF smolama. S povećanjem udjela bioulja do 30 % mase (ili težinskog udjela), čvrstoća na smicanje smanjila se s 12,08 na 11,76 N/mm². Prema normi TS EN 12765, čvrstoća na smicanje u suhim uvjetima treba biti najmanje 10 N/mm². Kombinacija bioulja s fenolformaldehidnim smolama nije negativno utjecala na svojstva slijepljenog spoja u suhim uvjetima i svi uzorci lijepljeni BPF smolama zadovoljili su zahtjeve klase trajnosti C1. U vlažnim uvjetima dodatak bioulja negativno je utjecao na svojstva slijepljenog spoja. Međutim, BPF smole ispunile su zahtjeve trajnosti za klase C1, C2 i C3 propisane normom EN 12765 (2002).*

Ključne riječi: *biofenol; svojstva lijepljenog spoja; fenolformaldehidna smola; čvrstoća na smicanje*

1 INTRODUCTION
1. UVOD

Currently, the global demand for chemicals is supplied largely from petroleum-based products. Because of the growing concern for the significant environmental problems and reduction of availability of fossil energy resources, researchers have been studying renewable feedstocks to replace petroleum. There are many similarities between biomass and crude oil in terms of their use as chemical feedstocks. Biomass offers viable greener, lower cost alternative feedstock to the chemical production (Gosselink *et al*., 2004; Bozell, 2002; Yanik *et al*., 2007; Connor and Piskorz, 1994).

Pyrolysis is thermal decomposition occurring in the nonexistence of oxygen to liquid, gaseous and solid fractions. Bio-oil acquired from pyrolysis includes phenols, aldehydes, alcohols and carboxylic acids that can be utilized for the production of adhesives, fertilizers, various chemicals, etc. (Bridgwater, 2003; Abu Bakar and Titiloye, 2013; Özbay, 2015; Rioche *et al*., 2005; Yaman, 2004).

Phenol-formaldehyde resins (PF) are cross-linkable polymeric resins made from phenol and formaldehyde in the presence of a catalyst. Depending on the pH of the catalyst, these monomers react to form one of two main resin types: resol and novolac reins. A basic catalyst is generally used in formulating the resol type of resins. They are used successfully for the production of wood composites, because of their high bonding strength and extreme resistance to moisture (Junming *et al*., 2010; Christjanson *et al*., 2010; Moubarik *et al*., 2009). They are, however, relatively expensive as regards the phenol price. Therefore, there have been many attempts to replace phenol with renewable resources, such as lignin, soybean, tannin or bio-oil, etc. in the production of phenol–formaldehyde (PF) resins (Alma *et al*., 2001; Wang *et al*., 2005; Tejado *et al*., 2007; Moubarik *et al*., 2009; Fan *et al*., 2009; Jiang *et al*., 2010; Hoong *et al*., 2011; Lee *et al*., 2011; Kouisni *et al*., 2011; Shahid *et al*., 2014; Aslan *et al*., 2015).

In the present study, bio-oil produced from vacuum pyrolysis of woody biomass has been investigated as a renewable chemical feedstock. The chromatography–mass spectrometry (GC/MS) analysis was carried out for the evaluation of the chemical composition of bio-oil. The bio-oil was chemically synthesized with phenol and formaldehyde at 10 wt%, 20 wt%, and 30 wt% phenol replacement levels under alkaline conditions. BPF resins were characterized by several thermal and chemical analyses such as TGA, DSC, and FT-IR. In addition, the shear strengths of wood samples were investigated under both dry and wet conditions.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Biomass and chemicals
2.1. Biomasa i kemikalije

In this study, pine sawdust was used for the pyrolysis process as woody biomass. Prior to the experiments, the raw material was dried and ground. The particles with the size of 1-2 mm were selected for the experiments.

A commercial PF and laboratory PF resins were considered as reference resins in this work. The commercial PF adhesive was provided by POLİSAN chemical company in Izmit, Turkey. BPF resins were prepared by using phenol (liquid) and formaldehyde aqueous solution (37 %) supplied by GENTAŞ chemical company, İzmit, Turkey. Sodium hydroxide pellets were purchased from Sigma Aldrich.

2.2 Bio-oil production from biomass
2.2. Proizvodnja bioulja od biomase

The pyrolysis experiments were implemented in a vacuum pyrolysis reactor having 24 cm × 36 cm interior diameter and depth, respectively. The reactor was electrically heated externally. During the pyrolysis process, pyrolysis temperature was operated with a Proportional–Integral–Derivative controller. The total pressure was fixed at about 10 kPa. For the pyrolysis; 2000 g sample of biomass was placed into the reactor and the experiments were performed with a heating rate of approximately 15 °C/min to the final temperatures of 500 °C and held for 60 min. The bio-oil was collected by condensation in a condenser connected to the reactor exit. The bio-oil was filtered through the filter paper with a mesh size of 75 μm.

2.3 Chemical properties of bio-oil
2.3. Kemijska svojstva bioulja

The chromatography–mass spectrometry (GC/MS) analysis was carried out for the determination of the chemical composition of bio-oil (Agilent 6890). Helium was used as the carrier gas. The oven temperature was set to start at 40 °C and gradually raised to the final temperature of 300 °C.

2.4 Chemical synthesis of resins
2.4. Kemijska sinteza smola

The reactions were performed in a glass reactor equipped with a stirrer, a reflux condenser, and a heating part. In a typical synthesis of a laboratory-made PF resin (lab. PF), the reactor was first filled with 1000 g of phenol and 1100 g formaldehyde (37 wt%). The temperature was increased to 60 °C and then 62.5 g of NaOH solution (50 wt%) was added to the process. The blend was mixed and heated up to 90 °C, and then held at that temperature for 90 min. Finally, the second part of NaOH (50 wt%.) solution was charged at a temperature of 60 °C. After the reaction, the process was cooled to room temperature. The same procedure was applied for bio-oil/PF resins synthesis. By varying the amount of bio-oil in the reaction mixture, a series of phenol substitutions were synthesized ranging from 10 to 30 wt%.

2.5 Physical characterization of resins
2.5. Određivanje fizičkih svojstava smola

The pH and dynamic viscosity values were determined with a digital pH meter and a rotational viscometer at 25 °C, respectively. Gel times were calculated at 100 °C. The solid contents of the resins were determined by weighing 2 g of the resin in a glass plate. The glass plate was placed in an oven at 120 °C for 120 min and it was desiccated and weighed to find the weight of dry resin remaining.

2.6 Thermogravimetric analysis (TGA)
2.6. Termogravimetrijska analiza (TGA)

The thermal decomposition behavior of resins was analyzed by using a HITACHI STA 7300. For the thermogravimetric analysis (TGA), nearly 10 mg of the sample was heated at a 5 °C/min heating rate up to the final temperature of 700 °C. The carrier gas was nitrogen with a flow rate of 25 ml/min.

2.7 Differential scanning calorimetry analysis (DSC)
2.7. Diferencijalna pretražna kalorimetrija (DSC)

DSC analyses were carried out using a DSC7000X. About 5 mg of samples (resin) was applied to a stainless-steel crucible. Scans were performed at a temperature of 50 – 550 °C at a 10 °C/min heating rate.

2.8 Fourier-transform infrared spectroscopy (FT-IR)
2.8. Fourierova transformacijska infracrvena spektroskopija (FT-IR)

FT-IR spectra were recorded on an Alpha FT-IR spectrometer by direct transmittance using KBr pellet technique. 10 scans were recorded for each sample with a resolution of 4 cm^{-1} over a range from 4000 to 400 cm^{-1}.

2.9 Sample preparation and property testing
2.9. Priprema uzoraka i ispitivanje svojstava

The beech wood (*Fagus orientalis* Lipsky) planks provided from a commercial company in Karabuk, Turkey were used as wood material. The lamellas (5 mm × 20 mm × 150 mm) were prepared from the planks for shear strength tests. Prior to tests, the lamellas were conditioned (20 °C and 65 % relative humidity) to reach the equilibrium moisture content of 12 %. The resin was implemented on one surface of the lamella using a hand brush at a rate of 180 g/m^2 as suggested by the manufacturer. The pressure, temperature, and duration were set as 0.2 N/mm^2, 130 ºC, and 15 min, respectively. Bonded samples were conditioned for 7 days in the standard climate room and then cut into samples. The dimensions and shape of a typical sample are shown in Figure 1.

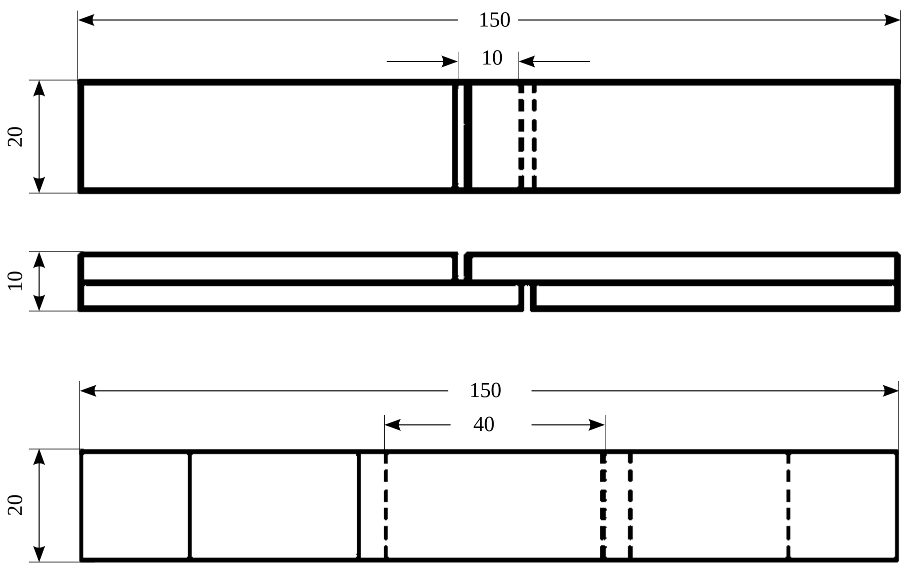

Figure 1 Shear strength test sample (size given in mm)
Slika 1. Uzorci pripremljeni za ispitivanje čvrstoće na smicanje (dimenzije su u milimetrima)

Table 1 Proposed scale to evaluate the quality of bond lines based on their strength and durability
Tablica 1. Predložene vrijednosti za ocjenu kvalitete lijepljenog spoja na temelju čvrstoće i trajnosti

Test number *Broj tretmana*	**Test conditions** *Uvjeti tretmana*	**Scale / Strength, N/mm²** *Razred / Čvrstoća,* N/mm²			
		C1	C2	C3	C4
Pre-treatment 1 *predobrada 1.*	7 days in standard conditions *7 dana u standardnim uvjetima*	≥10	≥10	≥10	≥10
Pre-treatment 2 *predobrada 2.*	7 days in standard conditions / *7 dana u standardnim uvjetima* 24 h in cold water at (20±5) °C/ *24* h *u hladnoj vodi pri* (20±5) °C	-	≥7	≥7	≥7
Pre-treatment 3 *predobrada 3.*	7 days in standard conditions / *7 dana u standardnim uvjetima* 3 h in boiled water / *3* h *u kipućoj vodi* 2 h in cold water at (20±5) °C / *2* h *u hladnoj vodi pri* (20±5) °C	-	-	-	≥4

Classified samples were divided into three subgroups for different pre-treatments, prior to the evaluation according to TS EN 12765 standard. Table 1 summarizes the proposed criteria for evaluating the quality of bonds according to this standard. The first sample groups (pre-treatment 1) was evaluated in dry conditions after conditioning for 7 days (65±5 % relative humidity, 20±5 °C standard climate); the second group of samples (pre-treatment 2) was soaked in cold water (20 °C) for 24 h; the third group of samples (pre-treatment 3) was boiled for 3 h, then cooled in water (20 °C) for 2 h. The determination of shear strength was performed in a universal testing machine, according to BS EN 205.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Chemical composition
3.1. Kemijski sastav

Table 2 presents the chemical characterization of the bio-oil. The bio-oil consists mainly of oxygenated organics (aldehydes, ketones, phenols, benzenes, alcohols, and polycyclic aromatic hydrocarbon). It was found that phenols were the main component in the bio-oil. The most abundant phenols in the bio-oil include phenol, 2-methyl-phenol, 4-methyl-phenol, 2-methoxy-phenol, 2,5-dimethyl-phenol, and 2-methoxy-4- methyl-phenol. The compounds found in the bio-oil correspond well to the literature (Ingemarsson *et al*., 1998; Kang *et al*., 2006; Ren *et al*., 2012; Kim *et al*., 2014; Fukuda, 2015; Özbay *et al*., 2015).

3.2 Characterization of resins
3.2. Karakterizacija smola

The results of the physical properties of the resins are displayed in Table 3. The pH values of all resins were similar due to the fact that pH values were continuously adjusted during the synthesis process. The viscosities of the BPF resins were higher than those of reference resins, and also, gradually increased with the increasing addition of bio-oil. This result may be due to the fact that high molecular weight compounds in the bio-oil cause high viscosity in bio-based resins. The solids content of 10-30 % BPF resins were 44.32 wt%, 46.61 wt% and 46.76 wt%, respectively. The solid content of the laboratory PF resin (40.67 wt%) was lower than that of BPF resins and the solids content increased as the bio-oil per-

Table 2 GC/MS characterization of bio-oil
Tablica 2. GC/MS karakterizacija bioulja

RT, min	**Name of compound** / *Naziv spoja*	**Area, %** / *Površina,* %	**Category** / *Kategorija*
14.65	5-Methyl-2-furancarboxaldehyde	2.00	Aldehyde
15.86	Phenol	7.33	Phenol
18.92	2-Methyl-phenol	4.15	Phenol
19.75	4-Methyl-phenol	9.82	Phenol
20.10	2-Methoxy-phenol	3.40	Phenol
20.72	1-Methoxy-3-methyl-benzene	0.16	Benzene
22.25	2,5-Dimethyl-phenol	3.16	Phenol
23.22	Naphthalene	4.09	Benzene
23.67	2-Methoxy-4- methyl-phenol	6.66	Phenol
23.88	1,2-Benzenediol	4.34	Alcohol
25.73	4-Methyl 1,2-benzenediol	2.06	Alcohol
26.30	Pyrazine	2.93	PAH
26.58	4-Methyl 1,2-benzenediol	3.85	Alcohol
26.63	1-Methyl-naphthalene	1.18	Benzene
28.77	2-Methoxy-4-propenyl-phenol	0.78	Phenol
29.15	4-Ethyl-1,3-benzenediol	2.74	Alcohol
30.81	Biphenylene	2.04	Benzene
32.96	1-(4-Hydroxy-3-methoxyphenyl)-2-propanone	0.52	Ketone
34.11	Fluorene	1.96	Benzene
38.50	Cyclopropenone	2.70	Ketone
40.99	3-Methyl-phenanthrene	0.99	Benzene

Table 3 Physical properties of PF resins
Tablica 3. Fizička svojstva PF smola

Properties *Svojstva*	**Reference resins** *Referentne smole*		**BPF resins** *BPF smole*		
	Com. PF	**Lab. PF**	**10 wt% bio-oil**	**20 wt% bio-oil**	**30 wt% bio-oil**
pH at 20 °C / *pri 20 °C*	11.90	11.96	11.83	11.78	11.75
Viscosity at 25 °C, cPs *viskoznost pri 25 °C*, cPs	310	240	340	366	398
Gel time at 100 °C, s *vrijeme želiranja pri 100 °C*, s	185	172	160	142	117
Solids content, % *sadržaj suhe tvari*, %	48.84	40.67	44.32	46.61	46.76

centage in the resin increased. This could be due to the lower reactivity of bio-oil when compared to phenol. Commercial PF resin had the highest solid content (48.84 wt%). Fan *et al*. (2010) reported that faster curing PF resins can be produced by the addition of urea during or after the resin synthesis process. The highest solids content might be caused by urea in the commercial PF resin. BPF resins had the shortest gel time when compared with the reference PF resins. These results were in good agreement with the literature data of the properties of the bio-based adhesives (Sarkar and Adhikari, 2000; Tejado *et al*., 2007; Wang *et al*., 2009; Zhao *et al*., 2010; Wang *et al*., 2011; Cheng *et al*., 2012; Yi *et al*., 2012).

The TGA curves of the resins (i.e. the bio-oil modified/commercial/lab.) are presented in Figure 2. The thermal behavior of the commercial PF resin was different from that of the laboratory PF resins and the BPF resins after the temperature was higher than approx. 150 °C. This higher thermal degradation is due to the fact that commercial PF resin contains an amount of urea decomposing easily at high temperatures. It was observed that the lab. PF resin and all of the BPF resins had a similar trend of thermal behavior. The highest thermal degradation of the BPF resins was determined in the 30 % bio-oil PF resin. In the literature, thermal degradation of bio-based PF resins obtained from the different renewable feedstocks were a rough match to our results (Wang *et al*., 2009; Domínguez *et al*., 2013; Zhao *et al*., 2013).

Figure 3 shows the DSC thermograms obtained at a heating rate of 10 °C/min for all resins from 50 to 550 °C. As shown in Figure 3, the DSC thermograms of all resins had a multiple peak structure. The main endothermic peak was detected between 125 and 136 °C for all resins. The formation of these peaks might be connected to the condensation of phenol or bio-oil with methylol groups in order to create a methylene bridge and the condensation of two methylol groups in order to create dibenzyl ether bridges and the cross-linking condensation of the methylene bridges (Christiansen and Gollob, 1985; Gabilondo *et al*., 2007; Wang *et al*., 2009). All modified resins showed the second peak at a lower temperature than commercial PF. DSC thermograms obtained in this study were consistent with the earlier research of thermal behavior of bio-based adhesives (Khan *et al*., 2004; Cheng *et al*., 2012; Lin *et al*., 2014).

BPF resins were fractionally and structurally characterized by FT-IR spectroscopy; the 4000-400 cm^{-1} infrared spectral region is shown in Figure 4. The reference resins (commercial and lab. PF resins) were also analyzed as a comparison.

The O–H stretching vibrations between 3600 and 3200 cm^{-1} represent the existence of phenols. The peak around 1600 cm^{-1} was assigned to the aromatic ring vibrations, indicating the existence of phenols in resins. A new peak was observed at around 1650 cm^{-1}, attributed to C=O stretching, indicating carbonyl compounds in the BPF resin. All the resins have the aromatic rings around 1450 cm^{-1}, phenolic C–O stretching around 1200 cm^{-1}, C–O stretching around 1000 cm^{-1}. The peaks around 900 cm^{-1}, 800 cm^{-1}, and 750 cm^{-1}

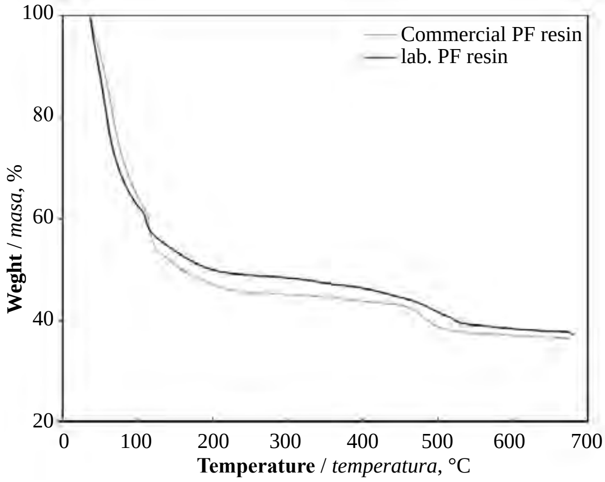

Figure 2 TGA analysis of resins
Slika 2. TGA analiza smola

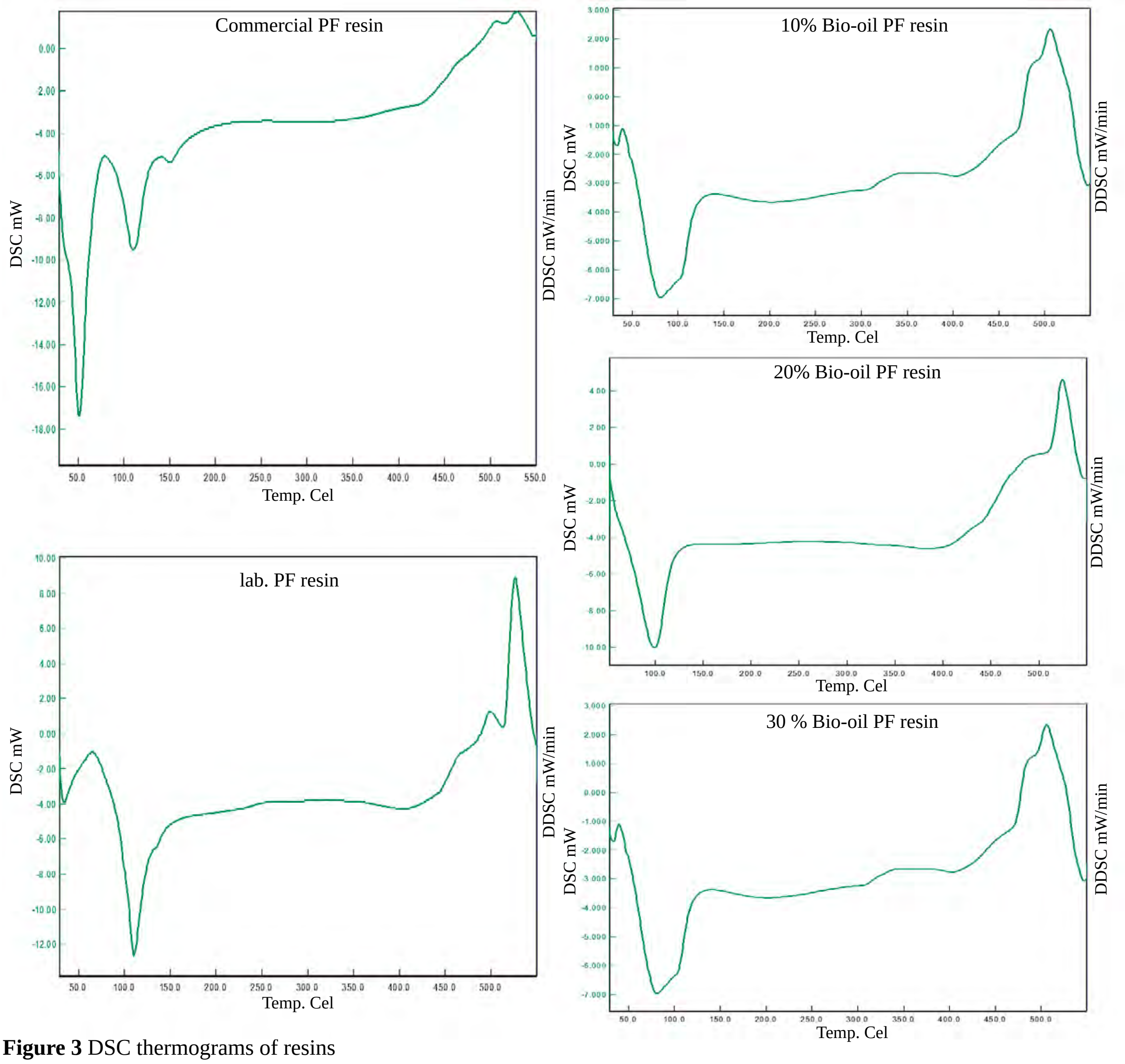

Figure 3 DSC thermograms of resins
Slika 3. DSC termogrami smola

were related to the bending vibration of C–H in the aromatic rings. Cui and co-workers reported that the BPF resins have similar FT-IR spectra as PF resin. This indicates that the BPF resins display a similar molecular structure as the PF resin (Cui *et al*., 2016). According to FT-IR analysis, it can be claimed that bio-based resol resins were successfully produced by polymerization of phenol, bio-oil and formaldehyde.

3.3 Bond performance
3.3. Svojstva lijepljenog spoja

The shear strength and wood failure of the samples bonded with the BPF, lab. PF and commercial PF resins are given in Table 4. Under dry conditions, the percentage of wood failure was almost 100 %, except for 30 wt% modified BPF resin that was a bit lower (97 %). According to Table 4, the bonding performances of all resins are satisfying. The highest shear strength was observed for the control samples bonded with the lab. PF resin. As the amount of the bio-oil was increased up to 30 wt%, the shear strength of the samples decreased from 12.08 to 11.76 N/mm^2. The bonding performance was not negatively affected by the combination of bio-oil under dry condition. According to TS EN 12765 standard, the relevant performance requirements for bonded samples under dry condition must be at least 10 N/mm^2. Relating to the standard, all samples bonded with BPF resins obtained the requirements for durability class C1.

The shear strength and wood failure values of all samples after 24 h soaking in water (pre-treatment 2) are presented in Table 4. The shear strength of wood bonded with the reference PF resins was higher than that of BPF resins. The shear strength was gradually decreased with increasing concentration of the bio-oil. For pre-treatment 2, the reference resins had the highest percentage of wood failure (100 % - 97 %). All the BPF samples showed a lower percentage of wood failure (especially samples bonded with 30 wt% BPF resin), The BPF resins containing 10-30 wt% bio-oil fulfilled the requirements for durability class C2 (EN 12765).

For pre-treatment 3, similar trends were observed as for pre-treatment 2. The strength values of the samples decreased after pre-treatment 3 as compared with pre-treatment 1 and 2. The bond line was more or less negatively affected by the presence of the bio-oil. As

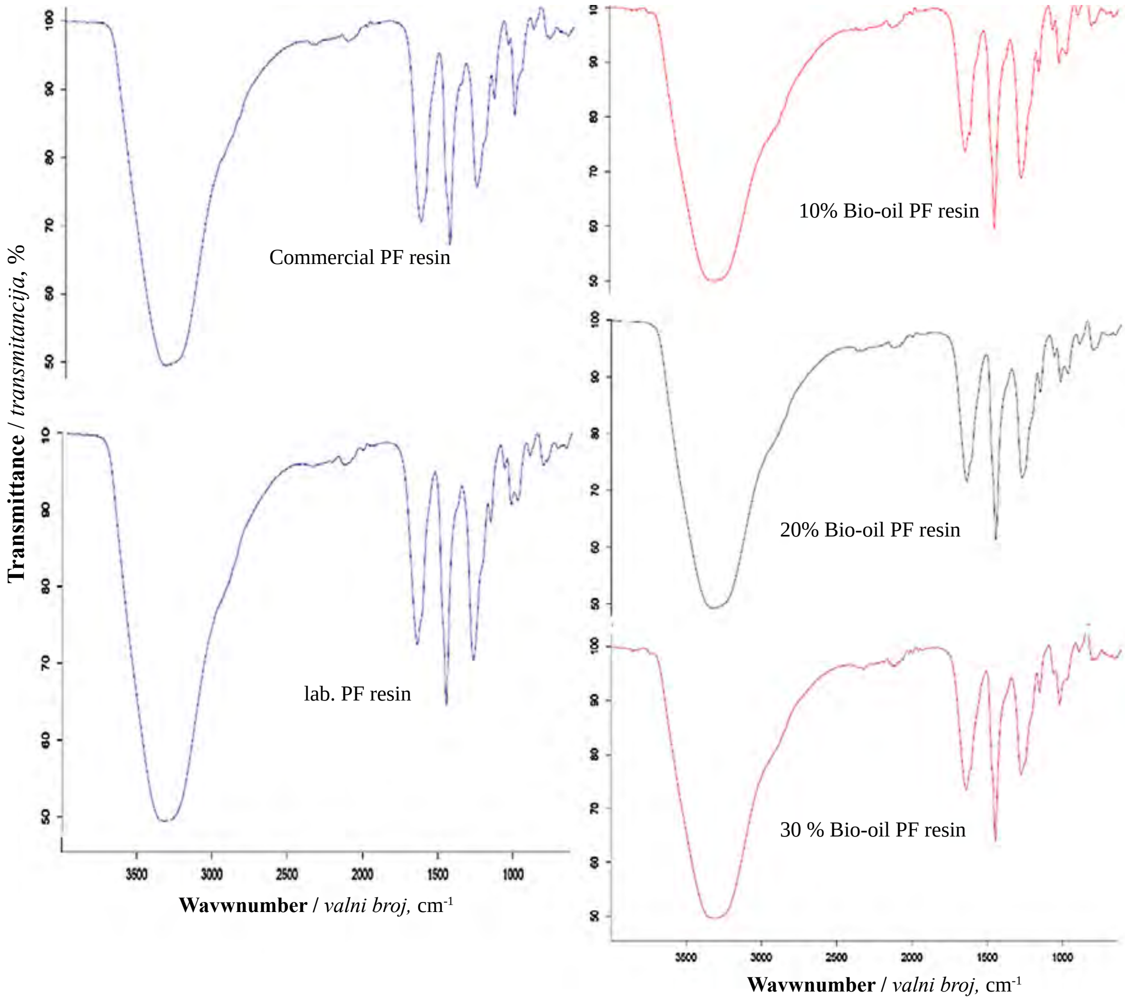

Figure 4 FT-IR spectra of resins
Slika 4. FT-IR spektri smola

Table 4 Shear strength and wood failure (%)
Tablica 4. Čvrstoća na smicanje i lom po drvu (%)

Type of resin *Vrsta smole*	**Shear strength, N/mm² / wood failure, %** *Čvrstoća na smicanje,* N/mm² */ lom po drvu,* %	**Conditions** / *Uvjeti*		
		Dry condition (Pre-treatment 1) / St. Dev *Suhi uvjeti (predobrada 1.) / standardna devijacija*	**24 h submersion in water (Pre-treatment 2) / St. Dev** *24 h potapanja u vodi (predobrada 2.) / standardna devijacija*	**3 h boiling and then 24 h submersion in water (Pre-treatment 3) / St. Dev** *3 h kuhanja i 24 h potapanja u vodi (predobrada 3.) / standardna devijacija*
Commercial PF resin *Komercijalna PF smola*	Shear strength / *čvrstoća na smicanje*, N/mm²	11.94 ± 0.13	8.17 ± 0.23	5.65 ± 0.39
	Wood failure / *lom po drvu*, %	100	100	96
Lab. PF resin *Laboratorijska PF smola*	Shear strength / *čvrstoća na smicanje*, N/mm²	12.04 ± 0.26	7.91 ± 0.31	5.78 ± 0.24
	Wood failure / *lom po drvu*, %	100	100	94
10 wt% bio-oil PF resin *PF smola s 10 wt% bioulja*	Shear strength / *čvrstoća na smicanje*, N/mm²	11.90 ± 0.11	7.73 ± 0.19	5.43 ± 0.21
	Wood failure / *lom po drvu*, %	100	96	85
20 wt% bio-oil PF resin *PF smola s 20 wt% bioulja*	Shear strength / *čvrstoća na smicanje*, N/mm²	11.88 ± 0.23	7.47 ± 0.21	5.37 ± 0.33
	Wood failure / *lom po drvu*, %	100	92	74
30 wt% bio-oil PF resin *PF smola s 30 wt% bioulja*	Shear strength / *čvrstoća na smicanje*, N/mm²	11.76 ± 0.19	7.12 ± 0.33	4.43 ± 0.36
	Wood failure / *lom po drvu*, %	97	84	70

the amount of bio-oil in the PF resin was increased by 30 wt%, the shear strength of the samples after pretreatment 3 decreased from 5.78 to 4.43 N/mm^2. However, these samples exceeded the minimum requirements for the durability class C3 (EN 12765). Cheng *et al*. (2012) reported that the methylolated bio-oil–phenol formaldehyde (MBPF) adhesives were more sensitive to water than the PF adhesive. They could be used as adhesives for the production of interior wood products. It can be concluded that renewable resources such as bio-oil have potential as a substitute for PF resin.

4 CONCLUSIONS
4. ZAKLJUČAK

In this work, bio-based PF resins were produced by substitution of phenol with the bio-oil at varying ratios (from 10 wt% to 30 wt%) in the synthesis of phenol–formaldehyde resins under alkaline condition. The following conclusions can be obtained:

The bio-oil produced from woody biomass was composed mainly of phenols, aldehydes, ketones, alcohols and, benzenes. The phenols accounted for the largest amount of compound in the bio-oil.

The viscosities of the BPF resins were higher than those of reference resins and gradually increased with the increasing addition of bio-oil.

The laboratory PF resin and all of the BPF resins had a similar trend of thermal behavior.

FTIR spectra demonstrated that bio-based resol resins were successfully produced by polymerization of phenol, bio-oil, and formaldehyde.

The shear strength values of the BPF resins were similar to the commercial PF and the lab. PF resins under dry condition. Under wet conditions, the shear strength and wood failure values of the samples bonded with BPF resins exhibited poorer performance as compared to samples bonded with the reference resins. However, the BPF resins fulfilled the requirements for C1, C2, and C3 specified in EN 12765.

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Effect of Water Repellents on Hygroscopicity and Dimensional Stability of Densified Fir and Aspen Woods

Utjecaj vodoodbojnih sredstava na higroskopnost i dimenzijsku stabilnost ugušćenog drva jele i drva jasike

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ABSTRACT • *This study investigated the effect of pre-impregnation with water-repellent agents on the hygroscopicity and dimensional stability of fir (Abies bornmulleriana Mattf.) and aspen (Populus tremula L.) woods. After pre-vacuum treatment, the samples were impregnated at atmospheric pressure with paraffin, linseed oil and styrene, and then densified at compression rates of 20 % and 40 % at 120, 150 and 180 °C. The results showed that water repellents significantly affected the hygroscopicity and dimensional stability of the densified wood samples. Compression recovery rate (CRR), thickness swelling (TS), equilibrium moisture content (EMC), and water absorption (WA) values of the densified samples decreased with impregnation pretreatments. The linseed oil treatment gave more positive CRR and TS results than paraffin. Lower EMC and WA values were found in the paraffin-treated samples. However, the most successful results for all tested properties were determined in the styrene pretreated samples in which hygroscopicity decreased and dimensional stability increased (especially for aspen) due to increases in the compression rate and temperature related to densification conditions. In the styrene pretreated samples, the high temperature (180 °C) and compression rate (40 %) significantly reduced CRR, TS, EMC and WA, total dimensional stability was nearly achieved and the water repellent effectiveness was close to 100 %.*

Keywords: *densification; dimensional stability; hygroscopicity; impregnation; water repellents*

SAŽETAK • *U radu se prikazuje istraživanje utjecaja predimpregnacije drva jele (Abies bornmulleriana Mattf.) i jasike (Populus tremula L.) vodoodbojnim sredstvima na njihovu higroskopnost i dimenzijsku stabilnost. Nakon vakuumske obrade uzorci su pri atmosferskom tlaku impregnirani parafinom, lanenim uljem i stirenom. Zatim je provedeno ugušćivanje sa stupnjevima ugušćenja 20 i 40 % pri temperaturi od 120, 150 i 180 °C. Rezultati su pokazali da vodoodbojna sredstva značajno utječu na higroskopnost i dimenzijsku stabilnost uzoraka ugušćenog drva. Predimpregnacijom uzoraka smanjili su se stupanj povrata ugušćenja (CRR), debljinsko bubrenje (TS), ravnotežni sadržaj vode (EMC) i apsorpcija vode (WA) ugušćenih uzoraka. Postupkom s lanenim uljem smanjeni*

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su povrat ugušćenja i debljinsko bubrenje u usporedbi s postupkom impregnacije parafinom. Na uzorcima impregniranim parafinom utvrđene su niže vrijednosti ravnotežnog sadržaja vode i apsorpcije vode. Međutim, najbolji rezultati svih istraživanih svojstava dobiveni su na uzorcima impregniranima stirenom, kojima se zbog povećanja brzine i temperature ugušćivanja smanjila higroskopnost i povećala dimenzijska stabilnost (posebice drva jasike). Na uzorcima impregniranima stirenom i ugušćenima pri temperaturi od 180 °C sa stupnjem ugušćenja 40 % znatno su se smanjili stupanj povrata ugušćenja, debljinsko bubrenje, ravnotežni sadržaj vode i apsorpcija vode te je postignuta gotovo potpuna dimenzijska stabilnost i učinkovitost odbijanja vode (blizu 100 %).

Ključne riječi: *ugušćivanje; dimenzijska stabilnost; higroskopnost; impregnacija; vodoodbojna sredstva*

1 INTRODUCTION
1. UVOD

Due to its superior properties, wood is used in many structural and non-structural applications. However, due to the difficulties in supplying high-quality wood and the increase in younger, fast-growing and less durable trees, studies on modifications for improving the properties of wood have been accelerated (Rowell, 2012). Many modification processes are currently applied, mainly to improve wood properties such as hygroscopicity, dimensional stability, mechanical strength, biological resistance and UV resistance. Various new technologies such as thermal modification, acetylation, furfurylation and different impregnation and densification processes have been successfully introduced to the market as modern technologies (Sandberg *et al.,* 2017; Lunguleasa *et al.,* 2018).

In order to increase the service life of wood, it is necessary to protect it from damp conditions and prevent dimensional changes (Koski, 2008). Unless necessary measures are taken with wood, high humidity causes undesirable physical changes such as bending, buckling and cracking. In addition, biological pests that require excess moisture to live and develop cause wood to break down. For this reason, it is important to remove excess moisture from the wood and keep its equilibrium moisture content at lower levels. The water absorption rate can be significantly reduced by forming a water repellent barrier in the wood (Williams and Feist, 1999; Koski, 2008).

On the other hand, the dimensional stability of wood can be achieved by blocking the wood cell lumen and reducing the water absorption or bulking and swelling of the cell wall. The impregnation of water-insoluble materials into the cell wall structure of wood is an effective method for keeping the wood cell wall in a swollen state. This can be achieved by impregnation with a variety of suitable agents, such as natural or synthetic resins, paraffin / wax and vinyl monomers. In this way, the dimensional changes due to moisture differentiation in the wood are significantly reduced (Stamm and Tarkow, 1947; Deka and Saikia, 2000; Kocaefe *et al.,* 2015).

Most properties of wood are closely related to its density. The hardness, wear resistance and other mechanical properties can be improved by modifying the wood via densification. Densification modification is important, especially in order to increase the strength properties of low-density wood species and to enable use in a larger area (Laine *et al.,* 2013; Sandberg *et al.,* 2013). Densification is based on increasing the material density by decreasing the void volume in the wood. The main aim of wood densification is to improve the mechanical properties of wood (Laine *et al.,* 2013). Wood is generally densified using three different methods. The first is mechanical compression of wood using high pressure under the effect of heat or steam. The second is filling the wood cell cavities with synthetic or natural resins via impregnation. The third is a combination of mechanical compression and impregnation methods (Rowell and Konkol, 1987; Kamke, 2006; Kutnar *et al.,* 2008). The main issue associated with mechanically densified wood is the fixation of the compressed thickness. When exposed to water or heat, mechanically densified wood tends to return to its original dimensions prior to compression (Navi and Heger, 2004; Laine *et al.,* 2013). In order to increase the dimensional stability of densified wood, thermal processes are applied at the time of compression or prior to and following compression. Due to these thermal processes, the dimensional stability of densified wood is significantly increased (Dwianto *et al.,* 1997; Navi and Girardet, 2000; Kamke and Sizemore, 2008; Welzbacher *et al.,* 2008; Fang *et al.,* 2012; Kutnar and Kamke, 2012; Pelit *et al.,* 2016; Kariz *et al.,* 2017). However, thermal processes generally have a negative effect on the hardness or mechanical strength properties of densified wood (Welzbacher *et al.,* 2005; Gong *et al.,* 2010; Kwon *et al.,* 2014; Dubey *et al.,* 2016; Pelit *et al.,* 2018). Another important method for fixing the compressed thickness in densified wood is impregnation with phenolic resins. In the case of wood treated with resins such as phenol and melamine formaldehyde prior to compression, dimensional stability is almost completely achieved. In addition, the mechanical properties of these materials are significantly increased. However, due to the resin properties, the friability of densified wood is also increased (Seborg *et al.,* 1962; Kollmann *et al.,* 1975). In addition, the cost of phenolic resin treatment is high, and the color change in the material to which it is applied is also an important disadvantage (Morsing, 2000).

The aim of this study was to contribute to the literature by determining the effect of pre-impregnation with water-repellent substances (linseed oil, paraffin) and a vinyl monomer (styrene) on the hygroscopicity and dimensional stability of fir (*Abies bornmulleriana* Mattf.) and aspen (*Populus tremula* L.) wood densified at different temperatures and compression rates.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood samples
2.1. Uzorci drva

This study used fir (*Abies bornmuelleriana* Mattf.) and aspen (*Populus tremula* L.) wood, both of which have relatively low densities (fir: 0.45 g/cm^3, aspen: 0.37 g/cm^3). The wood was selected randomly from a timber company in Düzce, Turkey. Fir and aspen samples were cut from sapwood in rough sizes, in accordance with the study methodology. Attention was paid to ensure that no rot, knots, cracks, or density differences were present in the samples (ISO 3129, 2012). The samples were subjected to natural drying to approximately 12 % moisture content, and then cut to the dimensions of 300 mm × 20 mm (longitudinal direction × tangential direction) and three different thicknesses 20 (for undensified samples), 25 and 33.3 mm (radial direction). Before impregnation, the samples were held in a drying oven at 70 °C until they reached a stable weight. The samples were then weighed using an analytical balance and their weights were recorded.

2.2 Impregnation of wood samples
2.2. Impregnacija uzoraka drva

As water repellents, paraffin (oil ratio: 25-35 %, melting point: 61-63 °C), linseed oil (density: 0.93-0.95 g/cm^3, drying time: 18-20 h at 20 °C, packing: in 17 kg tin) and styrene (density: 0.909 g/cm^3, boiling point: 140 °C, packing: in 15 kg tin) were used as impregnating agents. Pre-treatment procedures were applied to the water-repellent materials before impregnation. The paraffin in solid form was placed in a metal container and melted by exposure to heat. The linseed oil, which was at its packaged viscosity, was thinned by adding 100 % synthetic thinner. The styrene monomer was mixed with 1 % catalyst (methyl ethyl ketone peroxide) to allow polymerization to take place. Thus, the water repellents were made ready for impregnation. A cylindrical tank assembly with a vacuum holder was used in the impregnation of the wood samples in accordance with ASTM D 1413-76 (1976) standard. With this arrangement, a pre-vacuum equivalent pressure of 760 mmHg^{-1} was applied to the samples for 60 min. The impregnation solutions were then diffused into the samples by holding at atmospheric pressure for 24 h. In order to prevent the melted paraffin from solidifying again, the samples in the paraffin solution were held at 80 °C for 24 h.

Following the impregnation processes, the excess impregnation solutions were wiped from the samples and they were weighed again and their weights recorded. Afterwards, the paraffin- and linseed-oil treated samples were kept at a constant temperature of (20±2) °C and relative humidity (RH) of (65±3) % in accordance with ISO 13061-1 (2014). The samples treated with styrene monomer were wrapped in aluminum foil and then incubated in an oven at 90 °C for 2 h to initiate the polymerization process. These samples were then removed from the oven and immediately densified.

2.3 Densification process of wood samples
2.3. Proces ugušćivanja uzoraka drva

The impregnated samples were densified using special metal molds in a hydraulic test press having table dimensions of 60 cm × 60 cm (Figure 1a). Densification was carried out at three different temperatures and two

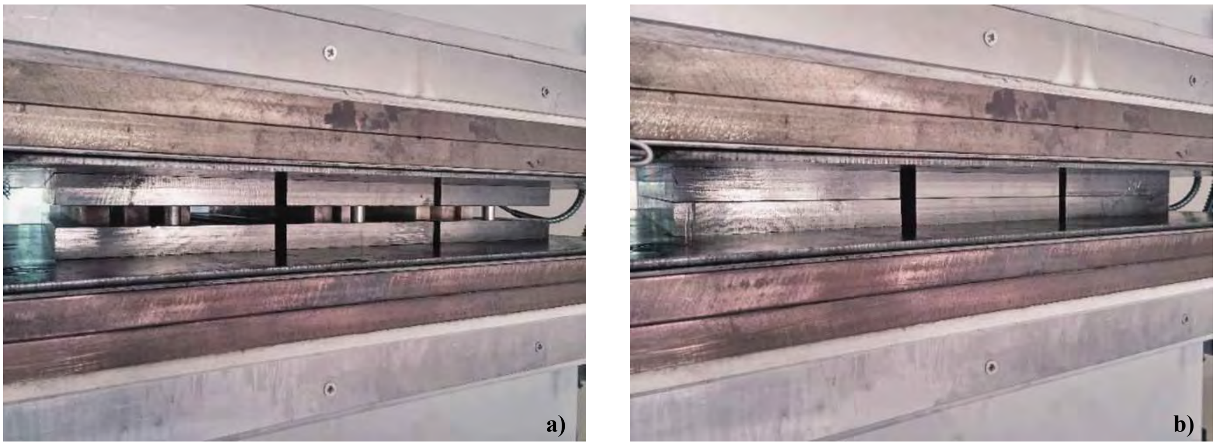

Figure 1 Densification of samples in hot press using metal molds
Slika 1. Ugušćivanje uzoraka u vrućoj preši uz pomoć metalnih kalupa

Table 1 Densification parameters
Tablica 1. Parametri ugušćivanja

Code in study *Oznaka u istraživanju*	**Pressing temperature, °C** *Temperatura prešanja,* °C	**Compression ratio, %** *Stupanj ugušćenja,* %	**Duration** *Trajanje*
A1	120	20	10 min heating + 20 min pressure *10 min zagrijavanje + 20 min prešanje*
A2	120	40	
B1	150	20	
B2	150	40	
C1	180	20	
C2	180	40	

different compression rates. The parameters applied in the densification of the samples are given in Table 1.

Channels 10 mm in depth and 20 mm wide were opened in the metal molds used for densification. The 25 and 33.3 mm thick samples were placed in the channels, the tables had been pre-heated at the specified temperatures for 10 min and the compression of the samples was then carried out in the radial orientation with a loading speed of 60 mm/min. In order to achieve the targeted thickness (20 mm), the load was maintained until the metal molds came into contact with each other (Figure 1b).

The compressed samples were kept under pressure for 20 min and then were removed from the press together with the molds and cooled to room temperature under an average pressure of 0.5 MPa in order to minimize the spring-back effect. According to ISO 13061-1 (2014), after the densification process, samples remained in a conditioning cabin at (20±2) °C and (65±3) % RH until they reached a stable weight. The impregnated and densified samples were then cut into smaller samples according to the standard of the selected tests. The test samples were prepared in a number sufficient to accommodate eight repetitions ($n = 8$) for each variable.

2.4 Determination of retention
2.4. Određivanje retencije

The retention values of the wood samples impregnated with water repellents were determined using Eq. 1,

$$Retention\ (\text{kg/m}^3) = (G \times C) / V \times 10 \qquad (1)$$

where G is the amount (g) of water repellent absorbed by the samples, C is the concentration of the water repellent solution, and V is the volume (cm^3) of the wood samples.

2.5 Determination of dimensional changes
2.5. Određivanje dimenzijskih promjena

Compressed wood has a tendency to partially regain its original shape after the removal of applied pressure due to elastic recovery. This behavior is known as spring-back and results in changes in the compressed dimensions (Garcia-Romeu *et al.,* 2007). The spring-back (*SB*) values of the samples were calculated using Eq. 2. In addition, compression recovery rate (*CRR*) (or set recovery) of the densified samples after immersion in water was determined using Eq. 3 (Pelit *et al.,* 2014),

$$SB\ (\%) = [(T_3 - T_2) / T_2] \times 100 \qquad (2)$$

$$CRR\ (\%) = [(T_4 - T_3) / (T_1 - T_3)] \times 100 \qquad (3)$$

where T_1 is the initial thickness of samples before pressing, T_2 is the thickness of samples under pressure (load), T_3 is the thickness of samples conditioned at (20±2) °C and (65±3) % RH for eight weeks after pressing, and T_4 is the thickness of samples after submersion in water for three weeks.

Thickness swelling (*TS*) of wood samples was determined according to ISO 13061-15 (2017). The *TS* value were calculated using Eq. 4,

$$TS\ (\%) = [(T_4 - T_0) / T_0] \times 100 \qquad (4)$$

where T_0 is the oven-dry thickness of samples after holding at 55 °C for 72 h.

2.6 Determination of hygroscopicity
2.6. Određivanje higroskopnosti

Equilibrium moisture content (*EMC*) of the samples was determined according to ISO 13061-1 (2014). The *EMC* was calculated using Eq. 5,

$$EMC\ (\%) = [(W_1 - W_0) / W_0] \times 100 \qquad (5)$$

where W_1 is the weight of samples conditioned at (20±2) °C and (65±3) % RH for eight weeks and W_0 is the oven-dry weight of samples after holding at 55 °C (a temperature below the melting point of paraffin) for 72 h.

Water absorption (*WA*) of the samples was determined in parallel with the thickness swelling test. The *WA* was calculated using Eq. 6. In addition, water repellent effectiveness (*WRE*) values calculated for impregnated samples as compared to untreated samples were determined using Eq. 7,

$$WA\ (\%) = [(W_2 - W_0) / W_0] \times 100 \qquad (6)$$

$$WRE\ (\%) = [(WA_c - WA_t) / WA_c] \times 100 \qquad (7)$$

where W_2 is the weight of samples after submersion in water for three weeks, WA_c is the percentage of water absorption of the untreated samples and WA_t is the percentage of water absorption of the impregnated samples.

2.7 Statistical analyses
2.7. Statistička analiza

Analysis of variance (ANOVA) tests were performed to determine the effect of water repellents on the hygroscopicity and dimensional stability of the densified fir and aspen wood at the 0.05 significance level. Significant differences between the groups were compared using Duncan's test.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Retention
3.1. Retencija

The retention values of the fir and aspen wood samples determined after impregnation with water repellents are shown in Table 2. According to the findings, the highest retention value for both wood species

Table 2 Retention values of fir and aspen wood (kg/m^3)
Tablica 2. Vrijednosti retencije drva jele i drva jasike (kg/m^3)

Wood species *Vrsta drva*	**Water repellents** *Vodoodbojno sredstvo*		
	Paraffin *Parafin*	**Linseed oil** *Laneno ulje*	**Styrene** *Stiren*
Fir / *jelovina*	148.08 (9.47)	230.09 (20.38)	300.37 (18.17)
Aspen / *jasikovina*	155.35 (10.04)	230.16 (21.41)	311.56 (21.71)

Values in parenthesis are standard deviations. / *Vrijednosti u zagradama standardne su devijacije.*

was obtained in samples impregnated with styrene and the lowest in paraffin-impregnated samples.

3.2 Spring-back, compression recovery rate and thickness swelling
3.2. Povrat, stupanj povrata ugušćenja i debljinsko bubrenje

According to ANOVA results, the effect of water repellent type and densification condition factors on the spring-back (*SB*), compression recovery rate (*CRR*) and thickness swelling (*TS*) for fir and aspen woods was statistically significant ($p \leq 0.05$). Duncan's one-way comparison results conducted for the factors of water repellents and densification are given in Table 3.

Regarding water repellents, for the fir wood, the highest *SB* average was determined in the non-impregnated (untreated) samples (5.49 %), and the lowest in the samples impregnated with paraffin (3.09 %). For aspen wood, the highest SB was obtained in the samples impregnated with linseed oil (5.42 %) and the lowest in the paraffin-impregnated samples (3.58 %) (Table 3). The *SB* values were higher in both wood species impregnated with styrene and compressed at 120 °C (under conditions *A1* and *A2*) (Figure 2a). However, the SB values were significantly reduced in samples that were impregnated with styrene and compressed at elevated temperatures (especially at 180 °C). Compared to the untreated samples condensed under *C2* conditions, the SB values in the styrene-impregnated fir and aspen wood samples decreased by 80.9 % and 81.1 %, respectively. The styrene monomer absorbed by the wood samples was more likely to evaporate from the material at a high compression temperature. As a result of this situation, it can be said that the SB results were affected by the decrease in high internal stresses formed in the compressed wood due to the excess impregnation chemical. In addition, the decrease in the *EMC* ratios of the samples due to the increase in the compression temperature may have affected the SB results. For fir wood, in general, the SB values were decreased in samples impregnated with paraffin and linseed oil compared to untreated samples. In fir wood impregnated with paraffin and densified under *C2* conditions, SB results close to those of the styrene-treated samples were obtained. For aspen wood, the SB value of samples impregnated with paraffin was found to be near to or lower than that of the untreated samples. However, compared to untreated samples, the SB values were higher in aspen samples impregnated with linseed oil. Generally, in the evaluation of water repellents, the untreated and paraffin-impregnated samples yielded more positive results with densification applications at a low temperature (120 °C), while quite successful results were obtained in samples impregnated with styrene via densification applications at a high temperature (180 °C). Moreover, in both tree species impregnated with paraffin, SB values were lower than those of linseed oil (Figure 2a).

With respect to densification variables, the highest SB average for fir wood was found in samples

Table 3 Duncan's test results for mean values of *SB*, *CRR*, and *TS*
Tablica 3. Rezultati srednjih vrijednosti za *SB*, *CRR* i *TS* prema Duncanovu testu

Wood specie *Vrsta drva*	**Factor** *Čimbenik*	***SB*, %**		***CRR*, %**		***TS*, %**	
		Mean	SG	Mean	SG	Mean	SG
Fir wood *drvo jele*	Water repellents / *Vodoodbojna sredstva*						
	Untreated / *netretirano*	5.49	a	93.32	a	34.43	a
	Paraffin / *parafin*	3.09	c	87.27	b	31.51	b
	Linseed oil / *laneno ulje*	4.45	b	71.42	c	26.32	c
	Styrene / *stiren*	4.44	b	31.26	d	10.56	d
	Densification / *Ugušćivanje*						
	Undensified / *neugušćeno*	-	-	-	-	3.37	g
	A1	3.14	e	85.36	a	20.93	d
	A2	5.28	b	75.79	c	48.49	a
	B1	4.21	d	81.29	b	18.65	e
	B2	5.66	a	68.84	d	42.28	b
	C1	3.22	e	64.03	e	15.01	f
	C2	4.70	c	49.60	f	31.21	c
Aspen wood *drvo jasike*	Water repellents / *Vodoodbojna sredstva*						
	Untreated / *netretirano*	4.40	b	88.59	b	32.62	a
	Paraffin / *parafin*	3.58	d	91.37	a	32.20	a
	Linseed oil / *laneno ulje*	5.42	a	80.07	c	27.69	b
	Styrene / *stiren*	3.99	c	30.39	d	8.43	c
	Densification / *Ugušćivanje*						
	Undensified / *neugušćeno*	-	-	-	-	3.11	g
	A1	3.99	d	92.29	a	21.71	d
	A2	5.53	a	75.02	c	47.12	a
	B1	3.57	e	80.97	b	17.20	e
	B2	5.25	b	67.02	d	40.10	b
	C1	3.37	f	67.09	d	14.85	f
	C2	4.37	c	53.25	e	32.55	c

SG: statistical group (different letters denote a significant difference). / *SG: statistička grupa (različita slova označavaju značajnu razliku).*

densified under *B2* conditions (5.66 %) and the lowest in the samples densified under *A1* and *C1* conditions (3.14 % and 3.22 %). The highest SB for aspen wood was determined in the samples densified under *A2* conditions (5.53 %), whereas the lowest was for samples densified under *C1* conditions (3.37 %) (Table 3). The SB values of the densified fir and aspen samples varied depending on the compression rate and temperature. For both tree species, SB values were higher in the samples densified at the compression rate of 40 % compared to the 20 % compression rate (Figure 2a). In other words, the SB values had increased due to the

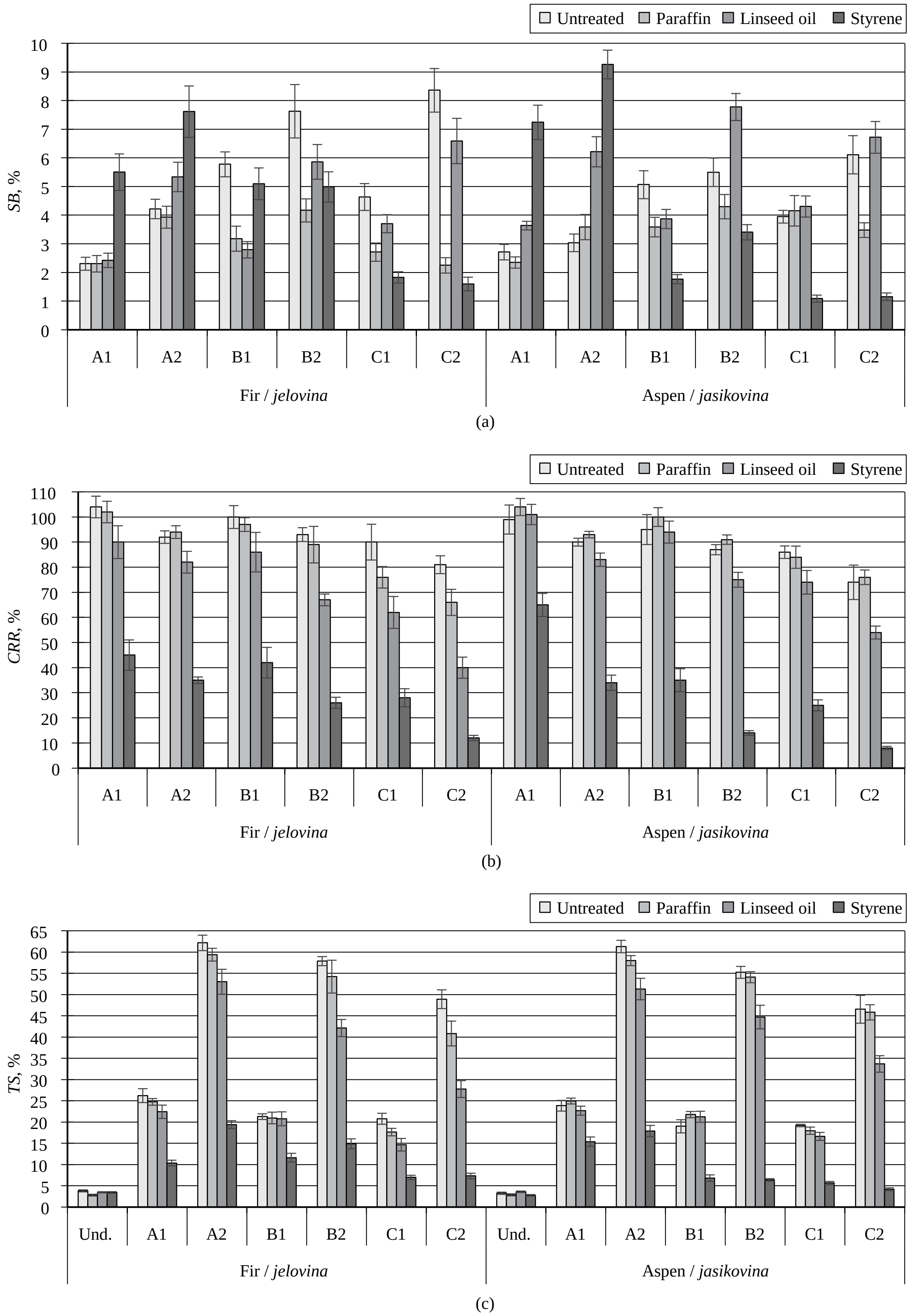

Figure 2 *SB*, *CRR* and *TS* for fir and aspen wood depending on densification conditions
Slika 2. *SB*, *CRR* i *TS* za drvo jele i drvo jasike u ovisnosti o uvjetima ugušćivanja

increase in the compression rate. In the literature, it has been reported that increased internal stress in the material during the wood densification process resulting from increase in the compression rate leads to higher *SB* values (Wolcott *et al.,* 1989; Nairn, 2006; Pelit *et al.,* 2016). In the untreated samples and in those impregnated with linseed oil, SB values increased due to an increase in the compression temperature. However, especially in samples impregnated with styrene, as a result of the higher compression temperature, SB values decreased significantly.

With respect to water repellents, the highest *CRR* average for fir wood was found in untreated samples (93.32 %), and for aspen wood in samples impregnated with paraffin (91.37 %). The lowest *CRR* average was determined in styrene-impregnated samples for both wood species (31.26 % for fir and 30.39 % for aspen) (Table 3). In both species impregnated with water repellent agents (except for the paraffin-impregnated aspen samples), the *CRR* values were reduced (Figure 2b). The *CRR* values in the samples impregnated with linseed oil were lower than in the untreated samples. However, the most significant reduction in *CRR* values was detected in the styrene-treated samples. The *CRR* values of the styrene-impregnated fir and aspen woods were reduced by 85 % and 89 %, respectively, compared to untreated samples densified under the same conditions. With the styrene pretreatment, the compressed thickness of the densified samples exposed to water over a long period was almost completely retained (Figure 2b). As for the results, it can be said that the significantly reduced water absorption of the styrene-treated samples was effective (Figure 3b). Chao and Lee (2003) reported that the polymerized hydrophobic styrene monomer remained in the cell wall and lumen of the impregnated wood and formed a barrier on the wood surface, resulting in less water entering the wood. This greatly reduced the water absorption and dimensional changes of wood. Furthermore, water repellency and dimensional stability have been reported to increase significantly in wood treated with vinyl monomers compared to untreated wood (Rowell, 2012).

Regarding densification conditions, the highest *CRR* average was determined for both tree species in samples densified under *A1* conditions (85.36 % for fir and 92.29 % for aspen) and the lowest for samples densified under *C2* conditions (49.60 % for fir and 53.25 % for aspen) (Table 3). At all temperature levels, *CRR* values were significantly lower in the fir and aspen samples compressed at a higher rate (40 %) (Figure 2b). In the densification process, with the higher compression rate, deformations such as fractures, cracking and collapse of the wood cell wall also increased (Tabarsa and Chui, 1997; Dogu *et al.,* 2010; Budakci *et al.,* 2016; Bekhta *et al.,* 2017). It can be said that the increase in the amount and size of deformation in the densified wood reduced the tendency of the cell to recover its initial shape and this situation had an effect on the *CRR* results. In addition, at the same compression rate (20 % or 40 %), the *CRR* values were lower in the samples which were densified at a higher temperature. The increase in densification temperature had a positive effect on the *CRR* results of both untreated and impregnated samples, especially in those treated with styrene.

Regarding water repellents, the highest *TS* average in the untreated samples was 34.43 % for fir and 32.62 % aspen, while the lowest was obtained in the styrene-impregnated samples with 10.56 % for fir and 8.43 % for aspen (Table 3). It was observed that impregnation with water-repellents did not have much impact on the *TS* values of the undensified samples (Figure 2c). However, the pre-impregnation processes in the densified samples generally reduced the *TS* values. More positive results were obtained in linseed oil-treated samples compared to paraffin-treated samples. Positive results for the *TS* values were mainly determined in the styrene-treated samples. The *TS* values decreased significantly in these samples depending on the compression rate and temperature. In particular, under *C2* conditions, the *TS* values of the densified styrene-pretreated samples were close to those of the control (undensified) samples. The *TS* values of styrene-treated fir and aspen samples were reduced by 85 % and 91 %, respectively, compared to the untreated samples densified under the same conditions. In the literature, it was reported that in agathis wood impregnated before compression with vinyl monomers (styrene and methyl methacrylate), dimensional stability increased due to changes in the cellular structure and chemical components (i.e., cellulose crystallinity, microfibril angle and preferred orientation of fibers) as well as degradation of cellulose (Khalil *et al.,* 2014). In addition, it was reported that polymerization of styrene in wood can result in the grafting of the styrene to cellulose, lignin, and pentosans (Rowell, 2012). Moreover, it was found that water-repellent efficacy and dimensional stability properties improved as a result of in situ polymerization of vinyl monomers filling wood cell voids (Rowell and Konkol, 1987).

With respect to densification conditions, the highest *TS* average was found in densified samples under *A2* conditions (48.49 % for fir and 47.12 % for aspen), whereas the lowest was in undensified samples (3.37 % for fir and 3.11 % for aspen) (Table 3). According to Figure 2c, the *TS* values of all the densified samples were higher than those of the undensified samples. In densified samples, *TS* values increased with the higher compression rate. In general, a higher *TS* was obtained at the compression rate of 40 % than at 20 %. The fact that the densified samples exposed to water tended to return to their initial pre-compression dimensions can be said to affect the results (Seborg *et al.,* 1962; Kollmann *et al.,* 1975; Pelit *et al.,* 2014). As an exception, *TS* values were found to be lower in the styrene-pretreated aspen samples densified under *B2* and *C2* conditions. This can be explained by the fact that the polymerization of the styrene monomer within the densified wood was more effective at high temperatures (150 °C and 180 °C). In terms of compression temperature, the highest *TS* value was determined in the samples densified at 120 °C and the lowest in the samples densified at 180 °C. In the densified fir and aspen samples, the *TS* values were reduced due to the increase in compression temperature.

3.3 Equilibrium moisture content, water absorption and water repellent effectiveness
3.3. Ravnotežni sadržaj vode, upojnost uzoraka i učinkovitost vodoodbojnih sredstava

The effect of water repellent type and densification condition factors on the equilibrium moisture content (*EMC*), water absorption (*WA*), and water repellent effectiveness (*WRE*) for both wood species was statistically significant. Duncan's one-way comparison results conducted for mean values of *EMC*, *WA*, and *WRE* are shown in Table 4.

Regarding water repellents, the highest mean *EMC* was found for untreated samples (10.22 % for fir and 9.77 % for aspen) and the lowest for styrene-impregnated samples (6.63 % for fir and 5.43 % for aspen) (Table 4). The *EMC* decreased in all samples impregnated with water repellents (Figure 3a). A lower *EMC* was determined in the paraffin-treated samples compared to the linseed oil-treated samples. The lowest *EMC* for both wood species was measured in the styrene-treated samples. Due to the increase in the compression rate and temperature, the *EMC* was significantly reduced in the styrene-pretreated wood samples, while the hygroscopicity resistance of the samples increased. In the styrene pre-treated fir and aspen wood densified under *C2* conditions, the *EMC* was reduced by 53 % and 67 %, respectively, relative to untreated samples.

Regarding densification variables, the highest *EMC* average was determined in undensified samples (48.49 % for fir and 47.12 % for aspen), while the lowest was in densified samples under *C2* conditions (3.37 % for fir and 3.11 % for aspen) (Table 4). According to Figure 3a, the *EMC* value of the densified samples was generally lower than that of the undensified samples. The effect of the compression rate on *EMC* was not significant in the paraffin- and linseed-treated samples. However, the *EMC* decreased in the styrene-treated samples due to a higher compression rate. Similarly, the effect of the compression temperature on *EMC* in the paraffin- and linseed oil-treated samples was not apparent, while in the styrene-treated fir and aspen samples, the *EMC* was decreased due to a high compression temperature. The lowest *EMC* was determined in the samples compressed at 180 °C.

With respect to water repellents, the highest *WA* average was found in untreated samples (137.98 % for fir and 171.61 % for aspen) and the lowest in the styrene-impregnated samples (52.67 % for fir and 52.59 % for aspen) (Table 4). The *WA* was also reduced in both tree species impregnated with water repellents (Figure 3b). Depending on the substances used and their quantities, water repellents fill the cell cavities and are stored on the outer surfaces and partially on the inner surfaces. Thus, the wood surface exhibits hydrophobicity and the water intake rate is reduced (Dizman Tomak and Yıldız, 2012). In general, the *WA* was found to be

Table 4 Duncan's test results for mean values of *EMC*, *WA*, and *WRE*
Tablica 4. Rezultati srednjih vrijednosti za *EMC*, *WA* i *WRE* prema Duncanovu testu

Wood species *Vrsta drva*	**Factor** *Čimbenik*	***EMC*, %**		***WA*, %**		***WRE*, %**	
		Mean	SG	Mean	SG	Mean	SG
Fir wood *drvo jele*	Water repellents / *Vodoodbojna sredstva*						
	Untreated / *netretirano*	10.22	a	137.98	a	-	-
	Paraffin / *parafin*	8.14	c	92.01	c	33.25	b
	Linseed oil / *laneno ulje*	9.02	b	96.17	b	29.94	c
	Styrene / *stiren*	6.63	d	52.67	d	61.07	a
	Densification / *Ugušćivanje*						
	Undensified / *neugušćeno*	9.94	a	82.23	e	54.55	a
	A1	8.98	b	96.46	c	36.82	d
	A2	8.66	c	105.97	a	40.14	cd
	B1	8.69	bc	96.81	c	30.81	e
	B2	7.86	d	101.39	b	41.32	c
	C1	8.06	d	90.09	d	37.69	d
	C2	7.33	e	90.01	d	48.59	b
Aspen wood *drvo jasike*	Water repellents / *Vodoodbojna sredstva*						
	Untreated / *netretirano*	9.77	a	171.61	a	-	-
	Paraffin / *parafin*	7.57	c	114.29	c	33.12	b
	Linseed oil / *laneno ulje*	8.57	b	127.29	b	25.59	c
	Styrene / *stiren*	5.43	d	52.59	d	69.44	a
	Densification / *Ugušćivanje*						
	Undensified / *neugušćeno*	9.46	a	126.77	a	43.76	b
	A1	8.34	b	125.50	ab	37.17	c
	A2	7.57	d	121.87	bc	41.84	b
	B1	7.86	c	109.64	d	41.54	b
	B2	7.42	d	119.87	c	42.58	b
	C1	7.53	d	107.04	de	41.66	b
	C2	6.68	e	104.42	e	50.47	a

SG: statistical group (different letters denote a significant difference). / *SG: statistička grupa (različita slova označavaju značajnu razliku).*

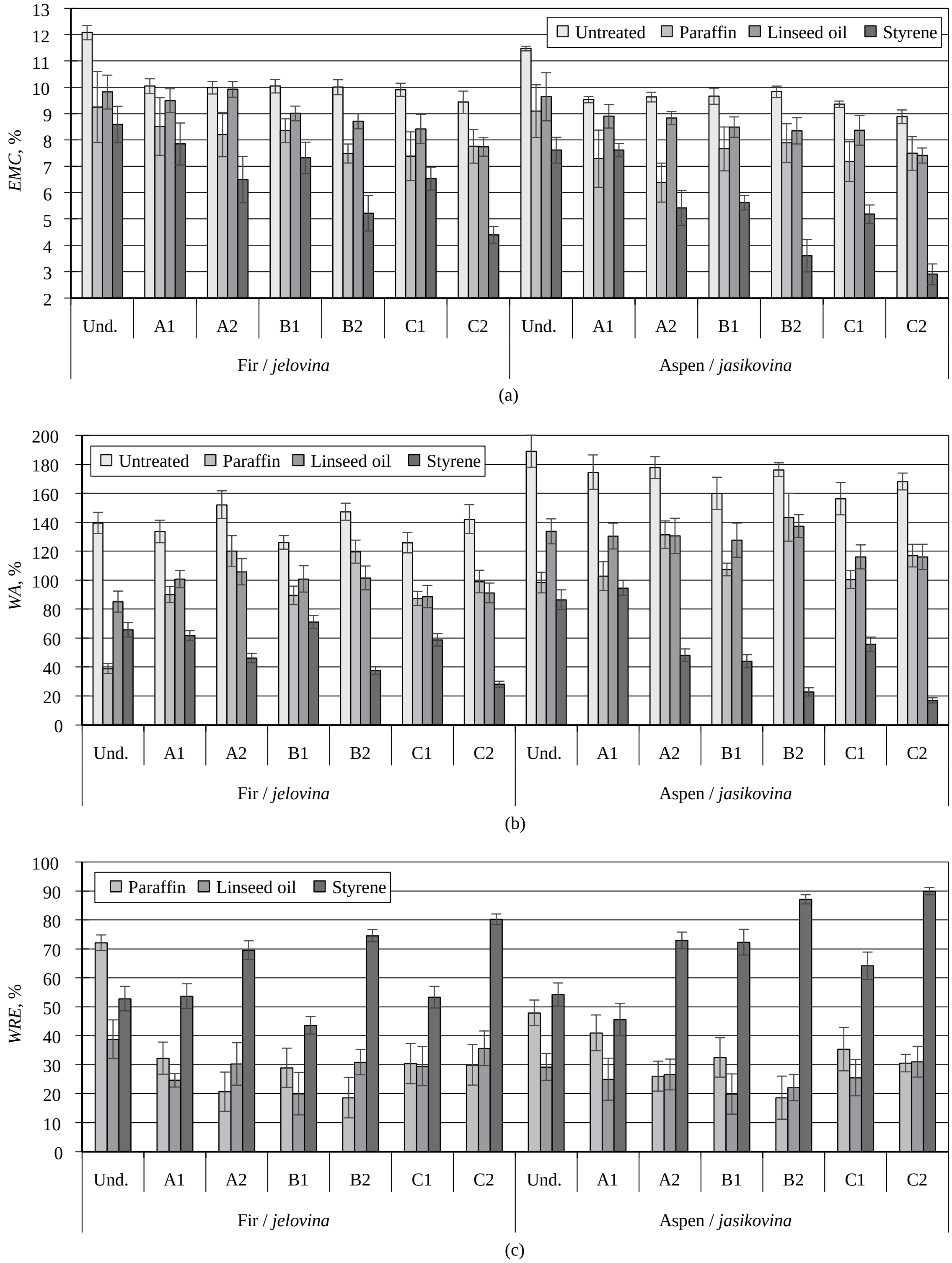

Figure 3 *EMC*, *WA* and *WRE* for fir and aspen wood depending on densification conditions
Slika 3. *EMC*, *WA* i *WRE* za drvo jele i drvo jasike u ovisnosti o uvjetima ugušćivanja

lower in paraffin-treated samples compared to linseed oil-treated samples. However, the most positive results for *WA* were determined in the styrene-treated samples. In these samples, the *WA* was significantly reduced, especially after high temperature (180 °C) and high compression (40 %). Compared to untreated samples, the *WA* decreased 80 % and 90 %, respectively, in styrene pre-treated fir and aspen woods densified under *C2* conditions (180 °C / 40 %). When wood is impregnated with vinyl monomers, the polymer is located almost completely in the lumen of the wood and only a small amount is polymerized in the cell wall. Consequently, the *WA* is significantly reduced in woods with polymers filling the volume of the cavities (Baysal *et al.,* 2007; Rowell, 2012). In previous studies, it was reported that water absorption decreased significantly in styrene-treated wood compared to untreated wood. (Yalinkilic *et al*. 1998; Chao and Lee, 2003; Baysal *et al.,* 2006).

Regarding densification factors, the highest *WA* average for fir wood was found in samples densified under *A2* conditions (105.97%) and for aspen wood in undensified samples (126.77 %). The lowest *WA* average was determined in undensified samples for fir wood (82.23 %) and for aspen wood in samples densified under *C2* conditions (104.42 %) (Table 4). In densified samples (except for styrene-pretreated samples), the *WA* values increased due to a higher compression rate. The *WA* was generally higher at 40 % compression rate than at 20 % (Figure 3b). It can be said that the increase in the amount of water-repellent agents moving away from the wood with the increase of compression rate affect the results. Depending on the amount of water repellent impregnated into wood, hydrophobic properties of wood increase (Koski, 2008). The effect of the compression temperature on the *WA* in the untreated, paraffin-treated and linseed oil-treated samples was not very pronounced. However, in the styrene-treated samples, the *WA* was reduced as a result of a higher compression temperature.

Regarding water repellents, the highest *WRE* average was found in samples impregnated with styrene (61.07 % for fir and 69.44 % for aspen), and the lowest in samples impregnated with linseed oil (52.67 % for fir and 52.59 % for aspen) (Table 4). In samples impregnated with water repellents, the *WRE* was the highest with styrene, followed by paraffin and linseed oil, respectively, compared to the untreated samples. After densification, the *WRE* decreased in the samples with paraffin and linseed oil treatment. On the other hand, depending on the compression rate and temperature, the *WRE* was significantly increased in the styrene-treated samples. After impregnation with styrene, the *WRE* was found to be close to 100 % in the wood samples (especially aspen) densified under *C2* conditions (Figure 3c).

With respect to densification conditions, the highest *WRE* average was obtained in undensified samples for fir wood (54.55 %) and in samples densified under *C2* conditions for aspen wood (50.47 %). The lowest *WRE* average was determined in the samples densified under *B1* conditions for fir wood (30.81 %) and in the samples densified under *A1* conditions for aspen wood (37.17 %) (Table 4). According to Figure 3c, the *WRE* was found to be higher at the 20 % compression rate in the paraffin-treated samples. However, the *WRE* was higher in the linseed- and styrene-treated samples at the 40 % compression rate. The *WRE* increased significantly depending on the compression rate, especially in the styrene-treated samples. On the other hand, while the effect of compression temperature on *WRE* was insignificant in the paraffin- and linseed oil-treated samples, the *WRE* decreased in the styrene-treated samples due to a higher compression temperature.

4 CONCLUSIONS
4. ZAKLJUČAK

This study investigated the effect of pre-impregnation with water-repellent agents on dimensional stability and hygroscopicity in densified wood compressed at different rates and temperatures. Water repellents significantly influenced the physical properties of densified fir and aspen wood. In the densified samples, the *CRR* and *TS* values were generally reduced with impregnation pretreatments. More positive *CRR* and *TS* results were obtained from the linseed oil-treated samples than from those treated with paraffin. However, the most successful results were determined in the styrene-pretreated samples. The *CRR* values of the styrene-treated fir and aspen woods decreased by 85 % and 89 %, respectively, compared to the undensified (untreated) samples under the same conditions. In the same samples, the *TS* values were decreased by 85 % and 91 %, respectively. Thus, the dimensional stability of the styrene pre-treated and densified samples was almost completely achieved depending on the compression conditions. These results can be shown as one of the most important outcomes of the study.

The *EMC* and *WA* were reduced in both wood species impregnated with water repellents. The *EMC* and *WA* were lower in the paraffin-treated samples than in the linseed oil-treated samples, while the lowest values for both wood species were found in the styrene-treated samples. In the densification process, due to the increased compression rate and temperature, the *EMC* and *WA* were significantly reduced in the styrene-pretreated wood samples, whereas the *WRE* of the samples increased. After impregnation with styrene, the *WRE* was close to 100 % in the wood samples (especially aspen) densified under *C2* conditions (180 °C / 40 %).

Regarding densification conditions, the most positive results on the physical properties of the wood samples were obtained at a high temperature (180 °C) and high compression rate (40 %). Due to the increased compression rate and temperature, the hygroscopicity was reduced and the dimensional stability increased in the fir and aspen samples.

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Sunflower (*Helianthus Annuus*) Stalks as Alternative Raw Material for Cement Bonded Particleboard

Suncokretove stabljike (*Helianthus annuus*) kao alternativna sirovina za cementom vezane ploče iverice

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ABSTRACT • *Sunflower stalks (Helianthus annuus) were studied as an alternative raw material for cement bonded particleboard. Experimental cement bonded particleboards measuring 500 mm × 500 mm × 12 mm with nominal density of 1300 kg/m³ were produced using different ratios of sunflower stalk particles with wood. Properties of the cement bonded particleboards evaluated include water absorption, thickness swelling, screw withdrawal strength and bending properties. Results of the study showed that the addition of small amount of sunflower stalks in the production of cement bonded particleboard does not significantly influence the properties tested. Inclusion of more stalks in the mixture significantly decreases mechanical properties and raises thickness swelling and water absorption values of the cement bonded particleboard. Results indicate that boards which include a small amount of sunflower stalks provide properties required by the standards for general purpose-use cement bonded particleboards.*

Keywords: *cement-bonded particleboard; physical and mechanical properties; sunflower stalks*

SAŽETAK • *U radu se opisuje istraživanje stabljike suncokreta (Helianthus annuus) kao alternativne sirovine za proizvodnju cementom vezanih ploča iverica. Eksperimentalne cementom vezane ploče iverice dimenzija 500 mm × 500 mm × 12 mm i gustoće 1300 kg/m³ izrađene su s različitim omjerima iverja od suncokretovih stabljika i drva. Pritom su istraživana ova svojstva tih ploča iverica: sposobnost upijanja vode, debljinsko bubrenje, izvlačna sila vijaka i savijanje. Rezultati istraživanja pokazali su da mali dodatak suncokretovih stabljika u proizvodnji cementom vezanih ploča iverica ne utječe znatnije na ispitivana svojstva. Dodavanjem veće količine stabljika u smjesu bitno slabe mehanička svojstva te se povećava debljinsko bubrenje i upojnost cementom vezanih ploča iverica. Rezultati pokazuju da ploče s malom količinom suncokretovih stabljika zadovoljavaju propisane zahtjeve za opću uporabu cementom vezanih ploča iverica.*

Ključne riječi: *cementom vezana ploča iverica; fizička i mehanička svojstva; suncokretove stabljike*

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1 INTRODUCTION
1. UVOD

The increasing demand for wood based products, due to the growth of world population and deforestation, requires development of more ecologically friendly building materials based on natural renewable raw materials. A wide variety of resources such as agricultural residues, plantation of fast growing and annual plants and recycling of wood products may be an alternative to wood. Thus, lately attention has been increasingly focused on the research for the development of new bio-sourced materials. During the last few decades, utilization of plant fibers such as flax, hemp, jute, corn stalks, etc. in the production of particleboard, medium density fiberboard, wood plastic composites, etc. has been widely investigated (Klimek and Wimmer, 2017). Although agricultural residues have some advantages such as availability, low density, etc., most of their properties are mostly inferior to other resources (Sun *et al*., 2013).

Wood-cement boards are usually made of wood fibers or particles mixed with cement, water and some additives in order to speed up the bonding process (Marteinsson and Gudmundsson, 2018). They have been already used almost everywhere in the world mainly for roofs, floors and walls (Nazerian *et al*., 2018). Their advantages compared to composites produced with organic resins including durability, dimensional stability, acoustic and thermal insulation properties and low production cost make them attractive (Lee, 1984; Ramirez-Coretti *et al*., 1998; Savastano *et al*., 2003; Okino *et al*., 2005; Del Menezzi *et al*., 2007).

Many alternative raw materials have been studied for suitability of possible use in manufacturing cement bonded particleboard for the last few decades. These include resources from those widely available such as wheat straw (Soroushian *et al*., 2004), to local ones such as tea residue (Yel *et al*., 2011). Most of these lignocellulosic raw materials, however, contain soluble sugars that inhibit cement hydration, thus resulting in undesirable board properties. According to Del Menezzi *et al*. (2007), extractives and polysaccharides inhibit the reaction between wood and cement. To overcome inhibition effects, several physical, chemical, and biological pretreatment methods (Moslemi *et al*., 1983; Lee, 1984; Zhengtian and Moslemi, 1985; Lee and Short, 1989) applicable on the woody particles have been developed, making possible the utilization of a wider variety of plant-based materials for cement bonded particleboard production.

According to Klimek and Wimmer (2017), sunflower stalks are one of the most abundant biomass available. Utilization of sunflower stalks in the production of organic bonded particleboard was the subject of several investigations (Gertjejansen *et al*., 1972; Gertjejansen, 1977; Khristova *et al*., 1996; Bektas *et al*., 2005; Güler *et al*., 2006) and sunflower stalks were found technically suitable in the manufacture of particleboard, but their use in the cement bonded particleboard has been never investigated. In this study, the use of particles produced from sunflower stalks with or without wood particles was investigated in the production of cement bonded particleboard.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Wood-cement composites measuring 12 mm × 500 mm × 500 mm with target density of 1300 kg/m^3 were prepared in the laboratory conditions. The amount of sunflower stalk particles added to wood particles was 0, 25, 50, 75 and 100 % based on the wood particle weight. The ratio between the wood/stalk particles and cement by mass were 1:3 and 1:2. Additional material as cement setting accelerator, $CaCl_2$, was used at the ratio of 5 % based on the cement weight. Water sprayed on to the mix was 40 % of the cement weight.

The cement used in the mixture was commercial Portland cement (CEM I 42.5). Red pine (*Pinus brutia*) coarse particles which, were used as core layers of commercial organic bonded particleboard, were obtained from a local particleboard factory. The size distribution of the wood particles used in the production of experimental panels is given in Table 1. Sunflower stalks were collected from Kahramanmaraş province. They were dried and passed through a hammer mill and screened. Stalk particles left between 3-5 mm sieves were used in the experiments.

Table 1 Size distribution of wood particles used in the study
Tablica 1. Udio pojedine veličine iverja upotrijebljenoga u istraživanju

Particle size, mm *Veličina iverja,* mm	%
6.3	0.62
4	4.53
2	28.55
1	48.86
0.85	6.5
0.5	8.35
0.25	1.76
0.125	0.83

The mixing of all samples was carried out as follow: First, wood and sunflower particles were mixed and sprayed with water containing accelerator. Then, cement was added and mixing continued until a homogeneous distribution. After mixing, fresh mixtures were cast to the forms and cured for 2 days. The amount of pressure provided during curing of the mixture was 1.8-2.0 N/mm^2. The cured boards were then left for conditioning in the laboratory climate at approximately 20 °C, relative humidity (RH) of 65 %. Cement bonded particleboards were cut down after curing to required size in order to determine some physical and mechanical properties.

The effects of sunflower stalks on water absorption and thickness swelling tests were determined on 50 mm × 50 mm samples according to TS EN 317, which is similar to ASTM D 1037. Water absorption and thickness swelling tests were conducted by submerging specimens horizontally in water at room temperature for 24 hours. After each submersion period, samples were drained of excess water and measured for change in thickness and amount of water absorbed.

The effects of sunflower stalks on modulus of elasticity and modulus of rupture (*MOE* and *MOR*) were evaluated using a three point bending test following TS EN 310. *MOE* and *MOR* were determined for each specimen using load–deformation curves. Screw withdrawal strength of the 50 mm × 50 mm samples was also determined. Five replicates were used for each test and the obtained data were subjected to an analysis of variance. Experimental results were analyzed using ANOVA tests to identify their statistical significance. Duncan's multiple range tests were performed in order to find the least significant difference between all the variables.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 2 shows some physical properties of the laboratory manufactured cement bonded particleboard samples. Density of the manufactured boards ranged from 1257 to 1407 kg/m^3 and varied with the amount of the addition of stalk as well as wood to cement ratio.

The dimensional stability of the boards produced was measured using water absorption (*WA*) and thickness swelling (*TS*) tests. *WA* (%) values after 24 hours of soaking of the manufactured boards were significantly increased as the amount of sunflower particles used in the mixture increased (P<0.001; R Squared = 0.935). Boards containing no sunflower stalks had lower *WA* values than other groups.

Test results indicate that sunflower stalks significantly influence the *WA* capacity of the cement bonded particleboards (P<0.001; R Squared = 0.935). Since sunflower stalks have lower density than wood, increase of proportion in the mixture means more particles and thus more space for water molecules to bond. Addition of sunflower stalks creates more surfaces for potential engagement of water, thus yielding higher water absorption. According to Savastano *et al*. (2003), *WA* is increased by particle content increase. In general, *WA* capacity of cement-bonded particleboards decreased with the increase in cement content (Moslemi and Pfister, 1987; Olorunnisola, 2009). Some chemical additives besides type of wood particle and wood-cement ratio may also influence *WA* capacity (Olorunnisola, 2009).

24 hour *TS* (%) values of the manufactured boards were significantly affected by the proportion of sunflower stalks used in the study (P<0.001; R Squared = 0.696). *TS* values after 24 hours of soaking were the highest for the group containing 100 % sunflower stalks. Compared to the boards manufactured using 100 % wood particles with wood to cement ratio of 1:2, the addition of sunflower stalks to the mixture slightly lowers *TS* rate. Boards manufactured using 100 % sunflower stalks are an exception. In general, higher cement content in the mixture diminishes *TS* of cement bonded particleboard (Moslemi and Pfister, 1987). Boards manufactured with 1:3 wood/cement ratio, in comparison with 2:1 wood / cement ratio, seemed to cause increasing *TS* after 24 hours immersion in water. Higher swelling rate may be due to the higher density. Huang and Cooper (2000) claim that *TS* rate may be higher for denser boards because they are exposed to higher compression during production. Higher *TS* rate may also be attributed to a high amount of $CaCl_2$ used, which is highly hygroscopic (Davies and Davies, 2017).

The mechanical test results including the bending properties and screw withdrawal strength of cement bonded particleboard are presented in Table 3. While the addition of a small amount of stalks seems to increases the mechanical properties, the addition of more stalks significantly diminishes the properties. Higher cement ratio seemed to yield better mechanical properties for the boards tested. In general, *MOE* of the cement bonded particleboards was significantly affected by the addition of sunflower stalks (P<0.001; R Squared = 0.888). Addition of sunflower stalks also significantly influences the *MOR* of the cement bonded particleboards (P<0.001; R Squared = 0.913). There is no significant difference between the bending properties of control groups and those which contain 25 % stalk particles. Both groups have higher bending properties than required by the standards (TS EN 634-2).

Table 2 Physical properties of manufactured cement bonded particleboards
Tablica 2. Fizička svojstva proizvedenih cementom vezanih ploča iverica

Particle / cement ratio *Omjer iverja i cementa*	**Wood / stalk particle ratio** *Omjer iverja drva i stabljika suncokreta*	**Density, kg/m^3** *Gustoća,* kg/m^3	***WA*, %**	***TS*, %**
1:2	100/0	1257 (18.47)	10.90 (0.29) A	6.78 (0.54) BC
	75/25	1356 (26.32)	14.29 (0.85) B	5.71 (0.14) B
	50/50	1278 (32.00)	16.21 (0.8) B	5.7 (0.62) B
	25/75	1341 (18.28)	16.42 (0.86) B	5.13 (0.89) B
	0/100	1263 (36.84)	26.7 (3.64) D	7.7 (0.74) BC
1:3	100/0	1407 (7.46)	9.02 (0.99) A	4.53 (0.43) A
	75/25	1398 (15.93)	10.25 (0.75) A	5.14 (1.43) B
	50/50	1358 (37.52)	21.9 (2.92) C	7.1 (1.07) BC
	25/75	1267 (40.13)	22.06 (1.49) C	7.14 (0.73) BC
	0/100	1395 (17.36)	23.4 (1.24) CD	7.79 (0.85) BC

Values in parenthesis are standard deviations, capital letters indicate Duncan grouping. / *Vrijednosti u zagradama standardne su devijacije, a velika slova označuju grupiranje prema Duncanovu testu.*

Table 3 Mechanical properties of manufactured cement bonded particleboards
Tablica 3. Mehanička svojstva proizvedenih cementom vezanih ploča iverica

Particle / cement ratio *Omjer iverja i cementa*	**Wood / stalk particle ratio** *Omjer iverja drva i stabljika suncokreta*	**Density, kg/m³** *Gustoća,* kg/m³	***MOE*, N/mm²**	***MOR*, N/mm²**	**Withdrawal strength, N** *Izvlačna sila,* N
1:2	100/0	1257 (18.47)	4205 (291) C	11.21 (0.56) C	1395 (85) C
	75/25	1356 (26.32)	3274 (864) C	9.42 (0.35) C	1184 (66.6) C
	50/50	1278 (32.00)	2628 (235) B	6.44 (0.41) B	909 (64.4) B
	25/75	1341 (18.28)	3063 (183) C	7.01 (0.54) B	1058 (26.1) C
	0/100	1263 (36.84)	1364 (210) A	5.79 (0.79) B	654 (61) A
1:3	100/0	1407 (7.46)	5152 (1001) CD	11.18 (2.02) C	1376 (256) C
	75/25	1398 (15.93)	6317 (1322) D	12.11 (1.61) C	1463 (186) C
	50/50	1358 (37.52)	2205 (345) B	5.61 (0.82) B	815 (80) B
	25/75	1267 (40.13)	1442 (192) A	3.83 (0.47) A	538 (40) A
	0/100	1395 (17.36)	1645 (138) A	5.26 (0.38) B	838 (58) B

Values in parenthesis are standard deviations, capital letters indicate Duncan grouping. / *Vrijednosti u zagradama standardne su devijacije, a velika slova označuju grupiranje prema Duncanovu testu.*

MOE of the cement bonded particleboards manufactured with 100 % stalk particles were inferior to other groups tested.

The average *MOE* of wood boards for higher cement ratio was 5152 N/mm², while the highest average *MOE* of 6317 N/mm² was obtained with the addition of 25 % sunflower stalks. An increase of 22 % in *MOE* was reached with the addition of stalk particle although the difference between the densities of the corresponding boards was less than 1 %. When considering an increase of 8 % for bending strength and of 6 % for withdrawal strength of the corresponding boards, it can be concluded that the addition of a small amount of sunflower stalks increases the board performance. In general, the *MOE* of cement bonded boards increase with decreasing wood content (Al Rim *et al*., 1999) or density increase and higher cement content lower *MOR* (Moslemi and Pfister, 1987; Oyagade, 1990). According to Bejo *et al*. (2005), higher wood densification means improved bonding between cement matrix and wood, and thus also better mechanical properties. Sun *et al.* (2013) claim that although natural resources may have some advantages, their mechanical properties are usually inferior as a result of lower cellulose content. A

Table 4 Properties of cement bonded boards manufactured from alternative raw materials
Tablica 4. Svojstva cementom vezanih ploča iverica proizvedenih od alternativne sirovine

Source *Izvor*	**Density, kg/m³** *Gustoća,* kg/m³	***MOE*, N/mm²**	***MOR*, N/mm²**	***WA*, %**	***TS*, %**	**References** *Literatura*
Red iron wood sawdust and palm kernel shell *Piljevina crvenog drva i ljuske palmine jezgre*	1051-1639	82-428	2.1-8.8	4.9-1.92	0.5-6.84	Atoyebi *et al*., 2018
Jerusalem artichoke *Jeruzalemska artičoka (*čičoka*)*	1250	3390-4710	9.09-11.01	8.86-14.80	0.35-1.38	Cabral *et al*., 2018
Bamboo / *Bambus*	-	-	6-9.7	-	-	Ranjan *et al*., 2017
Lantana camara	-	-	10-12.47	-	-	Ranjan *et al*., 2017
Grapevine / *vinova loza*	1200	1702-3185	2.71-9.1	-	1.09-7.72	Wang *et al*., 2013
Rattan waste *ostaci ratana*	1050-1200	480-3563	0.5-1.6	31-51	1.1-8.6	Olorunnisola and Adefisan, 2002
Abaca fiber / *vlakna abaka*	-	-	2.4-6.9	-	-	Cabalo, 2015
Coco coir / *kokosovo vlakno*	-	-	2.1-7.6	-	-	Cabalo, 2015
Rice husk / *rižina ljuska*	1020-1530	391-1339	4.56-11.52	1.65-6.47	2.94-6.82	Bamisaye, 2007
Eucalyptus oil waste *ostaci proizvodnje ulja eukalipta*	1200-1310	1893-2467	22.84-47.82	22-28	0.13-0.38	Setiadji and Husin, 2012
Date palm midribs *središnja vlakna lista datulje*	1100-1300	3146-4142	9.87-12.28	21.42-24.70	0.91-1.54	Nasser, 2014
C. erectus prunings *granje C. erectus*	1100-1300	4562-5645	9.60-13.95	15.67-21.06	0.31-0.38	Nasser, 2014
Oil palm veins *žile palme uljarice*	1100	2399-7656	4.24-8.01	4.3-8.2	3.3-5	Ayrılmış *et al*., 2017
Coir *kokosovo vlakno*	1040-1790	4171-13063	28.1-80.3	23.4-61.8	2.9-12.3	Erakhrumen *et al*., 2008
Tea residue / *ostaci biljke čaja*	800-1200	254-2979	0.8-10.99	28-43.5	1.3-8.08	Yel *et al*., 2011

possible contributory factor to the relatively low bending properties of the boards could be low stiffness of sunflower stalks (Sun *et al*., 2013).

Generally, withdrawal strength of the cement bonded particleboards significantly altered by the addition of sunflower stalks (P<0.001; R Squared = 0.899). There is no significant difference between the withdrawal strength of control groups and those that contain 25 % stalk particles. Other groups had similar withdrawal strength properties. Withdrawal strength is an indicator of internal bond strength and can be affected by several factors as follows; density, water/cement ratio, type of cement, use and ratio of accelerators, type and dimensions of wood particles (Ashori *et al*., 2012; Davies and Davies, 2017). The decrease in withdrawal strength could be attributed to poor bonding between sunflower stalk particles and cement.

The mechanical properties of the cement bonded particleboard manufactured in this study are usually higher than most of the tested alternative materials (Table 4). Mechanical properties of cement bonded products manufactured from agricultural waste or residual are highly variable mostly depending upon the anatomical and chemical structure. According to Sun *et al*. (2013), lower cellulose content is responsible for lower mechanical properties. Klimek and Wimmer (2017) also claim that conventional particleboards manufactured from agricultural residues display lower mechanical properties.

The main reason for the lower mechanical properties, as explained by Kochova *et al*. (2015), is carbohydrates, especially the amount of sucrose, glucose and fructose. Liu and Moslemi (1986) also mentioned that the presence of sugars causes decreasing strength. Decrease in mechanical properties with the addition of sunflower stalk particles may be minimized by the application of pretreatments, which were found effective for many lignocellulosic materials (Moslemi *et al*., 1983; Lee, 1984; Zhengtian and Moslemi, 1985; Simatupang *et al*., 1987; Lee and Short, 1989).

4 CONCLUSIONS
4. ZAKLJUČAK

This study explored the feasibility of sunflower stalks in cement-bonded particleboard production, under laboratory conditions. Based on the results of their physical and mechanical properties, it is evident that the addition of 25 % of sunflower stalks to wood cement mixture does not alter the properties of cement bonded particleboard tested. The inclusion of higher percentage of stalk particles in the mixture significantly drops the mechanical properties and increases water affinity, and thus also *WA* and *TS* of the boards tested. Undesirable board properties may be improved by some pretreatments applied to the stalk particles. The use of fine particles in the production may also enhance the board properties. The alternative resources such as sunflower stalks could serve as the balance between supply and demand for the manufacturing of cement bonded particleboards.

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Anatomical, Chemical and Mechanical Characteristics of Beech Wood Degraded by Two *Pleurotus* Species

Anatomska, kemijska i mehanička svojstva bukova drva degradiranoga gljivama roda *Pleurotus*

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ABSTRACT • *The aim of this study was to determine the destructive capabilities of the two white rot fungi Pleurotus cornucopiae (Pc) and P. eryngii (Pe) compared with the standard fungus Trametes versicolor (Tv) on beech wood samples after 60 days of incubation. Understanding of the white rot decay is important as it is necessary for the development of effective solutions for wood protection. Measurements of mass loss, chemical, mechanical properties and light microscopical investigations were conducted prior to and after incubation. Mass loss of samples was found to be 9-22 % depending on fungi species. Impact bending strength is not as sensitive as presumed in classical literature. Light microscopy analysis revealed that decay patterns were similar for both fungi. Wood cell wall thinning, fungal colonization hyphae were also the same for both fungi. Results indicated considerable wood attack by both Pleurotus species, Pc being more destructive than Pe.*

Keywords: *Pleurotus cornucopiae; Pleurotus eryngii; Trametes versicolor; wood decay; chemical analysis; light microscopy*

SAŽETAK • *Cilj rada bio je utvrditi učinak dviju gljiva bijele truleži – Pleurotus cornucopiae (Pc) i P. eryngii (Pe) – na uzorcima bukova drva nakon 60 dana inkubacije u usporedbi s učinkom standardne gljive Trametes versicolor (Tv). Razumijevanje degradacije drva zbog bijele truleži iznimno je važno za razvoj učinkovitih rješenja zaštite. U pokusu su prije i nakon inkubacije drva provedena mjerenja gubitka mase, kemijskih i mehaničkih svojstava te je obavljeno ispitivanje svjetlosnim mikroskopom. Utvrđeno je da je gubitak mase uzoraka iznosio 9 – 22 %, ovisno o vrsti gljive. Čvrstoća drva na savijanje nije toliko osjetljiva na utjecaj gljiva kao što se navodi u klasičnoj literaturi. Analiza slika dobivenih svjetlosnim mikroskopom pokazala je da su procesi propadanja drva pri zarazi objema gljivama slični. Stanjivanje stijenki drvnih stanica i hife kolonizacije obiju gljiva također su bile jednake. Rezultati su pokazali znatnu degradaciju drva napadnutoga gljivama roda Pleurotus, s tim da je gljiva Pc destruktivnija od gljive Pe.*

Ključne riječi: *Pleurotus cornucopiae; Pleurotus eryngii; Trametes versicolor; propadanje drva; kemijska analiza; svjetlosna mikroskopija*

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1 INTRODUCTION
1. UVOD

Wood is one of the most important building materials. It has been used for various applications such as construction, furniture, poles, and sports equipment. However, non-durable and susceptible wood species are prone to fungal degradation. Degradation develops if the moisture content of wood exceeds certain limit, which is associated to fiber saturation point (Schmidt 2006). Wood-decaying fungi play a prominent number of ecological roles in forest ecosystems that affect the health, diversity, productivity, and development of their biotic communities such as mycorrhizal associations with vascular plants, pathogens of commercial tree species, decomposers of coarse organic material, and food resources for wildlife (Marcot, 2017).

There are various classifications of wood degrading fungi, and the most important is based on the color of degraded wood; white-, brown-, and soft-rot, blue-stain and sap-stain fungi (Zink and Feng, 1989; Schmidt, 2006). The white-rot fungi predominatly associated with hardwood wood species, where two degradation patterns are described, namely, selective and non-selective white rot as described by Eriksson *et al*. (1990). The selective fungi degrade and consume predominately hemicellulose and lignin, while the non-selective white rot fungi, beside hemicellulose and lignin, degrades cellulose as well (Eriksson *et al*., 1990; Zabel and Morrell, 1992; Eaton and Hale, 1993; Schwarze *et al*. 2004; Schmidt, 2006; Bari *et al*., 2019). In the nature, different fungal species colonize a variety of substrates. Some fungi are more specialized than the others (Bari *et al*., 2019). In this regards, *Pleurotus* species are reported as one of the most important and robust white rot fungi. For example, in the Northern forests of Iran, a colony of them can be found on beech, hornbeam, oak, and aspen wood, clearly proving their flexibility (Ershad, 2009).

Most of forests in Iran are located in the northern parts, bordering the coastal plain at the Caspian Sea and on the northern slopes of the Alborz Mountain range. These forests cover an area 850 km long and vary in width from 20 to 70 km. The forests of this region are known as Hyrcanian forests. These Hyrcanian forests comprise a little more than 1.9 million ha of almost 100 % hardwoods, mainly beech (*Fagus orientalis*) and hornbeam (*Carpinus betulus*) (Kiaei and Samariha, 2001). *Pleurotus* genus is one of the most important basidiomycetes from commercial perspective, due to their gastronomic, nutritional and medicinal properties. Another factor that contributes to their commercial importance is the fact that they can be easily cultivated on a wide range of substrates, from straw to wood (Solár *et al*., 2007; Aghajani *et al.*, 2018; Humar, 2013) Preferential degradation of wheat straw lignin was studied by Martinez *et al.* (1994), who concluded that *Pleurotus eryngii* and *P. ostreatus* are the most promising fungi. They reported that *P. eryngii* was the most successful organism examined, exhibiting nearly 50 % reduction of Klason lignin during a solid-state fermentation (SSF) experiment.

Beech wood is an important wood species, but unfortunately it is very susceptible to fungal degradation; hence it was used in the respective study. The objectives of the present study were to screen the capabilities and decay patterns of the two *Pleurotus* species, *P. cornucopiae* and *P. erygii,* by applying them on beech wood samples and determine the biological, chemical, and mechanical properties of decayed wood as well as compare their degradation capacities to standard white-rot fungus *Treametes versicolor*. These data are important because of constructional and biotechnological reasons. Degraded wood can be used in various fermentation processes from biogas to bioethanol production (Taherzadeh *et al.,* 2008).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Fungi
2.1. Gljive

Fruiting bodies of *Pleurotus cornucopiae* (Paulet) Rolland (Pc) and *Pleurotus eryngii* (De) Quél. (Pe) were collected from living beech trees (*Fagus orientalis* Lipsky.) at Hezarjarib forests, (located in Neka, Iran) during the spring 2017. Macro- and microscopic identification was carried out in accordance with the keys of Eriksson and Ryvarden (1975), Gilbertson and Ryvarden (1986), Ryvarden (1991), Ryvarden and Gilbertson (1993).

2.2 Wood samples
2.2. Uzorci drva

Wood blocks were obtained from (*Fagus orientalis*) trees at breast height and air-dried to reach 23±2 % moisture content. Specimens of (5×2.5×1.5) cm^3 according to the EN113 standard (1997) were used for the determination of mass loss (ML), and (6×5×0.6) cm^3 according to ASTM-D256-04 standard (ASTM 2004) for testing impact bending strength. The specimens used to evaluate impact bending strength were cut in cross section. Ten replicate specimens were prepared from different disks for each test. They were kept in a conditioning chamber (25 °C, and 40±3 % RH) for 4 weeks before testing**.**

2.3 Mass loss after biological test
2.3. Gubitak mase nakon biološkog testa

In order to evaluate the degradation capabilities of the *Pleurotus* species, beech wood samples were oven dried at 103±3 °C for 24 h and weighed prior to fungal exposure. Wood blocks were sterilized at 121°C for 20 min and exposed to fungi according to EN113. Fungi were incubated for 60 days at 22±2 °C and relative humidity of 65±5 %. Ten replicates were used for each treatment. After exposure, surface mycelium was scraped off and wood samples were weighed before drying at 103 °C for 24 h to determine the final moisture content (*MC*). After drying, the mass loss (*ML*) was obtained (Eq. 1 and 2).

$$MC(\%) = \frac{M_w - M_d}{M_d} \times 100 \quad (1)$$

$$ML(\%) = \frac{M_i - M_d}{M_i} \times 100 \tag{2}$$

Where *MC* is moisture content (%), *ML* is mass loss (%), M_i dry mass before decay (g), M_w wet mass after decay (g), M_d dry mass after decay (g).

2.4 Chemical analyses
2.4. Kemijska analiza

Changes in the chemical constituents of the wood cell walls of sound wood controls and samples, following exposure to fungi, were evaluated according to TAPPI standards test methods. The Klason lignin was determined according to T-222 om-98 of TAPPI standard. Oven-dried, extractive-free sawdust (1g) was mixed with 15 ml of 72 % sulfuric acid for 2 h at room temperature. The mixture was diluted with 560 ml of distilled water, heated for 4 h, and the insoluble materials were filtered off. The residue was washed and dried at 103 °C. The lignin content was calculated using Eq. (3)

$$KL(\%) = \frac{S_d - KL}{S_d} \times 100 \tag{3}$$

Where S_d is the dried weight of sawdust and *KL* is the dried weight of extracted Klason lignin.

Cellulose content was determined in accordance with T-17 wd-70 of TAPP; 2 g of sawdust (free from extractives) were mixed with 96 % EtOH (100 ml) and 65 % nitric acid (50 ml). The mixture was heated under reflux for 1 h, cooled and filtered. The residue was washed with distilled water and dried at 103 °C. Cellulose content was then calculated by Eq. (4):

$$\text{Cellulose}(\%) = \frac{S_d - EC}{S_d} \times 100 \tag{4}$$

Where S_d is the dried weight of sawdust and *EC* is the dried weight of extracted cellulose.

2.5 Impact bending strength
2.5. Savojna žilavost

Impact bending strength was performed according to ASTM-D256-04 and calculated using Equation 3. Before the Impact bending strength test, all samples were conditioned in a standard climate at 20 °C and 65 % relative humidity until constant mass was achieved.

$$I = \frac{F_{max}}{A} \tag{5}$$

Where *I* is resistance to impact (J/m^2), F_{max} is force (J) and *A* is cross section area (m^2).

2.6 Light microscopy
2.6. Svjetlosna mikroskopija

In order to monitor wood degradation, a GSL-1 sliding microtome (WSL, Switzerland) was used to cut thin wood sections (10–15 μm) of the blocks ($20_l \times 10_r \times 8_t$ mm^3). The sections were stained with safranin (0.5 % aqueous), Astra Blue (0.3 % aqueous) solution and mixed in a 1:1 ratio, washed in distilled water for 1–3 min and dehydrated by an alcohol series. After rinsing in xylol for 1–2 min, sections were mounted in Mountalan glue (Kimianovin, Tehran, Iran) on microscope slides. To avoid buckling of the sample, a 50 g weight was placed on the cover glass edges while the slide was drying at 60 °C for 12 h. Dried sections were examined and photographed with an Olympus E−210 microscope and with an Olympus E−450 camera.

2.7 Statistical analyses
2.7. Statistička analiza

Comparison between mass loss and changes in chemical components of the wood was carried out using a Student t-test for each exposure period (95 % level of confidence). Two-way ANOVA was conducted to examine the effect of decay condition on mass and chemical losses. All statistical analyses were performed using the SPSS software program, version 23.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Mass loss
3.1. Gubitak mase

Wood density is one of the first and elementary information. The average dry density of beech wood was 0.63 g·cm^{-3}. The ring width was between 2.80 and 3.40 mm. Mass loss (*ML*) of beech wood samples exposed to the fungi after incubation is shown in Figure 1. Average mass losses were 17.40 %, 8.70 %, and 21.76 % after 60 days incubation for *P. cornucopiae* (Pc), *P. eryngii* (Pe) and *T. versicolor* (Tv), respectively. The results indicated that Pe were more effective than Pc. However, Tv caused most *ML*. The minimum *ML* of 20 % by Tv is necessary for beech wood after 16 weeks (112 days) of incubation in accordance with EN-113 (1997). On the other hand, the average *ML* was 20 % and 40 %, respectively, in size of 30×10×5 mm after 12 weeks of exposure (Bravery, 1978). Bari *et al*. (2019) showed that *Pleurotus ostreatus* and Tv produced the same *ML* in beech wood after 120 days of incubation.

3.2 Moisture content after decay
3.2. Sadržaj vode nakon razgradnje drva

The moisture content (*MC*) of wood blocks after fungal incubation is shown in Figure 2. Generally, the *MC* was 77.09 %, 65.80 %, and 108.51 % after 60 days of incubation for Pe, Pc and Tv, respectively. Since fungi need moisture for their enzymes to cleave the cell wall components (Baldrian, 2008), the water is necessary for their function. According to Figure 2, the results demonstrated that the *MC* of the decayed wood blocks increased with the mass losses caused by both decay fungi. The increase of the mass loss could increase the moisture content in wood blocks. Similar works (Bami and Mohebby, 2011) showed that white-rot fungi caused high water content in decayed wood samples.

3.3 Cell wall components analysis
3.3. Analiza dijelova stanične stijenke

Average lignin and cellulose contents of sound and decayed beech wood samples, after 60 days of degradation by fungi, is shown in Figure 3. The graph indicates that the three white-rot fungi severely degraded cellulose and lignin. With regard to lignin, average degradation by fungi was 16.73 %, 16.63 %, and 13.67 % after 60 days of incubation for Pe, Pc, and Tv, re-

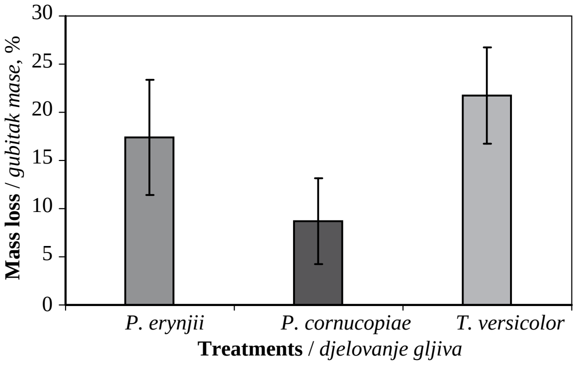

Figure 1 Average percent mass loss of beech wood samples decayed by white rot fungi after 60 days of incubation
Slika 1. Prosječni postotni gubitak mase uzoraka bukovine zbog djelovanja gljiva bijele truleži nakon 60 dana inkubacije

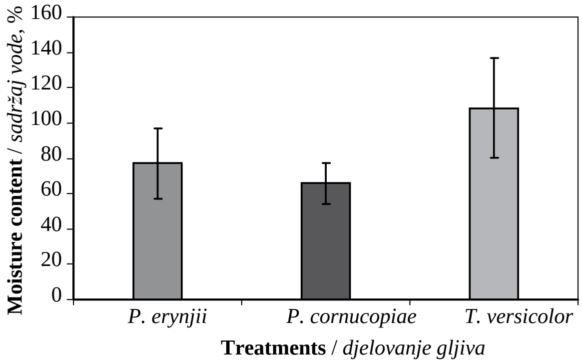

Figure 2 Moisture content of beech wood samples due to fungal metabolism after 60 days of incubation
Slika 2. Sadržaj vode u uzorcima bukovine zbog metabolizma gljiva nakon 60 dana inkubacije

spectively, while for the sound wood it was 23.63 %. According to Koshijima and Watanabe (2003) and Schmidt (2006), white-rot fungi are the most efficient lignin degraders in nature and they play a key role in carbon recycling on Earth. They break-down the lignin units by secretion of different enzymes to reach the necessary carbon. Average degradation of cellulose by fungi was 32.77 %, 34.53 %, and 28.64 % for Pe, Pc and Tv, respectively. Cellulose is the main carbon source for fungi, especially basidiomycetes (Schmidt, 2006). White rot fungi are divided in selective and simultaneous white-rot species (e.g. Eriksson *et al.* 1990; Schmidt, 2006). Figure 3 shows that the three fungi caused simultaneous white-rot in beech wood samples. Karim *et al.* (2016) showed that *Pleurotus ostreatus* decomposed beech and oak wood samples in natural and controlled conditions also follow a similar lignin degradation pattern. However, indications of selective digestion were also found in some wood cells. However, several researchers (e.g. Martinez *et al.* 2001, 2005) reported that many *Pleurotus* species caused the selective rot pattern. Cellulose, lignin content of decayed wood samples in the present study, is much lower than reported by Chen *et al.* (2017) and Hosseinihashemi *et al.* (2017). Olfat (2014) indicated that the mass loss of beech wood was 47.5 % after 16 weeks and 13.2 % after 10 weeks. Mass loss values of this study are comparable with the values given by Witomski *et al.* (2012).

3.4 Monitoring beech wood degraded by white-rot fungus
3.4. Praćenje uzoraka bukovine degradiranih djelovanjem gljiva bijele truleži

Wood density is one of the first and basic information. The average density of beech wood is 0.63 g. cm^{-3}. Growth rings are distinct because of the unusually light color of latewood. Two forms of degradation for white rot were described in this study. It is known that *P. eryngii* (Pe) and *P. cornucopiae* (Pc) caused selective lignin degradation. In the selective delignification type, lignin is degraded earlier than cellulose or hemicellulose in the process of decay. During the initial stages of decay, the cellulose is left unchanged during delignification. In some cases, hyphae in the cell lumen grow, so that lignin is separated from the adjacent cell wall (Anagnost, 1998; Schwarze, 2007). In

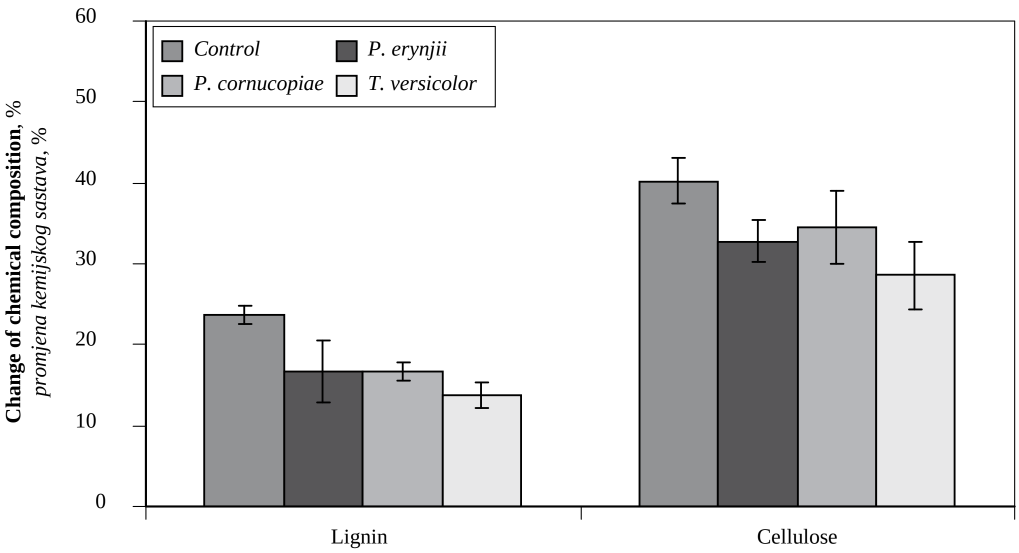

Figure 3 Average percentage of chemical composition in decayed beech wood samples after 60 days of incubation
Slika 3. Prosječni postotak promjene kemijskog sastava u uzorcima bukovine djelovanjem gljiva nakon 60 dana inkubacije

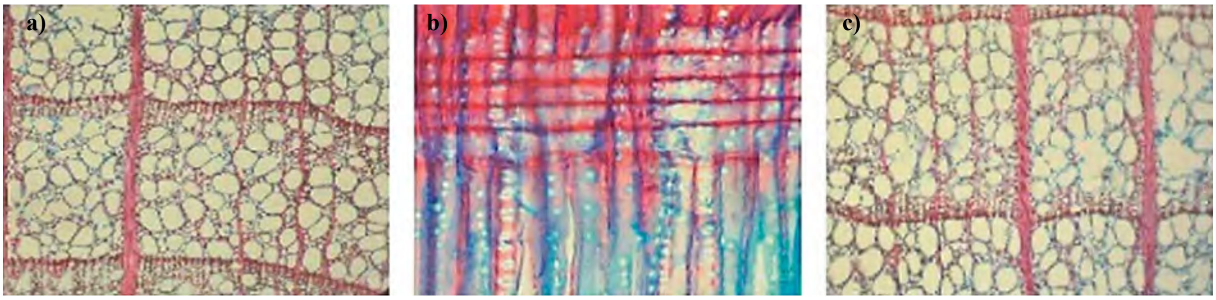

Figure 4 Light micrographs of beech wood degradation after 60 days of exposure to white-rot fungi; (**a**) Transverse section of beech wood incubated with *P. eryngii* (Pe). (**b**) Radial longitudinal section of beech wood incubated with *P. cornucopiae* (Pc) (**c**) Transverse section of beech wood incubated with *T. versicolor* (Tv)
Slika 4. Svjetlosne mikrografije degradacije uzoraka bukovine nakon 60 dana izlaganja gljivama bijele truleži: a) poprečni presjek uzorka bukovine inkubiranoga gljivom *P. eryngii* (Pe), b) radijalni uzdužni presjek uzorka bukovine inkubiranoga gljivom *P. cornucopiae* (Pc), c) poprečni presjek uzorka bukovine inkubiranoga gljivom *T. versicolor* (Tv)

the tangent section, the beech wood incubated with *P. eryngii*, as seen in Figure 4a. The hyphae, growing in the cell lumen of the fiber-tracheids, are seen in the early stages of delignification in the secondary walls. As seen in the radial section, the beech wood incubated with *P. cornucopiae*, the hyphae penetrate into the cell walls, and then first separate the middle lamella, so that the cells tend to separate from each other (Tuar *et al.* 1995; Seshikala and Charya1, 2012). Cellulose is relatively unchanged during selective delignation, at least in the early stages of decay (Figure 4b). *T. versicolor* cause simultaneous white rot in angiosperms, but only rarely in gymnospermous wood. In many studies, it was reported that this type of white decay degrades the adjacent cell wall for hyphae growing in contact with the lumen surface (Anagnost 1998; Schwarze 2007; Karim *et al.* 2017; Silva-Castro *et al.* 2018). The enzymes of *T. versicolor* cause the degradation in all the components of the lignified cell wall. The decomposition of cellulose, hemicellulose and lignin occurs at almost the same rate. As erosion proceedes on the lumen surface, the cell wall becomes thin evenly, as opposed to forming channels (Anagnost, 1998; Schwarze, 2007). This degradation form of *T. versicolor* in beech wood is characterized in Figure 4c. In the transverse sections, advanced thinning resulted in the localized removal of the cell wall and middle lamella.

3.5 Mechanical evaluation
3.5. Ocjena mehaničkih svojstava

Figure 5 shows the effects of the cell wall degradation on the impact bending strength after exposure to the white-rot fungi. The average decrease of impact bending strength by the fungi was 3.32 %, 3.68 %, and 3.17 for Pe, Pc, and Tv, respectively, while it was 4.59 % for the control sample. Overall, both fungi showed a similar effect on the reduction of impact strength. Toughness or impact strength is the ability of wood to absorb the force of impact bending and characterizes the ability of material to withstand impact loads. Impact strength is expressed as the energy consumed while breaking wood with defined dimensions. This mechanical property is most sensitive to decay and, unlike other strength properties that decrease gradually as decay progresses, impact strength declines rapidly during incipient wood decay (Rowell, 2005).

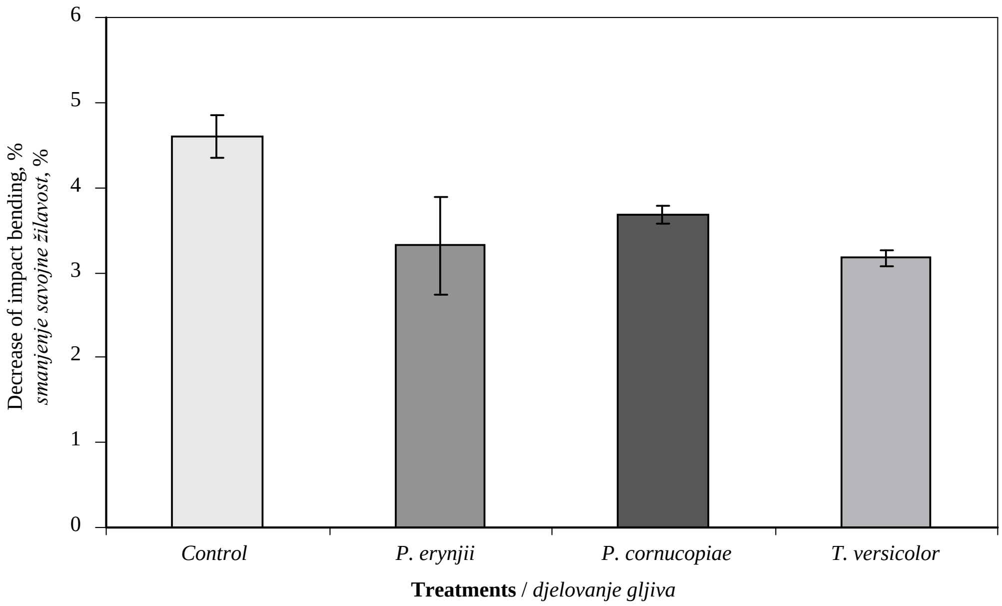

Figure 5 Average percentage of impact bending strength in decayed beech wood samples after 60 days of incubation
Slika 5. Prosječni postotak smanjenja savojne žilavosti degradiranih uzoraka bukovine nakon 60 dana inkubacije

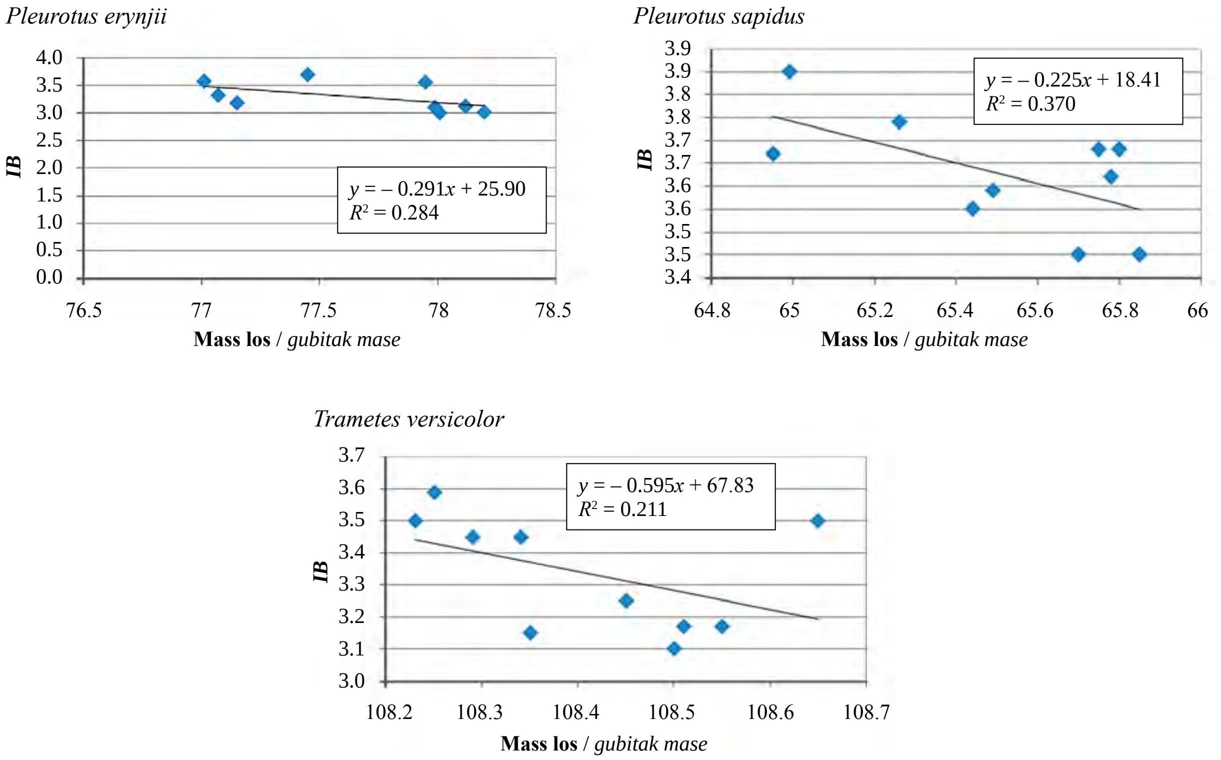

Figure 6 Relationship between mass loss and impact bending strength
Slika 6. Odnos između gubitka mase i savojne žilavosti uzoraka bukovine

Figures 6 shows the correlation between mass loss and impact bending strength data. As can be seen in these figures, the correlation is not very tight.

4 CONCLUSION
4. ZAKLJUČAK

Anatomical, chemical and mechanical properties were investigated of beech wood exposed to the two white-rot fungi for 60 days of incubation. The fungus clearly caused simultaneous decay pattern of cell wall polymers in the wood. Results indicated that both *Pleurotus* species created a considerable mass loss, which was accompanied by losses in chemical and mechanical properties. Altogether, under the conditions of the present research, it was concluded that the decay capacity of *P. eryngii* was more aggressive than that of *P. cornucopiae* in some test cases. According to the obtained results of the present study, the capability of wood rotting fungi for biotechnological applications such as biopulping, bioremediation, biochelation and recycling of treated wood is indisputable. However, their advantages and disadvantages should be considered before attempting industrial-scale operations.

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BERNARDA
KREVETI I MADRACI
dobar san za zdrav život
CHILLOUT
TIME OUT
DREAMING
RELAX
• inovativni individualno prilagođeni kreveti i madraci u veličinama prema želji
• visokokvalitetni kreveti i madraci za hotele, pansione i apartmane
• kutne garniture, pomoćni ležajevi
• vrhunski ergonomski antibakterijski jastuci
• dječji antibakterijski madraci
• medicinski antidekubitalni madraci i jastuci
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Fatih Yapici[1]

Experimental Study on Combustion Properties and Thermo-Gravimetric Analyses of Oriented Strand Board (OSB)

Eksperimentalna istraživanja svojstava gorenja i termogravimetrijska analiza ploča iverica s usmjerenim makroiverjem (OSB)

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ABSTRACT • *This study investigates the effects of types of adhesives on the combustion properties of oriented strand board panels (OSB). Combustion test was performed according to ASTM E69 standard. Mass reduction, change of temperature and released gas (CO, NO, O_2) were measured every 30 seconds during this test. Thermo-gravimetric analysis (TGA) of the OSBs was also carried out. While the highest temperature value of combustion was only obtained for the samples with phenol-formaldehyde at both outer and inner layer of test panels, the lowest temperature value was obtained for test samples with phenol-formaldehyde on the outer layer and isocyanate on the atinner layer. In the results of TGA, test mass reduction of OSBs was similar to each other, and most of the mass loss occurred at the temperatures between 200 and 400 °C.*

Key words: *oriented strand board; combustion; thermo-gravimetric analysis; phenol-formaldehyde*

SAŽETAK • *U ovom su istraživanju ispitivani učinci različitih adheziva na svojstva gorenja ploča iverica s usmjerenim makroiverjem (OSB ploče). Ispitivanje gorenja provedeno je prema normi ASTM E69. Tijekom ispitivanja svakih je 30 sekundi mjereno smanjenje mase, promjena temperature i ispušteni plinovi (CO, NO, O_2). Provedena je i termogravimetrijska analiza (TGA) OSB ploče. Dok su najveće vrijednosti temperature gorenja u vanjskome i unutarnjem sloju ispitivanih ploča zabilježene samo na uzorcima s fenol-formaldehidom, najniža vrijednost temperature izmjerena je za ispitne uzorke s fenol-formaldehidom u vanjskom sloju i izocijanatom u unutarnjim slojevima. Po rezultatima TGA analize testovi smanjenja mase OSB ploča bili su međusobno slični, a najveći gubitak mase dogodio se pri temperaturama između 200 i 400 °C.*

Ključne riječi: *ploča iverica s usmjerenim makroiverjem; gorenje; termogravimetrijska analiza; fenol-formaldehid*

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1 INTRODUCTION
1. UVOD

Wood is a very good material – it is easy to shape, it has good physical and mechanical properties, aesthetics, and it is environmentally friendly. In many countries, it is widely used as a building material, and in some areas as main construction and decoration material (Bednarek and Kaliszuk, 2007). Oriented strand boards (OSB) are engineered materials, which were designed for replacing plywood or solid wood in structural components. So, these boards must have sufficient mechanical properties. To meet these requirements, high quality strands must be used in their production (Mayers, 2001). The durability of the OSB depends on many factors such as type of binding agent, processing conditions, and additive materials. The type of adhesive used in the production also has a serious effect on their properties. The resins typically used for OSB production include phenol-formaldehyde (PF), four component melamine-urea-phenol-formaldehyde resins (MUPF), and isocyanates (Methylene Diphenyl Diisocyanate - MDI) (Mirski *et al*., 2017). OSB is a one of the world's most commonly used particularly engineered wood-based panel products in residential areas (Hiziroglu, 2009) and in many applications of the construction industry. First advantages of OSB are its equivalent mechanical properties and substantially lower cost compared to structural plywood. When OSB is used in roof or wall sheathing, it is exposed to environmental factors and degradation (Gunduz *et al.,* 2011). Plywood and OSB are used as structural sheathing. The use of the wood-based composite such as OSB has been increased since it is also widely used as the I-joints (White and Winandy, 2006).

One of the most negative features of the wooden materials is their combustibility. In order to eliminate this negative property of wooden materials, many chemicals are used to prevent their combustion and degradation. Many studies have been done with different combustion mechanisms on the combustion properties of wooden material. Fire tube mechanism is the most commonly used combustion mechanism. This mechanism is widely used and well-known in many countries (Ozcan *et al*., 2010). Uysal and Kurt (2005) have studied impregnation of Spruce (*Picea orientalis* L.) with boron compounds and the test samples that were applied to the combustion test. Uysal and Ozcifci (2000) have examined the combustion properties of laminated wood products made of different layers (both inner and outside) using PVAc adhesive.

During the first heat treatment process, many volatile organic compounds such as alcohols, resins, terpenes, etc. are released from the wood (Manninen *et al*., 2002). However, during this process, the decrease of hemicellulose content is not fully completed (Pavlo *et al*., 2003). The hemicellulose degrades between 160 and 260 ºC, since its low molecular weight and its branching structure facilitate a faster degradation when compared to the other components present in wood (Poncsak *et al*., 2006).

There are many important factors that affect physical and mechanical properties of wood composite materials. One of the most important factors is the type of adhesive used in production. Studies regarding resin content and type agree that increasing resin content or resin type can directly improve the stability by improving inter-particle bonding as it affects thickness swelling (Nemli, 2002). Although there are a lot of studies about the effects of resin types on physical and mechanical properties of particleboards, there is no adequate study on combustion and thermo-gravimetric properties of OSB. This paper focuses not only on the influence of adhesive types on combustion but also on the weight losses of OSBs during the thermo-gravimetric analysis (TGA).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Oriented strand board (OSB) test samples were manufactured from Scotch pine (*Pinus sylvestris* L.) wood. The used wood strands were approximately 80 mm long, 20 mm wide and 0.6 mm thick. First, the wood strands were dried up to 3 % moisture content before the adhesive was sprayed on them. The strands in the panels were made in three layers, and the inner ones were directed vertically to the outer ones. Phenol-formaldehyde (47 %) and isocyanate, without wax, were applied as adhesive materials to the oven-dried wood strands based on their 6 % weight. Three types of OSB panels were produced.

The OSB test sample #1 was only used with phenol-formaldehyde adhesive on both inner and outer layers. As for the OSB test samples #2, while phenol-formaldehyde was used on the outer layers, isocyanate adhesive was used on the inner layers. As for test samples #3, while isocyanate was used on the outer layers, phenol-formaldehyde adhesive was used on the inner layers. All the test panels were pressed for 5 min. at 40 kg/cm^2. The shelling ratio of the samples was 40 % for inner and 60 % for outer layers. All the test samples were pressed to a density of about 0.70 g/cm^3. The mats of OSBs were pressed in automatically controlled laboratory press plates heated at (182±3) °C.

2.2 Methods
2.2. Metode

The test samples were conditioned in a climate room with a temperature of (20±2) °C and relative humidity of (65±5) % until they reached the stable weight. Combustion test was carried out according to the principles of ASTM E69. However, some changes were made in the test stand. For this purpose, a digital balance having 0.01g sensitivity was used for the determination of mass reduction of materials during the burning process. Butane gas was used for ignition flame of test samples. The gas flow is standard for all test samples, and namely the height of flame is 25 cm and the temperature is approximately 1000 °C. The distance

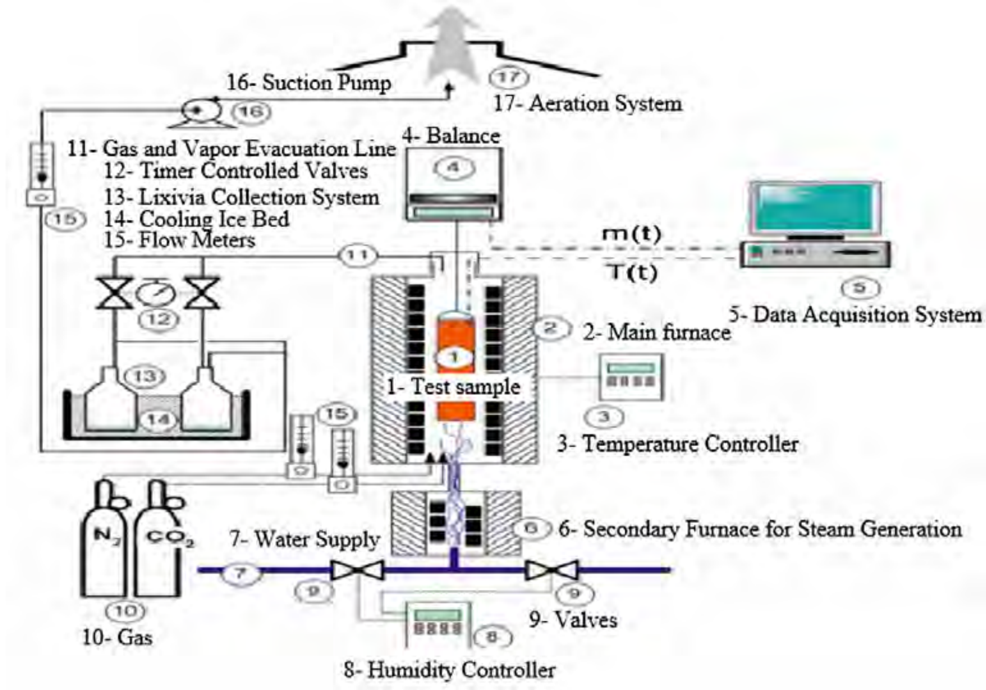

Figure 1 Schematic view of thermo-gravimetric system
Slika 1. Shematski prikaz termogravimetrijskog sustava (1 – ispitni uzorak; 2 – glavna peć; 3 – regulator temperature; 4 – vaga; 5 – sustav za prikupljanje podataka; 6 – pomoćna peć za proizvodnju pare, 7 – opskrba vodom, 8 – regulator vlage, 9 – ventili, 10 – plin, 11 – linija za uklanjanje plina i pare, 12 – vremenski upravljani ventili, 13 – sustav za skupljanje *Lixivia*, 14 – ledena kupka, 15 – mjerači protoka, 16 – usisna pumpa, 17 – sustav za odzračivanje)

between the bottom of the test samples (which were hanged inside of the fire tube) and the top of the gas pipe are adjusted to 2.54 cm.

During the test, release gases (CO, NO, O_2) and changes of the temperature were measured 20 times every 30 seconds. The test was conducted under a chimney where the flow of air blown was drawn with natural drift. At the beginning of combustion test, flame source was used for 4 minutes. Then, flame source was taken away and it took 6 minutes to make the measurements. Testo 350 M&XL flue gas analyzer was used for the measurement of the released gases and temperature variation.

The materials to be used in TGA, which weigh approximately 100 mg, were heated up to 800 ºC in a nitrogen atmosphere at a rate of 10 ºC/min and mass losses due to temperature increase were determined. TGA setup (Figure 1) was built to study the effects of the heat treatment parameters (maximum treatment temperature, heating rate, holding time, and gas humidity) on the test sample quality.

The variation of the temperature distribution in the wood and the weight loss of the test samples were recorded during the analysis. The test samples were suspended on the balance of the furnace. A programmable temperature controller assured the desired evolution of temperature in the furnace. The inert gas mixture (nitrogen, carbon dioxide, and water vapour) was used in order to prevent the oxidation reactions in the furnace. Nitrogen and carbon dioxide flow rates were controlled with flow meters. The gas humidity was adjusted by using a second furnace, which was placed directly under the main furnace. The outlet gas is evacuated from the system with a suction pump. An ice bed, as shown in Fig.1, was used to cool and collect condensed by-products, released from the test samples. Parallel lines, equipped with control valves, were used to separate condensed by-products collected at different temperature intervals.

Data obtained from experimental studies were statistically analyzed by using SPSS 20 program. First, distribution of the data was examined according to Test of Normality. Then descriptive statistics was performed.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The average air-density and moisture content values of OSBs were 0.72 g/cm^3 and 7.13 %, respectively. It can be said that the air-dry density and moisture content of test panels were found to be within the target limits. Results of the Test of Normality according to the Shapiro-Wilk are given in Table 1.

It can be seen that the changes in temperature and emerging gases, such as CO, NO, O_2 obtained as a result of combustion tests, did not show normal distribution according to the Shapiro-Wilk. The results of the Descriptive Statistics (Min., Max., Mean, Std. Dev., Skewness and Kurtosis) for temperature, ratio of O_2, CO and NO gases in the test chamber are shown in Table 2.

It is observed that the change of the temperature values is between 72 °C and 3021 °C. The higher temperatures were reached in the first 4 min., as this the time when the flame is applied in the combustion test.

Table 1 Test of normality
Tablica 1. Ispitivanje normalnosti raspodjele podataka

	Temperature, °C *Temperatura,* °C			**O_2, %**			**CO, ppm**			**NO, ppm**		
Type of panel / *Vrsta panela*	#1	#2	#3	#1	#2	#3	#1	#2	#3	#1	#2	#3
Statistics/ *Statistika*	0.35	0.91	0.90	0.88	0.74	0.84	0.90	0.79	0.86	0.84	0.78	0.84
df	80	80	80	80	80	80	80	80	80	80	80	80
Significance / *Značajnost*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 2 Results of descriptive statistics
Tablica 2. Rezultati deskriptivne statistike

Test parameters (*N*=240) *Parametri ispiti-vanja*	**Minimum** *Minimum*	**Maximum** *Maksimum*	**Mean** *Srednja vrijednost*	**Std. Deviation** *Standardna devijacija*	**Skewness** *Asimetrija*		**Kurtosis** Kurtozija	
					Mean*	Std. Error**	Mean	Std. Error
Temperature, °C	72	3021	269.79	286.20	7.50	0.15	70.34	0.31
O_2, %	9.52	20.87	17.68	3.33	-0.45	0.15	-0.10	0.31
CO, ppm	83	4755	1708.68	1401.79	0.53	0.15	-1.08	0.31
NO, ppm	5	195	55.27	52.79	0.89	0.15	-0.34	0.31

*Mean – *srednja vrijednost*; **Std. Error – *standardna pogreška aritmetičke sredine*

The average temperature is approximately 270 °C during the 10 min. interval of the test. The average values of emergent gases (O_2, CO, NO) were found to be approximately 18 %, 1708 ppm and 55 ppm, respectively. Kruskal-Wallis test was applied (since there were three variables and data did not show normal distribution) in order to determine the effect of the type of adhesives on the values of temperature, CO, NO and O_2 emerged from combustion test of OSB panels. Result of the Kruskal-Wallis test is given in Table 3.

The results of Kruskal-Wallis test, which was performed according to the combustion test, show that the effect of the type of adhesive on the temperature and the amount of CO and O_2 gases was significant, while the amount of NO gas was not statistically significant. Mann-Whitney U test was applied to determine which OSB test groups showed differences that occurred during the combustion tests (Table 4).

It is shown that, according to Mann-Whitney U-test, the effect of the adhesive type on the temperature

Table 3 Results of Kruskal-Wallis test
Tablica 3. Rezultati Kruskal-Wallisova testa

Type of panel *Vrsta panela*		**Dependent Variables** / *Zavisne varijable*			
		Temperature, °C	CO, ppm	NO, ppm	O_2, %
Mean Rank *Prosječni poredak*	#1	111.53	148.43	126.28	97.48
	#2	91.48	107.83	107.85	116.48
	#3	158.50	105.25	127.38	147.55
X^2		39.29	19.47	4.00	21.22
P		0.00	0,00	0.14	0.00

Table 4 Results of Mann-Whitney U-test
Tablica 4. Rezultati Mann-Whitneyjeva U-testa

Type of panels *Vrsta panela*		**Temperature, °C**	**CO, ppm**	**NO, ppm**	**O_2, %**
#1 and #2	Mann-Whitney U	2592	2026	2698	2560
	Wilcoxon W	5832	5266	5938	5800
	Z	-2.08	-4.01	-1.72	-2.18
	Asymp. Sig. (2-tailed)	0.04	0.00	0.09	0.03
#1 and #3	Mann-Whitney U	1874	2140	3160	1998
	Wilcoxon W	5114	5380	6400	5238
	Z	-4.53	-3.62	-0.14	-4.10
	Asymp. Sig. (2-tailed)	0.00	0.00	0.89	0.00
#2 and #3	Mann-Whitney U	1486	3040	2690	2238
	Wilcoxon W	4726	6280	5930	5478
	Z	-5.85	-0.55	-1.74	-3.28
	Asymp. Sig. (2-tailed)	0.00	0.59	0.08	0.00

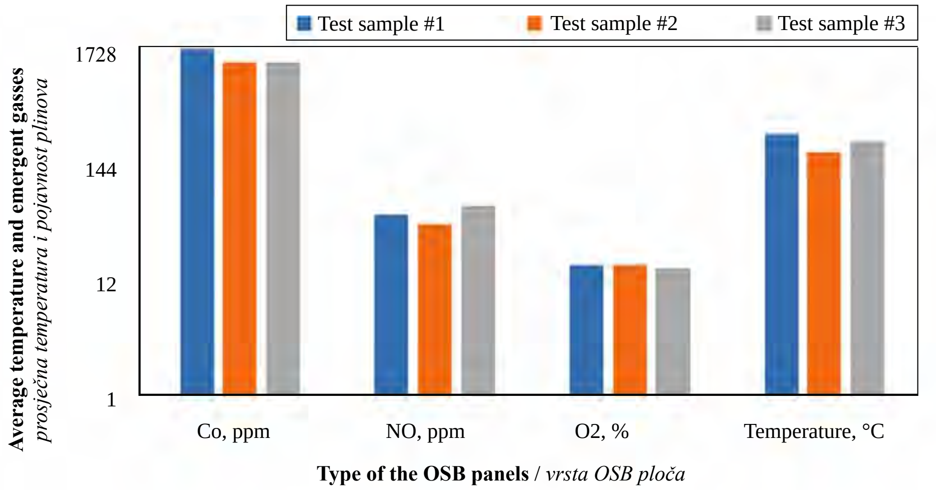

Figure 2 Change of CO, NO, O_2 and temperature
Slika 2. Promjena CO, NO, O_2 i temperature

and the amount of O_2 gas obtained from the combustion tests was significant in the test groups of test panels #1 & #2, #1 & #3 and #2 & #3, whereas the effect of the adhesive type on the amount of NO gas was not significant. The average values of temperature and emergent gases ratio are shown in Figure 1.

The highest CO value of 2081.65 ppm was obtained from the Test Sample #1, and the lowest value was measured as 1519.43 ppm from the Test Sample #3. The highest level of temperature was 317.23 °C from the Test Sample #1, produced by using only phenol-formaldehyde adhesive. As a result of combustion test, the highest value of O_2 was (18.39 %) obtained from the Test Sample #2. The average value of NO gas ranged between 44.73 and 66.15 ppm in this experimental study. All the results connected with these values are shown in Figure 1.

TGA is one of the most common techniques used to evaluate thermal behaviour during the pyrolysis of wood and other biomasses (Ertas and Alma, 2010; Ozbay, 2015). The mass reductions related to heat temperature used in thermo-gravimetric analyses is shown in Figure 2. It was determined that, as a result of gravimetric analysis of test panels, the weight losses of three different panels were similar and about 98 %. The reduction of mass turned out to be 98.44 % in the Test Sample #1 (first panel). Moreover, it was also identified that the mass reduction of the Test Sample #2 (second panel) was 98.07 %. In addition to this, it was measured that the mass reduction of the Test Sample #3 (third panel) was very close to the second panel (98.01 %).

Insoluble compounds act as a heat sink that decreases the combustion efficiency, but the soluble ionic compound can have a catalytic effect on the pyrolysis and combustion of wood (Shafizadeh, 1981). Song and Rao (1999) searched the effects of heat on constructional properties of plywood treated with fire retardant materials. Due to the increased use of wood-based composites such as OSBs, it becomes important to assess their fire performance after exposure to high temperatures. Since they are less massive than solid wood, they are less likely to resist a rapid temperature rise (Sinha *et al*., 2009). So, further study on the effect of high temperature on various properties of wood-based

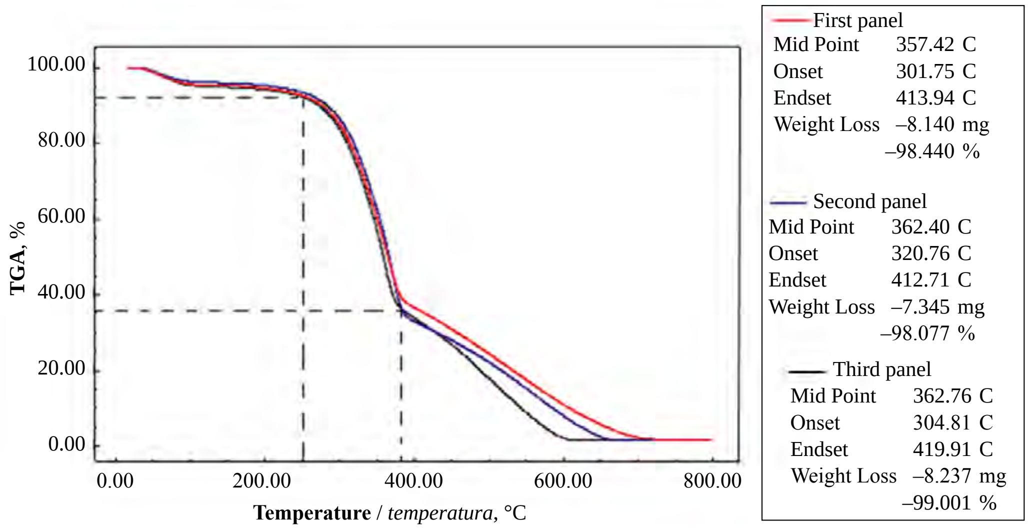

Figure 3 Mass reduction of panel related to heat temperature
Slika 3. Smanjenje mase ploče s obzirom na temperaturu zagrijavanja

composites is needed. Such thermal degradation studies involve understanding and predicting the behaviour of wood-based materials during their exposure to high temperatures.

They stated that the maximum mass reduction was between 300-380 °C after TGA tests. In addition, according to TGA, which was applied on OSB panels produced by using Scotch pine chips, the highest mass reduction was between 280-320 °C. The mass reduction obtained in the study is compatible with the literature, e.g. Tutus *et al*., (2010) stated that thermal degradation of Scots pine occurred between 300 and 500 °C.

4 CONCLUSIONS
4. ZAKLJUČAK

There are many studies in the literature that focus on the increase of the resistance of wood composite materials against environmental factors, and on the mechanical and physical properties of wood composite materials. This study investigated the combustion and thermo-gravimetric analysis of oriented strand boards manufactured from Scotch pine wood. So, this study is a preliminary work on the combustion and TGA of OSB panels. According to the results of combustion tests, the gas outcomes and changes of temperature are measured approximately as 17.68 % for O_2, 1708.66 ppm for CO, 55.27 ppm for NO and 269.79 °C. The mass reduction of test specimens was measured between 250-400 °C according to the results of TGA. The reason of the mass reduction at this range could be possible because of the degradation of wood components. It can be seen that the adhesive types used in the production of test panels have a considerable impact on similar properties in terms of mass loss according to the TGA test.

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Properties of Plywood Produced with Urea-Formaldehyde Adhesive Modified with Nanocellulose and Microcellulose

Svojstva furnirskih ploča proizvedenih s urea-formaldehidnim adhezivom modificiranim nanocelulozom i mikrocelulozom

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ABSTRACT • *Urea-formaldehyde adhesives are widely used in the wood-based materials industry. The study investigates the possibility of using cellulosic particles as a filler that modifies the properties of the resin and consequently improves the properties of plywood. Moreover, the study also examines the differences between microcellulose and nanocellulose used as a filler for UF adhesive. Based on the investigations, it was found that the addition of MFC and NCC significantly affected the curing process and rheological behaviour of adhesive mixtures. Modification led to increase of viscosity and extension of a gel time caused by lowering solid content of the resin. The experimental and reference plywood were tested in terms of bonding quality and mechanical properties such as modulus of elasticity and modulus of rigidity in accordance with applicable standards. The results of the tests confirmed that both the amount and the type of modifier added to the resin had a significant effect on the properties of plywood. The bonding quality and the above mentioned mechanical properties improved in all variants of modification; however the most effective was the addition of NCC in the amount of 10 %/100 g of solid resin. The slight decrease of formaldehyde emission was only observed for 5 % cellulosic particles added to 100 g of solid UF.*

Keywords: *nanocellulose; microcellulose; urea-formaldehyde resin; plywood; modification*

SAŽETAK • *Urea-formaldehidni (UF) adhezivi imaju široku primjenu u industriji materijala na bazi drva. U radu je opisano istraživanje mogućnosti upotrebe celuloznih čestica kao punila koje mijenja svojstva smole i posljedično poboljšava svojstva furnirske ploče. Nadalje, u istraživanju su ispitane razlike između mikroceluloze (MFC) i nanoceluloze (NCC) koje su upotrijebljene kao punilo za adheziv na bazi UF adheziva. Na temelju ispitivanja utvrđeno je da MFC i NCC dodatci znatno utječu na postupak stvrdnjavanja i reološko ponašanje adhezivnih smjesa. Modifikacija je rezultirala povećanjem viskoznosti i produljenjem vremena geliranja uzrokovanoga smanjenjem sadržaja čvrste smole. Ispitani su kvaliteta vezanja i mehanička svojstva eksperimentalne i referentne furnirske ploče poput modula elastičnosti i modula krutosti, sukladno odgovarajućim normama. Rezultati ispiti-*

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vanja potvrdili su da i količina i vrsta modifikatora dodanoga u smolu imaju znatan utjecaj na svojstva furnirske ploče. Kvaliteta vezanja i spomenuta mehanička svojstva poboljšana su pri svim varijantama modifikacija, no najučinkovitije je bilo dodavanje NCC-a u količini od 10 % na 100 g čvrste smole. Blago smanjenje emisije formaldehida uočeno je samo za 5 % celuloznih čestica dodanih u 100 g čvrstog UF adheziva.

Ključne riječi: *nanoceluloza, mikroceluloza, urea-formaldehidna smola, furnirska ploča, modifikacija*

1 INTRODUCTION
1. UVOD

Thanks to its unique properties, plywood is one of the most important products of the wood-based materials global industry. It is a valuable wood-based panel, widely used as a finishing and constructional material with very advantageous mechanical properties resulting from its layered structure (Bekhta *et al.,* 2016). The adhesion properties of veneers may seem similar to solid wood, and however, there are many operations during the plywood panel manufacturing processes, e.g. shearing and drying, that can affect the chemical and physical properties of the veneer surface (Munoz and Moya 2018). The commonly used adhesives for plywood production are urea-formaldehyde (UF) resins. The European production of aminoplastic adhesives was estimated to be 5.5×10^6 metric tons (Zhang *et al.,* 2011; Mahrdt *et al.,* 2016). The widespread use of these resins is due to their high reactivity, low cost, ease of processing and lack of colour (Dunky and Niemz, 2002; Dukarska, 2011). However, urea-formaldehyde adhesives are severely disadvantaged by the formaldehyde emissions from the manufactured wood-based panels (Gao *et al.,* 2018). The strength parameters of UF adhesive bonds is limited - it results from the stress concentrations along the bond line of wood adhesive joint and leads to deterioration of the mechanical properties (Veigel *et al.,* 2012). In the past, many studies have been carried out to improve the properties of resins, e.g. by chemical modifications (Dziurka and Mirski, 2010; Dziurka *et al.,* 2014) or addition of various kinds of fillers. The fillers for resins used in plywood industry are non-volatile, insoluble materials that can affect the reactivity and the viscosity of the plywood (Dukarska and Czarnecki, 2016). A number of studies considered fillers such as glass fibre, talc, TiO_2 and many more (Łęcka *et al.,* 2013), but due to their relatively large particles, it is hard to obtain a good level of homogenization. Without proper dispersion of the filler in the adhesive mixture, it is difficult to spread it properly on the surface of the veneer. In recent years, nanotechnology has been associated with very high expectations and the developments in this field have led to improvements of the properties of resins (Ahmad *et al.,* 2010; May *et al.,* 2010; Veigel *et al.,* 2011; Ates *et al.,* 2013; Bardak *et al.,* 2017). Nanoclay-reinforced urea-formaldehyde adhesive reveals increased water resistance, internal bonding of panels and improved thermal stability (Lei *et al.,* 2008; Zahedsheijani *et al.,* 2012). One of the most commonly used filler is nano-silicon dioxide. Addition of the silica can increase reactivity of the resin and leads to the possibility of reducing the amount of resin applied on the surface of veneers (Leonovich *et al.,* 2002; Lin *et al.,* 2006; Roumeli *et al.,* 2012; Dukarska and Czarnecki, 2016). Recently, it has been revealed that the addition of micro and nano fibres of cellulose may have advantageous effects on the properties of resin. Due to form and size, cellulose particles can be divided into three groups: MFC (microfibrillated cellulose), cellulose nanocrystals sometimes called whiskers (NCC) and nanofibrillated cellulose (NFC) (Hubee *et al.,* 2008; Pawlak and Boruszewski, 2018). Environmental friendliness has been a motivation for the use of cellulosic fillers (Ioelovich 2008). Resources of this natural polymer are estimated at 1.5×10^{12} tons per year (Klemm *et al.,* 2005). Pawlak and Boruszewski (2018) used MFC for reinforcing UF resin during the low-density particleboards production. Studies revealed that the addition of microcellulose had a positive effect on water resistance, modulus of rupture and modulus of elasticity. Moreover, the addition of MFC to UF resin made it more viscous (Mahrdt *et al.,* 2016). The addition of nanocellulose also improved the mechanical performance of particleboards and OSB boards (Veigel *et al.,* 2012). Also in case of low-density particleboards, standard particleboards and OSB boards, improvement in adhesive performance can reduce the amount of required resin and lead to significant cost reduction. Results of formaldehyde emission are not fully conclusive. Ayrilmis *et al.* (2016) revealed that MFC did not work for decreasing formaldehyde emission, and on the other hand Zhang *et al.* (2011) achieved a significant decrease of CH_2O emission because of the addition of NCC to UF resin. Thus, the aim of this work was to investigate the effect of the addition of MFC and NCC to urea-formaldehyde resin on the properties of manufactured plywood such as its mechanical performance and formaldehyde emission.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The adhesive used for research purposes was a commercially available urea-formaldehyde resin (Silekol, Kędzierzyn-Koźle, Poland) with the following characteristics: solid resin content 69 %, viscosity 610 mPas, gel time at 100 °C, 69 s, pH 8.09 and density 1.282 g/cm³. Two types of fillers were used: microfibrillated cellulose with a trade name ARBOCEL (Rettenmaier GmbH, Poland) with average particle sizes of 6 µm-12 µm and cellulose nanocrystals with a trade name NG01NC0101-1000 (Nanografi Nanotechnology Co. Ltd., Turkey) with average particle sizes, 10-20 nm wide and 300-900 nm long. Ammonium nitrate (20 wt%) was added as a hardener following the

Table 1 Variants of composition of adhesive mixtures
Tablica 1. Varijante sastava smjesa adheziva

Variant *Varijanta*	**Solid UF resin content, g** *Sadržaj* čvrste *UF smole,* g	**Amount of filler suspension, g/100 g d. m. of resin** *Količina suspenzije punila,* g/100 g *suhe tvari smole*		**Rye flour, g/100 g d. m. of resin** *Raženo brašno,* g/100 g *suhe tvari smole*	**H_2O, g/100 g d. m. of resin** *Voda,* g/100 g *suhe tvari smole*	**Hardener, g/100 g d. m. of resin** *Otvrđivač,* g/100 g *suhe tvari smole*
		MFC	NCC			
0	100	0	0	15	15	2
M5	100	5	0	2	0	2
M10	100	10	0	4	0	2
M20	100	20	0	8	0	2
N5	100	0	5	2	0	2
N10	100	0	10	4	0	2
N20	100	0	20	8	0	2

resin supplier recommendation. A number of tests were performed to determine the optimum amount of fillers. Due to the necessity of processing cellulosic particles in wet states, 10 % aqueous suspension was mixed with a magnetic stirrer (700 rpm, 10 min). Adhesive mixtures with an amount of MFC and NCC suspension, depending on the variant (Table 1), were prepared. The adhesive filled with cellulosic suspension was mixed with CAT-500 homogenizer at 1000 rpm for 2 minutes to achieve the high level of particles dispersion. In order to explain the effect of the modifier on the chemical structure of the cured UF resin, IR spectroscopy was used. Adhesive mixture in a form of powder was mixed with KBr (potassium bromide) at a 1/200 mg ratio. Spectra were registered using a Nicolet iS5 spectrophotometer (Thermo Fisher Scientific) with Fourier transform at a range of 500-4000 cm^{-1} at a resolution of 4 cm^{-1}, registering 16 scans. In order to assess the suitability of the reinforced adhesive mixture for plywood production, the following tests were carried out: viscosity and its changes for 8 hours with a Brookfield DV-II + Pro viscometer, gel time at 100 °C in accordance with Polish standard PN-C-89352-3, pH and solid content according to EN 1245:2011 and EN 827:2005, respectively.

Experimental three-layer plywood panels were manufactured from birch veneers with an average thickness of 1.5 mm and moisture content of 6 %. Veneers were glued with adhesive mixture in the amount of 170 g/m^2. Plywood was manufactured with the following pressing parameters: unit pressure 1.4 MPa, temperature 120 °C, time 4 min. Bonding quality (f_v) was assessed by shear test in accordance with EN 314-1:2004 on samples tested both dry and after soaking in water at temperature of 20 °C for 24 h (according to clause 5.1.1 of EN 314-1). In order to determine mechanical properties of plywood, such as modulus of elasticity (MOE) and modulus of rigidity (MOR), relevant tests were carried out according to EN 310 (1993), parallel and perpendicular to the grain. Statistical analysis of mechanical properties and bonding quality was carried out on 15 samples in each test. Average humidity content of plywood samples intended for tests was 5 %. Both in case of veneers and manufactured panels, the moisture content was calculated according to EN 322:1999. The amount of released formaldehyde was investigated using the flask method in accordance with EN 717-3:1996. Obtained results were subjected to statistical analysis using Statistica software. The Tukey test was carried out with the significance level $\alpha = 0.05$.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The IR spectra of both cured unmodified and modified UF resin are presented in Figure 1. The spectra of the UF resin without cellulosic particles and with MFC and NFC were almost the same. The spectra of adhesive mixtures revealed characteristic functional groups of typical cured UF resins such as a broad NH, OH stretching at around 3100–3500 cm^{-1}, amide I, II and C=O at 1650-1550 cm^{-1} and CH_2OH, CH_3 and CN at 1400-1360 cm^{-1}. IR-spectra confirmed that the addition of cellulose particles did not considerably affect the chemical structure of the cured UF resin. In future, it would be interesting to investigate the chemical interaction between modifier and adhesive using other spectroscopic methods.

While many research concerning the polymers modification with a natural fibre can be found, there is a very limited access to information about rheological behaviour and curing properties of the nanocellulose-reinforced adhesives intended for the production of wood-based materials (Richter *et al.,* 2009; López-Suevos *et al.,* 2010). Properties of urea-formaldehyde resin with the addition of different amounts of MFC and NCC are shown in Table 2.

Table 2 Characteristics of adhesive mixture
Tablica 2. Svojstva smjesa adheziva

Variant *Varijanta*	**Gel time, s** *Vrijeme geliranja,* s	**pH**	**Solid content, %** Čvrsta *tvar,* %
0	69	8.2	67.2
M5	69	8.4	61.5
M10	75	8.4	45.6
M20	93	8.5	42.2
N5	71	8.3	62.8
N10	94	8.2	56.9
N20	119	8.4	51.5

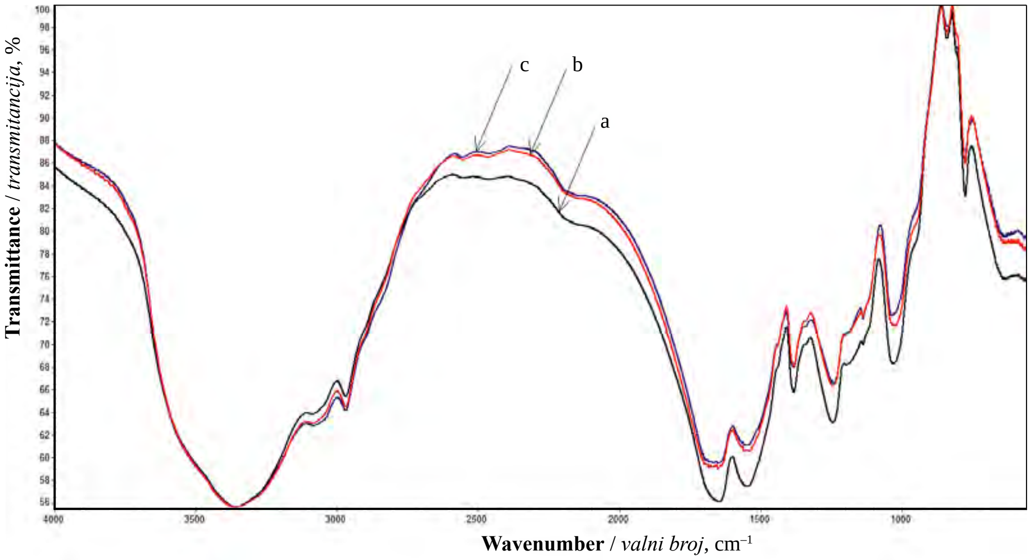

Figure 1 IR spectra of: (a) – unmodified UF resin; (b) – NCC+UF resin labelled as N10; (c) – MFC+UF resin labelled as M10
Slika 1. IC spektar: a) – nemodificirana UF smola; b) – NCC+UF smola označena kao N10; c) – MFC+UF smola označena kao M10

On the basis of data presented in Table 2, it was found that as the amount of MFC and NCC suspension is increased, the gel time of adhesive mixture is extended. This may be caused by lowering solid content of the resin due to extra water added with the aqueous cellulosic suspension, which was expected based on previous studies (Veigel *et al.,* 2012). In a recent study, Mahrdt *et al.* (2016) revealed that the addition of cellulosic particles had a significant effect on urea-formaldehyde adhesives cure kinetics. Moreover, due to the hydrophilic properties of cellulose, it was noted that cellulose micro- and nanoparticles can prevent water from evaporating during the pressing, which can be technologically disadvantageous and can affect the productivity. pH level of the adhesive mixtures remained stable regardless of the type and amount of filler addition. The results of viscosity and its changes are presented in Figure 2.

As expected based on the hydrophilic properties of fillers and earlier studies (Veigel *et al.,* 2012; Mahrdt *et al.,* 2016), viscosity has significantly changed during the test time. However, a different amount of rye flour added to adhesive mixture seems to reduce the differences between the variants and make reinforced adhesives comparable to control adhesive prepared in accordance with industrial recipe. Relatively high viscosity of MFC-UF and NCC-UF resins at the beginning of the test was caused by considerable interfibrillar interaction. Surfaces of cellulosic fibrils are covered with hydroxyl groups that can lead to the formation of temporary bonds between the adjacent fibrils (Iotti *et al.*, 2011). Fig 2 also shows a slightly higher viscosity in the case of NCC-UF compared to MFC-UF mixture. It can be caused by the fact that particles in a nanoscale have increased chemical reactivity of their surface. which leads to the formation of agglomerates (Shahbazi *et al.,* 2013).

Results of shear strength (f_v) of manufactured plywood are presented in Table 3. Studies revealed that modification of UF resin with cellulosic particles had a positive effect on the bonding quality in all variants, regardless of the amount and type of filler added to adhesive mixture.

The statistical analysis shows that the type of modifier had a significant effect on the bonding quality of plywood. Plywood manufactured with NCC-UF

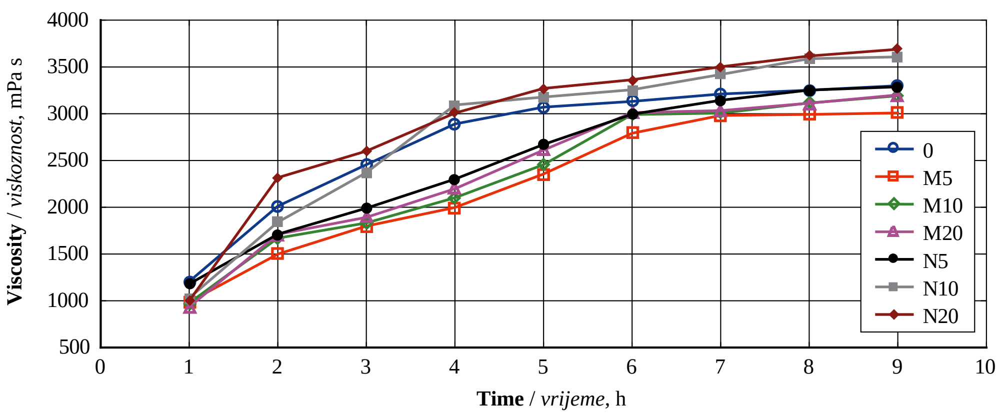

Figure 2 Changes in viscosity during 8-hour test depending on the variant of adhesive mixture
Slika 2. Promjene viskoznosti ovisne o varijanti smjese adheziva uočene tijekom 8-satnog ispitivanja

Table 3 Shear strength of plywood depending on the variant of used adhesive mixture
Tablica 3. Čvrstoća na smicanje furnirske ploče u ovisnosti o varijanti smjese adheziva

Variant *Varijanta*	f_v, **N/mm²**	
	Tested dry *Ispitivano nasuho*	**After 24h of soaking** *Nakon 24-satnog potapanja*
0	1.818 (0.264)a	1.558 (0.395)a
M5	1.978 (0.267)b	1.680 (0.285)ab
M10	2.313 (0.280)c	2.015 (0.262)cd
M20	2.171 (0.291)cb	1.824 (0.205)abc
N5	2.083 (0.301)cb	1.753 (0.309)abc
N10	2.612 (0.287)d	2.219 (0.389)d
N20	2.291 (0.212)c	1.890 (2.248)bc

(...) – Standard deviation / *standardna devijacija*; a,b,c,d – homogeneous groups (Tukey test, α = 0.05) / *homogenost skupina*

resin achieved considerable better shear strength results than control samples and samples with MFC-UF adhesive. However, both in case of plywood glued with resin modified by microcellulose and nanocellulose, the amount of modifier was also important similarly as in the research of Richter *et al.*, (2009). Addition of NCC and MFC in the amount of 5 %/100 g of solid resin led to a slight increase of shear strength. Regardless of the type of filler, the best results were obtained for the amount of 10 %/100 g of solid resin. Introducing 10 % of MFC caused the increase in bonding quality by about 27 % and 29 %, respectively, in case of samples tested dry and after soaking. The most significant change was noted in case of 10 % addition of NCC and it was approx. 44 % in comparison to plywood glued with unmodified resin. As expected based on the recent studies of Veigel *et al.* (2012), further addition of the filler led to a decrease of joint properties. Most importantly, regardless of the type and amount of added cellulosic particles, the results of all plywood shear strength exceeded a value 1 N/mm² required by the standard EN 314-2:1993.

Table 4 reveals an improvement of mechanical properties, i.e. modulus of elasticity and modulus of rigidity, caused by addition of both MFC and NCC to UF resin. Plywood samples were tested parallel and perpendicular to the grain of face layers.

Similarly as in the case of statistical analysis of bonding quality results, the type of filler had a significant effect on *MOR* and *MOE* values. Only in the case of modulus of elasticity assessed parallel to the grain, based on the Tukey's test performed, it was not possible to determine separate homogeneous groups with the significance level α = 0.05 as in the case of recent studies of Dukarska and Czarnecki (2016). The addition of NCC had more considerable effect on the *MOR* and *MOE* of plywood in comparison with the panels glued with MFC-UF resin and unmodified resin. On the basis of the data presented in Table 4, it can be concluded that the best results were obtained by the addition of 10 % NCC/100 g of solid resin. Values of modulus of rigidity were increased by about 34 % and 66 %, respectively, parallel and perpendicular to the grain of face veneer layer. Modulus of elasticity was mostly correlated with *MOR* and has shown similar results. In case of considered mechanical properties, the trend was very similar as in case of bonding quality of plywood. 5 % addition of MFC and NCC to 100 g of solid resin led to a slight increase of modulus of rigidity and modulus of elasticity. However, further filler addition at the level of 20 % caused a decrease of the above mentioned properties. Thus, as expected based on recent studies, the amount of nano-modifier had a significant effect on the mechanical performance of plywood.

The formaldehyde emission values from the manufactured plywood panels are presented in Table 5. To determine the amount of formaldehyde release, the flask method was used.

Applying small amounts of MFC and NCC (5 % by weight of solid resin) led to a slight decrease in formaldehyde emission, which is similar to recent studies on the addition of other nanoparticles to adhesives, e.g. nano-SiO_2 (Dukarska and Czarnecki, 2016). However, further addition of micro- and nanocellulose to UF resin resulted in an increase of formaldehyde emission compared to control samples. On the basis of the presented data, it cannot be clearly concluded that

Table 4 Modulus of Rigidity (*MOR*) and Modulus of Elasticity (*MOE*) depending on the variant of used adhesive mixture
Tablica 4. Modul krutosti (*MOR*) i modul elastičnosti (*MOE*) u ovisnosti o varijanti upotrijebljene smjese adheziva

Variant *Varijanta*	***MOR*, N/mm²**		***MOE*, N/mm²**	
	‖	⊥	‖	⊥
0	135.08 (15.3)a	23.01 (2.1)a	13342 (1547)a	1549.7 (208.1)a
M5	143.74 (24.5)ab	25.10 (3.4)ab	13753 (1447)a	1630.4 (263.2)ab
M10	163.81 (9.9)cd	32.18 (1.7)c	14149 (1907)a	1781.8 (177.5)abc
M20	150.09 (8.6)abc	27.39 (2.2)b	13813 (1462)a	1726.9 (192.7)abc
N5	150.61 (14.8)abc	25.31 (2.9)ab	13779 (1805)a	1746.8 (200.2)abc
N10	180.49 (13.1)d	38.14 (3.3)d	15059 (1401)a	1955.8 (164.5)c
N20	160.64 (10.2)bc	30.98 (2.1)c	14198 (1410)a	1881.1 (239.4)bc

(...) – Standard deviation / *standardna devijacija*; a,b,c,d – homogeneous groups (Tukey test, α = 0.05) / *homogenost skupina*

Table 5 Formaldehyde emission from manufactured plywood depending on the variant of used adhesive mixture
Tablica 5. Emisija formaldehida iz proizvedene ploče u ovisnosti o varijanti upotrijebljene smjese adheziva

Variant *Varijanta*	**Formaldehyde content, mg CH_2O/kg** *Sadržaj formaldehida*, mg CH_2O/kg
0	2.253
M5	2.045
M10	2.509
M20	2.653
N5	2.116
N10	2.255
N20	2.258

the addition of MFC or NCC significantly decreased the amount of formaldehyde emission, which is similar to recent studies of Ayrilmis *et al.* (2016). The possible reason of decrease in formaldehyde emission could be the fact that nanoparticles can absorb free formaldehyde from adhesives (Liu and Zhu, 2014). Moreover, it was previously reported that barrier properties of nanoparticles can reduce the amount of emitted formaldehyde due to the shielding effect. The slight increase of formaldehyde emission in some variants may be caused by aggregation of the particles in the adhesives mixture filled with cellulose (Ayrilmis *et al.,* 2016). As a future work, it would be interesting to modify the surface of cellulosic fibrils, e.g. with 3-aminpropyltriethoxysilane (APTES) or 3-methacryloxypropyltrimetoxysilane (MPS). The emission of CH_2O from plywood glued with UF resin modified with NCC was reduced by adsorption and chemisorptions, which seems to be caused by modification of nanoparticles with APTES (Zhang *et al.,* 2011).

4 CONCLUSIONS
4. ZAKLJUČAK

On the basis of the IR-spectra, it can be concluded that the addition of cellulose particles did not considerably affect the chemical structure of the cured UF resin. However, the presented results show that the addition of both MFC and NCC to UF resin made it more viscous, which can delay its gel time, and this limits the possible addition level of cellulosic particles. The addition of cellulose improved the bonding quality and mechanical properties of plywood in all variants of modification but definitely the best results were obtained for the addition of 10 % NCC per 100 g of solid resin. The use of 5 % NCC and MFC/100 g of solid resin led to a slight decrease in formaldehyde emission but further increase of the amount of modifier did not reduce the amount of formaldehyde emitted from the plywood.

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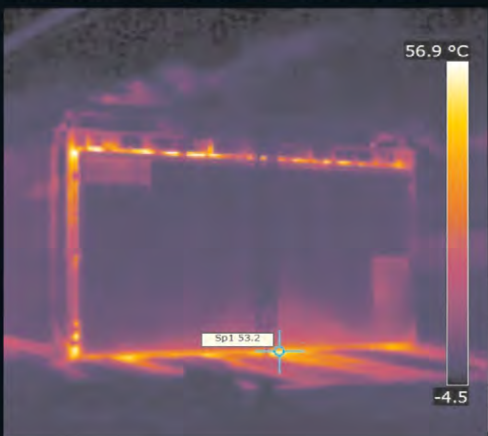

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Hygrothermal Treatment of Tepa (*Laureliopsis philippiana* Looser) Fibers: Effects on Chemical and Physical Properties

Hidrotermička obrada iverja drva tepe (*Laureliopsis philippiana* Looser): utjecaj na kemijska i fizička svojstva

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ABSTRACT • *The present study consisted in determining the effects of a hygrothermal treatment on wood fibers from the Laureliopsis philippiana Looser species. The fibers were treated in autoclave at 150 °C for 90 minutes at a pressure of 430 kPa, which was generated during the evaporation process of the water in autoclave. Physical properties, color, and water retention capacity of hygrothermically treated and untreated fibers were analyzed. The chemical properties determined were the extractable amount in sodium hydroxide, toluene ethanol, hot and cold water, the cellulose, holocellulose and lignin contents, the pH value, the percentage of volatile and washable acids, and the buffer capacity. In hygrothermically treated fibers, a change of color was detected as well as a reduction in the water retention capacity and an increase in the percentage of extractable, cellulose, lignin and a decrease of holocellulose. Also an increase in acidity, amount of volatile and washable acids and buffer capacity were determined. Due to the chemical changes observed in the treated fibers, these would present advantages in the manufacture of fiberboards, facilitating the setting of the amino resins.*

Key words: *hygrothermal treatment; Laureliopsis philippiana; fibers; physical and chemical properties; acidity; fiberboards*

SAŽETAK • *Cilj rada bio je utvrditi učinke hidrotermičke obrade na vlakna drva Laureliopsis philippiana Looser. Vlakna su tretirana u autoklavu, na temperaturi 150 °C tijekom 90 minuta, i pri tlaku 430 kPa, koji je nastao tijekom procesa isparavanja vode u autoklavu. Analizirana su fizička svojstva, boja i kapacitet zadržavanja vode u hidrotermički obrađenim i neobrađenim vlaknima. Od kemijskih svojstava određena je ekstrahirana količina u natrijevu hidroksidu, toluen-etanolu te u toploj i hladnoj vodi, zatim sadržaj celuloze, holoceluloze i lignina, pH vrijednost, postotak hlapljivih kiselina i kiselina koje se mogu isprati te kapacitet pufera. U hidrotermički tretiranim vlaknima zabilježena je promjena boje i smanjenje kapaciteta zadržavanja vode te povećanje postot-*

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ka ekstrakta, sadržaja celuloze i lignina, kao i smanjenje sadržaja holoceluloze. Također je utvrđeno povećanje kiselosti, količine hlapljivih kiselina i kiselina koje se mogu isprati te određen kapacitet pufera. Zbog kemijskih promjena uočenih na obrađenim vlaknima takva bi vlakna mogla imati prednost u proizvodnji ploča vlaknatica jer olakšavaju pozicioniranje amino smola.

Ključne riječi: *hidrotermička obrada, Laureliopsis philippiana, vlakna, fizička i kemijska svojstva, kiselost, ploče vlaknatice*

1 INTRODUCTION
1. UVOD

Heat treatment darkens the color of the wood (Akgül and Korkut, 2012; Karlsson *et al*., 2012a; Crespo *et al*., 2013), reducing the clarity and increasing the chromaticity (Karlsson *et al*., 2012a.). Darkening is proportional to the temperature and time of treatment, being uniform through the width and depth of the wood (Brauner and Conway, 1964), resulting in a greater darkening of hardwoods than of conifers (Schneider, 1973; Sandoval-Torres *et al*., 2010).

The wettability of heat treated wood particles decreases in treated fibers (Poblete, 1983; Crespo *et al*., 2013) as well as water retention capacity (Roffael and Kraft, 2012; Weigl *et al*., 2013). The higher the temperature and the exposure time of heat treatment, the lower the amount of water absorbed by the wood (Poblete, 1983; Kartal *et al*., 2007.).

Thermal decomposition of the constituent molecules of the wood begins at temperatures below 160 °C (Yamauchi *et al*., 2005; Esteves and Pereira, 2009). Constitution water loss begins at this temperature, leading to a decrease in the content of OH groups (Hill, 2006). The degradation of the chemical components causes the formation of acetic acid, formic acid and phenolic compounds, as well as the formation of other aromatic and extractable compounds (Jämsä and Viitaniemi, 2001; Hill, 2006; Awoyemi and Jones, 2011). The formation of organic acids catalyze the hydrolysis of pectins, hemicelluloses and to a lesser extent, the amorphous cellulose. Simultaneously, the lignin is softened and is partially depolymerized (Mitchell, 1988; Garcia-Jaldon *et al*., 1998). Furthermore, some components of the cell walls are reorganized, and the number of OH-H bonds decreases (Homan *et al*., 2000). Using an autoclave generates pressure, which has effects that can be important in regards to the composition, structure and properties of wood (Giebeler, 1983; Ding *et al*., 2011.). However, these treatments cause an improvement in certain physical properties (Burmester, 1973).

The production of acetic and formic acid at temperatures below 200 °C (Fengel and Wegener, 1989; Alén *et al*., 2002) decreases the pH value of the wood (Kollmann and Fengel, 1965; Weiland and Guyonnet, 2003; Wikberg and Maunu, 2004), increasing the amount of volatile and washable acids as well as the acidic buffer capacity (Poblete, 1983; Roffael, 1987a, b; Crespo *et al*., 2013.).

Acidity is an important factor to consider in the manufacture of wood panels, since the chemical reactions that occur during the setting of the adhesive follow an optimal course with a specific pH range for each type of adhesive. The variation in pH values affects the properties of fiber bonding, so knowing the acidity of the wood and its changes due to the form of processing are important in predicting the behavior of the wood and adhesive (Crespo *et al*., 2013).

Considering the changes in the physical and chemical properties of wood due to heat treatments, and its potential impact on production of boards, the aim of this study was to determine the effects of a hygrothermal treatment on fibers from *L. philippiana*, a species with unfavorable chemical characteristics for the production of boards with ureaformaldehyde (Pinto and Poblete, 1992; Poblete and Pinto, 1993). The effects on the physical and chemical properties that affect the production of boards made with *L. philippiana* fibers and amino resins were reported, considering the changes in color, in water retention capacity, in the main cell wall compounds, in the percentage of extractables, in varied pH values, in washable and volatile acids, and in buffer capacity.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

L. philippiana wood harvested in the region XIV of Los Rios Pre-Andean mountain range (Chile) was used. The wood was chipped and shredded through a mechanical process, using water to prevent temperature increase during the extraction of fibers. After obtaining the fibers, these were conditioned to room temperature and humidity.

2.2 Methods
2.2. Metode

The fibers were placed into a steel basket in an autoclave at 150 °C for 90 minutes. The autoclave contained water to a height leaving a space of 2 cm between the fibers and water. Due to the steam generated in the autoclave, there was an increase in pressure during the process, which was controlled and reached 430 kPa. After the treatment was finalized, the fibers were conditioned to room temperature and humidity. After being conditioned, the fibers with and without hygrothermal treatment were dried at 70 °C to 4 % moisture content.

The evaluation of color of the fibers before and after the hygrothermal treatment was performed using color tables for soils (Munsell, 1994) and an X-Rite spectrophotometer, with which the measurements were made using built in computer software with the D65/10 brightness option.

The water retention capacity was measured according to the methods employed by Poblete (1983). Therefore, a certain amount of fibers were left in the distilled water for 18 hours. Then, a sample was poured into a pulp testing apparatus and centrifuged at a speed of 2850 rpm for 5, 10, 15 and 20 seconds, to extract the water. After completing each centrifuging process, the fibers were taken to a pre-weighed beaker, then weighed again, and dried in an oven at 103 °C to constant weight. Finally, the beaker was cooled with the fibers in a desiccator and weighed. Water retention capacity (WRC-value) was calculated by the following equation:

$$WRC - Value = \frac{Weight\ of\ wet\ fibres - Weight\ of\ dry\ fibres}{Weight\ of\ dry\ fibres} \times 100$$

The chemical components were determined according to the standards and methods described below:

- Preparation of wood for chemical analysis (TAPPI 264 cm-97).
- Water solubility of wood and pulp (TAPPI 207 cm-99).
- Solubility in 1% of sodium hydroxide (0.25 N) of wood and pulp (TAPPI 212 om-98).
- Extractables in toluene ethanol (TAPPI 204 cm-97).
- Hoffer Kurschner cellulose method according to Hessler and Merola (1949).
- Poljak holocellulose method according to Haas *et al*. (1955).
- Insoluble lignin in acid (Klason lignin) (TAPPI 222 om-98).
- PH value of a filtered sawdust solution with water according to Roffael *et al*. (2000).
- Volatile and washable acids according to Poblete (1983).
- Buffering capacity, according to Roffael *et al*. (2000).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Color
3.1. Boja

According to the comparison made using the Munsell color tables for soils, a change in the color of the yellow fibers (2.5 Y 4/8) to a reddish yellow (10 YR 5/6) was detected. Measurements taken with the spectrophotometer confirm a darkening of the hygrothermically treated fibers, making them less clear (lower L^* value), redder (higher value of a^*), more blue (lower value of b^*), with a lower color saturation (C^*) and a lower hue angle ($h°$). The reduction in the hue angle indicates a change of color of the fibers from a greenish yellow to a reddish blue (Table 1).

Sullivan (1967a, b) states that the color variations in the wood will focus on the clarity and saturation, which coincides with the difference in lightness (L^*) and hue angle ($h°$) between the hygrothermically treated and untreated fibers.

The color changes observed in this experiment are consistent with those detected by different authors who found color changes from light to dark after solid wood vaporization at high temperatures (Brauner and Conway, 1964) and in solid wood subjected to a hygrothermal treatment (Momohara *et al*., 2003; Oelhafen *et al*., 2006a, b; Todorovic *et al*., 2012). Darkening was also determined in *L. philippiana* particles subjected to a hygrothermal treatment (Crespo *et al*., 2013). In a study with fibers, Widsten *et al*. (2001) stated that by increasing the temperature of defibration from 171-202 °C the fibers become darker, which indicates an increased frequency of chromophore groups, free radicals and quinonic structures on the surfaces of the fibers.

The color change in the heat treated *L. philippiana* fibers is related to the increased amount of extractables (Table 2), since according to Sundqvist and Morén (2002) the extractables participate in the color formation of the heat-treated wood. Karlsson *et al*. (2012a) claim that the degradation of the monosaccharides is an important factor in the formation of the color of the wood during heat treatment. Similarly, Dubey (2010) ensures that compounds degraded by heat, along with the extractables and other compounds such as sugars with low molecular weights and amino acids, tend to migrate to the surface of the wood during the heat treatment process, which results in a darkening.

Thermal oxidation of cellulose (Matsuo *et al*., 2012), the formation of colored degradation products of hemicelluloses (Sehlstedt-Persson, 2003; Sundqvist, 2004; Dubey, 2010), and the generation of chromophoric groups by oxidation, primarily the increase of lignin carbonyl groups, in particular the appearance of quinones (González-Peña and Hale, 2009; Dubey, 2010), also may have influenced the color change recorded in hygrothermically treated fibers to a lesser extent.

Considering that the market for furniture and construction prefer boards with light surfaces, the darkening recorded in the present study may result in a

Table 1 Color comparison of *L. philippiana* hygrothermically treated and untreated fibers
Tablica 1. Usporedba boje hidrotermički obrađenih i neobrađenih vlakana drva *L. philippiana*

Parameter / *Svojstvo*	**Untreated fibers** *Neobrađena vlakna*	**Treated fibers** *Obrađena vlakna*
L^* (lightness 100 “white” 0 “black”) / L^* *(svjetlina 100 “bijelo” 0 “crno”)*	60.56	48.36
a^* (chromaticity $+a^*$ “red” $-a^*$ “green”) *a^* (kromatičnost $+a^*$ “crveno” $-a^*$ “zeleno”)*	3.13	4.66
b^* (chromaticity $+b^*$ “yellow” $-b^*$ “blue”) *b^* (kromatičnost $+b^*$ “žuto” $-b^*$ “plavo”)*	13.11	9.00
C^* (color saturation) / C^* *(zasićenost boje)*	13.48	10.13
$h°$ (hue angle) / $h°$ *(kut boje)*	76.59	62.61

disadvantage for marketing boards made with these fibers.

3.2 Water retention capacity
3.2. Kapacitet zadržavanja vode

The variation of the water retention capacity of the fibers with and without hygrothermal treatment, after centrifugation at different times, is presented in Figure 1.

In Figure 1, it can be observed that the water retention capacity in hygrothermically treated fibers permanently decreases with the centrifugation time, which implies that less water is absorbed and retained. The water retention capacity of treated fibers was always less than that of untreated fibers, with an average difference of approximately 15.9 %.

The decrease in water retention capacity coincides with the reduction of wettability with ureaformaldehyde in hygrothermically treated *L. philippiana* particles, reported by Crespo *et al*. (2013). Similarly, in particles thermally modified at 180 °C for 1.5 hours, Weigl *et al*. (2013) reported a decrease of 28.0 % and 46.0 % of the water retention capacity, which is related to the reduction of polarity. Coincidentally, Roffael and Kraft (2012) indicate that the thermal modification of the wood leads to a marked decrease of the water retention capacity. After subjecting particles to heat treatment, these authors reported a decrease in water retention values (after 72 hours in water) of 27.0 % for *Fagus sylvatica*, 19.4 % for *Fraxinus excelsior* and 30.0 % for *Picea abies*.

Jayme and Fengel (1963) claim that excessive drying of wet pulp at 105 °C for 24 hours results in a substantial reduction in the water retention value, even though the fibers still presented expanded cellular walls showing an irregular lamellate structure, which suggests that the OH groups in the fibrils were partially inactivated. In this way, the resistance of the inner wall is adversely affected and the water retention capacity of the fiber walls is extremely reduced.

The wettability of the thermally modified wood decreases with treatment between 130 and 210 °C with a maximum of approximately 190 °C (Esteves and Pereira, 2009). Hakkou *et al*. (2005) affirm that the change in the wettability may be due to the conformational arrangement of the wood biopolymers resulting in the loss of residual water or, more likely, due to the plasticization of lignin. Meanwhile Chen *et al*. (2012) ensure that the formation of acetic acid, in addition to hydrolyzing the hemicelluloses, also leads to a loss of hydroxyl groups in the form of water, which is why heat treated wood becomes more hydrophobic.

From a practical point of view, the decrease in fiber wettability caused by heat treatment may affect the distribution of the adhesive in the production of boards, and may also have a negative effect on their painting.

3.3 Chemical components
3.3. Kemijski sastav

The average values of different chemical determinations of *L. philippiana* fibers with and without hygrothermal treatment are shown in Table 2.

Extractables in cold and hot water

In Table 2, the average values of extractables in different solvents are expressed as a percentage based on dry wood. An increase was found in hygrothermically treated fibers, from 0.4 % to 8.5 % in the percentage of extractables in cold water and from 0.9 % to 10.3 % in the percentage of extractables in hot water. Crespo *et al*. (2013) found similar variations in a previous study of hygrothermically treated *L. philippiana* particles. Coinciding with the trend found in the pre-

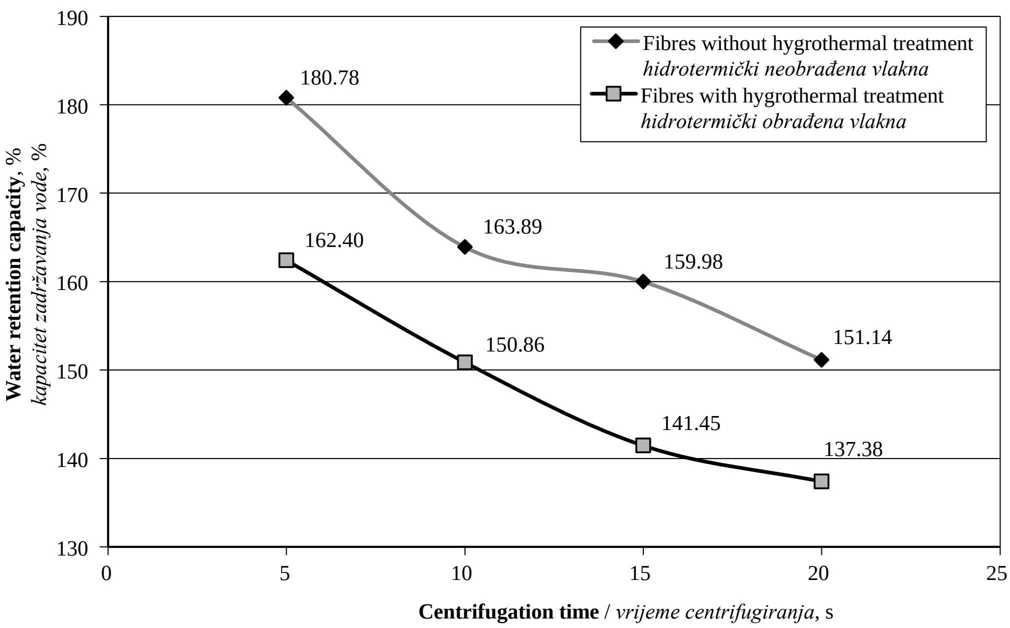

Figure 1 Values of water retention capacity of *L. philippiana* fibers hygrothermically treated and untreated after centrifugation at different times
Slika 1. Vrijednosti kapaciteta zadržavanja vode hidrotermički obrađenih i neobrađenih vlakana drva *L. philippiana* nakon različitog vremena centrifugiranja

Table 2 Chemical components of *L. philippiana* fibers with and without hygrothermal treatment
Tablica 2. Kemijski sastav hidrotermički obrađenih i neobrađenih vlakana drva *L. philippiana*

Property / *Svojstvo*		**Untreated fibers** *Neobrađena vlakna*	**Treated fibers** *Obrađena vlakna*
Extractables / *Ekstrakti* (% DWB)	Cold water / *hladna voda*	0.35	8.45
	Hot water / *topla voda*	0.90	10.29
	1% of sodium hydroxide (0.25 N) *1 %-tni natrijev hidroksid (0,25* N*)*	13.32	33.06
	Toluene ethanol / *toluen-etanol*	0.79	8.40
Wood polymers / *Drvni polimeri* (% DWBFE)	Cellulose / *celuloza*	57.39	64.11
	Holocellulose / *holoceluloza*	62.68	60.20
	Lignin / *lignin*	24.41	29.63
pH Value / *pH vrijednost*	Filtered sawdust solution with water after stirring for 4 h / *filtrirana otopina piljevine s vodom nakon 4-satnog miješanja*	5.65	3.52
Volatile acids, % *Hlapljive kiseline,* %	Acid as acetic acid *kisela kao octena kiselina*	0.026	0.071
Washable acids, % *Kiseline koje se ispiru,* %		0.018	0.207
Buffer capacity NaOH 0.01 mol/l (mmol / 100 g wood) *Kapacitet pufera NaOH 0,01* mol/l *(mmol / 100* g *drva)*	NaOH solution consumed *potrošena otopina NaOH*	0.75	11.91

DWB – Dry Wood Basis / *na bazi suhog drva*; DWBFE – Dry Wood Basis Free of Extractables / *na bazi suhog drva bez ekstrahiranog dijela*

sent investigation, other researchers found an increase in the number of extractables in hot water when treating solid *Cryptomeria japonica* wood (Yilgör and Kartal, 2010) as well as the extractables in water, in *Picea abies* and *Pinus sylvestris* fibers after a defibration process (Widsten *et al*., 2001). Karlsson *et al*. (2012b) state that the heat treatment of *Picea abies*, *Pinus sylvestris* and *Betula pendula* wood, in saturated steam at 160 and 170 °C, produced higher contents of water soluble carbohydrates, which correspond to the monosaccharides.

Extractables in 1 % of sodium hydroxide

The percentage of extractables in 1 % sodium hydroxide (0.25 N) increased from 13.3 % in untreated fibers to 33.1 % in thermally treated fibers. Crespo *et al*. (2013) also reported an important increase in the amount of these extractables in hygrothermically modified *L. philippiana* particles. Similarly, Yilgör and Kartal (2010), soon after heat treating *Cryptomeria japonica* wood, reported an increase of extractables in 1 % sodium hydroxide. The increase of extractables in 1% sodium hydroxide in the treated fibers is due to the degradation of the hemicellulose and cellulose that were subjected to high temperature. According to TAPPI 222 (om-98), hot alkali solution extracts low-molecular-weight carbohydrates consisting mainly of hemicellulose and degraded cellulose in wood. The solubility of wood could indicate the degree of fungus decay or of degradation by heat, light, oxidation, etc. As the wood decays or degrades, the percentage of the alkali-soluble material increases (Morgan, 1931; Procter and Chow, 1973 cited by TAPPI 222 om-98).

Extractables in toluene ethanol

An increase from 0.8 to 8.4 % in the amount of extractables in the toluene ethanol of hygrothermically treated *L. philippiana* fibers was detected, which is consistent with what Crespo *et al*. (2013) reported for *L. philippiana* particles. Other researchers also found increases in the amount of extractables in toluene ethanol following heat treatment, in *Pinus patula* wood in a nitrogen atmosphere (Mohareb *et al*., 2012), in *Pinus sylvestris* wood heat treated with steam and pressure (Ding *et al*., 2011) and in *Cryptomeria japonica* wood heat treated in an oven (Yilgör and Kartal, 2010).

Changes in extractable content reflect a change of the main chemical components of wood. The increase of extractables in the heat treated fibers is due to the temperature degradation of hemicelluloses; the molecular chains are then broken and extracted by the solvents used.

The increase in the percentage of extractables could affect the strength of the boards made from treated fibers, because during the hygrothermal treatment, the amount of hydrophobic extractables increases, which could prevent a good bond between the wood and adhesive.

Cellulose

In hygrothermically treated *L. philippiana* fibers, the percentage of cellulose increased from 57.4 % to 64.1 %. Crespo *et al*. (2013) also reported an increase in the percentage of cellulose in hygrothermically treated *L. philippiana* particles. Coincidentally, Yildiz *et al*. (2006) stated that heat treatment of *Picea orientalis* wood, in an oven at 150 °C for 2 hours in the presence of air, produced an increase in the cellulose content. According to Tjeerdsma and Militz (2005), the cellulose from *Fagus sylvatica* and *Pinus sylvestris* wood undergoes few changes at temperatures of 165 and 185 °C in wet and dry conditions with nitrogen gas. Fengel and Kollmann (1965) claim that cellulose undergoes significant changes starting from 180 °C treatments, with small changes at lower temperatures. The increase in percentage of the cellulose presented in Table 2 is not due to an increase of the cellulose content, but rather to the relatively high degradation of the hemicelluloses, which changes the percentage share of the compounds (Esteves *et al*., 2011).

Holocellulose

The percentage of holocellulose in hygrothermically treated fibers decreased from 62.7 % to 60.2 % in respect to the untreated fibers. In a previous study of hygrothermically treated *L. philippiana* particles, Crespo *et al*. (2013) reported a decrease in the percentage of holocellulose. Coinciding with the results obtained, Akgül and Korkut (2012), following a heat treatment at 150 °C, reported a decrease in holocellulose content, which they attributed to the degradation of hemicelluloses. With the increase of temperature and pressure, holocellulose content decreases (Mohareb *et al*., 2012; Ding *et al*., 2011).

The increased cellulose content and the general increase of the extractable compounds identified in this study should be produced by the depolymerization of hemicellulose, which is detected by the decrease in holocellulose.

Lignin

According to Table 2, the percentage of lignin determined in hygrothermically treated *L. philippiana* fibers increased from 24.4 % to 29.6 %. According to Windeisen *et al*. (2007), the lignin starts to degrade in the beginning of treatment but at a lower rate than the polysaccharides. Wienhaus (2005) stated that lignin softens and melts between 120 and 130 °C, and at higher temperatures, the softening is associated with reactions to condensation. Nuopponen *et al*. (2004) and Yilgör and Kartal (2010) state that the percentage share of lignin increases with temperatures above 140 °C, which is probably due to the degradation of hemicelluloses.

The increase in lignin content in hygrothermically treated *L. philippiana* fibers coincides with the increase registered in particles of this species reported by Crespo *et al*. (2013). Widsten *et al*. (2001) also recorded an increase in the amount of lignin, after thermomechanical defibration at 188 °C. However, at 202 °C, their share decreased.

Alén *et al*. (2002) and Nuopponen *et al*. (2004) reported increases in lignin content with increasing treatment temperature. With *Pinus sylvestris* wood, heat treated at 205 °C for 1.5 hours, Ding *et al*. (2011) also determined an increase in the lignin content of 6.6 %, when treated with steam without pressure, and 15.8 % when treated with steam at a pressure of 350 kPa, attributing this increase to the decreased holocellulose content.

The increase in the amount of lignin in hygrothermically treated fibers indicates the formation of polymerized products (Gosselink *et al*., 2004). In pressurized hygrothermal treatments, there is a correlation between the changes in the ultrastructure and the extractability of lignin. A low extractability of lignin is produced due to the formation of high molecular weight fractions (Košíková *et al*., 1990). The heat treated lignin determined in wood is probably not pure, since the reactions of polycondensation with other components of the cell wall result in reticulations, contributing to an increase in the apparent lignin content (Tjeerdsma and Militz, 2005; Boonstra and Tjeerdsma, 2006).

pH value

Table 2 shows that the pH value of the hygrothermically treated fibers is considerably more acidic than that of the untreated fibers. The reduction of pH value in hygrothermically treated *L. philippiana* fibers coincides with the decrease in the pH value of the same hygrothermically treated particle species (Crespo *et al*., 2013). Yilgör and Kartal (2010) also reported a decrease in the pH value after 2 hours of heat treating *Cryptomeria japonica* wood. Coincidentally, other researchers determined a decrease of the pH in particles coming from logs vaporized at 60 °C, for 16 hours (Çolak *et al*., 2007) and in fibers obtained through thermomechanical refinement with steam and pressure for 3 minutes (Xing *et al*., 2006).

The acidification of wood occurs because deacetylation of hemicelluloses and acetylated oligosaccharides is produced at temperatures of 145-190 °C, (Garrote *et al*., 2001), increasing the emission of formic and acetic acid from the wood (Roffael and Uhde, 2012), the acetic acid being the catalyst of depolymerization and condensation reactions of polysaccharides (Nuopponen *et al*., 2004).

The decrease in pH of hygrothermically treated *L. philippiana* fibers permits the prediction of better setting of amino resins, which may solve the problems reported by Poblete and Peredo (1990) and Pinto and Poblete (1992) when manufacturing boards with particles of this species.

Volatile and washable acids

The percentage of volatile and washable acids, determined as acetic acid, in hygrothermically treated *L. philippiana* fibers registered strong increases when hygrothermically treated (Table 2). The change in these compounds is an indicator of acidification caused by the treatment. In a previous study, hygrothermically treated *L. philippiana* particles in the same conditions as used in this study, registered an increase in the percentage of volatile and washable acids (Crespo *et al*., 2013). Poblete (1983) obtained similar results after drying *Fagus sylvatica* and *Picea abies* wood chips at 100 °C for 16 hours.

The percentage increase of volatile and washable acids is beneficial for the manufacture of boards made with *L. philippiana* and amino resins, since it provides the optimal pH environment for the setting of such resins.

Buffer capacity

While the pH of wood measures the specific level of acid activity under given conditions, the buffer capacity measures the resistance of wood to changes in the pH levels. Wood with a high buffering capacity requires the addition of a larger amount of acid catalyst to reduce the pH until the required level for optimal setting of the resin (Maloney, 1977). Determining the amount of sodium hydroxide consumed is an indirect way of determining the buffer capacity of the wood. The amount of NaOH (0.01mol/l), in mmol/100g of wood, added to reach a pH value of 7, represents the buffer capacity of the fibers whose values are shown in Table 2.

According to Table 2, in hygrothermically treated *L. philippiana* fibers, the buffer capacity increased drastically; these results being consistent with the registered increment of a previous investigation (Crespo *et al*., 2013). Xing *et al*. (2006) also showed an increase in the buffer capacity of fibers obtained through a thermomechanical refinement using steam and pressure for 3 minutes.

The decrease of the alkalinity of the fibers when subjected to hygrothermal treatment results in a significant increase in the consumption of NaOH, with a much greater equilibrium capacity of ionization (buffering capacity). This effect is determined by wood extractables. In addition to the decrease of the pH value and the increase of the volatile and washable acids, the decrease in alkalinity is an important parameter to optimally induce polymerization of the amino resins. These changes allow for better adhesion between the fibers and may positively influence the mechanical properties of the boards made with treated fibers. According to Çolak *et al*. (2007), wood acidity plays a very important role in generating the optimal pH environment for setting the ureaformaldehyde resins.

4 CONCLUSIONS
4. ZAKLJUČAK

Hygrothermically treated *L. philippiana* fibers at 150 °C for 90 minutes and 430 kPa of pressure, presented significant changes in their physical and chemical properties. There was a color change from greenish yellow to reddish blue, as well as a lowered water retention capacity. The percentages of extractables in cold and hot water suffered increases that far exceed the original value. The same trend was observed for the amount of extractables in sodium hydroxide and in toluene ethanol. The percentage of cellulose increased from 57.4 % to 64.1 % and lignin percentage increased from 24.4 % to 29.6 %, while the holocellulose percentage decreased from 62.7 % to 60.2 %. A significant decrease in pH value from 5.6 to 3.5 was determined, as well as a sharp increase in the percentage of volatile and washable acids, while the buffering capacity increased about 16 times.

The color change and the reduced water retention capacity of hygrothermically treated *L. philippiana* fibers reported in this study may present a disadvantage for the marketing of MDF as well as for the bonding process in manufacturing. However, the slight degradation of the cell wall components and the increased acidity of the treated fibers may be an advantage for producing MDF, as it would facilitate the setting of amino resins as adhesive and its reaction with wood. In general, the hygrothermal treatment of this species is presented as a viable alternative for the production of MDF and favors production with resin containing ureaformaldehyde.

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Preferences of Different Target Groups of Consumers in Case of Furniture Purchase

Sklonosti kupaca pri donošenju odluke o kupnji namještaja

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ABSTRACT • *In a market environment where changes are constant, understanding customer buying behaviour is crucial for companies in order to operate both successfully and effectively. We analysed how different age groups and net monthly incomes per household influence consumer decisions in Slovenia, Serbia and Croatia in the case of furniture purchases, when the three main factors are material, price and service. Each factor was further divided into three levels. In the case of material, the respondents could choose between solid wood, chipboard and fibreboard or other materials. In the case of price, they could choose between a low, middle or high price range, and in the case of services, they could choose between pre-sales, sales and after-sales services. With conjoint analysis, we analysed the markets in Slovenia, Serbia and Croatia. The important differences in consumer buying behaviour in these three countries were discovered. The results of the research will serve as a useful basis for wood sector companies to design more successful marketing strategies, which will help them to achieve their goals in different target markets.*

Keywords: *marketing; buying decision process; furniture; conjoint analysis*

SAŽETAK • *Razumijevanje ponašanja kupaca u današnjemu, vrlo promjenjivom tržišnom okruženju jedan je od odlučujućih elemenata za postizanje uspješnoga i učinkovitoga poslovnog rezultata tvrtke. Osnovni je cilj ovog istraživanja bio utvrditi kako u Sloveniji, Srbiji i Hrvatskoj različita dob potrošača te mjesečni neto prihod njihova kućanstva utječu na donošenje odluke o kupnji namještaja, i to promatrajući tri osnovna faktora proizvoda – materijal od kojega je izrađen, cijenu i uslugu. Nadalje, za svaki faktor proizvoda bile su ponuđene tri mogućnosti odabira. Tako su za faktor materijal izrade proizvoda ispitanici mogli odabrati između masivnog drva i ploča iverica ili ploča vlaknatica te drugih materijala; glede faktora cijena proizvoda ispitanici su se mogli odlučiti za niski, srednji ili visoki cjenovni razred proizvoda, dok su za faktor usluga mogli odabrati između pretprodajne, prodajne i postprodajne usluge. Rezultati su pokazali kako pri kupnji namještaja među promatranim grupama ispitanika postoje razlike u donošenju odluke, i to u sve tri promatrane zemlje. Rezultati provedenog istraživanja moći će poslužiti tvrtkama drvnoindustrijskog sektora za osmišljavanje i izgradnju uspješnih marketinških strategija.*

Ključne riječi: *marketing; proces donošenja odluke; namještaj; objedinjena analiza*

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1 INTRODUCTION
1. UVOD

1.1 Definition of the problem
1.1. Postavljanje problema

A house or apartment is not just a set of rooms but a home, where people spend their free time. That is why we try to arrange such spaces so as to feel good, and here furniture plays an important role. The choice of individual elements of furniture for the kitchen, living room, bedroom, children's bedroom, bathroom, corridor and other rooms, significantly influence the quality of our lives.

Furniture companies are experiencing strong global marketing competition, and thus they are forced to look for new ideas to convince customers to purchase their products. It is important to take into account the most important factors in the process of buying furniture. With this aim they should carry out analyses and surveys, and use their results for easier decision-making.

Research carried out in 2017 (Oblak *et al.*, 2017) showed that three factors are more important than others when making a purchase decision. These are quality, price and additional services, while the delivery time, reputation of the manufacturer and other factors are less important. If furniture companies want to prepare a successful marketing strategy, they need to determine which factor is the most important in the selected target market, worth to be taken into account when developing new products, and to be emphasized in advertising.

We often do not achieve the desired results when analysing consumer decision-making with classical research methods, as these focus on each factor individually, and thus overlook the more complex, interconnected reality of these decisions. This problem can be solved by conjoint analysis, where each product is defined by several factors and then the relative importance of each factor is calculated as well as its value attributed to decision-making. All the necessary data for creating a successful marketing strategy are obtained at one time and holistically. The results of such surveys can be surprising, and can reveal customer desires for products that are different than those currently offered in a particular market.

1.2 Decision-making process
1.2. Donošenje odluke

In a market environment where changes are constant, understanding customer buying behaviour is crucial for companies in order to operate both successfully and effectively. The decision-making process consists of a five-step route that consumers need to walk through when deciding which product they will buy (Figure 1). In doing so, they check and evaluate the functional benefit of the product, using a number of criteria for evaluating alternatives, and often spend quite a lot of time before making a final decision. This is especially true for more valuable products, including furniture, where customers choose very carefully between various alternatives (Oblak, 2012)

A better understanding of purchase decisions in the consumer market would enable furniture companies to influence consumers in the individual stages of the decision-making process. Firms thus need to be aware of the factors that affect buying behaviours and know how to convince consumers that a certain product they offer is the best choice. This is why it is necessary to study the needs and desires of potential consumers and at the same time investigate factors that influence the consumers in the process of making a purchase decision.

Research into the effects of purchase decision-making in terms of furniture (Al-Azzam and Fattah, 2014; Bednárik and Pakainé Kováts, 2010; Oblak *et al.*, 2017; Olsiaková *et al.*, 2016; Sinclair and Hansen, 2007; Zwierzyński, 2017) show that it is very important for furniture companies to gain a better understanding of such decisions, as this can help them create a combination of products and services that will satisfy consumer needs and desires. To achieve this, it is necessary to assess consumer behaviours at each of the five steps outlined above, as well as the factors that impact these at each level. At the level of recognising consumer needs, a company can prepare market strategies that arouse customers' interest and encourage them to purchase products that will satisfy their needs. Sales personnel can play an important role in the information search phase, and thus they need to be professionally trained and appropriately motivated. Furniture is a product that most people still buy after seeing it first, and if possible

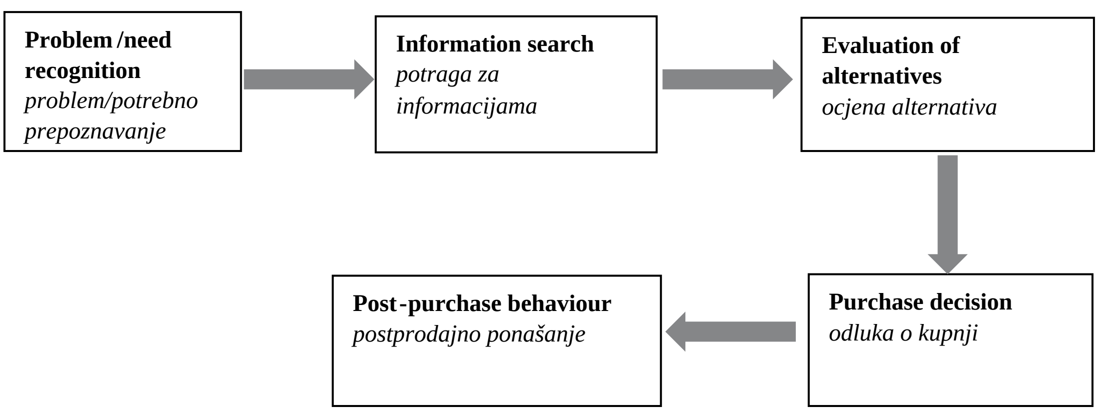

Figure 1 The process of purchase decision-making in the consumer market (Oblak, 2012)
Slika 1. Proces donošenja odluke o kupnji (Oblak, 2012.)

also testing it prior to making a decision. Potential consumers thus usually find information in furniture stores. Salespersons can also influence consumer decisions in the phase of evaluating alternatives, when customers are perhaps not completely convinced about an item, and a good salesperson is able to persuade them to buy a particular product. In the phase of the purchase decision, there is often a negotiation between the consumer and salesperson regarding the terms and conditions of sale, in particular the price, time and method of payment, the guarantee, delivery, the delivery time, and furniture assembly. If the terms of purchase are acceptable, then an actual purchase will occur. Since it is easier and cheaper to retain already existing customers than acquire new ones, companies should be aware that there is also a pre-assessment phase in the decision-making process. This often influences a consumer's decision as to whether he/she will stay faithful to the company or not.

Many studies have been carried out in the field of the decision-making process (Makovec Brencic and Zorko, 2009; Papafotikas *et al.*, 2014; Susjan and Lah, 1996; Warayuanti and Suyanto, 2015), with the results showing that the buying habits of individual consumer groups in different target markets are not the same.

The aim of our survey was thus to determine how consumers of different age groups and with different net monthly incomes per household from Slovenia, Serbia and Croatia make decisions in the case of purchasing furniture. The results are valuable when developing a marketing approach for individual target markets and consumers' groups.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Conjoint analysis
2.1. Objedinjena analiza

Conjoint analysis is one of the most commonly used research method in marketing for analysing consumer needs (Evans, 2008; Green *et al.*, 2001). According to Green and Srinivasan (1990), there were more than 400 commercial uses of conjoint analysis in the early 1980s. Large companies such as Ford, General Electric, General Foods, General Motors and Xerox started to use conjoint analysis for wide spectrum of products, while other companies used it for advertising, competitive analysis, designing new products, market segmentation and positioning of products (Green *et al.*, 2001). In addition to its use for commercial purposes, conjoint analysis has also been applied in a diverse range of areas. However, conjoint analysis is an especially good method for determining consumer preferences. When using other approaches, consumers evaluate each factor of the product separately, while a conjoint analysis gives a more comprehensive view of a certain product. In other words, the researcher asks a consumer to give his/her preferences with regard to a particular product as an assessment of the whole product, and this approach reflects the status of consumers in real life.

In this context, conjoint analysis aims to understand how people make decisions between products or services, so that companies can design new products or services that better meet the basic needs of consumers. It is a powerful tool in determining what drives people to buy a certain product and what the consumer appreciates most in a particular item. However, marketers often have difficulties with understanding the word "conjoin". It refers to the fact that the characteristics of products or services are CONsidered JOINTly by consumers. In fact, the adjective "conjoint" derives from the verb "to conjoin", which means "to join together". The key feature of conjoint analysis is that respondents evaluate product profiles, composed of several pooled elements (factors). Depending on the way in which respondents evaluate the combination of elements, we can understand their preferences for a particular product factor that would be the sum of all ratings (Orme, 1998). Conjoint analysis has thus become one of the most popular ways to develop and test new concepts, because it has many different applications.

Various authors have discussed steps or implementation of conjoint analysis (Green and Srinivasan, 1978; Gustafsson *et al.*, 2013; Hair *et al.*, 1998; Zadnik Stirn, 1998). Each author has a slightly different approach, but in general they are very similar to each other. In order to carry out conjoint analysis properly, the following steps should be followed:

(1) definition of research problem
(2) definition of factors and their levels
(3) definition of the basic model and collecting data
(4) evaluation of the obtained data and interpretation of the results.

The basic concept of conjoint analysis is that it is possible to describe each product or service with a certain relevant number of properties and property levels – giving the product or service profile. Gustafsson *et al.* (2013) noted that, when drawing up the levels, we have to pay attention to four criteria, as the levels of individual factors must be:

- independent (the value of one level should not depend on another)
- focused (levels should be focused on one factor)
- real (the levels can be defined numerically or descriptively) and
- in balance (a factor will gain importance if it has multiple levels, and it is therefore better if all factors have the same number of levels).

An example of a conjoint analysis profile is shown in Figure 2.

A discrete model was used for our research. This is used when the factor levels are represented by discrete values and the shape of the preference function of factor levels is unknown. This is true for the factors examined in this work (material, price, services), and it can be concluded that the relationships between the relative benefits are discrete. In this case, the IBM SPSS Statistics 25 software is used to calculate the relative usefulness of each factor:

$$u_{jk} = \begin{cases} a_{jk}, & k = 1,2,...,k_j - 1 \\ \sum_{j=1}^{k_j - 1} a_{jk}, & k = k_j \end{cases} \quad (1)$$

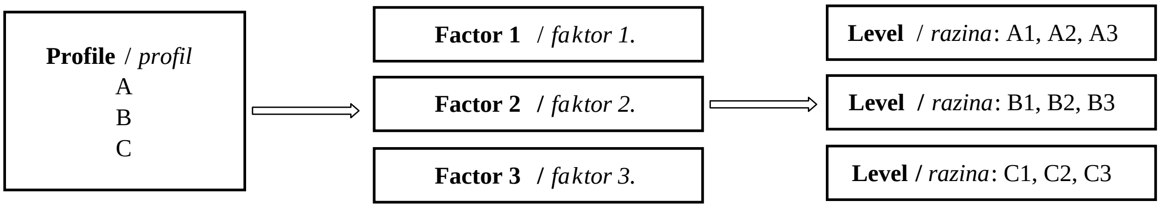

Figure 2 An example of a conjoint analysis profile
Slika 2. Primjer profila objedinjene analize

u_{jk} – the relative usefulness of the *k*-level factor *j*
a_{jk} – level of *k*-discrete factor j=1, ..., p
k_j – the number of *j* levels of this discrete factor
p – the number of discrete factors

We used the method of simultaneous assessment of all factors (full-profile), or a factorial design. With this method, the offer of possible product concepts is described with a combination of all the levels of the value of each product properties.

2.2 Definition of research problem
2.2. Definicija problema istraživanja

Psychologists, sociologists, economists and other researchers usually study purchase decision-making in relation to the different characteristics of consumers. Many authors have studied the influence of various factors on buying behaviour and decisions (Jaakkola, 2007; Neetu and Ashish, 2015; Olsiaková *et al.*, 2016; Ramya and Mohamed Ali, 2016; Rani, 2014; von Helversen *et al.*, 2018; Xu and Chen, 2017). In our research, special attention was paid to age of consumers and their net monthly income per household.

Age undoubtedly affects purchasing decisions, especially when buying more valuable products, such as furniture. People in different periods of their life buy different products and services. This can also be the consequence of a change in lifestyle of the individual or reference group to which the individual belongs.

The net monthly income of the household or its financial situation directly affects the product an individual can afford. The level of income defines the standard of living of an individual, and in particular how much can be spent after meeting the basic needs. Habjančič and Ušaj (2003) found out that consumers have their own idea of the lowest and highest acceptable prices of a product. A price that is lower than the lower limit can make consumers suspicious of the quality and origin of the product. In contrast, when the price exceeds the upper limit, the product is seen as unavailable.

2.3 Factor selection
2.3. Odabir faktora

The most important step in conjoint analysis is choosing the factors for the focal products and defining their levels. Factors in conjoint analysis are the characteristics that describe the product and define it in relation to competing products. A factor is a general feature of the focal product or service. Referring to Oblak *et al*. (2017), we chose three factors for this study: material, price and services. Each factor consists of different levels. The material factor includes furniture made of solid wood, made of chipboard or fibreboard, and made of other materials. The price factor is divided into low, middle and high price ranges. The services factor consists of pre-sales services (professional consulting, computer images of the furniture in their home, measurements at home, etc.), sales services (payment benefits, such as a discount on cash payments, instalment payments, etc.) and after-sales services (delivery, furniture assembly, warranty, etc.).

In this study Factor 1 stands for material, Factor 2 for price and Factor 3 for services. Factor 1 (material) is further divided into three levels: furniture made of solid wood, furniture made of chipboard or fibreboard, and furniture made of other materials (plastics, artificial mass, and so on). The levels of Factor 2 (price) were: low price range, middle price range and high price range. The levels of Factor 3 (services) were: pre-sales, sales services and after-sales.

A random profile for conjoint analysis in our case is shown in Figure 3.

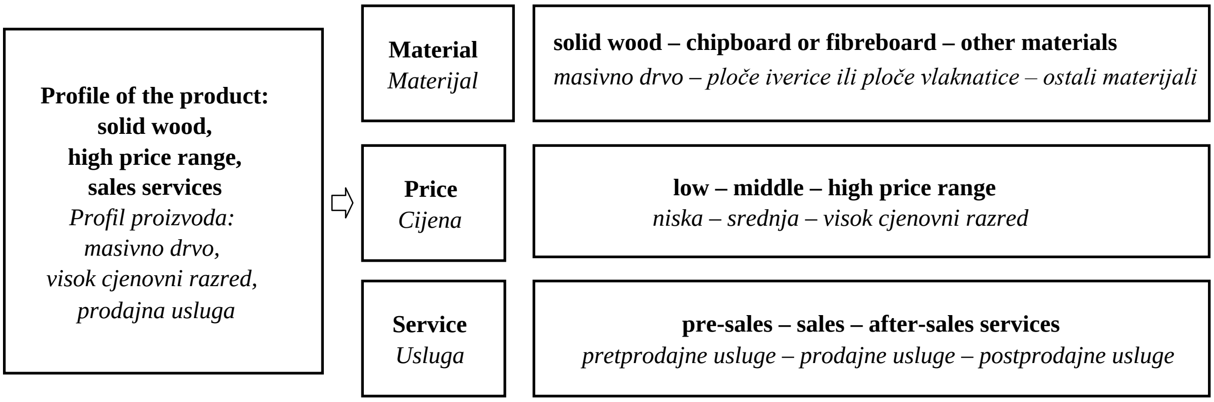

Figure 3 A random profile for our case of conjoint analysis
Slika 3. Slučajno odabrani profil za objedinjenu analizu

From the given factors and their levels, we created 3x3x3=27 different combinations or product profiles. Table 1 shows all 27 combinations.

2.4 Questionnaire and data collection
2.4. Anketni upitnik i prikupljanje podataka

For the purpose of our analysis, we used data obtained via a questionnaire. We compiled a short questionnaire, which was divided into two parts. The first part consisted of two questions, which determined the age of the respondents and the net monthly income in their household. In the second part, the respondents had to classify 27 profiles or manufactured furniture concepts, from the most to least favourable one.

The survey was carried out among potential furniture consumers in Slovenia, Serbia and Croatia. Data

Table 1 Combinations of factors and their levels, or profiles, of various products
Tablica 1. Kombinacija faktora i njihovih razina, ili profila, ili kategorija proizvoda

Profile 1 *Profil 1.*	solid wood, low price range, pre-sales *masivno drvo, nizak cjenovni razred, pretprodajne usluge*
Profile 2 *Profil 2.*	solid wood, low price range, sales services *masivno drvo, nizak cjenovni razred, prodajne usluge*
Profile 3 *Profil 3.*	solid wood, low price range, after-sales *masivno drvo, nizak cjenovni razred, postprodajne usluge*
Profile 4 *Profil 4.*	chipboard or fibreboard, low price range, pre-sales *ploča iverica ili ploča vlaknatica, nizak cjenovni razred, pretprodajne usluge*
Profile 5 *Profil 5.*	chipboard or fibreboard, low price range, sales services *ploča iverica ili ploča vlaknatica, nizak cjenovni razred, prodajne usluge*
Profile 6 *Profil 6.*	chipboard or fibreboard, low price range, after-sales *ploča iverica ili ploča vlaknatica, nizak cjenovni razred, postprodajne usluge*
Profile 7 *Profil 7.*	other materials, low price range, pre-sales *drugi materijali, nizak cjenovni razred, pretprodajne usluge*
Profile 8 *Profil 8.*	other materials, low price range, sales services *drugi materijali, nizak cjenovni razred, prodajne usluge*
Profile 9 *Profil 9.*	other materials, low price range, after-sales *drugi materijali, nizak cjenovni razred, postprodajne usluge*
Profile 10 *Profil 10.*	solid wood, middle price range, pre-sales *masivno drvo, srednji cjenovni razred, pretprodajne usluge*
Profile 11 *Profil 11.*	solid wood, middle price range, sales services *masivno drvo, srednji cjenovni razred, prodajne usluge*
Profile 12 *Profil 12.*	solid wood, middle price range, after-sales *masivno drvo, srednji cjenovni razred, postprodajne usluge*
Profile 13 *Profil 13.*	chipboard or fibreboard, middle price range, pre-sales *ploča iverica ili ploča vlaknatica, srednji cjenovni razred, pretprodajne usluge*
Profile 14 *Profil 14.*	chipboard or fibreboard, middle price range, sales services *ploča iverica ili ploča vlaknatica, srednji cjenovni razred, prodajne usluge*
Profile 15 *Profil 15.*	chipboard or fibreboard, middle price range, after-sales *ploča iverica ili ploča vlaknatica, srednji cjenovni razred, postprodajne usluge*
Profile 16 *Profil 16.*	other materials, middle price range, pre-sales *drugi materijali, srednji cjenovni razred, pretprodajne usluge*
Profile 17 *Profil 17.*	other materials, middle price range, sales services *drugi materijali, srednji cjenovni razred, prodajne usluge*
Profile 18 *Profil 18.*	other materials, middle price range, after-sales *drugi materijali, srednji cjenovni razred, postprodajne usluge*
Profile 19 *Profil 19.*	solid wood, high price range, pre-sales *masivno drvo, visok cjenovni razred, pretprodajne usluge*
Profile 20 *Profil 20.*	solid wood, high price range, sales services *masivno drvo, visok cjenovni razred, prodajne usluge*
Profile 21 *Profil 21.*	solid wood, high price range, after-sales *masivno drvo, visok cjenovni razred, postprodajne usluge*
Profile 22 *Profil 22.*	chipboard or fibreboard, high price range, pre-sales *ploča iverica ili ploča vlaknatica, visok cjenovni razred, pretprodajne usluge*
Profile 23 *Profil 23.*	chipboard or fibreboard, high price range, sales services *ploča iverica ili ploča vlaknatica, visok cjenovni razred, prodajne usluge*
Profile 24 *Profil 24.*	chipboard or fibreboard, high price range, after-sales *ploča iverica ili ploča vlaknatica, visok cjenovni razred, postprodajne usluge*
Profile 25 *Profil 25.*	other materials, high price range, pre-sales *drugi materijali, visok cjenovni razred, pretprodajne usluge*
Profile 26 *Profil 26.*	other materials, high price range, sales services *drugi materijali, visok cjenovni razred, prodajne usluge*
Profile 27 *Profil 27.*	other materials, high price range, after-sales *drugi materijali, visok cjenovni razred, postprodajne usluge*

were collected in several ways: through personal interviews in furniture stores, via paper mail, e-mail and online survey. The survey was conducted from March to June 2018. A total of 37 % of the questionnaires that were sent via paper mail or e-mail were correctly filled in. Regarding different countries, we got 123 responses from Slovenia, 136 from Serbia and 117 from Croatia.

The size of the sample in a conjoint analysis varies from example to example, but most authors (Akaah, 1988; Cattin and Wittink, 1982) agree that anything over 100 respondents is large enough to ensure the reliability of the results if the purpose of the research is to compare the groups surveyed and discover any significant differences.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The results obtained in the survey were further analysed using the conjoint analysis and IBM SPSS Statistics 25 software.

The first part of the survey referred to the age of the respondents and monthly income in their household. The results are presented in Tables 2 and 3.

We first analysed the importance of individual factors that influence the decision to purchase an item of furniture. Table 4 shows that the respondents in all three countries evaluated the price as the most important, material as the second and services as the least important factor.

In the second part of the survey, the respondents classified 27 profiles of furniture products, from the most to least liked. Table 5 shows the most liked profiles as classified by respondents in different age groups in Slovenia, Serbia and Croatia.

When choosing the material, most of the respondents from Slovenia and Croatia would choose solid wood, except those from the age group 31-40 years, who would rather choose some other materials. In Serbia, only those younger than 40 years or older than 60 years would choose solid wood. Potential customers in the age group 41-50 years would rather choose other materials, while those in the age group 51-60 years would choose chipboard and fibreboard.

When choosing a price range, the results showed much more diversity. In Slovenia, the respondents aged between 31-40 years and over 60 years preferred high price furniture, while the others preferred the middle price furniture. In Serbia, respondents aged up to 40 years favoured high price furniture. Potential customers aged between 41-60 years would buy middle price furniture and those aged over 60 years preferred low price furniture. In Croatia, high price furniture was chosen by respondents aged up to 30 years and those aged 31-40 years, while low price furniture was favoured by respondents aged between 41-50 years and older than 60 years.

In the case of services, most of the respondents from Slovenia would give priority to sales services, which mainly refer to payment benefits. However, this was not the case for respondents in the age group 31-40 years and those over 60 years, who would favour pre-sales services (expert consulting, computer images of the furniture in their home, measurements at home, etc.). In Serbia, respondents younger than 30 years were more interested in sales services, while other age groups preferred pre-sales services. In Croatia, respondents aged between 31-40 years put sales services in the first place, while all the other age groups chose pre-sales services.

Table 6 shows the most favoured profiles of furniture products, as classified by respondents with different net monthly incomes per household member in Slovenia, Serbia and Croatia.

Table 2 Age of respondents
Tablica 2. Dob ispitanika

	Up to 30 years *Do 30 godina*		**31 – 40 years** *31 – 40 godina*		**41 – 50 years** *41 – 50 godina*		**51 – 60 years** *51 – 60 godina*		**Over 60 years** *Više od 60 godina*		**Total** *Ukupno*	
Slovenia / *Slovenija*	32	26.0 %	27	22.0 %	23	18.7 %	22	17.9 %	19	15.4 %	123	100 %
Serbia /*Srbija*	34	25.0 %	41	30.1 %	30	22.1 %	15	11.0 %	16	11.8 %	136	100 %
Croatia / *Hrvatska*	38	32.5 %	31	26.5 %	22	18.8 %	16	13.7 %	10	8.5 %	117	100 %

Table 3 Net monthly income of respondents per household member (€)
Tablica 3. Mjesečni neto prihod ispitanika po članu kućanstva (u EUR)

	Up to 200 *Do 200*		**200 – 500** *200 – 500*		**501 – 1000** *501 – 1000*		**1001 – 1500** *1001 – 1500*		**Over 1500 €** *Više od 1500*		**Total** *Ukupno*	
Slovenia / *Slovenija*	5	4.1 %	32	26.0 %	60	48.8 %	16	13.0 %	10	8.1 %	123	100 %
Serbia / *Srbija*	23	16.9 %	46	33.8 %	35	25.7 %	26	19.1 %	6	4.4 %	136	100 %
Croatia / *Hrvatska*	15	12.8 %	36	30.8 %	33	28.2 %	20	17.1 %	13	11.1 %	117	100 %

Table 4 Importance of individual factors
Tablica 4. Važnost pojedinih faktora

	Slovenia / *Slovenija*	**Serbia** / *Srbija*	**Croatia** / *Hrvatska*
Material / *Materijal*	24.8 %	23.5 %	24.5 %
Price / *Cijena*	67.1 %	68.3 %	67.0 %
Service / *Usluga*	8.1 %	8.2 %	8.6 %

Table 5 The most preferred furniture product profiles by different age groups in three countries (Slovenia, Serbia and Croatia)
Tablica 5. Najčešće odabirane vrste namještaja prema različitim dobnim kategorijama ispitanika u promatranim zemljama (Sloveniji, Srbiji i Hrvatskoj)

	Age / *Starost*				
	Up to 30 / *Do 30*	**31 – 40**	**41 – 50**	**51 – 60**	**Over 60** / *Preko 60*
Slovenia *Slovenija*	solid wood middle price class sales services *masivno drvo, srednji cjenovni razred, prodajna usluga*	other materials high price class sales services *ostali materijali, visok cjenovni razred, prodajna usluga*	solid wood middle price size presales services *masivno drvo, srednji cjenovni razred, pretprodajna usluga*	solid wood middle price class sales services *masivno drvo, srednji cjenovni razred, prodajna usluga*	solid wood high price class presales services *masivno drvo, visok cjenovni razred, pretprodajna usluga*
Serbia *Srbija*	solid wood high price class sales services *masivno drvo, visok cjenovni razred, prodajna usluga*	solid wood high price class presales services *masivno drvo, visok cjenovni razred, pretprodajna usluga*	other materials middle price class presales services *ostali materijali, srednji cjenovni razred, pretprodajna usluga*	chipboard or fibreboard middle price class presales services *ploče iverice ili vlaknatice, srednji cjenovni razred, pretprodajna usluga*	solid wood low price class presales services *masivno drvo, nizak cjenovni razred, pretprodajna usluga*
Croatia *Hrvatska*	solid wood high price class presales services *masivno drvo, visok cjenovni razred, pretprodajna usluga*	other materials middle price class sales services *ostali materijali, srednji cjenovni razred, prodajna usluga*	solid wood low price size presales services *masivno drvo, nizak cjenovni razred, pretprodajna usluga*	solid wood high price class presales services *masivno drvo, visok cjenovni razred, pretprodajna usluga*	solid wood low price class presales services *masivno drvo, nizak cjenovni razred, pretprodajna usluga*

When choosing a material, the respondents from Slovenia and Serbia whose monthly income per household member was less than 1000 euros would choose furniture made of solid wood, while those with a higher income chose furniture made of other materials.

The majority of respondents from Croatia would choose solid wood, with the exception of those whose net income was in the range of 501-1000 euros.

When choosing the favoured price ranges of furniture, the opinions of the respondents from three countries were the same. Respondents whose monthly net income per household member was less than 500 euros would choose furniture in the low price range, while those with a higher monthly income (501 euros or more) would choose furniture from the high price range. Most of the respondents from Slovenia and Ser-

Table 6 The most popular furniture product profiles classified by respondents with different net monthly incomes from three countries (Slovenia, Serbia and Croatia)
Tablica 6. Najčešće odabirane vrste namještaja prema različitim kategorijama mjesečnih neto prihoda ispitanika u promatranim zemljama (Sloveniji, Srbiji i Hrvatskoj)

	Average household net income per household member (€) *Prosječni neto prihod po članu kućanstva (u EUR)*				
	Up to 200 *Do 200*	**200 – 500** *200 – 500*	**501 – 1000** *501 – 1000*	**1001 – 1500** *1001 – 1500*	**Over 1500** *Više od 1500*
Slovenia *Slovenija*	solid wood low price class presales services *masivno drvo, nizak cjenovni razred, pretprodajna usluga*	solid wood low price class presales services *masivno drvo, nizak cjenovni razred, pretprodajna usluga*	solid wood high price class presales services *masivno drvo, visok cjenovni razred, pretprodajna usluga*	other materials high price class presales services *ostali materijali, visok cjenovni razred, pretprodajna usluga*	other materials high price class sales services *ostali materijali, visok cjenovni razred, prodajna usluga*
Serbia *Srbija*	solid wood low price class presales services *masivno drvo, nizak cjenovni razred, pretprodajna usluga*	solid wood low price class presales services *masivno drvo, nizak cjenovni razred, pretprodajna usluga*	solid wood high price class presales services *masivno drvo, visok cjenovni razred, pretprodajna usluga*	other materials high price class presales services *ostali materijali, visok cjenovni razred, pretprodajna usluga*	other materials high price class sales services *ostali materijali, visok cjenovni razred, prodajna usluga*
Croatia *Hrvatska*	solid wood low price class sales services *masivno drvo, nizak cjenovni razred, prodajna usluga*	solid wood low price class presales services *masivno drvo, nizak cjenovni razred, pretprodajna usluga*	other materials high price class presales services *ostali materijali, visok cjenovni razred, pretprodajna usluga*	solid wood high price class presales services *masivno drvo, visok cjenovni razred, pretprodajna usluga*	solid wood high price class presales services *masivno drvo, visok cjenovni razred, pretprodajna usluga*

bia whose monthly income per household member was less than 1500 euros were more interested in pre-sales services, while those with a higher monthly income per household (more than 1500 euros) mostly chose sales services. This result was quite interesting because sales services consist of payment benefits. The situation in Croatia was a little different. The respondents whose monthly income per household member did not exceed 200 euros would focus on sales services, while those whose monthly income per household member was more than 200 euros would choose pre-sales services.

Based on the results presented above, furniture companies will be able to develop better marketing strategies for these target markets. In order to achieve its marketing objectives, a company needs to develop a marketing strategy by working on two key activities – segmentation of the target markets and creating a marketing offer for each target market. The proper choice of target markets is necessary to achieve specific marketing objectives. Many companies are unsuccessful in a particular market because they either ignore this activity or misjudge the target market. McCarthy (1978) brought together various marketing instruments that can be used to achieve a specific objective into four elements, named the 4Ps of marketing (product, price, place, promotion). A company, depending on the needs of the target market, changes the volume and quantity of each of the listed components. There are many possibilities how to achieve this objective. When a company gathers information about the target markets, it must decide how to assign the budget for marketing to the various parts of the marketing approach, in order to satisfy the target consumers as much as possible. In doing so, all four elements – product, price, place, and promotion – play an important role.

The results of our research, which are based on survey data from three countries and their target markets, show that the income and age of potential consumers affect their buying preferences. It is, therefore, necessary for companies to segment these three markets. This means that businesses should split the entire, heterogeneous market into market segments, groups of consumers with similar needs to buy certain product, as consumers are too heterogeneous in their own preferences, needs and purchasing power to be considered as one body. The main criteria for segmentation should be income and age. Companies should further decide whether to adopt a multi-segment approach, which means that they focus their marketing activities on a few segments and create a specific marketing offer for each of them. However, they can also decide to follow a focused approach in which all their marketing activities focus on only one market segment. This approach is recommended for smaller furniture companies interested in smaller market segments. This is how they can target small groups of consumers with expectations that such companies can best meet their specific needs.

4 CONCLUSIONS
4. ZAKLJUČAK

There are few wood products that are purchased without customers going through a long decision process. Nevertheless, furniture companies can influence the purchase decisions that consumer make, drawing them away from competing products. For this reason, companies must know well their customers and their particular desires, perceptions and behaviours during the decision-making process.

Conjoint analysis is one of the most commonly used methods for determining consumer preferences. The key advantage of such approach is its assumption that the consumer compares and evaluates the whole spectrum of characteristics and benefits associated with a product or service at the same time (i.e., jointly), with greater or lesser weight given to a certain property of the product or service at the expense of other characteristics. The basic idea of conjoint analysis is that each product or service can be described with thus specific number of properties and property levels – this producing product or service profiles.

Another important advantage of conjoint analysis is that the data collected with a conjoint survey can also be used for modelling. By changing the elements of a marketing offer, we can not only determine the most attractive combinations, but also predict what kind of response can be expected if a competitor chooses to offer new and improved product or service. The number of simulations and scenarios is endless. In the scenario analysis, we can also control external factors, such as the extent of promotion, intensity of advertising, coverage of the market, and so on.

The aim of our research was to find out how age and monthly net income per household affect purchasing decision-making in the case of furniture in Slovenia, Serbia and Croatia, when consumers choose between different materials, price ranges and services. We found that there are significant differences in the purchasing behaviour of potential furniture consumers in Slovenia, Serbia and Croatia with the exception of price range, where the opinions of the respondents in these three countries were similar.

The findings of this research will help furniture companies, which operate in three target markets, Slovenia, Serbia and Croatia, to design better their marketing strategies. A successful combination of promotional content components can be a decisive factor in achieving a company's goals and increasing its competitive advantages.

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School Furniture Ergonomics in Prevention of Pupils' Poor Sitting Posture

Ergonomija školskog namještaja u prevenciji lošeg držanja tijela učenika

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ABSTRACT • *Physical and psychological disorders in school-age children, as a consequence of prolonged sitting in class, denote one of the alarming issues of the today's civilization. Scientific and professional literature pays great attention to the causes and phenomena of postural disorders caused by prolonged sitting, such as musculoskeletal disorders and back pain (MSD/BP). This phenomenon in children is increasingly correlated with school furniture design. School furniture, especially the chair and desk, are one of the most important factors to achieve the right body posture of pupils during school education. Despite this, not much attention is paid to the ergonomic requirements in furniture design, which are a prerequisite for good health, motivation improvement and learning of students. The objective of this paper is to show the impact of unmatched school furniture on the development of health problems and poor pupils' posture through a review of scientific literature and previous studies concerning the issue. The results include a comparison of ten papers published in the period from 2004 to 2017 in Finland, Greece, Croatia, Slovenia, Nigeria, Brazil, Iran, Belgium, United Kingdom and India. Various databases have been used, including Pub Med, Google Scholar, Medline, Hrčak, Dabar, Science Direct and Science Citation Index. By reviewing the previous research of the selected authors dealing with sitting posture in school, an insight was gained into the effect of inadequate body postures on pupils' health that could be used as guidance for new school furniture design.*

Key words: *school furniture; pupils; poor posture; ergonomics; design; health*

SAŽETAK • *Tjelesni i psihički poremećaji koji se pojavljuju u djece školske dobi kao posljedica dugotrajnog sjedenja na nastavi jedan su od alarmantnih problema današnje civilizacije. Znanstvena i stručna literatura veliku pozornost pridaju uzrocima i pojavama poremećaja držanja tijekom sjedenja, poput mišićno-koštanih smetnji i bolova u leđima (engl. MSD/BP). Ta se pojava u učenika sve više povezuje i s oblikovanjem školskog namještaja. Ergonomski oblikovan školski namještaj, poglavito stolice i stolovi, jedan su od važnih preduvjeta ispravnog držanja tijela učenika tijekom školske nastave. Usprkos tome, pri oblikovanju namještaja nedovoljno se uzimaju u obzir ergonomski zahtjevi kao uvjet dobrog zdravlja i unapređenja učeničke motivacije i uspješnog učenja. Cilj rada jest pokazati utjecaj neodgovarajućega školskog namještaja na pojavu zdravstvenih tegoba i lošeg držanja učenika, i to na temelju pregleda znanstvene literature i dosadašnjih istraživanja te problematike. Rezultati obuhvaćaju usporedbu deset objavljenih članaka u razdoblju 2004. – 2017., a ta su istraživanja provedena u Finskoj, Grčkoj,*

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Republici Hrvatskoj, Sloveniji, Nigeriji, Brazilu, Iranu, Belgiji, Velikoj Britaniji i Indiji. Korištene su različite baze podataka, uključujući Pub Med, Google znalac, Medline, Hrčak, Dabar, Science Direct i Science Citation Index. Proučavanjem dosadašnjih istraživanja izdvojenih autora koji su se bavili problematikom sjedenja u školi dobiven je uvid o utjecaju neodgovarajućeg položaja tijela na zdravlje učenika, što može poslužiti kao smjernica u oblikovanju novoga školskog namještaja.

Ključne riječi: *školski namještaj; učenici; loše držanje; ergonomija; oblikovanje namještaja; zdravlje*

1 INTRODUCTION
1. UVOD

In the last thirty years, the poor posture of pupils during school lessons has become one of the most important research issues for many scientists. Classroom furniture affects children's postures, comfort, health, and ability to learn. Research indicates that many school children sit in furniture that does not fit them properly. Further, school children, who sit in awkward postures for a long period of time, are prone to experiencing back and neck discomfort and other musculoskeletal symptoms that may worsen with time and even progress into adulthood (Hedge and Lueder, 2007). The causes of development of poor posture that lead to numerous health problems are more and more researched. It has been proved that postural deviations are becoming more frequent with children of school age and that they are triggered by various aspects of modern lifestyle (Gh *et al.*, 2012; Latalski *et al.*, 2013; Quka *et al.,* 2015). School furniture (here mainly school desks and chairs are taken into consideration), which should enable the pupils to work during classes, presents an important issue from the point of design. Optimal school furniture design means an interaction of a number of various factors including pedagogy, medicine, industrial design, architecture, economics, ecology, technical standards, ergonometric, construction and production (Domljan *et al*., 2002). In most of the so-called "traditional" schools, pupils spend 92 % of time in classrooms in static sitting, 3 % in dynamic sitting, only 3 % in active sitting or walking and 2 % in standing (Domljan *et al.*, 2010a). Due to spending a lot of hours sitting in classroom and learning at home, especially in front of computers and other IT devices, motoric abilities of pupils are decreased and due to incorrect sitting posture, their backbone becomes curved (Herga and Fošnarič, 2017). The correct use of ergonomics and functional dimensions is indispensable for maintaining good health, improving academic accomplishments, learning and being motivated (Odunaiya *et al.*, 2014).

Although it is very important to modify school desk and chair dimensions according to pupils' bodies, in most schools the school furniture designed by the manufacturers often does not follow neither standards nor anthropometric dimensions of different age groups (Domljan *et al.*, 2008). As a result, the chairs and desks become uncomfortable for pupils who take improper posture during lessons. For a long time, it has been recommended to primary schools to provide tables and chairs that pupils can easily adjust, move or carry (Bajbutović, 1983). The school furniture, that can be easily moved and carried, can help in improving education and health quality of pupils (Dhara *et al.*, 2009: Purwaningrum *et al.*, 2015).

The purpose of the appropriate and ergonomically designed school furniture is to ensure proper and comfortable sitting at the desk, under the terms set by the contemporary curriculum, during writing, reading, listening or tutoring, drawing, individual or team work, during computer use or any other activity (Domljan and Grbac, 2003). Ergonomic and fully-fitted furniture is available in the world market but, due to extremely high prices, many schools cannot afford such furniture (Domljan *et al.*, 2015). The price of ergonomically adjusted furniture also depends on higher resources needed for systematic and comprehensive research of school children anthropometric measures in individual schools or across the country and the objective is to define educational guidelines and design standards for furniture (Domljan and Grbac, 2003).

Classroom chairs connect pupils to the classroom environment and therefore are a key factor in providing adequate physical support to pupils' behavior during classes (***, 2008). Sitting ergonomics also has the same validity for the younger generation – there is no correct posture in which a pupil would not feel fatigue and there is no perfect chair where the body fatigue would not appear (Walch, 1985). Children come to sit in school chairs directly from the kindergartens, where there was no six to eight hours of continuous sitting at the (school) desk. Therefore, especially young pupils (age 6 to 10) need a possibility to realize a dynamic and active position of the body when sitting (which teachers should never explain as "fidgeting during a teaching hour"). In other words, furniture should be designed to meet the needs of students of the 21st century (***, 2008; Domljan *et al.*, 2010a).

The problem is even bigger due to the impact of numerous external factors: changes in the pedagogical system of education, the economic and public system of a state, the culture of behavior, the traditional attitude of "adults" in terms of changing the habits of school equipment, the needs of any individual curricula and schedule in higher education when one classroom can be transformed and occupied by different age groups (and anthropometric groups) of pupils, unconsciousness of most bureaucratic staff concerning the importance of carrying out the knowledge of sitting position, the anthropometric changes (secular changes in growth and development), which were already noticed some twenty years ago. In the last 50 years, the children height of the same age group has been increasing; the average height of children aged 7 to 10 increased by an average of 5-7 cm, while the height of children aged 11 to 14 increased by as much as 7 to 10 cm. Furniture measurements in the classrooms should follow this data (Domljan *et al*., 2008).

The solutions in classroom sitting and furniture design should enable free movement and dynamics of the pupil's body while working. Chairs that can be quickly and easily moved and rotated are the essence of the modern design. The requirements for the school furniture construction are becoming more and more stringent, demanding distinctive stability and strength, in particular for desks and chairs, but also lightweight portability, collapsibility, and easy storing (Domljan and Grbac 2002; Vlaović *et al*. 2004; ***, 2008).

The aim of this paper is to determine and prove, by review of the scientific studies, how big is the impact of inadequate school furniture, primarily chairs and tables, on the health of pupils and their sitting postures during educational activities.

1.1 The consequences of mismatched dimensions of school furniture compared to anthropometric dimensions of pupils
1.1. Posljedice neusklađenosti dimenzija školskog namještaja s antropometrijskim značajkama učenika

Children of school age spend most of their school activities in sitting position, while writing, drawing, reading or listening to the teacher (Knight and Noyes, 1999). Problems that occur due to prolonged sitting arise mainly because children have to sit in classrooms around 5-10 hours in almost unvaried position as this is required by the norms (Grbac and Domljan, 2007). Muscle fatigue that occurs due to many hours of sitting results in back pain, postural discomfort, headache, pains in hands and feet (Murphy *et al.*, 2004). The professional literature pays much attention to postural disorders such as children bad posture as well as development of musculoskeletal disorders and back pain (MSD / BP) (Trevelyan and Legg, 2006; Domljan *et al.*, 2010b; Saes *et al.*, 2015; Yanto and Lu, 2016). Physical and psychological disorders that occur as a result of prolonged sitting are one of the pressing problems of today's civilization. Therefore, school furniture is an essential product for the education process but also for the preservation of health. However, still very little attention is paid to the issue of the appropriate ergonomic furniture design (Domljan *et al.*, 2015).

1.1.1 Musculoskeletal disorders and back pain
1.1.1. Mišićno-koštane smetnje i bol u leđima

Muscle and bone system syndromes, especially the occurrence of musculoskeletal disorders and back pain (MSD / BP), are an important issue of the contemporary society, being more accentuated in young people and school children (Jones and Macfarlane, 2005; Trevelyan and Legg, 2006; Domljan *et al.*, 2010b; Azabagić *et al.*, 2016). Musculoskeletal disorders are diseases affecting the tendons, muscles, joints and neck nerves, upper and lower back parts, chest, shoulders, arms, hands, hips, legs, knees, and feet (Murphy *et al.*, 2004). They mostly occur due to non-ergonomic environmental conditions. Neck pain is the most common musculoskeletal disorder in school children, followed by pain in the upper back, and pain in the lower back (Domljan *et al*, 2010b). A high prevalence of pain in the neck indicates the existence of a high level of cervical flexion as well as static and uncomfortable body posture of a child when sitting (Murphy *et al.*, 2002; Azuan *et al.*, 2010).

Although the back pain in children has been identified, this diagnosis was considered uncommon in the clinical practice in the past (Prebeg and Prebeg, 1985). However, studies showed that the pain in the lower back is an increasingly important and growing problem of school age groups and represents a serious health problem for the wider community (Burton *et al*., 2004). Low back pain includes the pain associated with problems in the lumbar region of the spine, discs between the vertebrae, the ligaments around the spine, the spinal column, and nerves, the lower back muscles, the internal organs of the pelvis and abdomen and/or the skin covering lumbar region. The back pain in children and adolescents, as well as in adults is rapidly increasing, mainly due to lifestyle changes and the evolutionary unsuitability to prolonged sitting (Watson *et al.*, 2002; Đapić *et al.*, 2013; Usman *et al.*, 2014), to the heavy school bags (Mačak- Hadžiomerović *et al.*, 2018), to less and less physical activity and other current problems. This is particularly evident when, after school and college school desks, the graduates start to work in offices and continue prolonged sitting at computer displays.

The prolonged sitting in a static posture, with the body tilted forward, was confirmed as the main cause of the low back pain. The discrepancy between the thigh length and the seat depth is also connected with this malaise, whereas the discrepancy between the elbow height in a sitting position and the desk height is associated with pain in the neck and shoulder (Ismaila *et al*., 2013).

1.1.2 Poor posture of school children
1.1.2. Loše držanje tijela u školske djece

In the last few years, the concern of parents, teachers and medical professionals about children posture has been growing, as the situation seems to be worse compared to previous generations (Jones and Macfarlane, 2005; Furian *et al.*, 2013). Based on the numerous studies carried out by different authors in the field of school-age children postural deviations, the obtained results show that the number of children with bad posture increases each year (Bajrić *et al.*, 2012). Non-ergonomic school furniture is often considered as one of the main causes of bad posture in adulthood. Improperly designed school desks and chairs, which are not harmonized with the anthropometric characteristics of children, have a negative impact on pupils' health (Domljan *et al.,* 2008; Kurban *et al.,* 2015).

Poor posture of preschool and school children is an indicator of health problems that can become very serious if not eliminated in time (Prebeg and Prebeg 1985; Burton *et al.*, 2004; Breithecker, 2005; Cardon *et al.*, 2007). However, very often these problems are not detected in time. In fact, the wrong body posture is one of the initial deformity stages (Bridger and Whistance, 1998). Malfunctions, caused by incorrect posture, will be reflected first on the spine, and then on the other parts of the locomotor apparatus (Dačević and Jovović, 2013; Nikšić *et al.*, 2015a; Nikšić *et al.*, 2015b). There are no changes in the bone structure of the spine because of the poor posture, but insufficient muscle strength can lead to the presence of bad posture (Popovič, 1998). When speaking about the incorrect body posture, it is usually referred to a variety of functionally bad positions of the spine such as the kyphotic (distortion of the upper part of the spine), the lordotic (curvature of the spine inwards in the cervical and the lumbar part of the spine) or scoliotic (lateral curvature of the spine) bad postures (Prebeg and Prebeg, 1985; Paušić *et al.*, 2009; Kujundžić and Paušić, 2011).

1.2. Preventive ergonomic measures against poor posture of school children
1.2. Ergonomske mjere za prevenciju lošeg držanja tijela u školske djece

The prevention against the development of postural disorders is a crucial element for children health as the disorders, in their progression, may advance to deformities, with consequences that are hard to imagine. Their impact is very important for the general psychic and physical development of the child (Gojković and Milinković, 2013; Protić-Gava, 2015).

Preventive measures imply the use of kinesiotherapy activities to prevent the occurrence of a bad posture (Breithecker, 2000). If a poor posture is not recognized in the preschool period, there is a risk of progression and serious changes in the spine. For this reason, practical suggestions should be directed to educational preventive programs for children as well as for parents, educators, teachers, trainers and other professionals working with children, to practice the corrective exercises and workout in order to help the children muscular system to accompany their physical growth (Cardon *et al.*, 2007). In preventive kinesiotherapy activities, the emphasis is placed on improving all segments of the musculoskeletal system. The main focus of treatment is to improve all components of the anthropological status (improvement of muscle tissue, connective tissue, flexibility and posture). Preventive kinesiotherapy procedures are most commonly used with children in stages of development for the prevention of the musculoskeletal system functional disorders (deviations from the correct posture, flat feet, etc.) (Pavlović, 2012; Terzija, 2015).

1.2.1 "Correct" sitting at a school desk - Traditional versus "moving" sitting
1.2.1. „Pravilno" sjedenje u školskoj klupi – tradicionalno sjedenje nasuprot sjedenju „u pokretu"

Using of the furniture that promotes healthy and correct body posture is more important to children than adults because a bad habit of sitting may be established at the young age. Bad seating habits acquired in childhood are very difficult to change later in adolescence or adulthood. Correct sitting posture is an important factor for prevention of musculoskeletal disorder symptoms (Mandal, 1982; Aagard-Hansen and Storr-Paulsen, 1995; Hänninen and Koskelo, 2003; Murphy *et al.,* 2004; ***, 2005; Al-Saleh *et al.*, 2013).

In most schools around the world, the traditional practice is to encourage (compel to be more accurate) children to sit in the body position of the so called ''three right angles'' – back straight, head up and look forward, i.e. when sitting, children have to:

- sit straight, with the thighs at an angle of 90° to the spine – forming the right angle
- have knees bent at an angle of 90°, keeping their legs straight – forming the second right angle
- have legs bent at ankle at an angle of 90°, resting on the floor – forming the third right angle (***, 2005; Grbac and Domljan, 2007).

Regrettably, despite this practice and the efforts of teachers, from the biomechanical and physical-medicine point of view, no child can keep such sitting position of his/her body for more than a couple of seconds (Walch, 1985, Attinger *et al*., 1993; Domljan *et al.*, 2010a). Fatigue occurs, the body begins falling in an uncomfortable and dangerous spine curve for the body, which, after frequent repetition, can cause serious consequences for the child's health, as already mentioned above.

The efforts of doctors, orthopaedists, physiatrists and designers have shown that the only correct way is to enable pupils to make easy movements of their body while sitting in class, which would not interfere with teaching on the one hand, and on the other hand the students would subconsciously have the feeling that they are moving and that the muscles of the body are constantly in an active position (Mandal, 1982). It has been proven that with such type of sitting, known as "dynamic sitting", children have a better memory, they continue to be active in the teaching process and are ready to work without any fatigue or pain (Dordel and Breithecker, 2002; Cardon *et al.*, 2004; ***; 2005; Domljan *et al.*, 2010a).

New manuals and standards (***, 2005; Domljan *et al*., 2015; Yanto *et al.*, 2017), revised standards for school furniture dimensioning (Molenbroek *et al.*, 2003; EN 1729-1:2015) and the contemporary furniture manufacturers focus on the design of school furniture that allows students unrestrained movements of body during sitting.

The European standard EN 1729-1:2015, which defines the functional dimensions of school desks and chairs, is consistent with the anthropometric proportions of school-age children and prescribes seven classes of size (size marks). Moreover, apart from a traditionally designed chair, which can have a fixed seat angle forward or backward at an angle of maximum 5 degrees, they recommend the design of the seat with a double-tilt (the so called double slope seat), which moves forward-backward together with the lower part of the sitter's body and thus prevents the static position of the back, spine and lumbar muscles (Domljan *et al.*, 2015).

However, regardless of the above, in many countries of the world, the general problem of inadequate pupils' sitting posture during their educational activities is still present. This paper seeks to highlight, through a comparative review of the results of previous scientific studies, the reasons of inadequate pupils' postures and the consequences arising therefrom.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Electronic databases, published from the year 2004 to 2017, were searched by keywords: school furniture, poor posture and ergonomics. Out of a total of 68 articles found, there were ten scientific papers that explored the issues: design and ergonomics of school furniture, matching furniture dimensions with pupils' anthropometric dimensions, the behaviour of children sitting in the classroom, the consequences of poor sitting on pupils' health. Based on these articles, consequences were highlighted and solutions were proposed. In preparing the paper, different databases have been used, including Pub Med, Google Scholar, Medline, Hrčak, Dabar, Science Direct, and Science Citation Index.

3 RESULTS
3. REZULTATI

By studying previous research of the authors, who have dealt with the issue of sitting in school classes, an overview of impacts of inadequate body posture on the pupils' health was obtained. Potential consequences shown by the results are outlined in conclusions (Table 1).

The results include comparison of ten articles published in the period 2004 – 2017. The research published in the studies reviewed were carried out in Finland, Greece, Croatia, Slovenia, Nigeria, Brazil, Iran, Belgium, United Kingdom and India.

4 DISCUSSION AND CONCLUSION
4. RASPRAVA I ZAKLJUČAK

The above studies showed that furniture of the appropriate dimensions is not available to a large number of students both in Europe and in the world. In the last 50 years, the height of children of the same age group has been increasing; the average height of children aged 7 to 10 increased by an average of 5-7 cm, while the height of children of 11 to 14 years increased by 7 to 10 cm (Domljan *et al.*, 2008). Year after year, the height of children changes, while, on the other hand, the dimensions of the existing furniture remain the same, which can lead to poor posture and other health problems.

In many countries of Europe and the world, it has been proven that the existing standards to produce school furniture are outdated and should be revised because there is a significant degree of mismatch between the anthropometry of children and standard dimensions of school furniture (Yanto *et al.*, 2017). Guided by the fact that children spend in school most of the time during the day, it is important to use ergonomically designed furniture that suits their anthropometric sizes, and therefore it is necessary to adopt new standards for the production of school furniture. Due to the mismatch between the school furniture and the anthropometry of school children, they sit in an unfavorable posture most of the time during school classes, which leads to health problems (Saarni *et al.*, 2007). Panagiotopoulou *et al*. (2004) dealt with the same issues and their results proved that badly designed school furniture adversely affects the correct posture at sitting, which leads to a poor posture, especially while reading or writing.

Many authors deal with incorrect sitting and other factors that cause muscular and skeletal disorders of elementary school pupils caused by non-ergonomic sitting conditions, overweight of school bags, sedentary lifestyle, reduced physical activity, and lack of exercise. Kurban *et al*. (2015) outlined that non-ergonomic school furniture is one of the main causes of bad posture in adulthood. The use of furniture that does not meet the anthropometric characteristics of its users has a negative impact on health. Domljan *et al*. (2010a) used in their research video recordings as a method of observing the posture of children during classes, and owing to the mentioned research method, detected even 43 distinguishing postures of pupils during classes. Based on their research, the conclusion was that any new design of school furniture has to stimulate the dynamics of sitting and thus prevent the poor posture of pupils in performing their school tasks. In a study conducted by Koskelo *et al*. (2007), it was concluded that the adjustable school desks and chairs provide better seating and thus prevent poor posture, increase muscle strength and relieve pain. The mismatch between the measurements of school furniture and anthropometry of the student's body may be the reason for the presence of poor posture. It can be concluded that an ergonomic intervention is needed to redesign school furniture in order to prevent bad posture and other health disorders (Dhara *et al.*, 2009).

The scientific literature review has shown that in most schools in Europe and the world there is a large discrepancy between the anthropometric dimensions of students and the functional size of school furniture, which results in consequences outlined in this paper. Some of them are: fidgeting in classes, restless sitting in the desire to find a suitable comfortable posture, body aches, musculoskeletal disorders, lower back pain (MSD/LBP), headache and similar complaints. School furniture, especially the chairs and desks that are mostly manufactured and supplied to schools around the world, do not provide seating comfort and focus on work over a long period of time. Moreover, the application of ergonomic principles and anthropometric dimensions of school age children in the design is still not a guarantee that the children will sit comfortably and feel pleasure (Knight and Noyes, 1999, Domljan *et al*., 2010a). There is no simple answer to the question: "What kind of furnishings should be offered to the school classroom environment to make children

Table 1 Overview of research studies and outcomes
Tablica 1. Pregled istraživanja i rezultata

Citation *Referenca*	**Country** *Država*	**Main aims and purpose** *Glavni cilj i svrha*	**Materials and methods** / *Materijali i metode*	**Results** / *Rezultati*	**Conclusion** / *Zaključak*
Panagiotopoulou *et al.*, 2004 *Panagiotopoulou i sur., 2004.*	Greece *Grčka*	To compare pupils' dimensions to the dimension of school furniture in primary school and determine whether this type of furniture is well-designed and wheter it promotes good sitting posture at school by taking into account the dimensions of children. *Usporediti dimenzije učenika s dimenzijama školskog namještaja u osnovnoj školi i utvrditi je li današnji namještaj dobro dizajniran i promiče li ispravno sjedenje, uzimajući u obzir dimenzije učenika.*	A total of 180 pupils (90 boys and 90 girls), aged from 7 to 12 years, from three primary schools participated in the study. The anthropometric measures of pupils and furniture dimensions were compared in order to identify any mismatch between them. *Sudjelovalo je ukupno 180 učenika (90 dječaka i 90 djevojčica) u dobi od 7 do 12 godina iz tri osnovne škole. Antropometrijske mjere učenika i dimenzije namještaja uspoređivane su kako bi se utvrdila neusklađenost njihovih veličina.*	The data indicate a mismatch between the pupils' body dimensions and classroom furniture. The chairs are too high and too deep, and desks are also too high for the pupils. *Podatci pokazuju neusklađenost između tjelesnih mjera učenika i namještaja u učionici. Stolice su previsoke i preduboke, a stolovi su također previsoki za učenike.*	The obtained data indicate that this condition has negative effects on the sitting posture of the children especially when reading and writing. *Dobiveni podatci pokazuju da to stanje ima negativne učinke na položaj tijela učenika pri sjedenju, posebno pri čitanju i pisanju.*
Murphy *et al.*, 2004 *Murphy i sur., 2004.*	Great Britain *Velika Britanija*	To identify the extent of back pain in schoolchildren, and establish the intensity, duration and frequency of exposure to physical risk factors present in schools. *Identificirati opseg bolova u leđima u školske djece i utvrditi njegov intenzitet, trajanje te učestalost izloženosti fizičkim čimbenicima rizika koji postoje u školama.*	The sitting postures of 66 children aged 11 – 14 years were recorded in usual lessons using the Portable Ergonomic Observation Method (PEO). *Istraživani su sjedeći položaji 66 učenika u dobi od 11 do 14 godina pri uobičajenim predavanjima, uz primjenu tzv. prijenosne ergonomske metode promatranja (PEO).*	Significant associations were found between flexed postures and low back pain. Static postures and neck and upper back pain were also associated. This study has implications for schools, designers and people in the field of work-related musculoskeletal disorders. *Pronađene su važne poveznice između tijela u savijenom položaju i bolova u donjem dijelu leđa. Pokazalo se također da su statički položaji povezani s bolovima u vratu i gornjem dijelu leđa. Ova studija ima utjecaj na škole, dizajnere i ljude koji se bave poremećajima mišićno-koštanih sustava povezanih s radom.*	Further research is required to examine the association between sitting posture and pain reported at different spinal locations. *Potrebna su dodatna istraživanja kako bi se ispitala povezanost položaja sjedenja s bolovima uočenim u različitim područjima kralježnice.*
Koskelo *et al.*, 2007 *Koskelo i sur., 2007.*	Finland *Finska*	To determine whether adjustable furniture affects the correction of certain irregularities and reduces muscle tension during sitting. *Utvrditi utječe li prilagodljivi namještaj na ispravljanje određenih nepravilnosti i smanjuje li napetost mišića tijekom sjedenja.*	15 (8 female and 7 male) high-school students and 15 anthropometrically and gender matched control students from neighbouring schools were observed in the period of 25 month. Comparison of the effect of adjustable school desks and chairs use (the intervention) and traditional non-adjustable use (the control condition) on sitting and standing postures, muscle strength, muscle tension, pain and learning. *U razdoblju od 25 mjeseci promatrano je 15 srednjoškolaca (8 učenica i 7 učenika) te 15 kontrolnih studenata odgovarajućeg spola i dimenzija iz susjednih škola. Uspoređeni su učinci korištenja prilagodljivih školskih stolova i stolica (intervencija) i tradicionalnoga, neprilagodljivog namještaja (kontrolni uvjeti) na sjedenje i stajanje, snagu i napetost mišića, bol i učenje.*	The results showed that trunk muscle strength increased in the intervention students whose muscle tension fell significantly in the trapezius and lumbar muscles during classes, whereas in control students' lumbar tension increased. *Rezultati su pokazali da se snaga mišića trupa u učenika intervencijske grupe povećala, a napetost u mišićima trapeza i lumbalnog zgloba tijekom nastave znatno se smanjila, dok se u kontrolnoj grupi učenika lumbalna napetost povećala.*	It is concluded that the adjustable school desks and chairs promoted better sitting and standing postures, increased muscle strength, alleviated pain and appeared to be associated with better overall academic marks. *Zaključeno je da su prilagodljivi školski stolovi i stolice pridonijeli ispravnom sjedenju i stajanju, povećali snagu mišića, ublažili bol te se pokazalo da su povezani s boljim ukupnim akademskim ocjenama.*

Cardon *et al.*, 2007 *Cardon i sur., 2007.*	Belgium *Belgija*	To evaluate the effects of combining a back-care program with a physical activity promotion program in elementary schoolchildren. *Procijeniti učinke kombiniranja programa preventivnih vježbi za leđa s programom promicanja tjelesne aktivnosti učenika u osnovnoj školi.*	In a pre-post design over two school years, back care knowledge, back care behavior, fear avoidance beliefs and back pain reports were evaluated in children (mean age (9.7±0.7) years) classified into three categories: those who received a back care and a physical activity promotion program (n=190), those who received only a back care program (n=193) and those in a control group (n=172). *Provedena je procjena unutar tri skupine promatrane djece (srednja starosna dob (9,7 ±0,7) godina) u trajanju dvije školske godine o stanju prije i poslije uvođenja preventivnih vježbi. Prva skupina je provodila vježbe za pravilno održavanje zdravih leđa uz program promoviranja fizičkih aktivnosti (n=190), druga skupina je samo provodila program održavanja zdravih leđa (n=193), dok je treća skupina bila kontrolna (n=172).*	The back-care program and the physical activity promotion program were both comprehensive ones. In both intervention groups, the scores for back care related knowledge and back care behavior were significantly higher than in the control group. *Oba programa, i program održavanja zdravih leđa i program promoviranja fizičke aktivnosti, vrlo su kompleksni. U obje interventne grupe rezultati znanja i pravilnog održavanja zdravlja leđa bili su znatno viši nego u kontrolnoj grupi.*	The present study findings favor the addition of a physical activity promotion program to a back-care program in elementary schools within the scope of early back pain prevention efforts. *Poruka studije glasi: u sklopu preveniranja pojave rane boli u leđima programu za zdravija leđa u osnovnim školama korisno je dodati i program promicanja tjelesne aktivnosti.*
Dhara *et al.*, 2009 *Dhara i sur., 2009.*	India *Indija*	To evaluate the degree of mismatch between the different dimensions of school furniture and anthropometric measures of school children. To evaluate health problems and the cause of postural disorders among school children while attending classes related to furniture. *Procijeniti stupanj neusklađenosti različitih dimenzija školskog namještaja i antropometrijskih mjera školske djece. Procijeniti zdravstvene probleme i uzroke posturalnih poremećaja školske djece tijekom pohađanja nastave koji su povezani s neadekvatnim namještajem.*	621 male schoolchildren (age range 10-15 years) were selected at random from 20 rural secondary schools. The subjective evaluation of health problems of school children was made by questionnaire technique. Postural analysis of the children during classwork was made by video-photographic method as well as direct observation method. *U 20 seoskih srednjih škola nasumično je odabran 621 školarac (dobni raspon 10-15 godina). Subjektivno ocjenjivanje zdravstvenih problema tih učenika obavljeno je tehnikom upitnika. Posturalna analiza djece tijekom nastave provedena je video-fotografskom metodom i metodom izravnog promatranja.*	It has been shown that children, due to a mismatch between school furniture and anthropometry, suffered from various ailments, and that often changed the position of the body during use of such furniture. *Dokazano je da su djeca zbog neusklađenosti školskog namještaja i svojih antropometrijskih značajki patila od različitih tegoba, pa su tijekom korištenja takvog namještaja često mijenjali položaj tijela.*	An ergonomic intervention is required to redesign the classroom furniture for school children of different age groups in order to reduce furniture-related health complaints. *Za redizajn školskog namještaja namijenjenoga različitim dobnim skupinama učenika potrebna je ergonomska intervencija kako bi se umanjili zdravstveni problemi koji su posljedica neodgovarajućeg namještaja.*
Domljan *et al.*, 2010 *Domljan i sur., 2010.*	Croatia *Hrvatska*	To identify main pupils' working postures and define them as notable criteria when designing school furniture for the future. *Prepoznati glavne radne položaje učenika i primijeniti ih kao uočene kriterije pri dizajniranju školskog namještaja u budućnosti.*	18 pupils from the 2nd to 8th grades in one elementary school in Zagreb. The method employed was video recording. Focus was primarily on the pupils' behavior at work, their movements and frequent activities while using tables and chairs in primary school classrooms. *Uzorak je činilo 18 učenika od 2. do 8. razreda jedne osnovne škole u Zagrebu. U istraživanju je primijenjena metoda videosnimanja. Fokus je ponajprije bio na ponašanju učenika pri radu, njihovim pokretima i čestim aktivnostima tijekom korištenja stolova i stolica u učionicama.*	43 characteristic postures and semi-postures, classified in four main groups were recorded as the evidence that children have different biomechanical postures while sitting and working in classrooms. *Promatrana 43 karakteristična položaja i međupoložaja, razvrstana u četiri glavne skupine, zabilježena su kao dokaz da djeca zauzimaju različite biomehaničke položaje tijela dok sjede i rade u učionicama.*	New school furniture design has to encourage sitting dynamics and fit psychological, ergonomic, physical, social and cognitive aspects of their users. *Novi dizajn školskog namještaja mora poticati dinamiku sjedenja i odgovarati psihološkim, ergonomskim, fizičkim, socijalnim i kognitivnim zahtjevima korisnika.*

Gh *et al.*, 2012 *Gh i sur., 2012.*	Iran *Iran*	To assess the presence of musculoskeletal deformities in lower extremities and to detect faulty posture in schoolchildren. *Procijeniti učestalost mišićno-koštanih deformiteta donjih ekstremiteta i otkriti neispravno držanje tijela u školske djece.*	172 schoolchildren aged 5-20 years, (66 boys and 106 girls) living in a rural region of Iran, were screened for deviations in the musculoskeletal system. The postural muscles including the hamstring and gastroc-soleus were examined for finding any shortness. *Pregledana su odstupanja u mišićno-koštanom sustavu 172 djece školske dobi od 5 do 20 godina (66 dječaka i 106 djevojčica) koji žive u ruralnoj regiji Irana. Ispitivani su posturalni mišići, uključujući mišiće stražnje lože i gastrocnemiusa soleusa, kako bi se uočila skraćenja tog mišića.*	The prevalence of cervical lordosis, FHP, thoracic kyphosis, and genu varum increased with age; in the case of genu valgum, the situation was reversed. *Prevalencija cervikalne lordoze, protruzije glave prema naprijed, torakalne kifoze i genu-varuma (O-noge) s godinama se povećavala; glede genu-valguma (X-noge), uočena je obrnuta situacija.*	More attention should be paid to implementing school-based screening programs aimed at early detecting of any musculoskeletal-related abnormalities and taking preventive steps to reduce their negative consequences. *Više pozornosti treba pridati provedbi školskih programa usmjerenih na rano otkrivanje svih vrsta anomalija mišićno-koštanog sustava i poduzimati preventivne mjere za smanjenje njihovih negativnih posljedica.*
Odunaiya *et al.*, 2014 *Odunaiya i sur., 2014.*	Nigeria *Nigerija*	To determine the ergonomic suitability of educational furniture in the lecture theatres. *Utvrditi ergonomsku prikladnost namještaja u predavaonicama obrazovnih ustanova.*	A total of 240 students (120 males and 120 females) at the University of Ibadan. *Ispitivanjem je obuhvaćeno ukupno 240 studenata (120 muškaraca i 120 žena) na Sveučilištu u Ibadanu.*	A significant difference in height between males and females was found, but no significant difference between other anthropometric variables was measured. *Utvrđena je značajna razlika u visini između muškaraca i žena, ali nije izmjerena značajna razlika među ostalim antropometrijskim varijablama.*	It is recommended that further studies, including more universities across a wide spectrum of society, should be performed to determine the effect of furniture on student health. *Preporučuju se daljnja istraživanja koja će uključiti više sveučilišta u širokom društvenom spektru kako bi se utvrdio učinak namještaja na zdravlje studenata.*
Saes *et al.*, 2015 *Saes i sur., 2015.*	Brazil *Brazil*	To estimate the adequacy of school desks and chairs regarding to students' anthropometric characteristics and its possible association with musculoskeletal pain in different parts of the body. *Procijeniti adekvatnost školskih stolova i stolica u smislu antropometrijskih karakteristika učenika i moguću povezanost neodgovarajućih stolova i stolica s mišićno-koštanim bolovima na različitim dijelovima tijela.*	A survey was carried out with 625 students and the furniture of 69 classrooms. The simplified Nordic Questionnaire for AOS* was used for the analysis of musculoskeletal symptoms, and parameters recommended by standard NBR 14006** were used to analyze furniture. *Provedeno je istraživanje sa 625 učenika i s namještajem u 69 učionica. Pojednostavnjeni Nordijski upitnik za AOS * upotrijebljen je za analizu mišićno-koštanih simptoma, a za analizu namještaja primijenjeni su parametri preporučeni standardom NBR 14006 **.*	This study has shown that 87.2 % of chairs and 45.6 % of desks were totally inadequate. *Istraživanje je pokazalo da je 87,2 % stolica i 45,6 % stolova bilo potpuno neprimjereno.*	It is recommended that public authorities be informed of this situation and requested that school furniture be urgently brought into line with prevailing legislation. *Preporučuje se obavješťavanje javnih tijela o nalazima istraživanja i traženje da se školski namještaj hitno uskladi s važećim zakonodavstvom.*
Herga *et al.*, 2017 *Herga i sur., 2017.*	Slovenia *Slovenija*	To identify adequacy of school furniture dimensions with the help of anthropometric measurements. *Antropometrijskim mjerenjima utvrditi podudaranje dimenzija školskog namještaja sa standardima.*	192 pupils in the 6th and 7th grade (11 - 12-year-old) of primary schools in North-Eastern Slovenia. Measurements were made on certain pupils' anthropometric dimensions, including posture, popliteal height, buttock-popliteal length, elbow height sitting, thigh thickness, subscapular height and hip width. *Uzorak je obuhvatio 192 učenika u 6. i 7. razredu (11. – 12. godina) osnovnih škola sjeveroistočne Slovenije. Provedena su mjerenja određenih antropometrijskih dimenzija učenika, uključujući držanje, visinu potkoljenice, duljinu natkoljenice, visinu lakta, debljinu bedara, visinu supskapularnog mišića i širinu kukova.*	According to ISO 5971, size 6 corresponds to the pupil's height 173 - 184 cm. The results of anthropometrical measurements showed that pupils in the 6th grade were 152 cm high, and pupils in the 7th grade 160 cm. *Prema ISO 5971, veličina 6 odgovara visini učenika 173 – 184 cm. Rezultati antropometrijskih mjerenja pokazali su da su učenici u 6. razredu prosječno visoki 152 cm, a učenici u 7. razredu 160 cm.*	The research showed high mismatch of school furniture and anthropometrical dimensions, which may have serious consequences on the development of pupils. *Istraživanje je pokazalo visoku neusklađenost školskog namještaja i antropometrijskih mjera učenika, što može imati ozbiljne posljedice za njihov razvoj.*

* AOS – Analysis of Osteomuscular Symptoms; ** NBR – Brazilian Association of Technical Standards / ** AOS – analiza koštano-mišićnih simptoma; ** NBR – Brazilsko udruženje tehničkih standarda*

feel good?" The solution for a part of the problem is the production of ergonomically designed school furniture that complies with the relevant standards, the furniture appropriate to the size and body dimensions of different age students, which provides safety, comfort, improves quality of sitting and thus preserves students' health. There are, however, many other requirements related to the way of teaching, functional arrangement in school interiors, ecological and sustainable environment, social and psychological prerequisites and other designer parameters (Domljan *et al*., 2015).

This study provides an overview of one segment - what happens when anthropometric and ergonomic principles of furniture design are not followed, especially when the furniture does not comply with students' body dimensions. However, open issues still remain related to the requirements of school furniture design to provide children comfort, satisfaction and well-being in the school environment. In any case, the issue of adequate school furniture design is more complex than it seems, and necessarily involves an inter- and multi-disciplinary approach of experts from the areas of pedagogy and contemporary teaching methods, public health and school medicine, occupational therapy and physio-therapy, ergonomics and children anthropometry, architecture of educational facilities, interior design and product/furniture design, ecology and sustainable natural materials, technology and production, and others, as well as pupils, parents and teachers above all.

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Drvo moabi (*Baillonella toxisperma* Pierre)

NAZIVI

Baillonella toxisperma Pierre naziv je drva botaničke vrste iz porodice *Sapotaceae.* Trgovački su nazivi te vrste također: moabi (Gabon, Francuska, Nizozemska, Njemačka, Italija, Velika Britanija,); dimpampi (Belgija, Demokratska Republika Kongo); adza, oréré (Gabon); djave (Gabon, Nigerija); ayap (Ekvatorijalna Gvineja); adjab, njabi (Kamerun).

NALAZIŠTE

Stabla *Baillonella toxisperma* Pierre nalazimo u sjevernoj Africi, i to od Nigerije, Kameruna, Gabona i Konga do Angole. Raste u nizinskim tropskim zimzelenim kišnim šumama na suhim i vlažnim tlima.

STABLO

Visina stabla doseže do 50 m. Čisto deblo dugo je 25 do 30 m, a prsni mu je promjer od 0,8 do 1,5 m. Debla su cilindričnog oblika. Kora drva uzdužno je izbrazdana, na starijim je stablima poprečno ispucana i ljušti se u obliku pločica. Kora mladih stabala je crvenkastosiva, a na starim je stablima tamnosmeđa. Debljina kore iznosi od 1,5 do 3 cm.

DRVO

Makroskopska obilježja

Drvo je rastresito porozno. Bjeljika je svjetloružičasta do tamnosiva, a široka je 4 – 6 cm. Srž drva je tamnocrvena do crvenosmeđa, katkad išarana finim prugama. Tekstura je jednolična i manje-više ukrasna. Granica goda je neuočljiva ili teško uočljiva. Pore i drvni traci vidljivi su povećalom.

Mikroskopska obilježja

Traheje su pojedinačno raspoređene i pojavljuju se u radijalnim nizovima do 8 pora, ali mogu biti i u paru ili u grupama. Promjer traheja je 50...100...130 mikrometara, gustoća im je 7...10...15 na 1 mm^2 poprečnog presjeka. Volumni udio traheja iznosi oko 15 %, a često su ispunjene tilama i sržnim tvarima.

Aksijalni parenhim drva apotrahealno je ljestvičast, širine 1 – 2 stanice. Volumni udio aksijalnog parenhima iznosi oko 19 %. Staničje drvnih trakova je heterogeno. Drvni su traci difuzno raspoređeni, visoki su 85...200...335 mikrometara odnosno od 2 do 15 do 40 stanica, a široki 18...24...31 mikrometara, odnosno 1 – 3 stanice. Gustoća drvnih trakova je 8...9...10 na 1 mm. Njihov volumni udio iznosi oko 25 %. Parenhimske stanice drvnih trakova mogu biti ispunjene kristalima silicija. Drvna su vlakanca libriformska, a katkad su to i vlaknaste traheide. Dugačka su 1175...1625...2055 mikrometara. Debljina staničnih stijenki vlakanaca iznosi 2,5...3,6...4,8 mikrometara, a promjeri njihovih lumena su 9,0...11,0...19,0 mikrometara. Volumni je udio vlakanaca oko 41 %.

Fizička svojstva

Gustoća apsolutno suhog drva, ρ_o	700...780 kg/m^3
Gustoća prosušenog drva, $\rho_{12\text{-}15}$	730...830...900 kg/m^3
Gustoća sirovog drva, ρ_s	950...1100 kg/m^3
Poroznost	oko 51 %
Radijalno utezanje, β_r	5,8...6,0 %
Tangentno utezanje, β_t	6,9...8,5 %
Volumno utezanje, β_v	12,5...14,5 %

Mehanička svojstva

Čvrstoća na tlak	57...69...86 MPa
Čvrstoća na savijanje	130...150...180 MPa
Tvrdoća (po Brinellu), okomito na vlakanca	oko 43 MPa
Tvrdoća (po Brinellu), paralelno s vlakancima	oko 79 MPa
Modul elastičnosti	15...15,4 GPa

TEHNOLOŠKA SVOJSTVA

Obradivost

Drvo se dobro ručno i strojno obrađuje, no kristali silicija mogu zatupiti alate. Stoga se pri obradi preporučuje uporaba pila s vrhovima zubaca od tvrdog metala. Najpovoljnija brzina tračnih pila je 25 – 30 m/s, uz razmak zubaca 30 – 35 mm i prednji kut zubaca od 22°. Drvo se dobro ljušti, reže, blanja, tokari, brusi i polira. Piljevina i bruševina mogu iritirati oči i kožu. Sirovo drvo korodira metal.

Sušenje

Drvo se prirodno sporo suši. U sušionicama se suši kontinuirano i polako. Ubrzano sušenje nije preporučljivo zbog mogućeg raspucavanja i vitoperenja.

Trajnost i zaštita

Prema normi HRN 350-2, 2005, srž drva moabi vrlo je otporna na gljive uzročnice truleži (razred otpornosti 1) i otporna na na napad termita (razred otpornosti D). Srž je vrlo slabo permeabilna (razred 3-4). Po trajnosti pripada razredu 4 i stoga se nezaštićeno drvo može upotrebljavati u interijeru i eksterijeru.

Uporaba

Drvo se upotrebljava kao furnirsko drvo, služi za izradu unutrašnjeg namještaja, parketa, oplate, stepenica, vrata i prozora, a rabi se i kao konstrukcijsko drvo za vanjsku i unutarnju namjenu te za izradu vagona, brodova, mostova, skija, intarzija, skulptura i drvenih igračaka.

Sirovina

Drvo se isporučuje u obliku trupaca duljine 4 – 7 m, najčešće srednjeg promjera 60 – 130 cm.

Napomena

Drvo *Baillonella toxisperma* za sada se ne nalazi na popisu ugroženih vrsta međunarodne organizacije CITES, niti na popisu međunarodne organizacije IUCN. Drvo sličnih svojstava imaju i vrste *Autranella congolensis* A. Chev., *Manilkara* spp., *Tieghemelia heckelii* Pierre, *T. africana* A. Chev., *Letestua durissima* H. Lec., *L. mabokoensis* Aubrév.

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Primjer

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

Knjige: Prezime autora, inicijal(i) osobnog imena, godina: Naslov. (ev. izdavač/editor): izdanje (ev. svezak). Mjesto izdanja, izdavač (ev. stranice od – do).

Primjeri

Krpan, J., 1970: Tehnologija furnira i ploča. Drugo izdanje. Zagreb, Tehnička knjiga.

Wilson, J. W.; Wellwood, R. W., 1965: Intra-increment chemical properties of certain western Canadian coniferous species. U: W. A. Cote, Jr. (Ed.): Cellular Ultrastructure of Woody Plants. Syracuse, N.Y., Syracuse Univ. Press, pp. 551- 559.

Ostale publikacije (brošure, studije itd.)

Müller, D., 1977: Beitrag zür Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanstalt für Forstund Holzvvirt schaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

Web stranice

***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/department/docs/punctuation/node 00.html. First published 1997 (pristupljeno 27. siječnja 2010).

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***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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