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Vladislav Zdravković, Aleksandar Lovrić, Bojana Stanković[1]

Dimensional Stability of Plywood Panels Made from Thermally Modified Poplar Veneers in the Conditions of Variable Air Humidity

Stabilnost dimenzija ploča od uslojenog drva izrađenih od toplinski modificiranih topolovih furnira u uvjetima promjenjive vlažnosti zraka

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ABSTRACT • *Some properties of plywood panels made from untreated and thermally modified (90 min. at 200 ºC) poplar veneers and their combinations have been analyzed. The change in equilibrium moisture content and the change in dimensions of the samples conditioned above water in closed containers were examined. The analysis using F-test (ANOVA) at the significance level of 95% confirmed that, regarding moisture content, all combinations of plywood panels differed significantly from the control panels. However, the analysis of thickness swelling showed that there was no significant difference among the plywood panels of similar construction. The highest values of anti-swelling efficiency were shown by plywood panels made from thermally modified veneers.*

Key words: *thermal modification, poplar veneer, plywood panels, dimensional stability, ASE*

SAŽETAK • *U radu su istražena neka svojstva ploča izrađenih od nemodificiranih i od termički modificiranih (90 min pri 200 ºC) topolovih furnira te njihovih kombinacija. Istraživana je promjena ravnotežnog sadržaja vode i promjene dimenzija uzoraka u uvjetima iznad vode u zatvorenim posudama. Analiza uz pomoć F-testa (ANOVA) na razini značajnosti od 95 % potvrdila je da se, s obzirom na sadržaj vode, sve ispitne ploče znatno razlikuju od kontrolnih ploča. Međutim, analiza podataka o debljinskom bubrenju pokazala je da ne postoji značajna razlika između ploča slične konstrukcije. Najveću učinkovitost u sprječavanju debljinskog bubrenja pokazale su ploče izrađene od toplinski modificiranih furnira.*

Ključne riječi*: toplinska modifikacija, topolov furnir, ploče od uslojenog drva, dimenzijska stabilnost, ASE*

1 INTRODUCTION
1. UVOD

The purpose of thermal wood modification is to obtain the products of improved dimensional stability, decay resistance and durability. During thermal modification, the most thermally labile of wood polymeric components begin to degrade inside the cell wall (primarily hemicelluloses and in later stages also cellulose) resulting in the production of furan compounds, such as furfural and hydroxymethilfurfural

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(Rowell *et al*., 2009). At high temperatures, the links inside the lignin complex are degraded. This phase of increased lignin reactivity is characterized by the production of various condensation reactions between aldehyde and lignin, as well as by self condensation of lignin (Tjeerdsma *et al*., 2005).

The incurred chemical changes have a positive effect on the decrease in hydrofility of the treated material. According to Boonstra and Tjeerdsma (2006), the decrease in wood hygroscopicity during thermal treatments is the result of:

- depolymerization of carbohydrates (especially hemicelluloses), which results in the decrease in the number of free hydroxyl groups;
- increasing the share of crystal zone in the cellulose where hydroxyl groups are not readily available;
- further cross linking of the lignin, by which the availability of hydroxyl groups is additionally decreased.

The positive influence of thermal wood modification on the decrease in hydrofility, swelling and shrinkage of treated wood was confirmed by numerous researches (Kocaefe *et al*., 2008; Yongjian *et al*., 2010; Poncsak *et al*., 2010; Sinković *et al*., 2011; Zdravković and Lovrić, 2010). As opposed to these positive effects, thermal wood modification causes the decrease in most mechanical properties of wood. The two crucial factors affecting the final quality of treated wood are temperature and time (Kubojima *et al*., 2000; Poncsak *et al*., 2006; Shi *et al*., 2007; etc.).

Poplar (*Populus nigra*) is a species that, despite its relatively low density (ρ_0=0.41g/cm^3), significantly changes its dimensions in the conditions of variable air humidity (α_V=14.3%) (Šoškić and Popović, 2002). Also, poplar tends to form reaction wood (tension wood), which additionally complicates the drying process and influences the deformation of saw boards (Glavaški and Popadić, 1997). For this reason, poplar is most commonly used in the production of pulp and paper and in veneer and plywood production.

In the plywood panel production process, the crosslinking of adjacent veneer layers decreases plywood shrinkage, splitting and warping. In addition, thermal treatments cause the decrease in the treated material affinity for water. One of the measures for wood affinity for water is the contact angle. The measurements of contact angle in earlier papers showed that on the thermally treated veneers, (Zdravković and Lovrić, 2010), OSB panels (Unsal *et al*., 2010) and plywood panels (Candan *et al*., 2012), contact angle increases with increasing of temperature and treatment duration, which indicates decreasing treated material affinity for water. Improvement of physical properties of LVL made of thermally treated poplar veneers were proved by Nazerian and Ghalehno (2011).

In this paper the possibility of production of plywood panels composed of thermally treated veneers was investigated in an attempt to obtain the material of improved dimensional stability.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

The materials used in this study are poplar veneers with a nominal thickness of 3 mm. The veneers were selected by random sample method from the storage of plywood mill "Novi Drvni Kombinat" from Sremska Mitrovica. The materials were shipped to laboratory facility of the company "Tarket" at Bačka Palanka. Based on the previous laboratory research (Lovrić and Zdravković, 2009), it was found that thermal treatment at 200 ºC for 90 min gave the optimal ratio between the loss of volume shrinkage and the loss of mass of poplar veneer (loss of shrinkage was 7.62 % and loss of mass was 6.49 %). Most of the material was thermally treated by the above regime and some of the material was left untreated for the production of control samples.

Thermal modification was conducted in the presence of steam as protection agent, so the treatment can be assumed as steam-heat treatment. In the treatment regime, the conditioning phase was also included in addition to heating phase, thermal treatment phase and cooling phase. The conditioning phase of 2-hour duration started at the moment when the temperature dropped below 100 ºC.

After thermal modification, veneer sheets were cut into 80 cm by 80 cm and prepared for pressing. Melamine urea formaldehyde adhesive was applied by hand roller-spreader by spreading rate of 200 g/m^2, veneers were arranged into the corresponding lay-ups and pressed according to the following regime: pressing temperature t = 85 ºC, total pressure P_t = 15 MPa, pressing time Z_1=10 min for three-layer plywood and Z_2=13 min for five-layer plywood.

The following combinations of plywood were made: three-layer plywood composed of untreated veneers – 3N (control group), three-layer plywood composed of outer layers of thermally treated veneers and inner layer of untreated veneer – TNT, three-layer plywood composed of treated veneers – 3T, five-layer plywood of alternately composed treated and untreated veneers –TNTNT, five-layer plywood with outer layers of treated veneers and core layer of untreated veneers – T3NT, and five-layer plywood composed solely of treated veneers – 5T.

Twenty samples of 5 cm by 5 cm were cut from each panel. The mass and dimensions of all samples were measured and dried to oven-dry condition, and measured again. Based on the measurements, the board moisture content (*MC*) (EN 322) and density (EN 323) were calculated. After measurements, the samples were arranged in closed containers above water and the changes in their *MC* and dimensions were monitored. The measurements of mass (for *MC* calculations) and thickness were performed every day during the first week, and after that every seven days.

After seven weeks (when the sample mass and thickness became stable), the samples were left to float on the water surface. The sample mass and thickness were measured again in the following week, and then

they were immersed in water for another week. After this period, final measurements of mass and thickness were performed and the obtained data was used for calculations of swelling and *MC* for each plywood construction and for the construction of the corresponding curves representing the changes during the study period.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Initial plywood density, moisture content and thickness
3.1. Početna gustoća ploča, sadržaj vode i debljina

It is obvious that, with the increase in the content of thermally treated veneers in the lay-up, plywood density increases and *MC* decreases. The decrease in *MC* is expected because during the thermal treatment, the number of free hydroxyl groups decreases and the possibility of moisture absorption from outdoor environment is reduced.

The increase in plywood density is probably caused by the following factors:

- greater amount of plywood thickness loss during pressing due to diminished mechanical properties of thermally modified wood, caused by collapse of thermally modified cell walls, (Awoyemi and Jones, 2010);
- higher plywood plasticity (in the process of thermal modification, hemicelluloses and celluloses are first decomposed, and the effect on lignin is much lower), which causes a lower "spring back" effect (Table 2).

Average thickness of the samples cut from the corresponding plywood panels are shown in Table 2. It can be seen that, under the same pressing regime, plywood thickness decreases if the content of thermally treated veneers in the lay-up increases. The exception is plywood TNTNT, which is somewhat thicker than plywood T3NT.

3.2 Changes in plywood dimensions and *MC*
3.2. Promjene dimenzija ploča i sadržaja vode

To determine how the study plywood panels react to the conditions of higher air humidity, the plywood samples were arranged in closed containers above water. During the first week, *MC* and thickness of the samples increased rapidly, especially during the first three days (Figure 1). The control sample - 3N showed significantly greater changes in *MC* and thickness compared to other plywood construction. Similar results were shown in the research by Nazerian *et al*. (2011), who determined the highest values of radial, tangential and longitudinal swelling in LVL samples with untreated veneers.

After the seventh day, *MC* of the control sample was *MC* = 19.32 %, and thickness change accounted for β_S = 4.08 %. The lowest variations of *MC* and thickness were measured in three-layer and five-layer plywoods composed of thermally modified veneers only (3T – *MC*=13.15 %, β_S=2.71 %; 5T – *MC*=12.02 %, β_S=2.25 %).

Table 1 Density of plywood panels and MC at the moment of sample cutting
Tablica 1. Gustoća ploča i sadržaj vode u trenutku izrade uzoraka

Panel type *Vrsta ploče*	**Three-layer plywood panels** *Troslojne ploče*			**Five-layer plywood panels** *Peteroslojne ploče*		
	3N	TNT	3T	T3NT	TNTNT	5T
Density, g/cm^3 *Gustoća, g/cm^3*	0.394	0.425	0.466	0.385	0.426	0.506
MC, % *Sadržaj vode, %*	6.43	5.70	5.27	6.31	6.17	5.50

3N (control group) – three-layer plywood composed of untreated veneers / *troslojne ploče od nemodificiranih furnira*; TNT – three-layer plywood composed of outer layers of thermally treated veneers and inner layer of untreated veneer / *troslojne ploče s vanjskim toplinski modificiranim furnirima i unutarnjim nemodificiranim furnirom*; 3T – three-layer plywood composed of treated veneers / *troslojne ploče od toplinski modificiranih furnira*; TNTNT – five-layer plywood of alternately composed treated and untreated veneers / *peteroslojne ploče izrađene od kombinacije modificiranih i nemodificiranih furnira*; T3NT – five-layer plywood with outer layers of treated veneers and core layer of untreated veneers / *peteroslojne ploče izrađene s vanjskim modificiranim furnirima i unutarnjim nemodificiranim furnirima*; 5T – five-layer plywood composed solely of treated veneers / *peteroslojne ploče izrađene samo od modificiranih furnira*

Table 2 Average thickness of samples of different plywood panels
Tablica 2. Prosječna debljina uzoraka različitih ploča od uslojenog drva

Panel type *Vrsta ploče*	**Three-layer plywood panels** *Troslojne ploče*			**Five-layer plywood panels** *Peteroslojne ploče*		
	3N	TNT	3T	T3NT	TNTNT	5T
Thickness, mm *Debljina, mm*	8.71	8.52	8.48	13.77	14.08	13.28

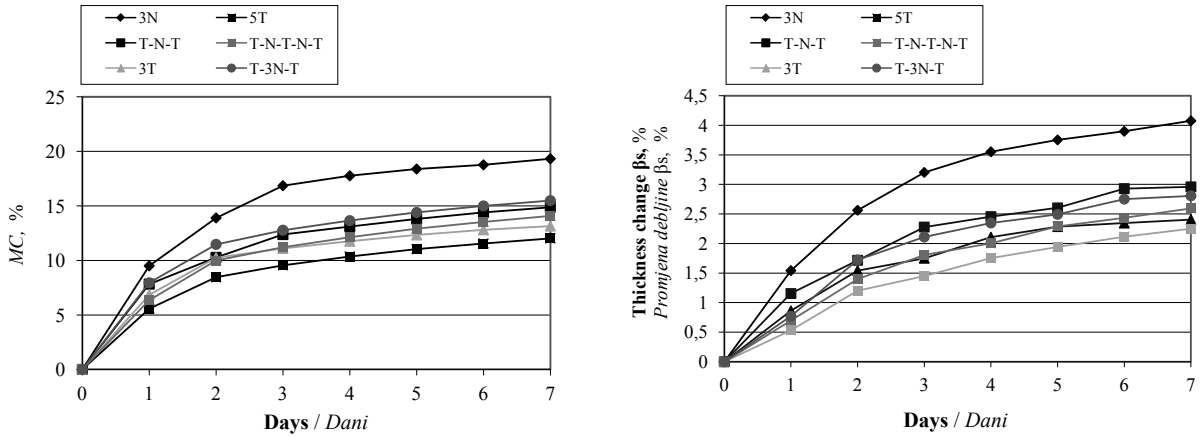

Figure 1 Changes in MC and thickness of boards during the first week
Slika 1. Promjene sadržaja vode i debljine ploča tijekom prvog tjedna

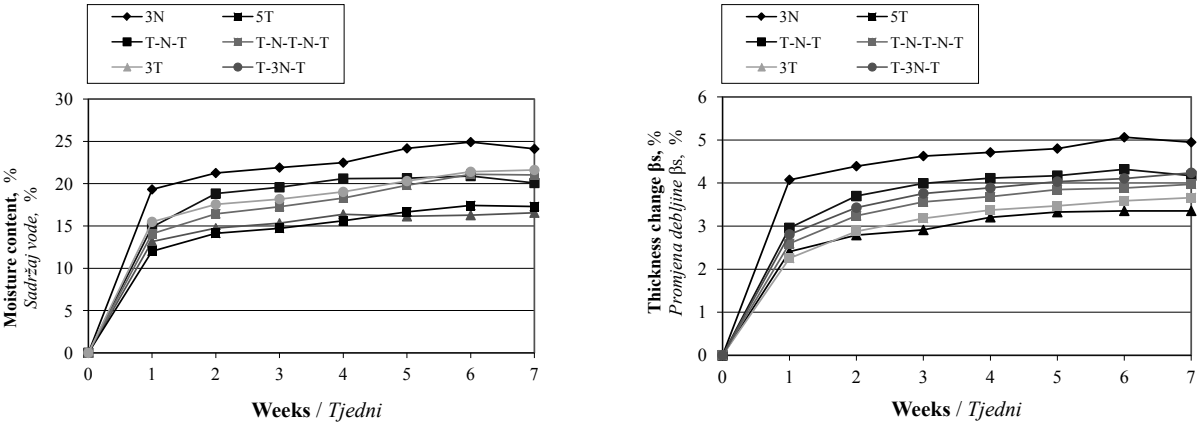

Figure 2 Changes in MC and thickness of boards during the whole experiment
Slika 2. Promjene sadržaja vode i debljine ploča tijekom cijelog eksperimenta

With the progression of the experiment, all the observed values were slightly increased until the end of the sixth week from the beginning, and they became stable in the seventh week (Figure 2). Plywood MC and total thickness swelling reached the maximum after floating and immersing of the samples for eight and nine weeks (Table 3).

The analysis of graphs in Figure 1 shows that the separation of the presented curves into three groups starts after the first week. The lowest values of thickness swelling were attained by the samples cut from plywood made exclusively of treated veneers (boards 3T and 5T), the middle group of curves consisted of plywood made of a combination of treated and untreated veneers (boards TNT, T3NT and TNTNT), while the highest values were shown by the control board (board 3N). This trend continued to the end of the seventh week when the measured values became stable (Figure 2).

Similar effect of thermal treatments on EMC of different wood species was stated by Kamdem *et al*. (2002), Akyildiz and Ates (2008), and on change of thickness swelling (TS) by Cao *et al*. (2010), Tjeerdsma *et al*. (1998) and Yildiz (2002).

Maximum changes in dimensions were achieved only after the samples were immersed in water (Table 3) without an essential effect on the observed trend. Figure 3 shows the effect of plywood composition on dimension

Table 3 The maximum MC and total thickness swelling of the samples
Tablica 3. Najveći sadržaj vode i ukupno debljinsko bubrenje uzoraka

Panel type *Vrsta ploče*		**Three-layer plywood panels** *Troslojne ploče*			**Five-layer plywood panels** *Peteroslojne ploče*		
		3N	TNT	3T	T3NT	TNTNT	5T
MC, %	Floating *plutanje*	122.91	118.43	110.36	129.05	109.63	91.11
	Immersing *uranjanje*	143.25	131.98	120.01	149.59	124.52	101.74
β_S, %	Floating *plutanje*	5.56	4.64	3.56	4.55	4.26	3.87
	Immersing *uranjanje*	5.62	4.70	3.71	4.69	4.47	4.00

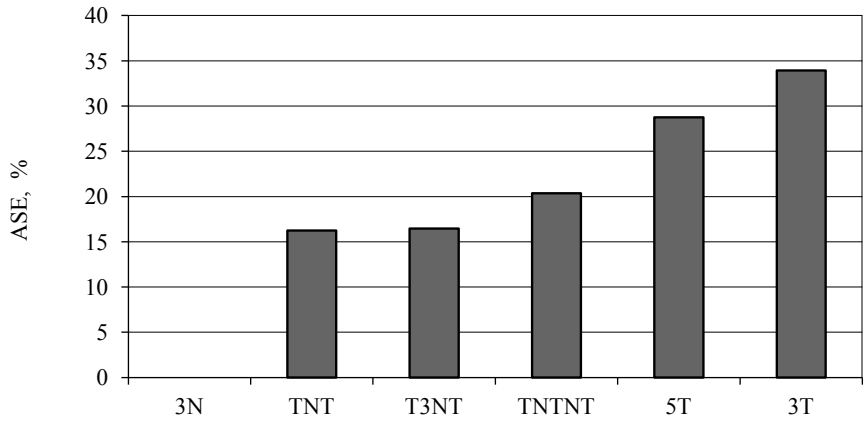

Figure 3 Achieved values of ASE after the sample immersion
Slika 3. Postignute vrijednosti ASE nakon uranjanja uzoraka

stability. The bars present the values of anti-swelling efficiency (ASE) calculated in relation to the achieved value of the control board (3N) thickness swelling.

The values of maximum *MC* (calculated after immersion – Table 3) were not so strictly grouped. The smallest value of *MC* was observed for five-layer plywood exclusively composed of thermally treated veneers (5T – *MC*=101.74 %). The three-layer plywood composed of only thermally treated veneers (3T) showed the maximum *MC* values, similar to plywood TNTNT, while plywood T3NT was the closest to the control plywood 3N.

Statistical analysis of the obtained values was performed to determine whether the calculated values of average changes in *MC* and thickness swelling were due to coincidence, or due to different behavior of the study boards. The values calculated after seven weeks from the beginning of the experiment were taken as the reference point. The main statistical indicators of *MC* and thickness swelling are shown in Table 4 and 5.

Table 4 The main statistics – MC after seven weeks
Tablica 4. Rezultati statističke analize podataka o sadržaju vode nakon sedam tjedana

Panel type *Vrsta ploče*	**Three-layer plywood panels** *Troslojne ploče*			**Five-layer plywood panels** *Peteroslojne ploče*		
	3N	TNT	3T	T3NT	TNTNT	5T
Number of samples *Broj uzoraka*	20	20	20	20	20	20
Average value *Srednja vrijednost*	24.12	20.08	16.56	21.62	21.03	17.30
Standard deviation *Standardna devijacija*	0.62	0.70	0.53	0.67	0.80	0.58
Coeff. of variation *Koeficijent varijacije*	2.59	3.46	3.17	3.08	3.82	3.37
Standard error *Standardna pogreška*	0.14	0.16	0.12	0.15	0.18	0.13

Table 5 The main statistics – thickness swelling after seven weeks
Tablica 5. Rezultati statističke analize podataka o debljinskom bubrenju nakon sedam tjedana

Panel type *Vrsta ploče*	**Three-layer plywood panels** *Troslojne ploče*			**Five-layer plywood panels** *Peteroslojne ploče*		
	3N	TNT	3T	T3NT	TNTNT	5T
Number of samples *Broj uzoraka*	20	20	20	20	20	20
Average value *Srednja vrijednost*	4.95	4.17	3.35	4.24	3.97	3.66
Standard deviation *Standardna devijacija*	0.82	0.36	0.55	0.52	0.30	0.63
Coeff. of variation *Koeficijent varijacije*	16.61	8.58	16.52	12.20	7.48	17.23
Standard error *Standardna pogreška*	0.18	0.08	0.12	0.12	0.07	0.14

Table 6 Calculated *p*-values according to the attained *MC*
Tablica 6. *p*-vrijednosti pri usporedbi podataka o sadržaju vode

Panel type *Vrsta ploče*	**3N**	**TNT**	**3T**	**5T**	**TNTNT**	**T3NT**
3N	-	0.0000 yes	0.0000 yes	0.0000 yes	0.0000 yes	0.0000 yes
TNT	-	-	0.0000 yes	0.0000 yes	0.0003 yes	0.0000 yes
3T	-	-	-	0.0002 yes	0.0000 yes	0.0000 yes
5T	-	-	-	-	0.0000 yes	0.0000 yes
TNTNT	-	-	-	-	-	0.0159 yes

Table 7 Calculated *p*-values according to the attained thickness swelling
Tablica 7. *p*-vrijednosti pri usporedbi podataka o debljinskom bubrenju

Panel type *Vrsta ploče*	**3N**	**TNT**	**3T**	**5T**	**TNTNT**	**T3NT**
3N	-	0.0004 yes	0.0000 yes	0.0000 yes	0.0000 yes	0.0023 yes
TNT	-	-	0.0000 yes	0.0032 yes	0.0649 no	0.6417 no
3T	-	-	-	0.1086 no	0.0001 yes	0.0000 yes
5T	-	-	-	-	0.0524 no	0.0031 yes
TNTNT	-	-	-	-	-	0.0552 no

The statistical ANOVA was performed using *F*-test (Statgraphics software) at the significance level of 95 %. Table 6 and 7 show the calculated *p*-values for *F*-test. All the values below 0.05 are bolded in the Tables and they show that there are significant differences among the observed samples.

Based on the analysis of data on *MC* reached after seven weeks (Table 6), it can be concluded that there is a significant difference among all boards, i.e. that in the conditions of variable air humidity each board behaves differently. However, the conclusions are different if the data on thickness swelling reached during the study period (Table 7) are considered.

All types of boards were significantly different compared to the control board 3N, while there was no difference among the boards of similar construction. So, there was no significant difference between the boards 3T and 5T (boards composed of treated veneers only), nor in the comparison of boards composed of different combinations of thermally treated and untreated veneers - TNT, TNTNT and T3NT. It is interesting that there was no significant difference in the comparison of 5T and TNTNT boards, which means that the middle veneer sheet, in spite of the lowest exposure to environmental moisture, contributed to the decrease in thickness swelling of the observed board.

As in practice, the change in thickness is more important than the change in moisture content, it can be concluded that the observed categories of boards present the boards of similar properties.

4 CONCLUSIONS
4. ZAKLJUČAK

Based on the examination of plywood panels produced by combining the thermally treated and untreated poplar veneers, it was concluded that the thermal modification process had a positive effect on the decrease in moisture absorption of the panels. It was also concluded that, with the increased amount of thermally treated veneers in the plywood panels, the values of the observed properties decreased.

The calculated values of ASE (anti-swelling efficiency) showed that the three-layer board exclusively composed of thermally treated veneers (3T), and the five-layer board (5T) achieved the highest values, which was expected.

The analysis using *F*-test at the significance level of 95 % confirmed that all boards had significantly different moisture contents. However, the analysis of thickness swelling showed that there were no significant differences among the boards of similar construction.

The results presented in this paper proved that the use of thermally treated veneers in plywood production contributed to the improvement of their properties and their resistance to higher air humidity and moisture.

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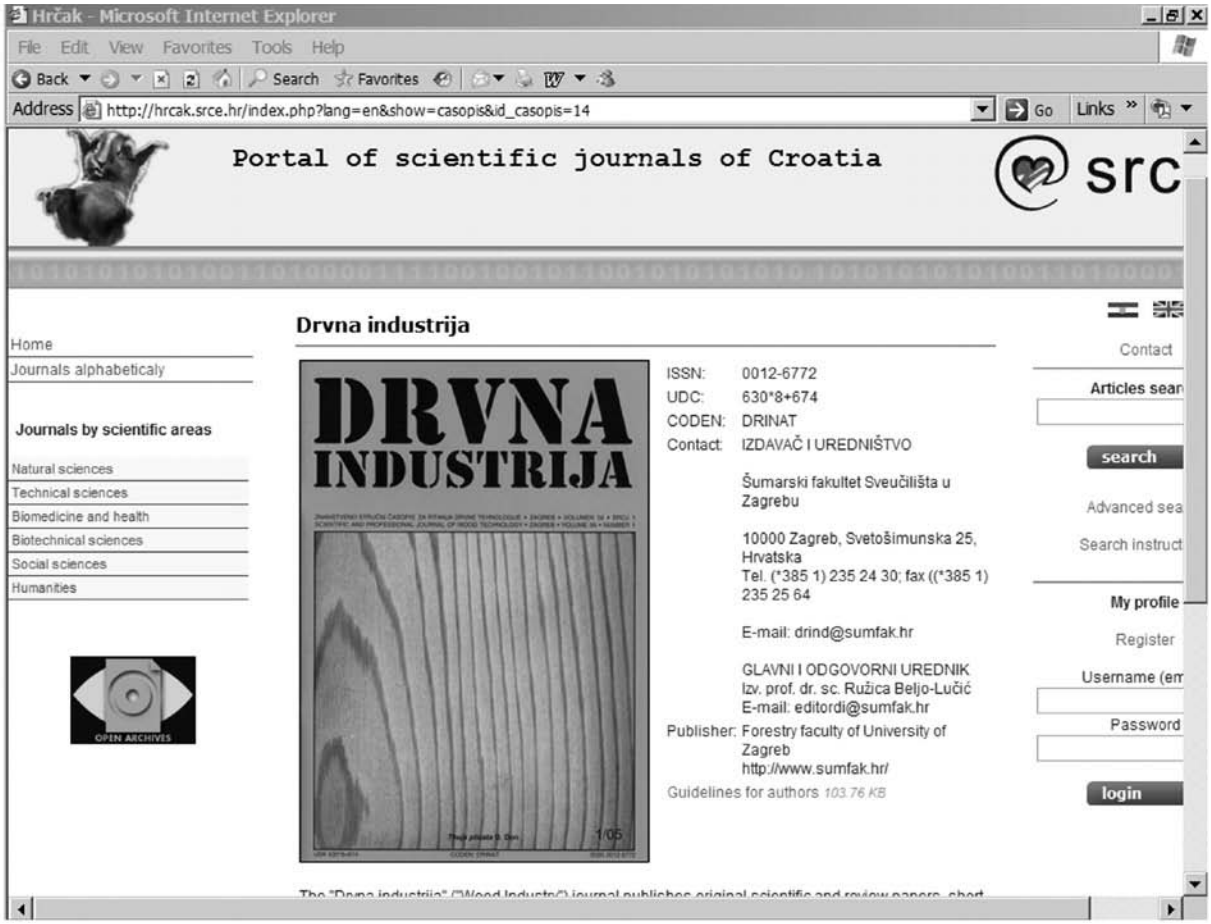

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Effect of Seed Source on Physical Properties of Scots Pine (a Case Study in Neka, Iran)

Utjecaj podrijetla sjemena na fizikalna svojstva drva običnog bora (studija slučaja u Neki, Iran)

Original scientific paper - Izvorni znanstveni rad
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ABSTRACT • *This study investigated the seed source effect on the physical properties of exotic Scots pine (Pinus sylvestris). For this purpose, nine clear pine trees grown from the Spanish, Armenian and Serbian (part of former Yugoslavia) seed sources were selected from the Vanamak-Neka (eastern part of Mazandaran province) and a disc was cut from each tree at breast height. Testing samples were prepared based on the ISO standard to estimate the oven-dry density, basic density, volumetric shrinkage and volumetric swelling. Then, the results were studied by using the variance analysis test (ANOVA) and Duncan's table. The results indicated that the effect of seed sources on the above mentioned properties were significant. All of the physical properties of Scots pine grown from the Spanish seed source were higher. There were no significant differences between the Armenian and Serbian seeds in the density and dimensional changes of the wood (volumetric swelling and volumetric shrinkage). The relationships between different wood properties were analyzed by applying the linear regression. There was a weak and negative relationship between oven-dry and basic density and longitudinal and diametrical growth of the trees. The correlation between oven-dry density and dimensional changes of the wood showed that there was a positive relationship between the mentioned properties in all the three seeds, while the correlation coefficient of the Armenian seed was stronger than that of the other two seeds.*

Keywords: *seed sources, Scots pine, oven-dry density, basic density, volumetric shrinkage, volumetric swelling*

SAŽETAK • *U radu se prikazuje istraživanje utjecaja podrijetla sjemena na fizikalna svojstva egzotičnog drva običnog bora (Pinus sylvestris). Za tu svrhu sa staništa Vanamak-Neka (istočni dio pokrajine Mazandaran) izdvojeno je devet čistih stabala običnog bora čije je sjeme podrijetlom iz Španjolske, Armenije i Srbije (bivša Jugoslavija) te je ispiljen disk na prsnoj visini svakog stabla. Ispitni uzorci pripremljeni su na temelju ISO standarda za određivanje gustoće apsolutno suhog drva, standardne gustoće, volumnog utezanja i volumnog bubrenja. Zatim su rezultati analizirani uz pomoć testa analize varijance (ANOVA) i Duncanove tablice. Rezultati su pokazali da je*

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utjecaj izvora sjemena na navedena svojstva značajan, tako da su sva istraživana fizikalna svojstva imala najveće vrijednosti za drvo običnog bora od sjemena iz Španjolske. Nije bilo značajne razlike između gustoće i promjena dimenzija (volumno utezanje i volumno bubrenje) za drvo čije je sjeme podrijetlom iz Armenije i Srbije (bivša Jugoslavija). Odnosi među različitim svojstvima drva analizirani su primjenom linearne regresije. Utvrđena je slaba i negativna ovisnost gustoće apsolutno suhog drva i standardne gustoće o visini i promjeru drveća. Korelacija između gustoće apsolutno suhog drva i promjena dimenzija drva pokazala je da postoji pozitivna ovisnost za sva tri sjemena različitog podrijetla, s tim da je koeficijent korelacije veći za sjeme iz Armenije nego za sjeme s druge dvije lokacije.

Ključne riječi: *podrijetlo, sjeme običnog bora, gustoća apsolutno suhog drva, standardna gustoća, volumno utezanje, volumno bubrenje*

1 INTRODUCTION
1. UVOD

About 60 years ago, afforestation was carried out of various exotic coniferous species in Iran, particularly in the Iranian three major provinces of Giulan, Mazandaran and Golestan, in order to produce quality wood. One of these species is Scots pine, which has been cultivated in the Saravan (in Giulan province), and Garagpas, Ajabit, Azarak and Atrachal in Chaloos, Sangdeh in Sari (Mazandaran Province) and Ramian and Golidagh (Golestan province). The advent of this species was instigated by seeds from different countries such as Yugoslavia (Serbia), Armenia, Spain, Turkey and France.

Scots Pine (*Pinus sylvestris*) is a fast growing coniferous tree with a straight trunk reaching to a height of 50 meters and 1.2 meters in diameter. This species has spread in a wide area of Europe from western Scotland to eastern Siberia, and from Scandinavian countries to the south of Spain. In Scotland, these trees provide valuable and unique forests replacing other native coniferous species (Sindair, 1999), they cover an area of about 1.28 million hectares of forests in Scotland and 700,000 to 650,000 hectares of plantation forests in Spain (Alia *et al*., 2000; Montrero *et al*., 2001; Munoz *et al*., 2008). Nowadays, Scots pine has spread in the mountainous regions of North, Central and West Europe (at the altitude from 500 to 2400 meters), and in southern Europe and in Eurasia and other continents in the south-eastern and north-eastern Canada and the United States through planting and cultivating (Steven and Carlisle, 1959). Scots pine is one of the most important commercial and woody species in Europe with a good quality and is used in various industries such as veneer, paper, furniture and parquet (Zare, 2001; Peltola *et al*., 2009).

Wood density is an important feature of wood quality affecting the strength properties of wood, swelling and pulp yield (West, 2006). In softwoods, the growth rate increase with changes in the early wood causes a reduction in density and mechanical properties of the wood (Panshin and de Zeeuw, 1980). In softwoods (Bouffier *et al*., 2003; Hashemi and Kord, 2011; Kiaei, 2011; Kiaei *et al*., 2012), particularly Scots pine (Mutz *et al*., 2004; Repola, 2006; Munoz *et al*.; 2008), wood density along radial direction increases from the pith to the bark and decreases in the longitudinal axis of the tree from the bottom to the top. *Pinus sylvestris* grown in the central part of Lithuania has lower density, more lignin and extractives, and equal amounts of cellulose and ash in comparison to *Pinus contorta* (Sable *et al*., 2012).

In literature, few researches have been conducted on the effect of seed sources on different properties of softwoods worldwide. For example, Matziris *et al*. (1979) in a research entitled "Seed Source Effect on *Pinus Radiante* Density in Two Sites of Greece" reported that the effect of seed sources (Australian, New Zealand and Spanish seeds) on the *Pinus radiate* density was not significant, while the site-independent effects on the density and interactions between seed source and site were significant.

In Iran, researches were conducted on longitudinal growth, diameter and survival of Scots pine of different seed sources, as for example the researches by Kiasri *et al*. (2011) and Rezaei Taleshi (2012), while there has been no particular study about the seed source impact on wood properties of Scots pine in Iran. This study sought to examine the seed source effect on physical properties of Scots pine species (seed source: Spain, Armenia and Serbia) and was conducted to determine the relationship among various properties of the wood.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, nine clear non-native Scots pine trees (without zone lines, reaction wood, decay, and insect damage, or fungal infection) of three different seed sources (Spain, Serbia and Armenia) were chosen from Venmek forestry projects in Neka (three trees from each seed source) and a disk of 5 cm thickness was cut from each tree at breast height. The related features (height, diameter and tree age) of each tree of various seed sources are shown in Table 1. All of the trees have juvenile wood due to low age. Due to the trees small diameter, the samples were spread across the disks based on the standard ISO-3131 to determine and calculate the physical properties (oven-dry density, basic density, volumetric shrinkage and volumetric swelling). A total of 150 samples were selected, 50 for each different seed source.

Vanamak-Neka is a region located in Neka in the eastern part of Mazandaran province. Mazandaran province is located in Northern Iran. The average annual temperature is about 15.7 °C and the total annual rainfall reaches 1186 mm, meaning that this region has a cold-humid climate with cool winters. The altitude is 760 meters from the sea level. The soil depth in this

Table 1 Tree characteristics of three different seed sources for Scote pine (*Pinus sylvestris* L.)
Tablica 1. Obilježja stabala običnog bora (*Pinus sylvestris* L.) od tri sjemena različitog podrijetla

Seed source *Podrijetlo sjemena*	**Diameter, cm** *Promjer, cm*	**Height, m** *Visina, m*	**Age, years** *Starost, god.*
Serbia *Srbija – ex Jugoslavija*	10.47	7.47	16
Armenia *Armenija*	10.06	7.20	16
Spain *Španjolska*	8.03	4.32	16

region ranges from deep to very deep and the clay soil content increases with the increase of the depth (Kiasari *et al*., 2011).

After preparing the samples, the relevant experiments, including weighing and measuring the dimensions, were conducted. In the first stage, the sample volumes and weights (after cutting the sample) were measured. Then, the samples were placed in water for 48 hours so as to be completely immersed in water or become saturated with water. After that, the sample weight and saturated volume were determined using a digital scale and caliper. The third stage included putting the samples in an oven for 48 hours at103±2 °C to completely dry the samples and afterward the sample volume and weight were measured in a dry state. Finally, the oven-dry density, basic density, volumetric shrinkage and volumetric swelling were calculated by using the following formulas:

$$D_0 = M_0 / V_0 \quad (\mathrm{kg/m^3})$$

Where M_0, and V_0 are the oven-dry weight (kg) of the specimen and volume (m^3) of specimen, respectively.

$$D_b = M_0 / V_s \quad (\mathrm{kg/m^3})$$

Where D_b is the basic density, M_0 is the oven dry weight and V_s is the saturated volume of specimen.

$$\beta_v = (V_s - V_0) / V_s \quad (\%)$$
$$\alpha_v = (V_s - V_0) / V_0 \quad (\%)$$

Where β_v, α_v, V_s, V_0 are the volumetric shrinkage, volumetric swelling, saturated volume and oven-dry volume, respectively.

2.1 Statistical analysis
2.1. Statistička analiza

To determine the seed source effect on the physical properties (oven-dry density, basic density, volumetric shrinkage and volumetric swelling), statistical analysis was conducted using the SPSS programming method in conjunction with the analysis of variance (ANOVA) techniques. Duncan's multiple range test (DMRT) was used to test the statistical significance at $\alpha = 0.05$ and $\alpha = 0.01$ levels. The linear regression was used to analyze the relationship among various properties of the wood.

3 RESULTS
3. REZULTATI

3.1 Oven-dry density
3.1. Gustoća u apsolutno suhom stanju

The mean oven-dry density of Scots pine samples of various seed sources from Spain, Armenia and

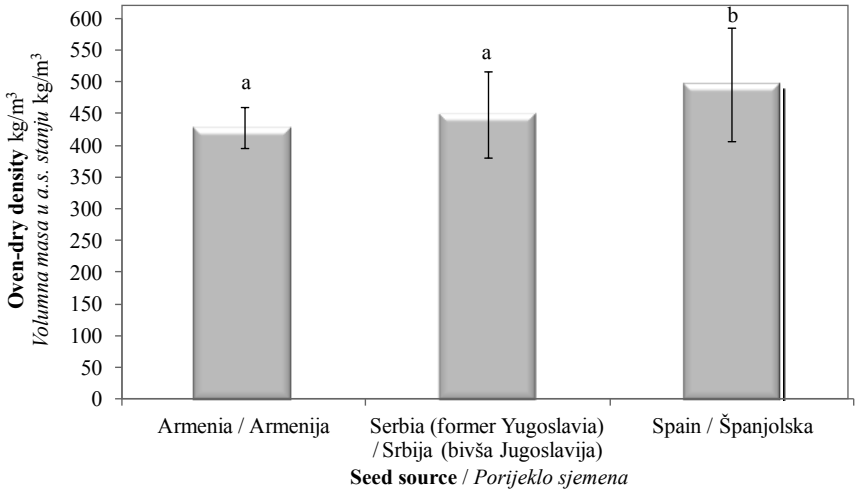

Figure 1 The average basic oven-dry density for different seed sources of Scots pine (Results with different letters (a and b) are significantly different by Duncan's test)
Slika 1. Prosječne vrijednosti gustoće drva u apsolutno suhom stanju običnog bora od sjemena različitog podrijetla (rezultati označeni različitim slovima, a i b, značajno se razlikuju prema Duncanovu testu)

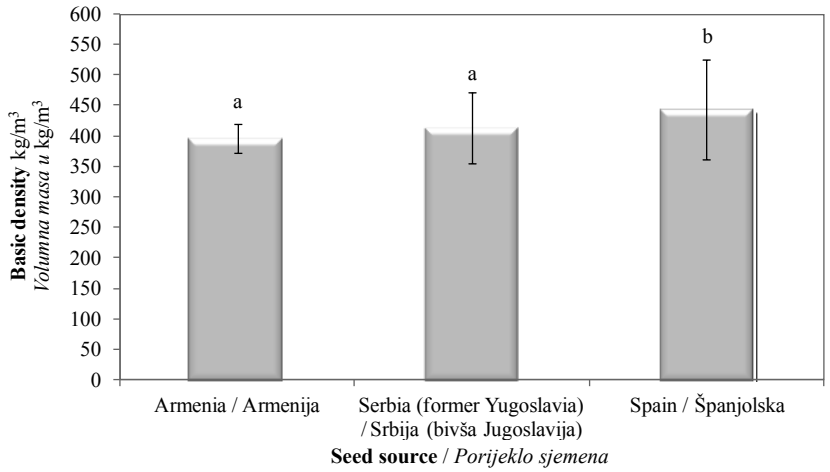

Figure 2 The average basic density for different seed sources of Scots pine (Results with different letters (a and b) are significantly different by Duncan's test).
Slika 2. Prosječne vrijednosti standardne gustoće drva običnog bora od sjemena različitog podrijetla (rezultati označeni različitim slovima, a i b, značajno se razlikuju prema Duncanovu testu)

Serbia are shown in Figure 1. The variance analysis results showed that the seed source effect on the Scots pine oven-dry density was significant (F= 6.108, $p \leq 0.01$); so the wood oven-dry density of the Spanish seed source (496 kg/m3) was 10.4 % and 15.8 % higher than the Serbian and Armenian seeds, respectively. The Duncan table classified the average oven-dry density of the Armenian and Serbian seeds in one group, and the average oven-dry density obtained from the Spanishseeds in another group.

3.2 The basic density
3.2. Standardna gustoća

The mean basic density of Scots pine samples of various seed sources from Spain, Armenia and Serbia are presented in Figure 2. The variance analysis results showed that the seed source effect on the Scots pine basic density was significant (F= 3.594, $p \leq 0.05$); so the wood basic density of the Spanish seed source (443 kg/m³) was 7.2 % and 11.8 % higher than the average of the Serbian and Armenian samples, respectively. The Duncan table classified the average basic density of the Armenian and Serbian seeds in one group, and the average basic density obtained from the Spanish seeds in another group.

The linear regression between the oven-dry density and basic density with the tree longitudinal and diametrical growth is shown in Figure 3. The results showed that there is an insignificant (weak and negative correction) relationship between wood density and the tree diameter and height. The strongest correlation was observed between oven-dry density and longitudinal growth of trees (-0.243) and the weakest correlation was observed between the basic density and tree diameter (-0.138).

3.3 Volumetric shrinkage
3.3. Volumno utezanje

The average volumetric shrinkage for Scots pine wood samples of various seed sources from Spain, Armenia and Serbia are given in Figure 4. The variance analysis results showed that the seed source effect on the Scots pine volumetric shrinkage was significant (F=

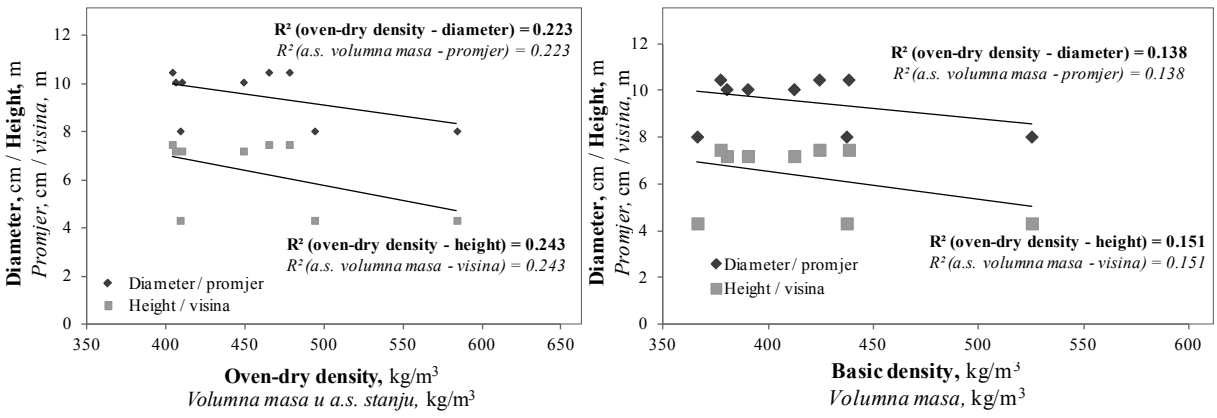

Figure 3 The relationship between oven-dry density (left) and basic density (right) with tree longitudinal and diametrical growth in combined seed sources; there are no significant differences
Slika 3. Odnos gustoće apsolutno suhog drva (lijevo) i standardne gustoće (desno) te visine i promjera stabala za sjemena različitog podrijetla; ne postoji značajna ovisnost

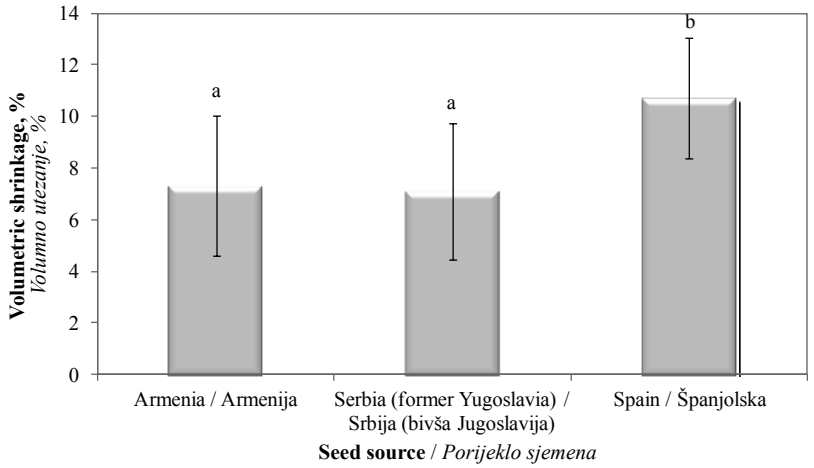

Figure 4 The average volumetric shrinkage for different seed sources of Scots pine (Results with different letters (a and b) are significantly different by Duncan's test).
Slika 4. Prosječne vrijednosti volumnog utezanja drva običnog bora od sjemena različitog podrijetla (rezultati označeni različitim slovima, a i b, značajno se razlikuju prema Duncanovu testu)

17.449, $p \leq 0.01$); so the wood volumetric shrinkage of wood samples of the Spanish seed source (10.70 %) was 7.2 % and 11.8 % higher than the average of wood samples of the Serbian and Armenian seed sources, respectively. The Duncan table classified the average volumetric shrinkage of the Armenian and Serbian samples in one group, and the average volumetric shrinkage gained from the Spanish wood samples in another group.

3.4 Volumetric swelling
3.4. Volumno bubrenje

The average volumetric swelling for Scots pine wood samples of various seed sources from Spain, Armenia and Serbia are given in Figure 5. The variance analysis results showed that the seed source effect on the Scots pine volumetric swelling was significant (F= 17.589, $p \leq 0.01$); so the wood volumetric swelling of samples of the Spanish seed source (12.06 %) was 55.8 % and 50.9 % higher than the average of the Serbian and Armenian seeds, respectively. The Duncan table classified the average volumetric swelling of the Armenian and Serbian seed samples in one group, and the average volumetric swelling acquired from the Spanish seed samples in another group.

3.5 Relationship between wood density and swelling/shrinkage
3.5. Odnos između gustoće drva i bubrenja/utezanja

The relationship between oven-dry density and dimension variations (swelling and shrinkage) from the Armenian (Figure 6a), Serbian (Figure 6b) and Spanish seed sources (Figure 6c) showed that there is a positive and significant relationship between wood density and swelling/shrinkage, so that the correlation coefficient of Scots pine grown from the Armenian seed source was higher than that from the Serbian and Spanish seed sources. The correlation coefficients between wood density and swelling are slightly higher than those between wood density and shrinkage for the Armenian and Serbian seed sources, while the opposite applies for the Spanish seed sources.

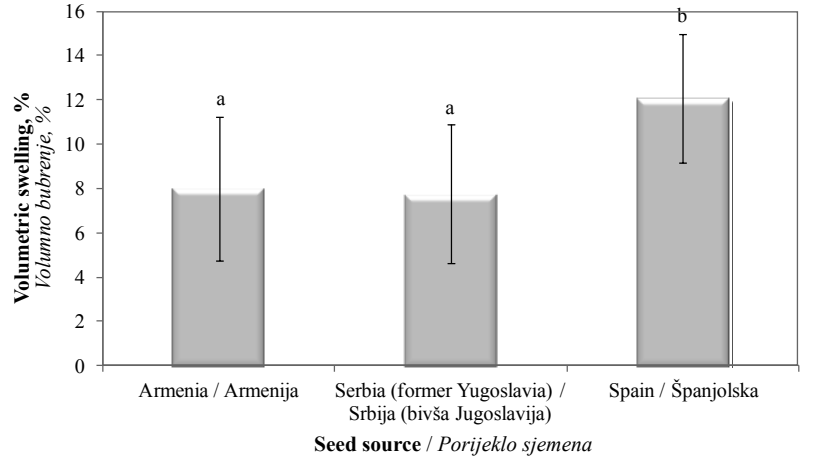

Figure 5 The average volumetric swelling for different seed sources of Scots pine (Results with different letters (a and b) are significantly different by Duncan's test).
Slika 5. Prosječne vrijednosti volumnog bubrenja drva običnog bora od sjemena različitog podrijetla (rezultati označeni različitim slovima, a i b, značajno se razlikuju prema Duncanovu testu)

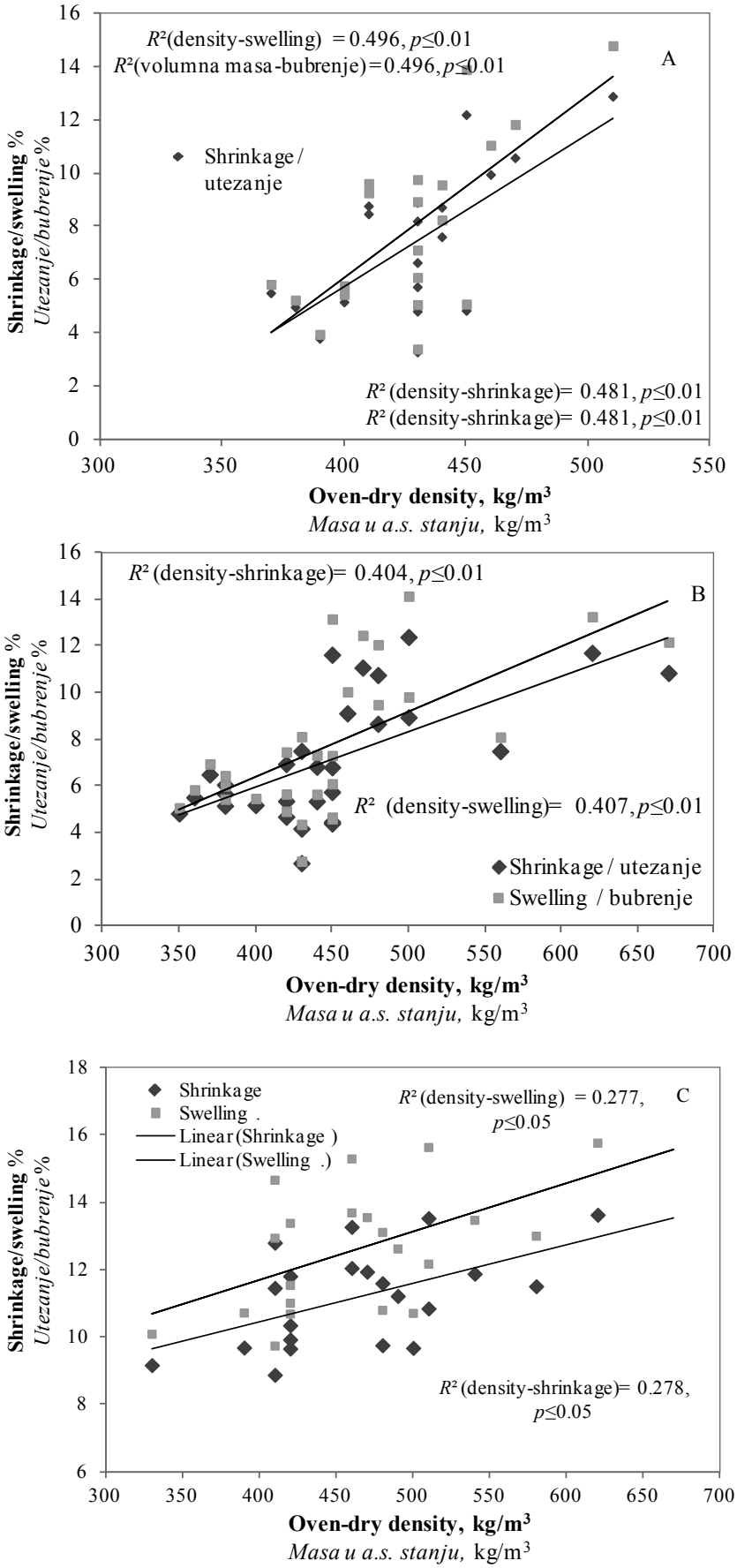

Figure 6 The relationship between density and swelling/shrinkage of wood from Armenian (A), Serbian (B) and Spanish (C) seed sources

Slika 6. Odnos između gustoće i bubrenja/utezanja drva od sjemena podrijetlom iz Armenije (A), Srbije - bivše Jugoslavije (B) i Španjolske (C)

4 DISCUSSION
4. RASPRAVA

Variations of wood properties of juvenile wood are much higher than those of mature wood. The juvenile wood has lower density and mechanical strength than mature wood (Zobel and van Buijtenen, 1989). All tree samples (studied seed sources) have juvenile wood due to lower age. Therefore, the transition age between juvenile and mature wood did not occur for these tree samples.

The present study showed that the impact of seed sources on the oven-dry density and the basic density of Scots pine was significant, which is inconsistent with the results of the study on *Pinus radiata* by Matziris (1979). The wood density of Scots pine wood grown from the Spanish seed source was higher than that from the Armenian and Serbian seed sources.

In general, the wood density is influenced by factors such as genotype, ageing of the cambium, cell walls thickness and growth rate, so that by increasing the cell wall thickness and decreasing of the early wood percentage, the wood density increases (Panshin and de Zeeuw, 1980). Therefore, it is expected that the cell wall thickness of Scots pine wood grown from the Spanish seed source would be higher than that of samples from the Armenian and Serbian seed sources.

Since all mechanical properties of wood are closely related to wood density and some wood strength factors are more associated with wood density, it is expected that wood strength of Scots pine grown from the Spanish seed source would be higher than wood grown from the Armenian seed source. This is an important issue in the design of wooden structures due to the fact that the interdependence between density and mechanical properties of wood has been proven for many coniferous species (*Abies fabri, Abies nephrolepis, Picea asperata, Piceae koraiensis, Larix gmelini, Larix olgensis, Pinus massoniana, Pinus yunnanensis, Pinus eldarica*) (Zhang, 1997; Kiaei, 2011). Various mechanical properties of wood are also dependent on tracheid dimensions such as length and diameter (Panshin and de Zeeuw, 1980; Quilho *et al.*, 2006).

The results show that there is a weak and insignificant relationship between oven-dry density / basic density and the tree height / diameter growth of Scots pine trees grown from combined seed sources (Armenian, Serbian and Spanish). Similar trend has been reported by Matziris (1979) and Burdon and Harris (1973). They state that the *Pinus radiata* density has a weak negative correlation with the tree breast height diameter and that it is not related to the tree height.

The average oven-dry density of Scots pine grown from the Armenian, Serbian and Spanish seed sources was 457 kg/m^3, which is similar to the average oven-dry density of Scots pine grown in Lithuania (Sable *et al.*, 2012). Also, this characteristic of Scots pine is lower than other pine species such as (Alden, 1997): *P. banksiana* (460 kg/m^3*), P. echinata* (540 kg/m^3*), P. elliotti* (660 kg/m^3), *P. palustris* (620 kg/m^3), *P. pungens* (550 kg/m^3), *P. resinosa* (510 kg/m^3*), P. rigida* (520 kg/m^3), *P.teada* (540 kg/m^3) and is higher than other pine species such as: *P. contorta* (430 kg/m^3)*, P. jeffreyi* (420 kg/m^3)*, P. lambertiana* (380 kg/m^3), *P. monticola* (420 kg/m^3), *P. strobes* (370 kg/m^3). Since wood density of Scots pine grown from the Armenian seed source is lower than the density of wood grown from other seeds, it may affect the wood pulp production. In a digester, an equal volume of Scots pine wood grown from the Spanish seed source (with higher density) produces more wood pulp. As most properties of the wood pulp are related to the density (Panshin and de Zeeuw, 1980; Zobel and van Buijtenen, 1989; Sable *et al*., 2002), there are positive relationships between wood density and bulk, freeness, bending stiffness, light scattering, opacity and tear index, while there are negative correlations with tensile index, burst and stretch (Wimmer *et al*., 2002).

The basic density of Scots pine grown from the Spanish seed source is about 433 kg/m3, which is almost similar to the basic density of the wood grown in Spain (430 kg/m3, Munoz *et al*, 2008) and in southern Finland (435 kg/m3, Repola, 2006). Wood with the basic density of 400-600 kg/m3 is suitable for pulp production (Downes *et al.*, 1997), which is the case of Scots pine grown from the Armenian, Serbian and Spanish seed sources. For more precise results, the tracheid dimensions, morphological coefficients and their chemical compounds must be investigated. A wood species can be considered suitable for pulp production if it has long fibers, high degrees of cellulose, and a low content of lignin, extractives and ash (Zobel and van Buijtenen, 1989; Sable *et al.*, 2012). There are positive relationships between fiber length and burst strength (Casey, 1952; Miyake, 1968; El-Hosseiny and Anderson, 1999; Ona *et al.*, 2001), tensile strength (Casey, 1952; Miyake, 1968), tear strength (Casey, 1952; Haygreen and Bowyer, 1996) and folding endurance (Dinwoodie, 1965; Ona *et al.*, 2001).

Shrinkage and swelling are related to changes in wood dimensions affected by changes in wood moisture, which occurs between the dry phase and moisture saturation point of wood (Pang, 2002). This phenomenon is affected by factors such as the heartwood and sapwood proportion, microfibril angle in the secondary layer, etc. (Bektas and Guler, 2001). However, density is the most important parameter that affects wood volumetric shrinkage and swelling (Guler *et al.*, 2007). Volumetric swelling and shrinkage rate of the Scots pine grown from the Spanish seed source was higher than that of Scots pine grown from the Serbian and Armenian seed sources, which can be attributed to the above factors. The results of the analysis of oven-dry density and volumetric swelling and shrinkage showed a significant positive correlation between these properties in Scots pine, which is consistent with the results of Munoz *et al.* (2008). They estimated the Pearson correlation coefficient for the relationship between the basic density and volumetric shrinkage of Spanish Scots pine to be R=0.624.

5 CONCLUSION
5. ZAKLJUČAK

This study evaluated the seed source effect on the density of non-native Scots pine wood and dimensional changes depending on the Spanish, Armenian and Serbian seed sources. The following results were obtained:

1. The seed source effect on the oven-dry density, basic density, volumetric swelling and shrinkage was significant so that the effect of these properties of the Spanish seed source is higher than that of the Armenian and Serbian seed sources. There is a positive and significant relationship between oven-dry density and dimensional changes of wood, but the values of correlation coefficient are stronger with the Armenian seed source than with the Spanish and Serbian seeds.

2. There is a weak and negative relationship between longitudinal and diametrical growth of trees grown from the combined seed sources (Spanish, Armenian and Serbian seeds) and the basic and oven-dry density.

3. The basic density of wood grown from the Spanish, Armenian and Serbian seeds is suitable for paper production. According to a short-term production of wood, Scots pine species with seeds originating from Armenia and Serbia are more suitable than those from Spain, because these species, in addition to being suitable for paper production, reach the desired diameter and length within a short time. As the Iranian forest resources are relatively poor, this fact can be decisive for the cultivation of Scots pine with seeds originating from Armenia and Serbia. Diameter and longitudinal growth of Scots pines from Armenia and Serbia are more than 10 cm and 7 cm, respectively, which is a higher growth than that of Scots pines from Spain.

4. Scots pine wood grown from the Spanish seed is more suitable for mechanical applications than the other two seed sources due to its high density.

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TEMATSKI PRILOZI

STRUČNI ČASOPIS

Aleš Ugovšek[1,2], Milan Šernek[1]

Influence of the Addition of Urea-Formaldehyde Adhesive to Liquefied Wood on Curing

Utjecaj dodatka urea-formaldehidnog ljepila u ukapljeno drvo na proces stvrdnjavanja

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ABSTRACT • *Urea-formaldehyde adhesive is one of the most frequently used types of amino resins for wood bonding. However, due to its synthetic origin, more environmentally friendly adhesives are desired. Liquefied wood is one of the natural-based alternatives. In this research, wood was liquefied using a procedure in which low solvent content liquefied wood was obtained. For the purpose of this study, urea-formaldehyde adhesive was added to the liquefied wood in proportions of 0, 10, 20, 30 and 40 %. Differential scanning calorimetry and rheological oscillatory test techniques were used to analyze the curing process and the hardening behavior of different adhesive mixtures. Additionally, wood lamellas were bonded with the same adhesive mixtures, and the shear strength of the bonds was evaluated. It was found that the addition of urea-formaldehyde adhesive to liquefied wood led to the occurrence of multiple chemical reactions during the curing process, and that the higher amount of urea-formaldehyde adhesive lowered the temperature at which gelation of the adhesive mixture occurred. It was also found that the adhesive mixtures with lower portions of urea-formaldehyde adhesive did not contribute to higher bond shear strengths compared to specimens bonded with pure liquefied wood, and that none of the specimens met the standard requirements for non-structural applications under dry conditions.*

Key words: *liquefied wood, urea-formaldehyde adhesive, differential scanning calorimetry, rheometry, shear strength*

SAŽETAK • *Urea-formaldehidno ljepilo jedna je od najčešće primjenjivanih aminosmola za lijepljenje drva. Međutim, zbog sintetičnog podrijetla tog ljepila, poželjnija su ekološki prihvatljivija ljepila. Ukapljeno drvo jedna je od alternativa na prirodnoj bazi. U ovom istraživanju drvo je ukapljeno primjenom postupka u kojemu se takvo drvo dobije uz mali sadržaj otapala. Za potrebe istraživanja, urea-formaldehidno ljepilo dodano je u ukapljeno drvo u omjerima od 0, 10, 20, 30 i 40 %. Diferencijalno skeniranje kalorimetrijom i reološko-oscilatorni ispitni postupak primijenjeni su za analizu procesa stvrdnjavanja i ponašanje različitih smjesa ljepila tijekom stvrdnjavanja. Osim toga, drvene su lamele slijepljene istim smjesama ljepila te je analizirana smicajna čvrstoća spoja. Utvrđeno je da je dodatak urea-formaldehidnog ljepila u ukapljeno drvo doveo do pojave višestruke kemijske reakcije tijekom procesa stvrdnjavanja te da je veća količina urea-formaldehidnog ljepila spustila temperaturu na kojoj počinje geliranje smjese ljepila. Također je utvrđeno da smjese ljepila s nižim udjelima urea-formaldehidnog*

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ljepila nisu pridonijele većoj smicajnoj čvrstoći spoja u odnosu prema uzorcima slijepljenima čistim ukapljenim drvom te da nijedan od spojeva ispitivanih uzoraka nije pokazao svojstva koja odgovaraju standardnim zahtjevima za nestrukturne primjene u suhim uvjetima.

Ključne riječi: *ukapljeno drvo, urea-formaldehidno ljepilo, diferencijalno skeniranje kalorimetrijom, reometrija, smicajna čvrstoća*

1 INTRODUCTION
1. UVOD

Liquefied wood is a natural-based product obtained by a process that involves the liquefaction and transformation of solid wood material into the liquid state. Due to its liquid properties, ability to wet the wood surface and to solidify, liquefied wood is a convenient material to be used as an adhesive for wood bonding (Ugovšek and Šernek, 2013a; Ugovšek *et al*., 2013a). Various types of blends of synthetic adhesives and liquefied wood, as well as synthesized liquefied wood based polymers and even pure liquefied wood, have been studied and used for the purpose of wood bonding. So far, melamine-formaldehyde and melamine-urea-formaldehyde adhesives have been blended with liquefied wood for the production of particleboards and up to 50 % of resin could be replaced by liquefied wood to produce the product in accordance with the requirements of the European Standard for particle boards (Kunaver *et al.*, 2010; Čuk *et al.*, 2011). Antonović *et al.* (2010) used different mixtures of urea-formaldehyde adhesive and liquefied wood with the same intention. Hassan *et al.* (2009) made a phenol-formaldehyde-type adhesive based on liquefied wood, and used it for the production of particleboards. Particleboards bonded with synthesized resins showed comparable results to particleboards bonded with urea-formaldehyde adhesive and the free formaldehyde emission was significantly lower. The synthesis of epoxy resins based on liquefied wood and the properties of such resins have been extensively studied (Kobayashi *et al.*, 2000; Kishi *et al.*, 2006; Wu and Lee, 2010; Kishi *et al.*, 2011) and all epoxy-liquefied wood resins showed comparable properties to epoxy resins. However, the portion of wood in such resins was relatively low. Therefore, Asano *et al.* (2007) synthesized epoxy resin based on ozone-treated liquefied wood with a high wood content and obtained the properties comparable to the properties of already mentioned epoxy-liquefied wood resins. Alkali-catalyzed liquefied wood has been used for the preparation of adhesives for plywood (Maldas *et al.*, 1997; Alma *et al.*, 2001). The dry bond strength of plywood met the standard requirements, whereas the strength of plywood after the boiling was problematic. Wood has also been bonded with liquefied wood as an independent component. In such cases it was found that the shear strength of the bonded assemblies failed to meet the standard requirements for non-structural applications, and high wood failure was present (Ugovšek *et al.*, 2011; Ugovšek and Šernek, 2013b). Such a phenomenon was ascribed to the degradation of the basic wood polymers in the wood cells where the liquefied wood had been applied. Consequently, a specific type of bond line containing a partly carbonized structure was present (Ugovšek *et al.*, 2013b).

Understanding of hardening behavior and of the curing process of adhesives and adhesive mixtures is of great importance for their further applications, e.g. for wood bonding. Dynamic mechanical analysis is a very useful method that can be used to monitor the physical properties of polymers. With this method different modules and other physical properties of material are measured as a function of temperature. Rheometry is a similar technique, in which various rheological parameters (viscosity, storage and loss modulus) can be determined by means of a rheometer (Malkin and Kulichikhin, 1991). Based on these parameters, which depend on the curing temperature and time, the whole curing process (and, in particular, gelation and vitrification) can be determined (Winter, 2003; Mravljak and Šernek, 2011).

Differential scanning calorimetry is another useful technique for studying the physical transformations and chemical reactions of various materials during curing. This is one of the most widely used thermal analysis techniques for the study of polymeric materials (Menczel and Prime, 2009). Differential scanning calorimetry was used to study liquefied wood/phenol/formaldehyde resins (Pan *et al*., 2008) and polyurethane resins based on liquefied wood (Wei et al., 2004). The thermal behavior of liquefied wood polymer composites (Doh *et al*., 2005), the kinetics of a blend of liquefied wood and melamine-urea-formaldehyde (Poljanšek *et al*., 2013), and the curing process of pure liquefied wood (Ugovšek and Sernek, 2013a) was also studied using differential scanning calorimetry.

The aim of the research described in this paper was to elucidate the curing process and hardening behavior of different adhesive mixtures made of liquefied wood and urea-formaldehyde adhesive by means of differential scanning calorimetry, rheometry, and the bond shear strength test.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Preparation of liquefied wood
2.1. Priprema ukapljenog drva

Wood was liquefied according to liquefaction procedure described by Ugovšek *et al*. (2011). Sawdust of the black poplar (*Populus nigra* L.) was used for the production of liquefied wood (LW). Prior to the liquefaction process, the sawdust was dried in a laboratory oven (103 °C, 24 h). Black poplar wood and ethylene

glycol (EG) as the solvent, in a mass ratio of 1:3, were used for liquefaction. 3 % of sulphuric acid, based on the EG mass, was added as a catalyst. All liquefied wood was obtained by a single process. Liquefaction was carried out for a period of 120 minutes in a 1000 mL three-neck glass reactor, which was immersed in an oil bath that had been preheated to 180 °C and was equipped with a mechanical stirrer. After liquefaction, the reactor was immersed in cold water in order to quench the reaction. The liquefied product was then diluted with a mixture of 1,4-dioxane and water (4/1, v/v), and filtered through filter disks (Sartorius filter disks 388 grade/84/mm^2) in order to remove the insoluble parts of the LW and to determine the liquefaction yield, which was 94 %. In order to obtain the LW without the mixture of 1,4-dioxane and water, a rotary evaporator (Büchi, Rotavapor R-210) was used for evaporation at 55 °C. Evaporation was performed at reduced pressure, from 100 kPa to 1 kPa, which was achieved by means of a vacuum pump (Vacuubrand, PC 3003 Vario). After evaporation of the 1,4-dioxane, the EG in the LW was also evaporated (at 120 °C, 1 kPa) so that a final wood/EG mass ratio of approximately 1:1 was achieved.

2.2 Preparation of adhesive mixtures
2.2. Priprema smjesa ljepila

Several adhesive mixtures were prepared as shown in Table 1. Mixing procedure was done using glass stick for 60 s and the percentage of components is based on the mass of components. Commercial urea-formaldehyde (UF) adhesive Lendur-200 was obtained from Nafta-petrochem, d.o.o. (Slovenia). No catalyst, extender or filler was used in the prepared adhesive mixtures.

Table 1 Adhesive mixtures prepared with a combination of LW and commercial UF adhesive
Tablica 1. Smjese ljepila pripremljene kombinacijom LW-a i komercijalnih UF ljepila

Adhesive mixtures *Smjese ljepila*
100 % LW
90 % LW, 10 % UF
80 % LW, 20 % UF
70 % LW, 30 % UF
60 % LW, 40 % UF

LW - liquefied wood / *ukapljeno drvo*
UF – urea-formaldehyde adhesive / *urea-formaldehidno ljepilo*

2.3 Differential scanning calorimetry (DSC)
2.3. Diferencijalno skeniranje kalorimetrijom (DSC)

DSC measurements were performed in order to investigate the physical transformations and chemical reactions, which occurred during the curing of the adhesive mixtures. A high-pressure differential scanning calorimeter - HP DSC 1 (Mettler Toledo) with 30 µl platinum crucibles was used for the curing of the adhesive mixtures within the temperature range from 30 to 350 °C, with a heating rate of 10 °C/min. An empty crucible served as a reference. A dynamic nitrogen atmosphere with a flow rate of 50 ml/min at normal pressure (1 bar) was used. The masses of the adhesive mixture samples for the HP DSC measurements were between 6.64 and 7.53 mg.

2.4 Rheological oscillatory test (RheOT)
2.4. Reološki oscilatorni test (RheOT)

Rheological measurements of the adhesive mixtures during curing were performed using a stress control rheometer ARES G2 (TA Instruments). Disposable aluminum plates with a diameter of 25 mm were used for the oscillation tests. A gap of 0.5 mm between the plates was used. All the RheOTs were performed at a frequency of 10 rad/s, at a strain of 1.0 %, and at a heating rate of 10 °C/min within a temperature range of up to 225 °C. The intention was to achieve the same temperatures as those used in the DSC measurements (up to 350 °C), but due to the high axial force that arose during the measurements, the transducer automatically turned off after its overload at temperatures higher than 225 °C.

2.5 Bonding and testing of specimens
2.5. Spajanje i ispitivanje slijepljenih uzoraka

Solid beech wood lamellas (*Fagus sylvatica* L.) with dimensions of 15 x 15 x 0.5 cm were used as a substrate for the preparation of two-layered test specimens, which were bonded according to EN 12765 by using a small laboratory conventional hot-press. Prior to bonding, all of the beech wood lamellas were planed in order to ensure smooth and flat surfaces. Two lamellas were then bonded together with different adhesive mixtures. Each of the adhesive mixtures was applied by means of a roller, using an application rate of 200 g/m^2. The press temperature was 180 °C, and the pressing time was 15 minutes. The specific pressure was 0.4 MPa. The bonded specimens (n=10) were tested after 7 days of conditioning in a standard climate (20±2 °C, relative humidity 65±5 %). All the shear tests were carried out on a ZWICK/Z005 universal testing machine according to the standard EN 205.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 DSC of adhesive mixtures during curing
3.1. DSC tijekom stvrdnjavanja različitih smjesa ljepila

The physical transformations and chemical reactions, which occurred during the curing of different adhesive mixtures using LW and UF adhesive, were investigated by means of calorimetrical response (Figure 1). The curing of pure LW (solid line) is divided into two phases. Evaporation of water can be observed as an initial broad and shallow endothermic signal, which is followed by another more prominent endothermic signal representing evaporation of the EG. At around 180 °C, the chemical curing of LW began, indicated by a broad exothermic signal with its maximum

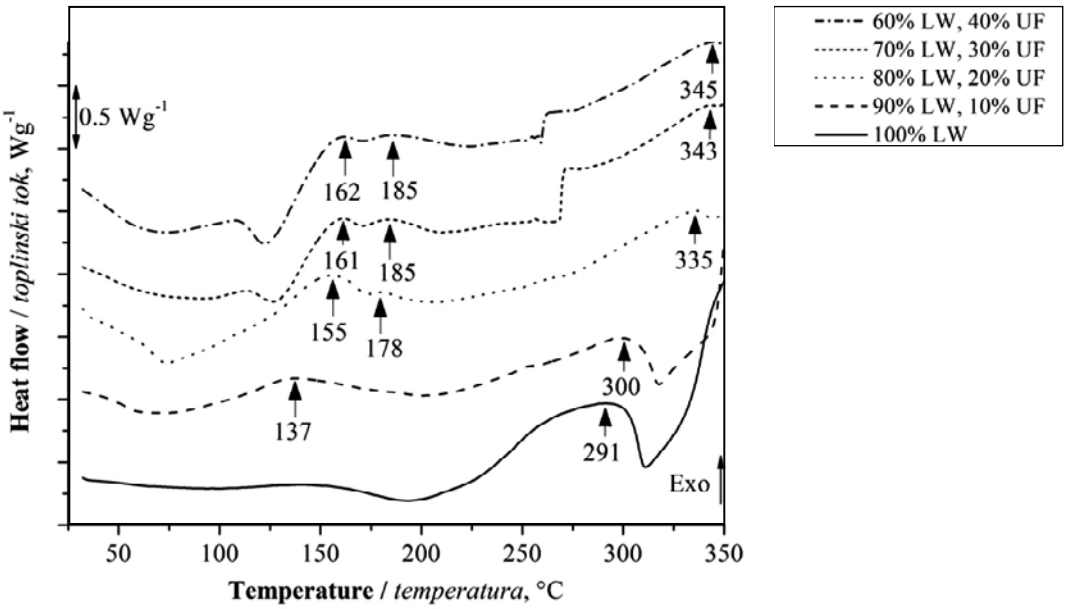

Figure 1 DSC thermograms – the curing process of different adhesive mixtures within a temperature range from 30 to 350 °C and at a heating rate of 10 °C/min

Slika 1. DSC termogrami – proces stvrdnjavanja različitih smjesa ljepila u intervalu temperature od 30 do 350 °C i pri brzini zagrijavanja od 10 °C/min

point at 291 °C (Ugovšek and Šernek, 2013a). The 10 % addition of UF adhesive to the LW was reflected in a shift of the exothermic signal related to the LW to a slightly higher temperature (300 °C), but a new exothermic signal was observed at 137 °C. This signal is related to the curing reaction of the UF adhesive, which was induced by the LW and its low pH value (Ugovšek and Šernek, 2013b). Additionally this might mean that the UF resin and LW were not completely miscible. It was observed that the increasing of UF portion in the adhesive mixture was reflected in a shift of the LW exothermic signal to even higher temperatures (335 °C, 343 °C and 345 °C), and also in a shift of the UF exothermic signal up to 162 °C. The reason for such high temperatures related to UF curing is that no catalyst, which is normally added when bonding wood with UF adhesive, was present in the prepared adhesive mixtures. Besides this, a new exothermic signal was observed at 178 °C (80% LW, 20% UF) and at 185 °C (70% LW, 30% UF and 60% LW, 40% UF), which indicated the presence of multiple chemical reactions during the curing of the LW-UF adhesive mixture.

3.2 Rheological response of LW during curing
3.2. Reološki odgovor ukapljenog drva tijekom stvrdnjavanja

RheOTs were used to obtain a curing profile of the adhesive mixtures by means of their rheological response to an oscillating load generated by the instrument. The curing of the investigated material can be monitored by means of two different parameters: the storage modulus (G') and the loss modulus (G''). G' represents the elastic behavior and is a measure of the deformation energy stored in the sample during the shear process, whereas G'' represents the viscous behavior of the sample and is a measure of the deformation energy used in the sample during the shearing process and afterwards lost to the sample (Mezger, 2002). The ratio between these two modules is called the loss tangent (tanδ), and it can be used to define the gel point. The latter occurs at the point where G' crosses G'' and where tanδ equals 1. At this point, tanδ should be independent of the applied frequency (Winter, 1987). Núnez *et al*. (2005) found that gel times calculated from the single-frequency experiment are in close relation with results obtained from multiple frequency experiments. Another useful parameter for describing hardening behavior of the adhesive mixtures is complex viscosity (η*). η* is the vectorial sum of the elastic and loss component of the dynamic viscosity, and a measure of the general resistance of a material to flow as a function of the stress rate (Garnier *et al*., 2002). According to Malkin and Kulichikhin (1991), viscosity starts to increase near the gel point. η* as a function of temperature was used for the interpretation of the hardening behavior of the adhesive mixtures (Figure 2), and the temperature of the gel points (gelation temperatures) based on the intersection of G' and G'' were also compared (Table 2).

Two visible changes occurred due to the addition of UF to LW (Figure 2). First, the value of η* at 50 °C was higher when there was an increased amount of UF adhesive in the adhesive mixture. Furthermore, in the case of UF additions of 30 % and 40 %, the gel time was so short that some gelling was already present by the time the sample had been placed and the measurement started. A second visible change among the adhesive mixtures was the temperature at which an increase of η* began. It is clear that the increased addition of UF adhesive to LW accelerated the curing reaction and simultaneously decreased the starting temperature of curing, which is not in relation to DSC results. The reason

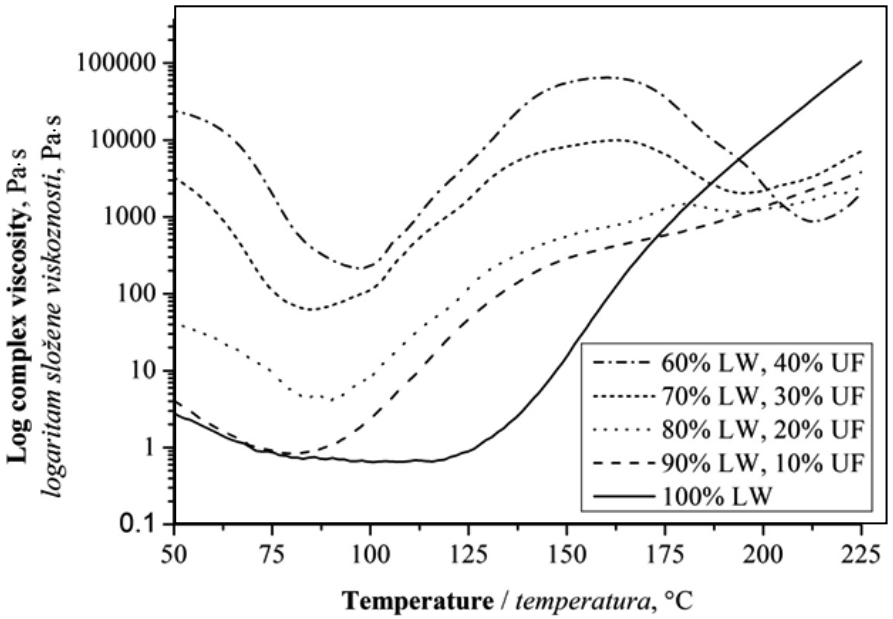

Figure 2 Hardening behavior (change of complex viscosity) of different adhesive mixtures
Slika 2. Ponašanje tijekom stvrdnjavanja (promjena složene viskoznosti) različitih smjesa ljepila

for this is the nature of the two techniques: chemical changes are measured with DSC, whereas the physical aspect is obtained with rheometry. In rheological test, a very important factor is the loss of moisture, which is correlated to the gelation of the specific resin. However, the most noticeable changes occurred between the adhesive mixtures without and with 10 % and 20 % of UF adhesive. The changes between the adhesive mixtures with 30 % and 40 % were not so significant. In the latter two cases a decrease was observed in the value of η* after the temperature of about 170 °C had been reached, which is correlated with the cracking of molecular bonds in the sample due to oscillatory loading.

The temperature of the gel point (gelation temperature) was calculated from the crossing point of *G´* and *G´´* i.e. the tanδ value of 1 (Table 2).

Table 2 Influence of the addition of different amounts of UF adhesive to LW on gelation temperature
Tablica 2. Utjecaj dodatka različitih količina UF ljepila u ukapljeno drvo na temperaturu geliranja

Adhesive mixture *Smjesa ljepila*	**Gelation temperature,** °C *Temperatura geliranja, °C*
100 % LW	141
90 % LW, 10 % UF	124
80 % LW, 20 % UF	113
70 % LW, 30 % UF	96
60 % LW, 40 % UF	91

LW – liquefied wood / *ukapljeno drvo*
UF – urea-formaldehyde adhesive / *urea-formaldehidno ljepilo*

It is clear that the addition of UF adhesive decreased the temperature of the gelation temperature. These results are in correlation with the η* results. Even a small amount of UF adhesive decreased the gelation temperature by more than 15 °C, whereas a 40 % addition of UF adhesive to the LW decreased gelation temperature by 50 °C.

3.3 Shear strength of specimens bonded with different adhesive mixtures
3.3. Smicajna čvrstoća uzoraka slijepljenih različitim smjesama ljepila

Beech wood lamellas were bonded with pure LW and the prepared adhesive mixtures with a combination of LW and UF adhesive. The results of the shear strength tests revealed that a 10 % and 20 % addition of UF adhesive to the LW did not improve the shear strength of the bonded specimens (Table 3). Adhesive

Table 3 Influence of different additions of UF adhesive to LW on shear strength and wood failure of bonded specimens (standard deviation is shown in parenthesis; adhesive mixtures marked with asterisk could not be used for bonding due to rapid gelation and inability to be applied to the wood surface)
Tablica 3. Utjecaj dodatka različitih količina UF ljepila u ukapljeno drvo na smicajnu čvrstoću i lom po drvu slijepljenih uzoraka (standardna devijacija dana je u zagradi; smjese ljepila označene zvjezdicom ne mogu se primjenjivati za lijepljenje zbog brzog stvrdnjavanja i nemogućnosti primjene na drvnim površinama)

Adhesive mixture *Smjesa ljepila*	**Shear strength** *Smicajna čvrstoća* N/mm²	**Wood failure** *Lom po drvu* %
100 % LW	7.4 (1.1)	100 (0)
90 % LW, 10 % UF	7.1 (1.0)	88 (27)
80 % LW, 20 % UF	7.1 (1.8)	38 (32)
70 % LW, 30 % UF*	0 (0)	0 (0)
60 % LW, 40 % UF*	0 (0)	0 (0)

mixtures with a 30 % and 40 % addition of UF adhesive to the LW were not suitable for bonding due to the rapid gelation, as well as their high viscosity and inability to be applied by a roller.

The specimens bonded with pure LW achieved a shear strength of 7.4 N/mm^2, whereas the specimens bonded with adhesive mixtures containing 10 % and 20 % of UF adhesive achieved a shear strength of 7.1 N/mm^2. However, the shear strength values did not show any significant differences between these adhesive mixtures, although attention needs to be paid to wood failure. Wood failure was very high in the case of pure LW. This has already been reported by Ugovšek *et al*. (2011), and is correlated to the low pH value of the LW and damage to the bonded surface (Ugovšek and Šernek, 2013b; Ugovšek *et al.*, 2013b). With the addition of UF adhesive, wood failure decreased due to the lower acidity of the adhesive mixture, and was also aggravated by the spreading and penetration of the adhesive mixtures due to increased viscosity correlated to gelling. Nevertheless, bond shear strength remained too low to meet the standard requirements (10 N/mm^2).

4 CONCLUSIONS
4. ZAKLJUČAK

Commercial urea-formaldehyde adhesive was added to low solvent liquefied wood, and the curing process and hardening behavior of adhesive mixtures with different proportions between these two components was evaluated using differential scanning calorimetry and rheological oscillatory tests. Shear strength tests of specimens bonded with different adhesive mixtures were also performed.

Differential scanning calorimetry showed a single exothermic signal that was correlated to the chemical reaction that occurred during the curing of pure liquefied wood, after evaporation of water and ethylene glycol at around 290 °C. A 10 % addition of urea-formaldehyde adhesive resulted in an additional exothermic signal at lower temperatures, whereas the addition of higher amounts of adhesive led to even more exothermic signals, indicating multiple chemical reactions. The results of rheological oscillatory tests showed that the addition of urea-formaldehyde adhesive accelerated the curing of the adhesive mixtures, since the temperature at which the gel point occurred was lower in the case of a higher proportion of synthetic adhesive. The specimens bonded with adhesive mixtures with a 10 % and 20 % addition of urea-formaldehyde adhesive to the liquefied wood achieved similar bond strengths to those of specimens bonded with pure liquefied wood, but all of them failed to meet the standard requirements for non-structural applications under dry conditions.

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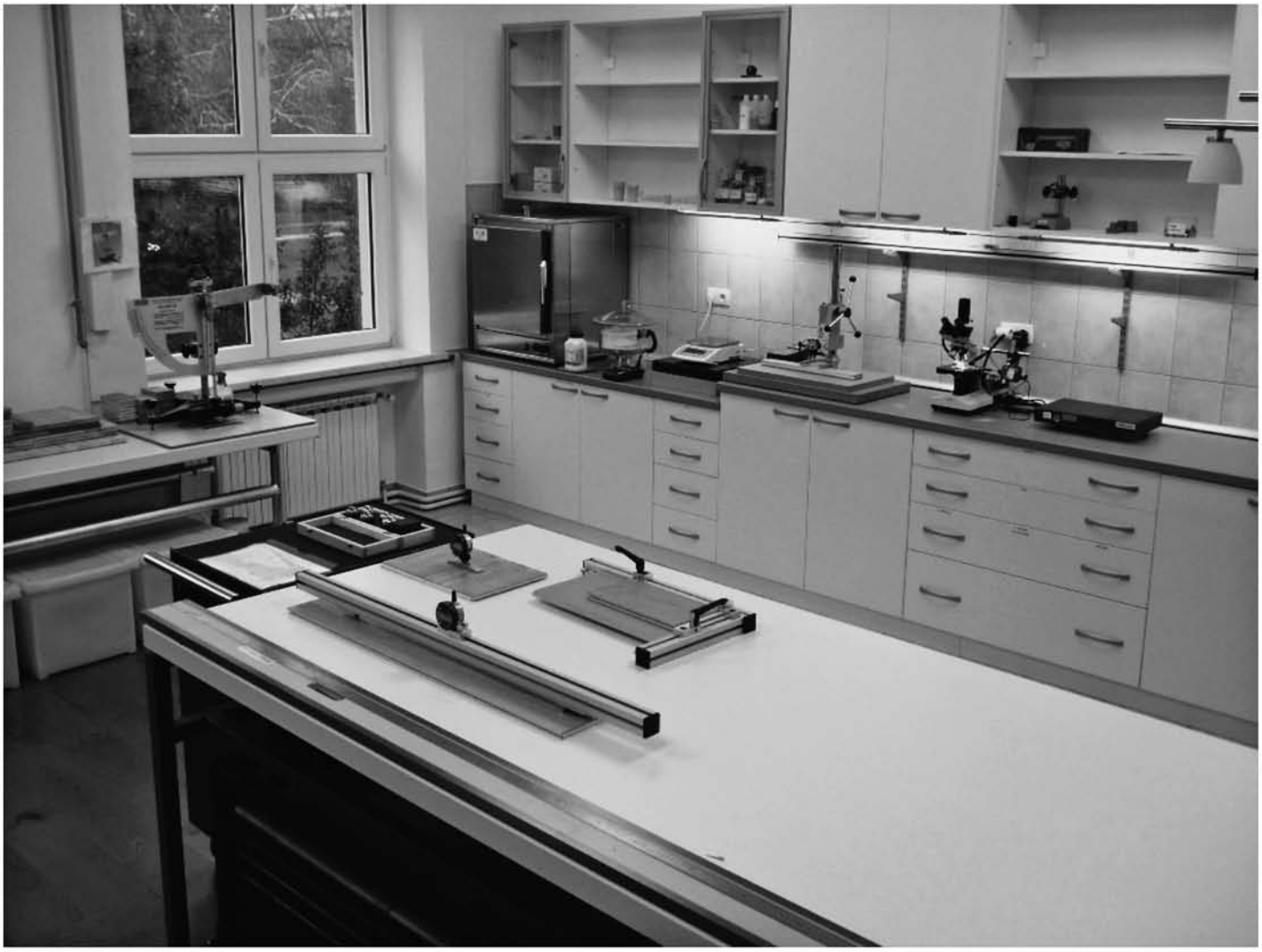

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CROLAB

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Effects of Aging of Polyurethane Foams in the Context of Furniture Design

Učinci starenja poliuretanske pjene u kontekstu dizajna namještaja

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ABSTRACT • *An ergonomic seat or bed must be capable of supporting optimally and evenly the user's body for sustained periods of time. The objective of the performed investigations was to ascertain the impact of natural aging on the stiffness of polyurethane foams in dwelling apartment conditions and, additionally, to determine regression equations describing this dependence. Seven types of furniture foams, differing with respect to their apparent density and stiffness, were selected for the experiment. Experimental foams were exposed to aging for the period of 730 days (two years) in climatic conditions typical for dwelling facilities. Foam stiffness was determined in a uniaxial compression test determining strain characteristics in the function of deformations. The performed experiments made it possible to establish percentage changes of stiffness of some foams as well as the time required for those changes to assume a significant character.*

Key words: *aging, polyurethane foam, stiffness*

SAŽETAK • *Ergonomsko sjedalo ili ležaj mora biti sposobno optimalno i ravnomjerno podržavati korisnikovo tijelo dovoljno dugo vrijeme. Cilj provedenih istraživanja bio je utvrditi utjecaj prirodnog starenja na čvrstoću poliuretanske pjene u stambenim uvjetima, a osim toga, i utvrditi regresijske jednadžbe koje opisuju tu ovisnost. Za eksperiment je odabrano sedam vrsta pjene za namještaj različite gustoće i krutosti. Odabrane su pjene izložene starenju u razdoblju od 730 dana (dvije godine), u klimatskim uvjetima tipičnim za zatvorene stambene objekte. Krutost pjena utvrđena je jednoosnim kompresijskim testom određivanja ovisnosti naprezanja o deformaciji. Provedenim je eksperimentom moguće utvrditi postotak promjene krutosti neke pjene, kao i vrijeme potrebno da te promjene postanu značajne.*

Ključne riječi: *starenje, poliuretanske pjene, krutost*

1 INTRODUCTION
1. UVOD

Polyurethane foams are plastics consisting of polyetheretherketone skeleton surrounded by gaseous bubbles, most frequently of carbon dioxide. At the present time, they constitute a key constructional material applied in upholstered furniture, including wheelchairs, various vehicles or aircraft improving comfort of their use. An ergonomic seat or bed must optimally and evenly support the user's body for sustained periods of time and, hence, it is important to recognize the influence of aging of polyurethane foams used in seats and/or beds on their physical-mechanical properties. However, the available literature on the subject is dominated by articles dealing, primarily, with issues con-

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nected with the selection, modeling or stiffness analysis of foams for upholstered furniture (Alderson and Alderson, 2007; Bezazi and Scarpa, 2007, 2009; Brandel and Lakes, 2001; Choi and Lakes, 1992; Chow and Odell, 1994; Chu, 2000; Ebe and Griffin, 2001; Ferrarin et al., 2000; Gonga and Kyriakidesa, 2005; Grujicic *et al*., 2009; Lakes, 1987, 1992; Linder-Ganz *et al*., 2005; Lusiak and Smardzewski, 2010; Petre *et al*., 2006; Scarpa *et al*., 2004; Schrodt *et al*., 2005; Silber *et al*., 2010; Smardzewski, 2009; Smardzewski *et al*., 2006, 2008, 2010a,b; Smardzewski and Grbac, 1998; Smardzewski and Matwiej, 2007; Smardzewski and Wiaderek, 2007; Verver *et al*., 2004; Vlaović *et al*., 2008; Wang and Lakes, 2004; Webber *et al*., 2008; Wiaderek and Smardzewski, 2008, 2010a,b). Moreover, studies have also been conducted on the impact of aging on changes in: thermal conductivity coefficient (Brandreth and Ingersoll, 1980, Herge 1985; Wilkes *et al*., 2000, 2002; Mukhopadhyaya *et al*., 2004), diffusion coefficient (Ostrogorsky *et al*., 1986) or foam cell structure (Dementyev *et al*., 1999). What is missing is a more comprehensive discussion on the effect of aging on stiffness of furniture foams. Only few articles (Garber *et al*., 1982; Noble *et al*., 1984) deal with changes in foam hardness as a result of aging.

The aim of this study was to determine the impact of natural aging on the stiffness of polyurethane foams in dwelling conditions and, additionally, to elaborate the regression equation describing this dependence.

2 METHODS AND MATERIALS
2. METODE I MATERIJALI

Seven types of polyurethane foams commonly used in furniture design were selected for the presented investigations. The experimental foams differed from one another in their density and stiffness. Major technical properties of these foams provided by the Polish manufacturer are given in Table 1. In the designation of foam types, the first two digits give information about the mean apparent density of a foam expressed in kg/m^3 and the second two digits give information about foam mean stiffness expressed in 10^{-1} kPa at the deformation of ε=0.4. Ten cubical samples were prepared for each type of experimental foams with the side of H=100 mm obtained from different places of a commercial block measuring 1.2 x 1.2 x 2 m, as shown in Figure 1

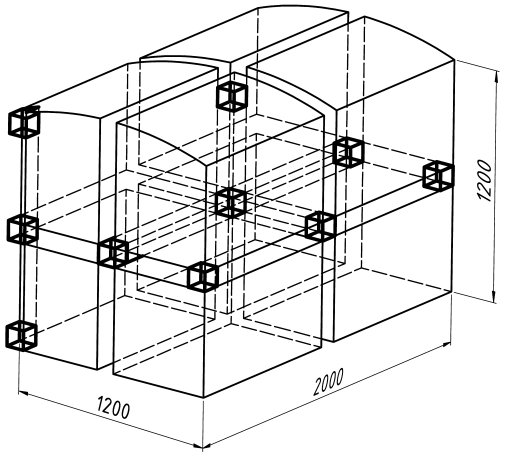

Figure 1 Commercial block of foam and places of sample collection (cm)
Slika 1. Komercijalni blok pjene s označenim mjestima uzimanja uzoraka (cm)

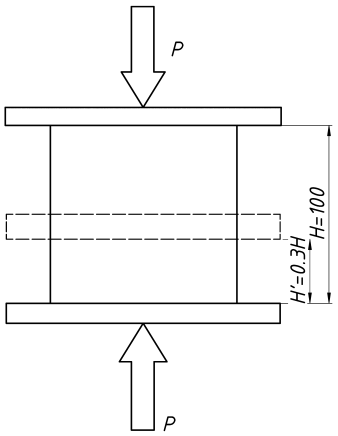

Figure 2 Diagram of uniaxial sample compression
Slika 2. Dijagram jednoosnoga kompresijskog testa

Table 1 Technical properties of selected foams (according to manufacturer's data)
Tablica 1. Tehnička obilježja odabranih pjena (prema podacima proizvođača)

Foam type *Vrsta pjene*	**Apparent density** *Prividna gustoća* PN-EN ISO 845:2000 kg/m^3	**Stiffness at ε=0.4** *Krutost pri ε=0,4* PN-EN ISO 3386-1:2000 kPa	**Resilience (min.)** *Elastičnost (min.)* PN-EN ISO 8307:2008 %	**Water content (max)** *Sadržaj vode (maks.)* %
T1823	15.5 - 18.5	1.8 - 2.5	40	1
T1830	15.5 - 18.5	2.8 - 3.5	40	1
T2315	20.5 - 23.5	1.3 - 2.0	40	1
T2538	22.5 - 25.5	3.3 - 4.3	40	1
T3037	27.5 - 30.5	3.3 - 4.3	45	1
T3538	32.5 - 35.5	3.3 - 4.3	45	1
T3546	32.5 - 35.5	4.0 - 5.0	50	1

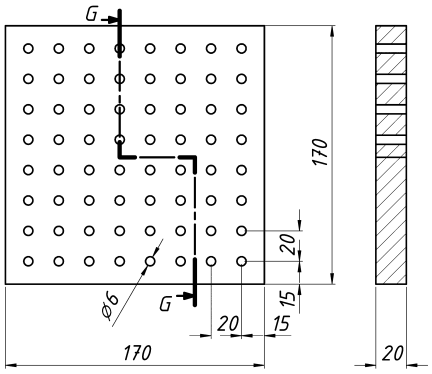

Figure 3 Pressing plates used in uniaxial compression test (mm)
Slika 3. Pritisne ploče koje se primjenjuju pri jednoosnom kompresijskom testu (mm)

As mentioned in the Introduction, in furniture design practice, stiffness is the most important criterion for selecting the foams. In accordance with the PN-EN ISO 3386-1:2000 standard, this stiffness is determined during the uniaxial compression test (Fig. 2) applying pressure beams in the form of drilled plates (Fig. 3). Individual experimental foams were compressed on a ZWICK 1445 testing machine recording force P with 0.01 N accuracy and dH displacements with 0.02 mm accuracy. The loading was terminated once the compressed sampled achieved the height of $H' = 0.3$ H. The course of compression was illustrated in the form of the σ=f(ε) dependence assuming that: $\sigma=P/H^2$, $\varepsilon=dH/H$ and $dH=H-H'$. The stiffness of individual foams was determined on the basis of the σ=f(ε) dependence as the value of strain in kPa at the deformation of ε=0.4. Following the first stiffness evaluation of samples conducted on the 20th of August 2009, they were exposed to climatic conditions natural for dwelling facilities. Stiffness tests of experimental foams were carried out at quarterly and annual intervals, namely: after 123 days (2009. 12. 20), 244 days (2010. 04. 20), 366 days (2010. 08. 20) and 730 days (2011.08.20). Throughout this period, the values of relative humidity and air temperatures were recorded. The above parameters were recorded with the assistance of a Datalogger AZ 8829 Bacto Laboratories Pty Ltd taking measurements with up to 0.1 °C and 0.1 % accuracy. The results of measurements were collected and presented on a single diagram indicating days on which investigations of the selected foams were carried out. The significance of the impact of aging on foam stiffness was evaluated by the *t*-test for dependent samples using the Statistica 9.1 StatSoft. Inc. statistical package.

3 RESULTS AND DISCUSSION
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Figure 4 presents the changes in relative humidity and air temperature during the period of 730 days. On the day of the first measurement (Aug. 20, 2009), the recorded air temperature reached 27.9 °C, and relative air humidity – 37.1 %. During autumn (until Dec. 12, 2009), air temperature dropped from 27.9 °C to 17.0 °C, while air humidity ranged between 55.5 % and 15.9 %. During winter, i.e. until April 20, 2010, as a result of the operation of the central heating system, air temperature ranged between 17.0 °C and 23.0 °C, while air humidity increased from 9.3 % to 28 %. During summer, i.e. until Aug. 20, 2010, the temperature increased significantly and ranged between 22.7 and 33.8 °C and air humidity increased from 32.5 % to 57.8 %. In the following year, until Aug. 20, 2001, the measured values were slightly different, but their trends were similar to the trends in humidity and temperature changes from the previous year. Changes in the stiffness of the selected foams were observed against this background. On the first day of investigation, a σ=f(ε) dependence was determined for each experimental foam as shown in Figure 5.

As evident from Figure 5, the dependence of strain on deformation for all the tested types of foam is of non-linear nature. During the initial stage of com-

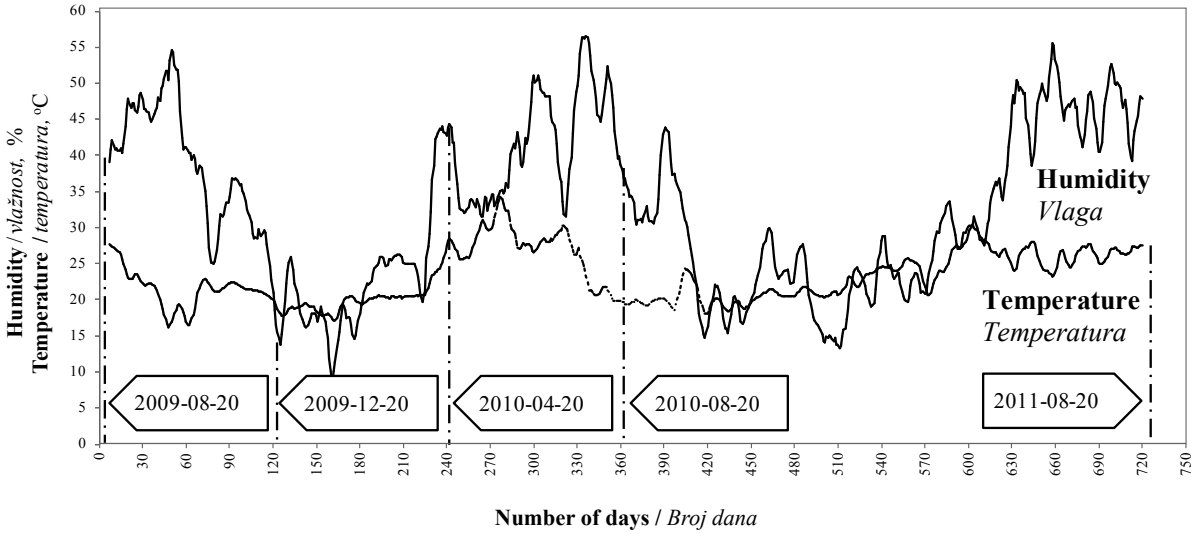

Figure 4 Changes in runs of temperature and relative air humidity in the laboratory facility
Slika 4. Promjene temperature i relativne važnosti zraka u laboratoriju

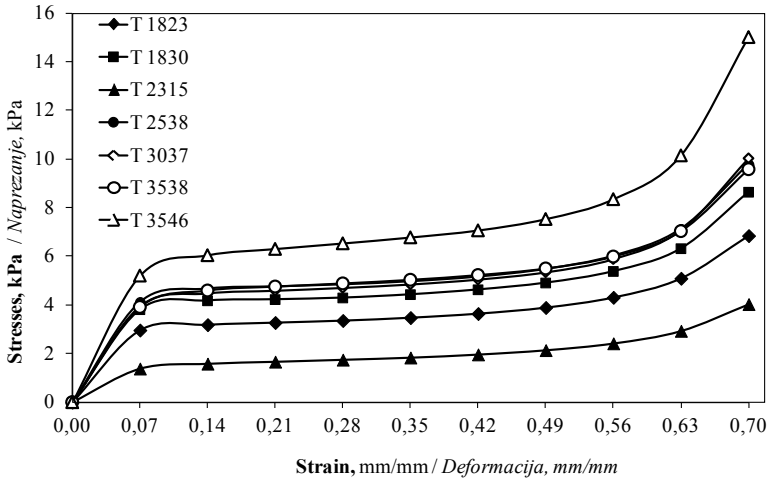

Figure 5 Dependence of strain on deformation for the tested types of foam
Slika 5. Ovisnost naprezanja o deformaciji za ispitivane vrste pjena

pression, for $0<\varepsilon\leq0.07$, foam stiffness increased distinctly because the polyurethane skeleton transferred all the external loads. Within the range of deformations from $0.07<\varepsilon\leq0.63$, cell walls lost their stability and allowed large displacements under the influence of even small loads. Another increase of foam stiffness occurred for $\varepsilon>0.63$, i.e. after the concentration of the matter and crushing of cell walls. Furthermore, this drawing clearly shows that foam stiffness did not always depend on its density. For further analyses, Figure 6 collates foam stiffnesses determined at deformations of $\varepsilon=0.4$ at five consecutive measuring periods. It can be clearly seen that in the observed periods, individual foams differed considerably among themselves with respect to their stiffness. It is worth stressing that foam stiffnesses established on the first day of testing exceeded considerably maximum values given by the manufacturers in the product card. These differences are collated in Table 2. It is evident that stiffness of the manufactured foams exceeded by 110 to 217 % catalogue values provided by manufacturers. Simultaneously, it can also be noted from Table 2 that small values of standard deviations (0.08 to 1.00 kPa) as well as of coefficients of variability (1.31-13.78 %) confirmed high uniformity of each group. Therefore, the applied number of samples, 10 for each type of foam, was adequate to obtain reliable research results. Figure 6 also illustrates that quality relationship between foam stiffnesses was maintained stable during the period of aging of 730 days. However, the process of foam natural aging caused stiffness depreciation meaning that stiffness of some of the tested foams was reduced to values comparable to the initial stiffness of other foams. This occurred in the case of T2538 and T3538 foams, which reached stiffness comparable or lower to the stiffness of the T1830 foam determined on the first day of testing after 366 and 730 days of aging.

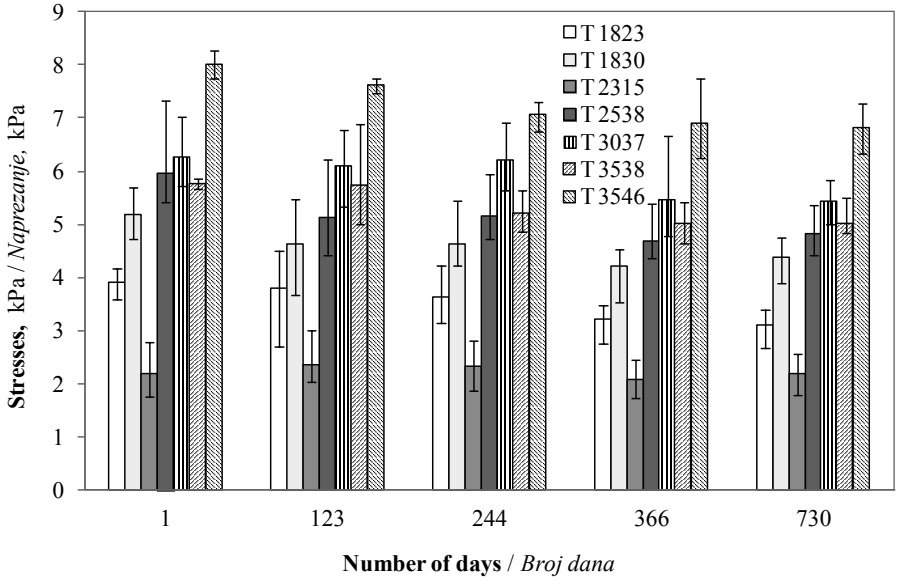

Figure 6 Stiffness of foams in individual periods of observation
Slika 6. Krutost pjena u pojedinim razdobljima promatranja

Table 2 Foam stiffness at ε=0.4 according to data provided by the manufacturer and obtained in the course of experimental studies
Tablica 2. Krutosti pjena pri ε=0,4 prema podacima proizvođača i podacima dobivenim u ovom istraživanju

Foam type *Vrsta pjene*	**Stiffness at ε=0.4, kPa** / *Krutost pri ε=0.4, kPa*				**Stiffness, kPa** *Krutost, kPa* F=C-A
	Manufacturer's data *Podaci proizvođača*	**Investigations results**/ *Rezultati istraživanja*			
		Mean *Srednja vrijednost*	Standard deviation, kPa *Standardna devijacija, kPa*	Coefficient of variability, % *Koeficijent varijabilnosti, %*	
A	B	C	D	E	
T1823	1.8 - 2.5	3.90	0.18	4.57	1.40 - 2.10
T1830	2.8 - 3.5	5.19	0.37	7.11	1.69 - 2.39
T2315	1.3 - 2.0	2.19	0.30	13.78	0.18 - 0.89
T2538	3.3 - 4.3	5.97	0.58	9.75	1.67 - 2.67
T3037	3.3 - 4.3	6.27	0.54	8.59	1.97 - 2.97
T3538	3.3 - 4.3	5.76	0.08	1.31	1.46 - 2.46
T3546	4.0 - 5.0	8.05	1.00	12.48	3.05 - 4.05

Table 3 Results of the *t*-test for dependent samples indicating lack of significance of differences between foam stiffnesses (an example for the T1823 foam)
Tablica 3. Rezultati *t*-testa za zavisne uzorke koji pokazuju nesignifikanost razlika među krutostima pjena (primjer za pjenu T1823)

Type of foam *Vrsta pjene*	**Number of days** *Broj dana*	***t*-test for dependent samples** / *t-test za zavisne uzorke* **Marked differences are not significant at *p* <0.05** / *Označene razlike nisu značajne pri p <0,05*							
		Average *Prosjek* kPa	Std. *St. dev.* kPa	Difference *Razlika* kPa	Std. Difference *St. dev. razlike* kPa	*t*	*p*	Confidence *Pouzdanost* -95 %	Confidence *Pouzdanost* +95 %
T1823	1	3.90	0.18						
	123	3.80	0.57	0.10	0.61	0.51	0.624	-0.363	0.569
T2315	1	2.20	0.30						
	123	2.35	0.34	-0.15	0.39	-1.19	0.268	-0.454	0.145
	1	2.20	0.30						
	244	2.33	0.35	-0.13	0.46	-0.87	0.407	-0.488	0.220
	1	2.20	0.30						
	366	2.08	0.24	0.12	0.35	1.01	0.341	-0.150	0.385
	1	2.20	0.30						
	730	2.19	0.26	0.01	0.24	0.12	0.904	-0.172	0.192
T3037	1	6.27	0.54						
	123	6.09	0.59	0.18	0.73	0.54	0.617	-0.733	1.088
	1	6.27	0.54						
	244	6.22	0.53	0.05	0.53	0.21	0.840	-0.611	0.713
T3538	1	5.76	0.08						
	123	5.75	0.94	0.01	0.99	0.02	0.986	-1.216	1.232
T3546	1	8.00	0.28						
	366	6.91	0.77	1.09	0.61	3.11	0.090	-0.420	2.607
	1	8.00	0.28						
	730	7.26	0.59	0.74	0.51	2.55	0.126	-0.512	2.000

Table 3 presents the results of the t Test (p<0.05) for dependent samples indicating high probability of the lack of significance of differences between stiffnesses of some foams subjected to aging. It is evident that only the T2315 foam turned out to be completely insensitive to a change in its stiffness as shown by the result of aging. The stiffness of T 1823 and T3538 foams did not change during the first 123 days (4 months) of aging, the T3037 foam exhibited resistance to aging during the first 244 days (8 months) of this process, whereas the T3546 foam returned to its original stiffness after 366 and, then, after 730 days of aging. For the remaining foams, there is high probability of a significant impact of aging on their stiffness. This impact is shown in Figure 7-9.

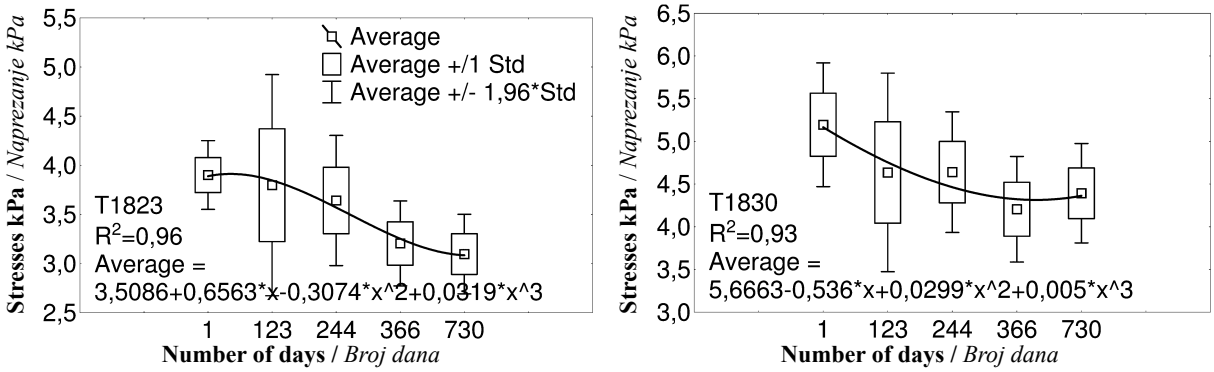

Figure 7 Impact of aging on stiffness of foams of 18 kg/m³ density
Slika 7. Utjecaj starenja na krutosti pjena gustoće 18 kg/m³

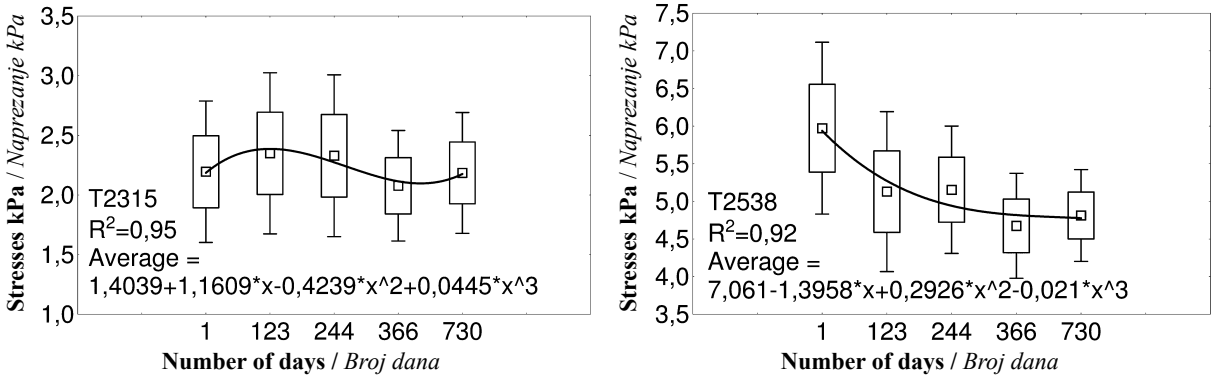

Figure 8 Impact of aging on stiffness of foams of 23 and 25 kg/m³ density
Slika 8. Utjecaj starenja na krutosti pjena gustoće 23 i 25 kg/m³

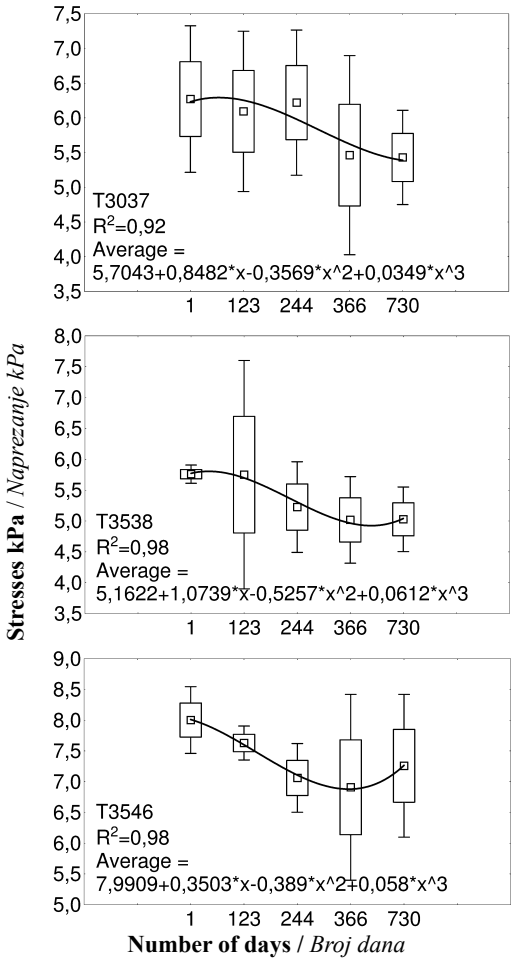

Figure 9 Impact of aging on stiffness of foams of 30 and 35 kg/m³ density
Slika 9. Utjecaj starenja na krutosti pjena gustoće 30 i 35 kg/m³

Figure 7 presents the influence of aging on the stiffness of foams of 18 kg/m³ density. As shown in Table 3, the T1823 foam was not sensitive to aging only during the first 123 days. After 730 days, the stiffness of this foam decreased with respect to the initial value by 26 %. The T1823 foam distinctly reduced its stiffness during the entire period of aging. The greatest decline of stiffness (23 %) occurred after 366 days of aging. After another year passed (730 days in total), foam stiffness increased slightly (by 4.5 %) and this difference was statistically significant.

The influence of aging on changes in the foam stiffness of 23 and 25 kg/m³ apparent density is shown in Figure 8. This Figure corroborates information from Table 3 that the T2315 foam did not undergo statistically significant changes in its stiffness as a result of aging. On the other hand, the T2538 foam of only slightly higher density lost stiffness as a result of aging. After 366 days, the loss of stiffness in relation to the initial value amounted to 27 %. After the following 364 days of aging, the stiffness of this foam increased by 2.9 %, and however at $p<0.05$, this difference was not statistically significant.

In the case of the foam characterized by 30 kg/m³ apparent density, statistically significant differences in their stiffness only took place after 366 days of aging and more (Fig. 9). This drop amounted to 14 % in relation to the initial stiffness. Continued aging lasting up to 730 days did not cause further changes in the foam stiffness, which remained at the same level of 5.4 kPa. A similar tendency was observed in the case of the

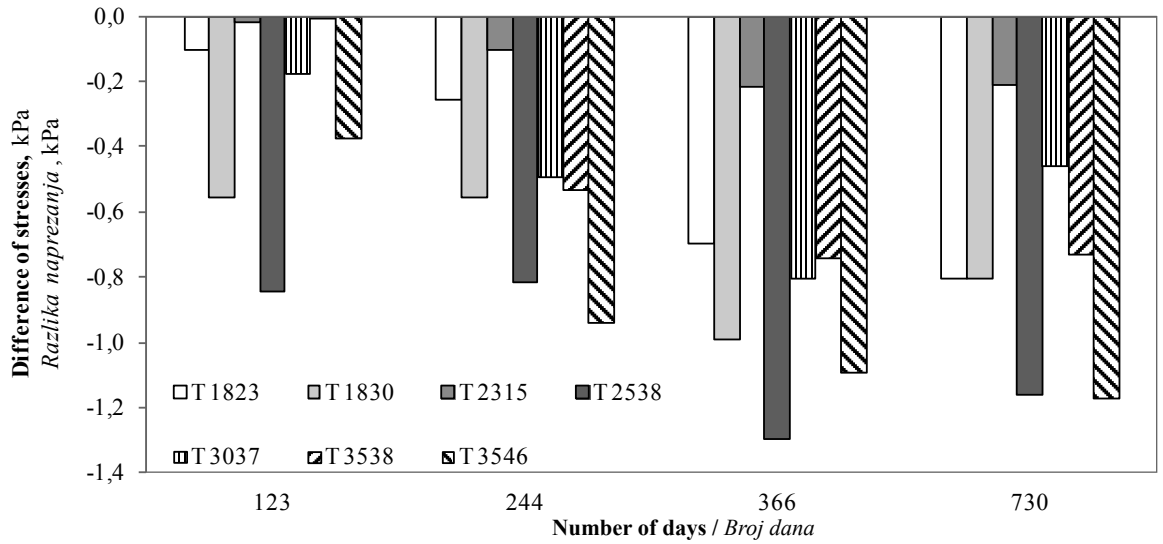

Figure 10 Differences in foam stiffness in individual periods of observation
Slika 10. Razlike u krutosti pjena za pojedina razdoblja promatranja

T3538 foam. Its stiffness decreased by 14% after 366 days of aging and remained at a constant level of 5 kPa for the consecutive 364 days. The T3546 foam turned out to be the most sensitive to aging and, after each period of aging, as well as quantitative and qualitative changes in its stiffness, changes were statistically significant at $p<0.05$. The greatest drop of stiffness of this foam amounting to 16 % occurred after 366 days of aging. After the second successive year of aging, the stiffness of this foam increased slightly so that the difference between the initial stiffness and the stiffness after 730 days of aging amounted to 10 %.

Quantitative differences in foam stiffnesses in relation to their initial stiffness are presented in Figure 10. It is evident that the greatest differences took place after 366 and 730 days of aging. In the case of foams characterized by apparent density of 18 kg/m^3, similar differences in stiffness occurred after 730 days of aging. On the other hand, in the case of foams of 35 kg/m^3 apparent density, changing differences of stiffness occurred during the entire period of aging indicating high sensitivity of this material to aging.

Contemporary offices involved in designing of daily necessities commonly apply computer engineering techniques (for example CAD or CAE), which constitute an element of rapid prototyping techniques. For simulation purposes of the impact of aging of foam materials on the functional properties of upholstered furniture, it is necessary to gain knowledge about stiffness of these materials as well as its variability under the influence of aging in dwelling conditions. The regression equations presented in Figure 7, 8 and 9, providing the correlation between foam stiffness and the number of days of the aging period, will make it possible to estimate future stiffness of foams used in dwelling facilities if climatic conditions are similar to those occurring in the described investigations.

4 CONCLUSIONS
4. ZAKLJUČAK

On the basis of the analysis of the obtained research results, the following conclusions can be drawn:

1. Aging of foams exerts a significant impact on decreasing their stiffness and, consequently, on their functional value.
2. The most significant drops of foam stiffness were observed after one year of aging. Depending on the type of foams, these drops reached values ranging from 14 % to 27 %.
3. In the second year of aging of foams, their stiffness usually remained at the same level or increased slightly in relation to the stiffness observed after one year of aging.
4. The T2315 foam turned out to be completely insensitive to aging. In such circumstances, its small density and low stiffness are favorable for use in upholstered furniture.
5. Bearing in mind the highest (27 %) decline of stiffness of the T2538 foam, it should be applied with care for sitting and lying furniture.

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LABORATORIJ ZA ISPITIVANJE NAMJEŠTAJA I DIJELOVA ZA NAMJEŠTAJ

Kvaliteta namještaja se ispituje i istražuje, postavljaju se osnove normi za kvalitetu, razvijaju se metode ispitivanja, a znanost i praksa, ruku pod ruku, kroče naprijed osiguravajući dobar i trajan namještaj s prepoznatljivim oznakama kvalitete. Kvalitete koja je temelj korisniku za izbor namještaja kakav želi. Taj pristup donio je Laboratoriju za ispitivanje namještaja pri Šumarskom fakultetu međunarodno priznavanje i nacionalno ovlaštenje te članstvo u domaćim i međunarodnim asocijacijama, kao i usku suradnju s njemačkim institutom LGA. Laboratorij je član udruge hrvatskih laboratorija CROLAB čiji je cilj udruživanje hrvatskih ispitnih, mjeriteljskih i analitičkih laboratorija u interesu unaprjeđenja sustava kvalitete laboratorija te lakšeg pridruživanja europskom tržištu korištenjem zajedničkih potencijala, dok je Šumarski fakultet punopravni član udruženja INNOVAWOOD kojemu je cilj doprinijeti poslovnim uspjesima u šumarstvu, drvnoj industriji i industriji namještaja s naglaskom na povećanje konkurentnosti europske industrije.

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Shape Stability of Particleboards Covered with Decorative Veneers

Stabilnost oblika ploča iverica površine obrađene dekorativnim furnirima

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ABSTRACT • *This paper summarizes the results of research aimed at determining the shape stability, modulus of rupture (MOR) and modulus of elasticity (MOE) of components made of particle boards, covered on their front side with decorative veneer of American walnut (Juglans nigra), 0.6 mm thick, and on the underside with decorative veneers of other species (Picea abies and Fagus sylvatica), 0.6–1.5 mm thick, or by a countermove foil of 85–90 g/m^2 surface weight. Subsequently, measurements were carried out of the shape stability (warping) of test specimens cut from various combinations of surface-finished boards. These test specimens were air conditioned in three different environments. At the same time, values were determined of bending strength and modulus of rupture with respect to the direction of fibres of sheathing materials. It has been found that the lowest warping values were achieved with combinations consisting of American walnut of a thickness of 0.6 mm on the tight side and alder (Alnus glutinosa), 0.6 mm thick, on the underside.*

Keywords: *veneer, veneering, panels, warping, shape stability*

SAŽETAK • *U radu se prikazuju rezultati istraživanja s ciljem utvrđivanja stabilnosti oblika, modula loma (MOR) i modula elastičnosti (MOE) komponenti proizvedenih od iverice, koje su na vanjskoj strani furnirane dekorativnim furnirom američkog oraha (Juglans nigra) debljine 0,6 mm, a na unutarnjoj strani dekorativnim furnirom drugih vrsta (Picea abies i Fagus sylvatica) debljine 0,6 - 1,5 mm ili folijom površinske mase 85 - 90 g/m^2. Nakon toga provedena su mjerenja stabilnosti oblika (izvitoperenosti) uzoraka pripremljenih od ploča različitih kombinacija površinske obrade. Ispitni uzorci klimatizirani su u tri različita okruženja. U isto vrijeme utvrđene su i vrijednosti čvrstoće na savijanje te modula loma s obzirom na smjer vlakanaca materijala kojim su iverice obložene. Utvrđeno je da su najniže vrijednosti izvitoperenosti izmjerene u ploča obrađenih furnirom američkog oraha debljine 0,6 mm na vanjskoj strani i furnirom johe (Alnus glutinosa) debljine 0,6 mm na unutarnjoj strani.*

Ključne riječi: *furnir, furniranje, ploče, savijanje, stabilnost oblika*

1 INTRODUCTION
1. UVOD

Demand for aesthetically pleasing wood is high abroad. However, considerable costs for logging operations, certification, transport and limited supplies of exotic wood are the cause of increasing prices of input raw materials for the manufacture of decorative veneers. For these reasons, the production and application of modified veneers develops, which makes possible to use less attractive veneers particularly on hidden surfaces. At present time, manufacturers make great efforts to re-

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place expensive veneers on hidden surfaces by countermove materials. The function of these materials is to provide shape stability of furniture elements.

A basic question is which countermove material can be chosen among specific kinds of wood and what relationships exist between them.

Determination of these relationships will contribute to create suitable combinations of veneers to provide shape stability, which will enable the production of products of competitive advantages by means of decreasing production costs (Král and Hrázský, 2005)

Generally, warping is the undesirable shape deformation of elements. All manufacturers try to produce and supply shape-stable elements to customers. These elements keep their shape and dimensions at moisture-heat stress, which can occur both in manufacture and during storage, transport and use. An area element was examined, and it consisted of a particleboard as the bearing (supporting) part and two covering veneer layers or a countermove foil as one layer. From the aspect of shape stability, the main problem of veneered elements consists in different dimensional changes of materials occurring in particular layers. Particleboards swell by 0.2–0.3 % of board dimensions at moisture changes of 1% in both main directions (Požgaj *et al*., 1997), while wood swelling ranges at higher values. Changes in dimensions of longitudinal, radial and tangential swelling are in a ratio of 1:10:20. According to Ugolev (1975), coefficients of swelling and shrinking of selected kinds of wood are shown in Table 1.

Table 1 Coefficients of shrinking and swelling
Tablica 1. Koeficijenti utezanja i bubrenja

Coefficients of shrinking *β* and swelling *α*, %/1% moisture / *Koeficijenti utezanja β i bubrenja α, %/1% sadržaja vode*				
	Radial *Radijalno*		Tangential *Tangencijalno*	
kind of wood / *Vrsta drva*	K_β	K_α	K_β	K_α
Spruce / *smreka*	0.16	0.17	0.28	0.31
Beech / *bukva*	0.17	0.18	0.32	0.35

If the layers were not stuck (connected) together, moisture changes would become evident in the change of their dimensions. However, dimensional changes of decorative surface layers would be even larger. After connecting the layers by means of bonding in the process of hot pressing into one compact unit, the shift of layers of the composite material is prevented. At the same time, however, it is necessary to take into account that due to this firm connection, a certain stress occurs in the layers at moisture changes, which affects this sheet composite material. If the sum of planar static moments is equal to zero, then the element maintains its planeness. This condition is valid provided that the surface composite material is compiled (put together) symmetrically, i.e. using identical surface layers. In case the sum of planar static moments is not equal to zero, the element is deformed. Therefore, efforts are made to create a composite material, which is most consistent with the theory of veneering, i.e. to achieve a symmetrical lay-out of materials (Avramidis *et al*., 2011). At the application of countermove materials, it is necessary to replace a veneer by another material or another veneer of the same properties as the veneer used on the front part of the board. In this way, it is possible to find suitable countermove materials for specific kinds of decorative veneers (Šrajer, 2013). In order to provide the shape stability of elements, it is most important to maintain stable relative moisture and temperature of the environment. In case of using countermove foils, unbleached sulphate pulp impregnated

Table 2 Combination of veneers and foil
Tablica 2. Kombinacija furnira i folije

Veneer and foil combination *Kombinacija furnira i folije*		
Tight side *Vanjska strana*	**Underside (countermove side)** *Donja strana*	**Countermove layer thickness, mm** *Debljina furnira na donjoj strani, mm*
Nut (NU) / *orah*	Nut (NU) / *orah*	0.6
Nut (NU) / *orah*	Alder (AL) / *joha*	0.6
Nut (NU) / *orah*	Spruce (SP) / *smreka*	0.6
Nut (NU) / *orah*	Spruce (SP) / *smreka*	1.2
Nut (NU) / *orah*	Spruce (SP) / *smreka*	1.5
Nut (NU) / *orah*	Beach (BE) / *bukva*	0.6
Nut (NU) / *orah*	Beach (BE) / *bukva*	0.9
Nut (NU) / *orah*	Beach (BE) / *bukva*	1.2
Nut (NU) / *orah*	Beach (BE) / *bukva*	1.5
	Countermove foil 85–90 g/m^2 *Folija 85–90 g/m^2*	-

by synthetic resin of emission class E 1 is the basic material. Countermove foils are manufactured in basic weight of 70 to 250 g/m² (Zemiar *et al*., 2009). The reason for creating asymmetrically veneered elements is to use financially less demanding (cheaper) materials on hidden surfaces.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

To determine shape stability, bending strength and modulus of elasticity in bending elements, various combinations of veneers or countermove foils were manufactured under laboratory conditions. To determine relationships between the veneer and countermove foil thickness, two thickness series of beech and spruce veneers were developed. These variants are shown in Tab. 2. From each of the variants, two elements were manufactured with 16 mm particleboards as the bearing (supporting) part of the elements. The elements were manufactured from particleboards 2800 x 2070 mm.

Properties and composition of urea -formaldehyde (UF) adhesive resin used for gluing:
- solid resin (dry mater content) 63 %
- viscosity 450–1100 mPa·s at 20 °C
- density1120–1150 kg/m³

Glue was applied by a manual glue applicator, average glue spread being 155 g/m². The amount of applied glue was determined by a weight method on check samples. With the countermove foil, the glue spread was 80 g/m².

A one-stage press was used for pressing the sets under following parameters:
- pressing time 60 s/1 mm veneer thickness + 300 s
- pressing temperature 110 °C
- working pressure 0.6 N/mm²

After pressing, the elements were stored in a stack for balancing the temperature and moisture and for curing the glue. After the air-conditioning, all elements were trimmed to a size of 400 x 760 mm. This size was subsequently used for cutting test specimens for the determination of bending strength and modulus of elasticity in bending according to the CSN EN 310 standard. Seven test specimens were prepared with the perpendicular direction of fibres and 8 test specimens with the longitudinal direction of fibres of each combination.

The determination of warping (shape stability) was carried out according to the CSN 490148 Standard. To prevent the penetration of water vapours into test specimens, their lateral surfaces were painted with a water-soluble white paint. Thus, porous lateral edges of particleboards were sealed. The measurement of warping was carried out by means of an aluminium lath and digital slide gauge measuring to 0.01 mm. The coordinates of measurement points are presented in Fig. 1.

The principle of the measurement of shape stability is presented in Fig. 2.

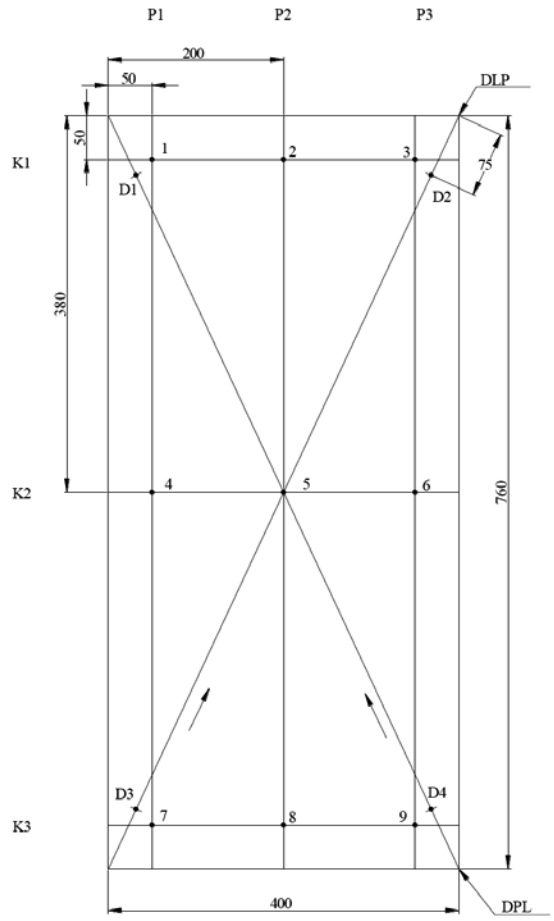


Figure 1 Measurement points of shape stability (1, 2, 3, 4, 5, 6, 7, 8, 9 – measurement points, D1, D2, D3, D4 – measurement in diagonal direction, P1, P2, P3 – measurement in longitudinal direction, K1, K2, K3 – measurement in perpendicular direction, DPL – measurement value in diagonal direction – from right to left, DLP5 – measurement in diagonal direction – from left to right)
Slika 1. Mjerne točke stabilnosti oblika (1, 2, 3, 4, 5, 6, 7, 8, 9 – mjerne točke, D1, D2, D3, D4 – mjerenja u dijagonalnom smjeru, P1, P2, P3 – mjerenja u uzdužnom smjeru, K1, K2, K3 – mjerenja u poprečnom smjeru, DPL – mjerna vrijednost u dijagonalnom smjeru – zdesna ulijevo, DLP5 – slijeva udesno)

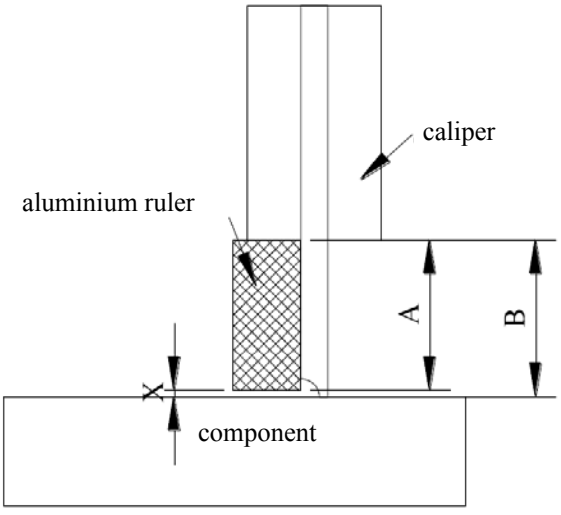


Figure 2 Warping measurement principles
Slika 2. Načelo mjerenja izvitoperenosti

The measurement was carried out on three positions of the ruler. At each position of the ruler, three points were measured on the element/component.

The size of deformation was calculated according to the relation:

$$X = A - B$$

Where:
A – aluminium ruler height 22.47 mm
B – value measured by the calliper (depth gauge)
X – deformation

To determine the size of warping corn-wise, the following relation was used

$$Y = DPL5 - DLP5$$

Where:
DLP5 – measured value on the diagonal position of the ruler – point 5 (from right to left)
DLP5 – measured value on the diagonal position of the ruler – point 5 (from left to right)

The size of the difference between these values is dependent on the size of warping corn-wise. The larger the difference between diagonal measurements *Y,* the larger is corn-wise warping.

The measurement of warping was carried out before air conditioning and subsequently three times after 7 days of air conditioning. The last measurement was carried out after 6 days of air conditioning. The air conditioning was carried out in a SANYO MTH 2400 climatic chamber. The conditioning regime is presented in Tab. 3.

Air conditioning was carried out with the aim to create stress in surface layers of elements/components causing different levels of warping. The test specimens were placed in the air-conditioning box on the shorter side so as to prevent the development of forces that could prevent warping. Gaps between specific layers were avoided by a locking latch, so that changes in gap dimensions could not occur for the period of measurement. According to the CSN 490148 Standard, the warping value in a respective direction is always the highest determined deviation in this direction. It is rounded to 0.1 mm with 1 meter length (mm/m).

Table 3: Air conditioning regime
Tablica 3. Uvjeti kondicioniranja

Moisture, % *Vlažnost, %*	**Temperature, °C** *Temperatura, °C*	**Time, days** *Vrijeme, dani*
85 ± 5	30 ± 2	7
85 ± 5	30 ± 2	7
30 ± 5	30 ± 2	7
95 ± 5	30 ± 2	6

Bending strength and modulus of elasticity in bending of specific test specimens were determined according to the CSN EN 310 Standard by a ZWICK Z 050 press with 3-point bending.

The measured data were statistically analysed by the STATISTICA version 8 and the Calc 2.0 (OpenOffice). An exploratory data analysis (EDA) was done, assessment of basic characteristics and comparisons were made by Anova, Mann–Whitney U tests, Wald–Wolfowitz tests and Kolmogorov–Smirnov tests.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Measurement and warping calculation were conducted according to the standard CSN 490148. The determined warping values depending on the countermove veneer thickness are given in Tabs. 4 to 7 and in Fig. 3.

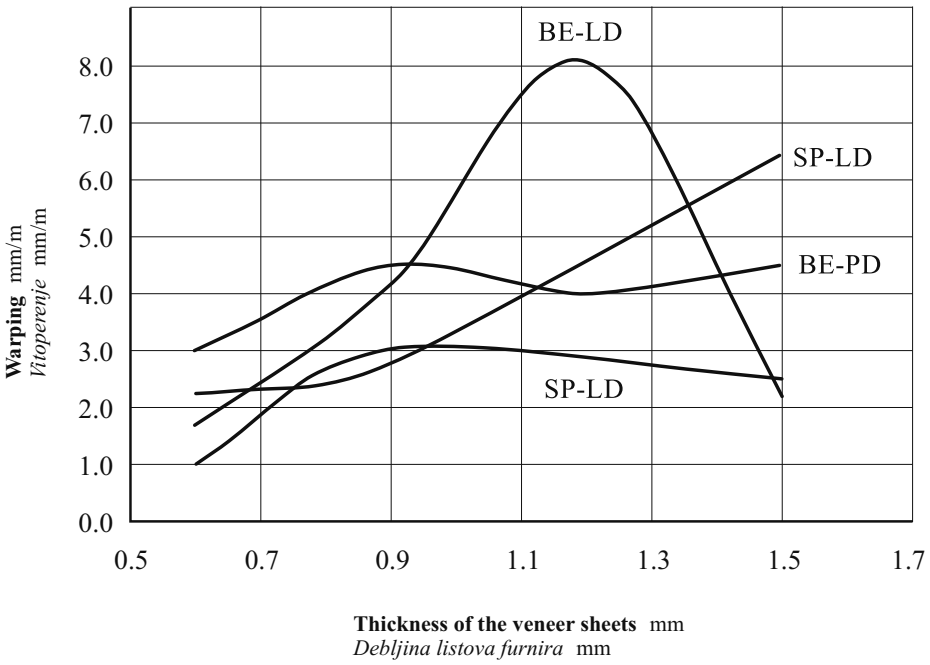


Figure 3 Dependence of warping on countermove veneer thickness
Slika 3. Ovisnost izvitoperenosti o debljini furnira na donjoj strani ploče

Table 4 Warping values after 14 days of air conditioning
Tablica 4. Vrijednosti izvitoperenosti nakon 14 dana kondicioniranja

Warping values in mm/m after 14 days of air conditioning *Vrijednosti izvitoperenosti izražene u mm/mm nakon 14 dana kondicioniranja*		
Countermove layer *Površinska obrada donje strane*	Direction of measurement *Smjer mjerenja*	
	Longitudinal *Uzdužni* (LD)	Perpendicular *Poprečni* (PD)
SP 0.6 mm	2.2	1.0
SP 1.2 mm	2.8	3.0
SP 1.5 mm	6.4	2.5
BE 0.6 mm	1.7	3.0
BE 0.9 mm	4.2	4.5
BE 1.2 mm	8.1	4.0
BE 1.5 mm	2.2	4.5

Note: SP – spruce / *smreka*, BE – beech / *bukva*

Table 5 Evaluation of warping after 14 days of air conditioning
Tablica 5. Procjena izvitoperenosti nakon 14 dana kodicioniranja

Evaluation of warping in mm/m after 14 days of air conditioning *Procjena izvitoperenosti izražene u mm/mm nakon 14 dana kondicioniranja*			
Countermove layer *Površinska obrada donje strane*	Direction of measurement *Smjer mjerenja*		
	Longitudinal *Uzdužni*	Perpendicular *Poprečni*	*Y*
SP 0.6 mm	2.2	1.0	1.0
BE 0.6 mm	1.7	3.0	0.7
NU 0.6 mm	1.9	1.5	0.4
AL 0.6 mm	1.7	2.5	0.1
Foil / *folija*	26.4	1.5	0

Note: SP – spruce / *smreka*, BE – beech / *bukva*, NU – walnut / *orah*, AL – alder / *joha*

Table 6 Warping values after 21 days of air conditioning
Tablica 6. Vrijednosti izvitoperenosti nakon 21 dana kondicioniranja

Warping values in mm/m after 21 days of air conditioning *Vrijednosti izvitoperenosti izražene u mm/mm nakon 21 dan kondicioniranja*			
Countermove layer *Površinska obrada donje strane*	Countermove layer *Površinska obrada donje strane*		
	Longitudinal *Uzdužno*	Perpendicular *Poprečno*	*Y*
SP 0.6 mm	1.1	0.5	0.2
BE 0.6 mm	0.3	1.0	0.2
NU 0.6 mm	1.7	0.5	0.3
AL 0.6 mm	0.8	1.5	0.2
Foil / *folija*	14.4	1.5	0

Note: SP – spruce / *smreka*, BE – beech / *bukva*, NU – walnut / *orah*, Ol – alder / *joha*

Table 7 Warping values after 27 days of air conditioning
Tablica 7. Vrijednosti izvitoperenosti nakon 27 dana kondicioniranja

Warping values in mm/m after 27 days of air conditioning *Vrijednosti izvitoperenosti izražene u mm/mm nakon 27 dana kondicioniranja*			
Countermove layer *Površinska obrada donje strane*	Countermove layer *Površinska obrada donje strane*		
	Longitudinal *Uzdužno*	Perpendicular *Poprečno*	*Y*
SP 0.6 mm	2.8	1.5	0.7
BE 0.6 mm	1.7	2.0	0.3
NU 0.6 mm	1.4	1.0	0.4
AL 0.6 mm	1.4	2.0	0.3
Foil / *folija*	26.4	2.0	0

Note: SP – spruce / *smreka*, BE – beech / *bukva*, NU – walnut / *orah*, AL – alder / *joha*

Some results (examples) of the measurement of density, bending strength and modulus of rupture including characteristics of descriptive statistics are given in Tabs. 8 to 13.

Table 8 Values of density, modulus of elasticity in bending (*MOE*) and modulus of rupture (*MOR*)
Tablica 8. Vrijednosti gustoće, modula elastičnosti pri savijanju (*MOE*) i modula loma (*MOR*)

Countermove layer – walnut (NU) 0.6 mm / *Površinska obrada donje strane – orah (NU) 0,6 mm*										
	Longitudinal direction of fibres *Uzdužni smjer vlakanaca*					Perpendicular direction of fibres *Poprečni smjer vlakanaca*				
Stat. value	F_{max} N	*MOR* N/mm²	*MOE* N/mm²	ε mm	ρ kg/m³	F_{max} N	*MOR* N/mm²	*MOE* N/mm²	ε mm	ρ kg/m³
n	8	8	8	8	8	7	7	7	7	7
$\bar{x}$	729.94	26.92	3437.9	11.92	633.6	361.33	13.22	2579.79	6.97	650.57
s	51.98	1.95	80.12	1.19	2.83	33.66	1.21	72.82	0.7	9.98
V (%)	7.12	7.23	2.33	9.96	0.45	9.3	9.17	2.82	10.05	1.50
Min.	644.06	23.76	3303.29	9.99	630.0	321.9	11.8	2454.63	6.06	639.0
Max.	786.03	29.18	3548.83	13.62	639.0	409.41	14.92	2682.63	7.71	664.0

Table 9 Values of density, modulus of elasticity in bending (*MOE*) and modulus of rupture (*MOR*)
Tablica 9. Vrijednosti gustoće, modula elastičnosti pri savijanju (*MOE*) i modula loma (*MOR*)

Countermove layer – foil / *Površinska obrada donje strane - folija*										
	Longitudinal direction of fibres *Uzdužni smjer vlakanaca*					Perpendicular direction of fibres *Poprečni smjer vlakanaca*				
Stat. value	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²
n	8	8	8	8	8	7	7	7	7	7
$\bar{x}$	427.84	16.65	3091.6	7.83	636.4	407.32	15.95	2922.77	7.94	631.57
s	13.13	0.5	70.89	0.44	7.44	13.48	0.6	67.93	0.31	4.39
V (%)	3.1	2.98	2.29	5.55	1.17	3.31	3.75	2.32	3.91	0.70
Min.	415.57	16.17	2971.8	7.48	620.0	394.034	15.39	2861.45	7.60	625.0
Max.	446.57	17.5	3203.0	8.71	644.0	430.39	17.01	3017.28	8.46	637.0

Table 10 Values of density, modulus of elasticity in bending (*MOE*) and modulus of rupture (*MOR*)
Tablica 10. Vrijednosti gustoće, modula elastičnosti pri savijanju (*MOE*) i modula loma (*MOR*)

Countermove layer – spruce (SP) 0.6 mm / *Površinska obrada donje strane – smreka 0,6 mm*										
	Longitudinal direction of fibres *Uzdužni smjer vlakanaca*					Perpendicular direction of fibres *Poprečni smjer vlakanaca*				
Stat. value	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²
n	8	8	8	8	8	7	7	7	7	7
$\bar{x}$	736.57	26.72	3511.94	11.41	629.5	383.29	13.86	2505.45	7.61	629.43
s	84.08	2.99	116.5	1.8	2.07	11.8	0.44	15.75	0.35	3.41
V (%)	11.42	11.21	3.32	16.1	0.33	3.08	3.16	0.63	4.6	0.54
Min.	591.69	21.66	3379.72	8.5	627.0	367.54	13.28	2482.69	7.16	625.0
Max.	811.13	29.39	3713.13	13.11	634.0	399.8	14.49	2525.67	8.15	634.0

Table 11 Values of density, modulus of elasticity in bending (*MOE*) and modulus of rupture (*MOR*)
Tablica 11. Vrijednosti gustoće, modula elastičnosti pri savijanju (*MOE*) i modula loma (*MOR*)

Countermove layer – beech (BE) 0.6 mm / *Površinska obrada donje strane – bukva 0,6 mm*										
	Longitudinal direction of fibres *Uzdužni smjer vlakanaca*					Perpendicular direction of fibres *Poprečni smjer vlakanaca*				
Stat. value	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²
n	8	8	8	8	8	7	7	7	7	7
$\bar{x}$	889.82	32.51	3819.06	13.44	642.5	394.5	14.54	2609.9	7.72	637.29
s	78.09	2.94	218.87	1.36	3.3	16.8	0.6	48.79	0.62	11.7
V (%)	8.78	9.06	5.65	10.08	0.51	4.26	4.15	1.87	8.07	1.84
Min.	798.37	29.03	3525.32	11.88	639.0	370.42	13.66	2542.57	6.83	624.0
Max.	1029.43	37.7	4205.61	15.71	648.0	424.45	15.61	2680.01	8.75	657.0

Table 12 Values of density, modulus of elasticity in bending (*MOE*) and modulus of rupture (*MOR*)
Tablica 12. Vrijednosti gustoće, modula elastičnosti pri savijanju (*MOE*) i modula loma (*MOR*)

Countermove layer – beech (BE) 1.2 mm / *Površinska obrada donje strane – bukva 1,2 m*m										
	Longitudinal direction of fibres *Uzdužni smjer vlakanaca*					Perpendicular direction of fibres *Poprečni smjer vlakanaca*				
Stat. value	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²
n	8	8	8	8	8	7	7	7	7	7
$\bar{x}$	1293.34	43.86	5569.99	12.21	666.38	252.52	8.5	1960.75	5.23	665.0
s	205.22	6.84	318.78	2.18	13.84	19.5	0.66	37.2	0.46	1.73
V (%)	15.87	15.59	5.72	17.82	2.08	7.72	7.8	1.9	8.78	0.26
Min.	814.28	27.93	5130.73	6.92	646.0	231.07	7.77	1905.58	4.68	663.0
Max.	1472.94	50.10	6054.73	13.65	688.0	277.23	9.36	2007.39	5.81	668.0

Table 13 Values of density, modulus of elasticity in bending (*MOE*) and modulus of rupture (*MOR*)
Tablica 13. Vrijednosti gustoće, modula elastičnosti pri savijanju (*MOE*) i modula loma (*MOR*)

Countermove layer – alder (AL) 0.6 mm / *Površinska obrada donje strane – joha 0,6 mm*										
	Longitudinal direction of fibres *Uzdužni smjer vlakanaca*					Perpendicular direction of fibres *Poprečni smjer vlakanaca*				
Stat. value	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²	F_{max} N	*MOR* N/mm²
n	8	8	8	8	8	7	7	7	7	7
$\bar{x}$	821.27	30.08	4201.24	10.71	643.0	285.63	10.46	1965.57	7.09	641.57
s	48.8	1.78	166.79	1.0	10.01	19.18	0.72	19.46	0.68	2.7
V (%)	5.94	5.91	3.97	9.36	1.56	6.72	6.92	0.99	9.63	0.4
Min.	743.38	27.29	3953.57	8.74	633.0	259.22	9.46	1936.0	6.17	638.0
Max.	890.16	32.57	4447.75	11.7	661.0	313.59	11.55	1993.18	8.05	645.0

The longest period of air conditioning with constant parameters (according to Tab. 3) was 14 days. The measured warping values of veneered particleboards (different variants) are summarized in Tab. 4. According to values given in the table, it is evident that warping of individual elements in longitudinal direction increases with the thickness of the countermove spruce veneer. The highest values were found with spruce veneer, 1.5 mm thick (6.4 mm/m), and also with beech veneer, 1.2 mm thick (8.1 mm/m). With the use of a countermove beech veneer, 1.5 mm thick, the warping value dropped to 2.2 mm/m. In perpendicular direction, the highest warping values were determined with the use of a countermove spruce (SP) veneer, 1.2 mm thick (3.0 mm/m), and beech (BE), 0.9 mm in thick (4.5 mm/m). A variant with the use of a countermove walnut (NU) veneer, 0.6 mm thick, was selected as a reference variant to compare the warping values. It refers to a symmetric variant, i.e. a walnut (NU) veneer, 0.6 mm thick, was also used on the tight side of the particleboard. Evaluations of *P*, *K* and *Y* warping of individual variants were compared with warping values of this reference variant.

Tab. 5 presents the warping values of the elements after a 14-day air conditioning. It follows that alder (AL), 0.6 mm thick, appears to be the most suitable countermove. An element (component) veneered in this way shows lower warping values in longitudinal direction (1.7 mm/m) and low values of *Y* (0.1 mm/m), which expresses the level of corn-wise warping. In perpendicular direction, however, a higher warping value was determined (2.5 mm/m).

According to Tab. 6 (air conditioning for 21 days), an element veneered on the underside with a countermove beech (BE) veneer, 0.6 mm thick, showed the lowest warping values. In the longitudinal direction, warping of 0.3 mm/m was found, while 1.0 mm/m was found in perpendicular direction and the relative *Y* value expressing corn-wise warping was 0.2 mm/m.

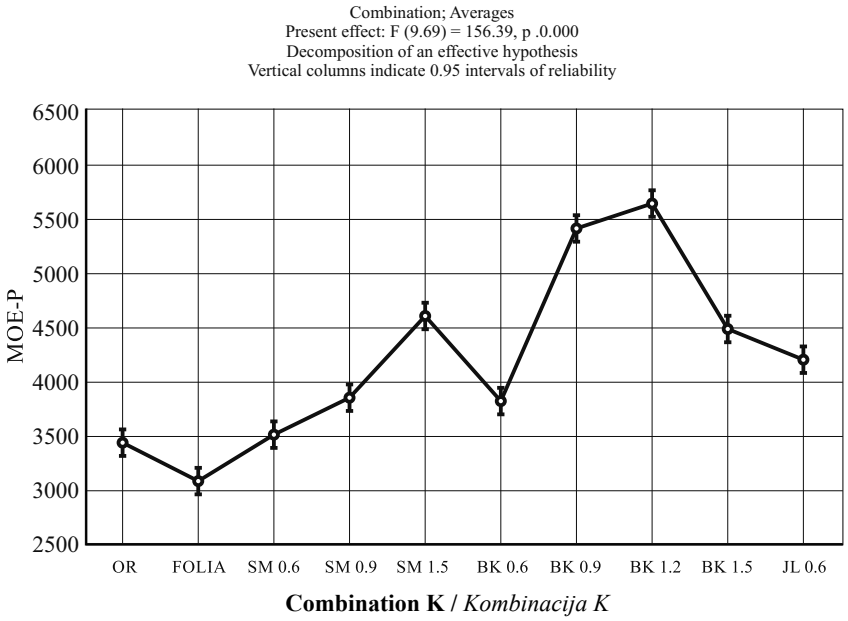
According to Tab. 7 that presents the warping values after 27 days of air conditioning, an alder (AL) veneer, 0.6 mm thick, appears to be the most suitable countermove material. In longitudinal direction, warping of 1.4 mm/m was determined, while 2.0 m/m was found in perpendicular direction and the *Y* value expressing corn-wise warping was 0.3 mm/m.

With the use of a countermove foil, surprisingly high warping values were found in longitudinal direction. After a 14-day air conditioning of elements, these values were up to 13.89 times higher than those of the reference symmetrically veneered element. In our opinion, the cause of warping was the low surface density of countermove foil.

Dependence between sheathing materials and values of *MOR* and *MOE* of veneered materials warping values and *MOE* and *MOR* were also compared in both longitudinal and perpendicular directions. Statistical evaluation of the modulus of elasticity of test specimens with the longitudinal direction of fibres (*P*) is presented in Tabs. 14 to 15. First, the one-dimensional test of significance was carried out (Tab. 14), and then the Tuckey HSD test of multiple comparisons (Tab. 15).

Table 14 One-dimensional test of significance for MOE-P (longitudinal direction)
Tablica 14. Jednodimenzionalni test značajnosti MOE-P (uzdužni smjer)

Effect	One-dimensional tests of significance for MOE – P Sigma-limited parameterisation Decomposition of an effective hypothesis				
	Value of variance	Degree of freedom	Value of variance effect of the factor	*F*	*p*
Absolute term	1.392855E+09	1	1.392855E+09	40803.48	0.00
Combination	4.804689E+07	9	5.338543E+06	156.39	0.00
Error	2.355363E+06	69	3.413570E+04		



Note: OR – Walnut, Foil, SP – spruce, BK – beech, JL – elm, OL – alder
Legenda: OR – orah, folija, SP . smreka, BK – bukva, JL – brijest, OL - joha

Figure 4 Relationship between mean values of MOE–P
Slika 4. Prikaz srednjih vrijednosti MOE-P

The value of p is smaller than the value of α, which implies that the assessed factor (combination) shows a statistically significant effect on the measured value. In this case, tests of multiple comparisons were subsequently made (Tab. 15). The relationship between mean values of MOE–P is shown in Fig. 4.

Table 15 Tuckey's HSD test of multiple comparisons
Tablica 15. Tuckeyev HSD test višekratnih usporedbi

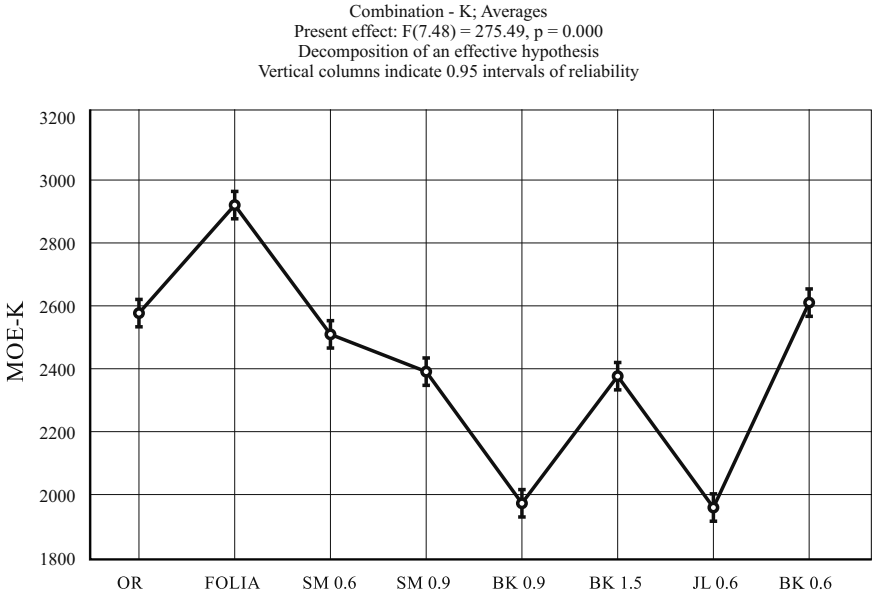
Cell number	Tuckey's HSD test; variable MOE – P Approximate probabilities for post hoc tests Error: intergroup PČ = 34136; sv = 69.000										
	Kombi-nace	{1} 3437.9	{2} 3091.6	{3} 3511.9	{4} 3851.6	{5} 4591.9	{6} 3819.1	{7} 5393.3	{8} 5632.9	{9} 4491.9	{10} 4201.1
1	NU		**0.012710**	0.998398	**0.001249**	**0.000164**	**0.003870**	**0.000164**	**0.000164**	**0.000164**	**0.000164**
2	FOLIA	**0.012710**		0.001004	0.000164	0.000164	0.000164	0.000164	0.000164	0.000164	0.000164
3	SP 0.6	0.998398	**0.001004**		0.015720	0.000164	0.043010	0.000164	0.000164	0.000164	0.000164
4	SP 0.9	**0.001249**	**0.000164**	**0.015720**		**0.000164**	0.999998	**0.000164**	**0.000164**	**0.000164**	**0.011419**
5	SP 1.5	**0.000164**	**0.000164**	**0.000164**	**0.000164**		**0.000164**	**0.000164**	**0.000164**	0.984929	**0.002784**
6	BE 0.6	**0.003870**	**0.000164**	**0.043010**	0.999998	**0.000164**		0.000164	0.000164	0.000164	0.003771
7	BE 0.9	**0.000164**	**0.000164**	**0.000164**	**0.000164**	**0.000164**	**0.000164**		0.283974	**0.000164**	**0.000164**
8	BE 1.2	**0.000164**	**0.000164**	**0.000164**	**0.000164**	**0.000164**	**0.000164**	0.283974		0.000164	0.000164
9	BE 1.5	**0.000164**	**0.000164**	**0.000164**	**0.000164**	0.984929	**0.000164**	**0.000164**	**0.000164**		0.068853
10	AL 0.6	**0.000164**	**0.000164**	**0.000164**	**0.011419**	**0.002784**	**0.003771**	**0.000164**	**0.000164**	0.068853	

Note: NU – Walnut / *orah*, Foil / *folija*, SP – spruce / *smreka*, BE – beech / *bukva*, AL – alder / *joha*

Statistical evaluation of the modulus of elasticity of test specimens with the perpendicular direction of fibres (K) is shown in Tabs. 16 to 17. First, one-dimensional test of significance was carried out (Tab. 16), and subsequently the Tuckey's HSD test of multiple comparison (Tab. 17). The relationship between mean values is shown in Fig. 5. Test specimens with countermove spruce (SP) of 1.5 layer and beech (BE) of 1.2 layer were excluded from the evaluation, on the ground of the countermove veneer disturbance in the gap of the glued veneer sheets. The relationship between mean values of MOE–K is shown in Fig. 5.

Table 16 One-dimensional test of significance for MOE – K (perpendicular direction)
Tablica 16. Jednodimenzionalni test značajnosti MOE-K (poprečni smjer)

Effect	One-dimensional tests of significance for MOE – K Sigma-limited parameterisation Decomposition of an effective hypothesis				
	SČ	Degree of freedom	PČ	*F*	*p*
Absolute member	326768841	1	326768841	123279.6	0.00
Combination	5111581	7	730226	275.5	0.00
Error	127230	48	2651		



Combination K / *Kombinacija K*

Note: OR – Walnut, Folia - Foil, SM – spruce, BK – beech, JL – elm
Legenda: OR – orah, folija, SM – smreka, BK – bukva, JL – brijest

Figure 5 Relationship between mean values of MOE–K
Slika 5. Prikaz srednjih vrijednosti MOE-K

Table 17 Tuckey's HSD test of multiple comparisons
Tablica 17. Tuckeyev HSD test višekratnih usporedbi

Cell number	Tuckey's HSD test; variable MOE – P Approximate probabilities for post hoc tests Error: intergroup PČ = 2650.6; sv = 48.000								
	Combination	{1} 2579.9	{2} 2922.6	{3} 2505.7	{4} 2392.3	{5} 1973.3	{6} 2375.6	{7} 1965.6	{8} 2610.0
1	NU		0.000134	0.149465	**0.000134**	**0.000134**	**0.000134**	**0.000134**	0.954778
2	FOLIA	**0.000134**		0.000134	0.000134	0.000134	0.000134	0.000134	0.000134
3	SP 0.6	0.149465	**0.000134**		0.003523	0.000134	0.000617	0.000134	0.009347
4	SP 0.9	**0.000134**	**0.000134**	**0.003523**		**0.000134**	0.998668	**0.000134**	**0.000134**
5	BE 0.9	**0.000134**	**0.000134**	0.000134	0.000134		**0.000134**	0.999993	**0.000134**
6	BE 1.5	**0.000134**	**0.000134**	**0.000617**	0.998668	**0.000134**		0.000134	0.000134
7	OL 0.6	**0.000134**	**0.000134**	**0.000134**	**0.000134**	0.999993	**0.000134**		0.000134
8	BE 0.6	0.954778	**0.000134**	**0.000134**	**0.000134**	**0.000134**	**0.000134**	**0.000134**	

Note: NU – Walnut / *orah*, Foil / *folija*, SP – spruce / *smreka*, BE – beech / *bukva*, AL – alder / *joha*

Tabs. 15 and 17 present *p* values of the selected test of multiple comparisons for all combinations of selection. If *p* values >α, a hypothesis of the congruence of mean values is accepted, so that values marked black are larger than α.

When considering the same relationships between sheathing materials in MOE values of veneered materials and their warping values, it would be easier to find a suitable countermove material and not to test the shape stability (technically and financially rather demanding) of elements (components). On the basis of this consideration, relationships were compared between warping and values of MOE–P and MOE–K. Fig. 3 and data in Tab. 15 clearly show that there is a statistically significant congruence between MOE–P values of an element and countermove layers – walnut (NU) 0.6 and spruce (SP) 0.6. As samples (elements) with a countermove layer - spruce (SP) 0.6 and values MOE–P and MOE–K are significantly consistent with values MOE–P and MOE–K of elements with a countermove layer – walnut (NU) 0.6, the elements where spruce (SP) veneer 0.6 was used as a countermove layer were supposed to achieve the best shape stability. According to Tabs. 5 to 7, however, the lowest warping values are achieved with elements using the countermove layer – alder (AL) 0.6 mm. In Fig. 4, the points representing the mean value of MOE–P show that they would be consistent with curves for longitudinal warping (Fig. 3). It can be concluded that in this case values of MOE and warping correspond. Therefore, it is probable that the difference, caused by the determination of the most suitable material from the aspect of warping values and values of MOE, was the result of a small number of samples in measuring shape stability (warping).

The reason for creating asymmetrically veneered elements is to use financially less demanding (cheaper) materials on hidden surfaces. The function of this material is to provide shape stability.

4 CONCLUSION
4. ZAKLJUČAK

With increasing demands for decorative veneers, their resources become scarce and their price grows. Increasing efforts to lower production costs force producers to look for possibilities of reducing prices of inputs and searching for new technical solutions. This paper was aimed at searching suitable countermove materials for the underside of veneered elements. One of the tasks of the countermove layer is to provide the shape stability of an element (surface-finished) by veneering. Already in the production stage, it is necessary to eliminate the effects of factors influencing the shape stability of the elements. As asymmetrically veneered elements are more liable to shape changes (warping) than elements veneered symmetrically, it is more suitable to use materials that can minimize the development of moisture differences within an element, such as adhesive foils. At veneering specific elements, the thickness of used veneers has to be always the same. The results of the measurement of warping of the elements veneered by various combinations of veneers and a countermove foil showed that the combination of 0.6 mm American walnut and 0.6 mm alder provided the lowest warping values. Considerable savings can be achieved with this combination of materials. In searching for relationships between warping values and *MOE* values in longitudinal and perpendicular directions, *MOE* correspondence (congruence) was found with elements using countermove layers - 0.6 mm American walnut and 0.6 mm spruce.

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Mode I Critical Stress Intensity Factor of Beech Wood *(Fagus Sylvatica)* in a TL Configuration: A Comparison of Different Methods

Faktor kritičnog intenziteta naprezanja (I. mod) bukovine *(Fagus sylvatica)* u TL presjeku: usporedba različitih metoda

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ABSTRACT • *The paper presents a comparison between various methods of mode I critical stress intensity factor K_{IC} calculations of beech wood in the TL configuration. The first method is the stress intensity factor extrapolation to the distance of 0 mm from the crack tip; the second method is the use of the J integral; and the third method is based on the differences in deformation energies from which the strain energy release rate per unit of crack propagation length was obtained. The fourth method is the calculation of material deformation around the crack or the displacement of the triangle element node; and the fifth method uses a generally known equation for the CT specimen for plane-strain conditions in isotropic material. Using the finite element method, it was found that the J integral was least sensitive to the size and shape of the elements. It was used to calculate the critical stress intensity factor K_{IC} for beech wood in a TL configuration. The average value is 0.56 MPa$\sqrt{m}$ with a standard deviation of 0.047 MPa$\sqrt{m}$.*

Keywords: *fracture toughness, mode I critical stress intensity factor, fracture mechanics, beech wood*

SAŽETAK • *Rad donosi usporedbu različitih metoda izračuna faktora kritičnog intenziteta naprezanja (mod I.) K_{IC} za bukovo drvo na tangencijalno-longitudinalnom (TL) presjeku. Prva je metoda ekstrapolacija faktora intenziteta naprezanja na udaljenosti 0 mm od vrha pukotine, druga je primjena, J integrala a treća se metoda temelji na razlikama energija deformacije iz kojih je dobivena brzina oslobađanja energije deformacije po jedinici duljine širenja pukotine. Četvrta metoda temelji se na izračunu deformacije materijala oko pukotine ili pomaka vrhova elementa trokuta, a peta se koristi općepoznatom jednadžbom za CT uzorak za deformaciju u ravnini izotropnog materijala. Koristeći se metodom konačnih elemenata, utvrđeno je da je metoda J integrala najmanje osjetljiva na veličinu i oblik elemenata. Ta je metoda primijenjena za izračun faktora kritičnog naprezanja K_{IC} za bukovo drvo na TL presjeku. Dobivena je prosječna vrijednost od 0,56 MPa·$\sqrt{m}$, sa standardnom devijacijom od 0,047 MPa·$\sqrt{m}$.*

Ključne riječi: *lomna žilavost, faktor kritičnog intenziteta naprezanja (mod I.), mehanika loma, bukovina*

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1 INTRODUCTION
1. UVOD

Wood fracture has already been studied by several researchers. Porter (1964) measured critical strain energy release rate G_{IC} by measuring the force and length of crack in white pine. The specimens were TL and RL-oriented, which means that he loaded them in tangential and radial directions, respectively, and the crack propagated in a longitudinal direction. He researched the influence of length, thickness, and height of the specimen, as well as the crack length. The method of determining the critical strain energy release rate G_{IC} in pines was also studied by Stanzl-Tschegg *et al*. (1995). They calculated the strain energy release rate G_I by integrating the energy or the area under the curve, which describes the force depending on the specimen mouth opening. The energy obtained was divided by the size of the newly formed surface. Thuvander and Berglund (2000) researched pine fracture in the TR orientation. They stated that K_{IC} of silver fir wood in the TR orientation was between 30 % and 50 % higher than that in the TL direction, while in the case of pine and spruce the difference was supposed to be even greater. As the newly formed surface proved to be equal in the TR and TL orientations, i.e., in the RL plane, they wanted to know the reason for such great differences in K_{IC}. Fresh specimens were used because in dry specimens they encountered the problem of stable fracture due to microcracks resulting from the drying process. According to them, a specimen that has been dried and humidified again has a more brittle fracture due to microcracks formed during the process of drying. Similar tests in the TR orientation were also performed by Frühman *et. al.* (2003).

The influence of the moisture content of wood on K_{IC} was also researched by many researchers (Ozyhar *et. al.* (2012), Reiterer and Tschegg (2002), Scheffler *et.al.* (2004), Vasić and Stanzl-Tschegg (2007), Yeh and Schniewind (1992)). They found that with increasing moisture content, the critical stress intensity factor in the RL and TR orientation decreases. Vasić and Stanzl-Tschegg (2007) report a value of 0.9 MPa·√m with 6 % moisture content of beech wood in the RL configuration, and the value of 0.62 MPa·√m with 12 % moisture content.

In their work, Stanzl-Tschegg and Navi (2009) sum up their research of wood fracture in the RL configuration under various conditions such as moisture and density of wood, combined fracture modes I and II, and loading rate. They mention the work of Beikircher who thermally modified wood and found that thermal modification of beech decreases K_{IC} for the TL configuration from 0.8 MPa·√m to 0.6 MPa·√m. Likewise, Stanzl-Tschegg and Navi (2009) state that K_{IC} in the RL orientation is higher compared to the TL orientation because of the 'bridging' effect that the parenchyma causes in a radial direction. Majano-Majano *et.al.* (2012) found that K_{IC} of thermally modified beech wood in RL and TL configuration decreases and found that the K_{IC} for unmodified beech in TL configuration form ranged from 0.44 to 0.63 MPa·√m.

To determine the fracture properties of wood, the majority of the aforementioned authors use the critical strain energy release rate G_{IC}, determining the energy necessary for the formation of new surfaces on the basis of the force and mouth opening. A prerequisite for an experiment of this kind is a stable advance of the fracture, which means that the crack propagates in proportion to the crack mouth opening. However, the problem in the case of beech wood in the TL configuration is that after initiation the fracture process is distinctly unstable, during which the crack suddenly propagates to a certain unbalanced length. G_{IC} does in fact express the energy to be put in per unit of the newly formed surface, but provides little information about the fracture initiation, which is of essential significance in cutting. Under certain conditions, the result can be a chip of type I, II, or III, as classified by Franz (Koch, 1985). Regarding the material which is turned into a chip, a type I chip is discontinued, formed by alternating fracture and bending failures (Merhar and Bučar, 2012). Whether the fracture under the chip will progress or the chip will break depends on the critical stress intensity factor for fracture mode I. It was, therefore, decided to determine the K_{IC} of beech wood for the TL configuration in the manner enabling a direct determination of the value. First, the K_{IC} was going to be determined on one specimen using the five most frequently used methods. The results obtained were going to be used to determine the most suitable method that yielded a satisfactory result in a simple manner. The method obtained in this way would be used to determine the fracture toughness of the remaining specimens.

2 MATERIAL AND METHODS
2. MATERIJALI I METODE

Beech wood (*Fagus sylvatica*) specimens were taken from a peripheral part of one stem of 400 mm in diameter. The specimens moisture content was (9 ± 0.5) %, with a density of 630 kg/m^3. A conventional compact tension CT specimen (Hertzberg, 1996) of 115 mm in length, 100 mm in height, and 10 mm thick was made.

The specimens were TL-oriented, which means that load was applied in a tangential direction, and the crack propagated longitudinally. Since the board used to make specimens was only 80 mm thick, an additional 10 mm thick strip of wood was glued to each side of the specimen. The glued-on strip was obtained from the immediate vicinity of the specimen so that it had similar mechanical properties. The obtained CT specimen was modified to enable the mounting of the crack mouth opening displacement meter as shown in Figure 1a.

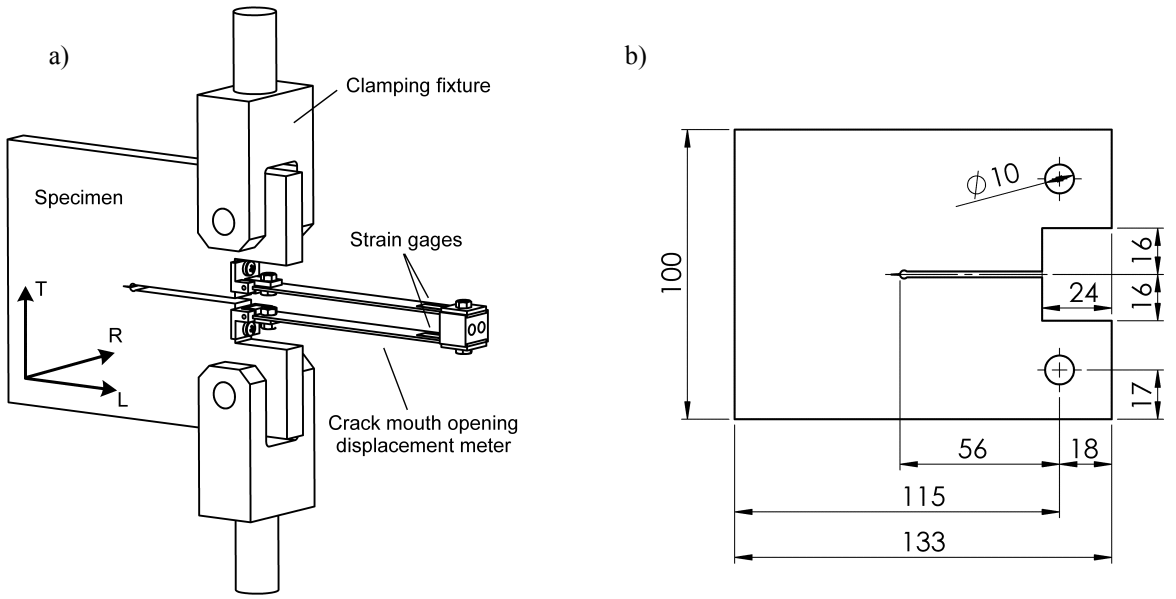

Figure 1 a) Experiment, b) Modified CT specimen
Slika 1. a) Skica eksperimenta, b) modificirani CT uzorak

A cut of approximately 56 mm in length was made in the specimen (Figure 1b). Then a razor blade was used to make a further 1 mm to 2 mm deep cut to obtain a sharp tip of the cut. After fracturing, the initial crack length was measured on each specimen.

The crack mouth opening displacement meter was made of two 1 mm thick and 90 mm long spring steel gauges. The length of the gauges was determined so as to make the meter measuring range of 10 mm, whereby the stress inside the gauge as a result of bending did not exceed 200-300 MPa. In this case each gauge was deformed by 5 mm. Strain gauges type 3/120LG11 produced by HBM, with the resistance of 120 Ω, were glued on the upper and lower side of both steel gauges, at the beginning or at the place of the maximum bending moment, and connected to the MES HPSC 3102 amplifier with full-bridge configuration. The displacement meter was calibrated by means of a reference dial gauge with the accuracy of 0.01 mm.

The specimen was placed on the tensile testing machine where the loading force was measured by a dynamometer, and the crack mouth opening displacement was measured by the previously described displacement meter. Data were captured by means of a personal computer, NI PCI-6014 measurement card and LabView software by National Instruments. The data capturing rate was 200 Hz, and the mouth opening velocity 15 mm/min.

The intersection of the measured data and a straight line with a 5 % smaller angle than the straight line representing a linear regression curve of the initial elastic part of the specimen loading, as laid down by the ASTM E 399 standard, was read from the measured data. At the same time the maximum force measured was read. When the maximum force was greater than the intersection of the measured data and straight line, or the difference between the value at the intersection and the maximum measured value was minimal, the maximum force measured was taken into account for the calculation.

The specimen was modelled by the finite element method using the Ansys program. The orthotropic properties of the wood were taken into consideration. The measured modulus of elasticity in a longitudinal direction, which has the greater influence on the K_{IC} calculation, was used in the model, while the data for moduli of elasticity in other directions, shear moduli and Poisson's ratios, which have minor influence on the K_{IC} calculation, were taken from Kollmann and Cote (1984). Thus:

$$\begin{aligned} &E_L = 14490 \text{ MPa},\\ &E_T = 1140 \text{ MPa},\\ &E_R = 2240 \text{ MPa},\\ &\nu_{LT} = 0.518, \\ &\nu_{TR} = 0.36,\\ &\nu_{LR} = 0.45,\\ &G_{LT} = 1055 \text{ MPa},\\ &G_{TR} = 460 \text{ MPa},\\ &G_{LR} = 1600 \text{ MPa}. \end{aligned} \qquad (1)$$

Since the aim of the first part of the research was to investigate the accuracy of determining the mode I critical stress intensity factor K_{IC}, the specimen was modelled with a linear elastic plane-strain state, where the modelled specimen thickness was 10. A PLANE183 higher-order 2D, 8-node brick element was used. The specimen had elements of 2mm and 1mm in size, with a combination of finer elements around the crack tip or special triangle elements for calculating the stress at the crack tip with an intermediate node at ¼ of the element's length. The tip of the crack was surrounded by two rows of 12 triangle elements each, whereby the elements length was 0.1 mm or 1/1000 of the crack length. The ratio between the size of the first row and the second one was set as 1.5.

The mode I critical stress intensity factor K_{IC} was calculated by five different and most frequently used methods of determining the critical stress intensity factor. The results of the comparison of these five methods were used to determine the most accurate and simple method, and this method was subsequently used to calculate the critical stress intensity factor for the remaining specimens.

The first method used to calculate the critical stress intensity factor K_{IC} was the stress intensity factor extrapolation to the distance of zero using equation 2 (Broek, 1989)

$$K = \lim_{r \to 0} \sqrt{2 \cdot \pi \cdot r} \cdot \sigma_y \tag{2}$$

where r is the distance from the crack tip, and σ_y is stress in y direction as shown in Figure 2, and it is expressed as follows

$$\sigma_y = \frac{K}{\sqrt{2\pi r}} \cdot \cos\frac{\theta}{2} \cdot \left(1 + \sin\frac{\theta}{2} \cdot \sin\frac{3\theta}{2}\right) \tag{3}$$

Since the specimen was TL-oriented, this means that it was loaded in a tangential direction, but due to tissue orientation the crack propagated in a longitudinal direction, the angle θ in equation 3 equals 0. Only stresses in nodes lying in the crack propagation plane were thus taken into account in the calculation.

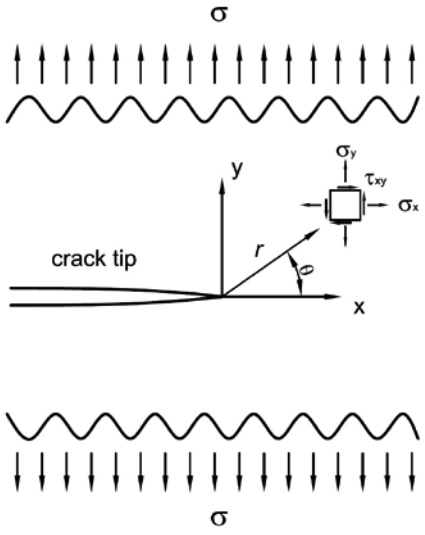

Figure 2 Stresses at the crack tip
Slika 2. Naprezanja na vrhu pukotine

The second method of the critical stress intensity factor calculation used the J integral according to equation 4 (Broek, 1989) and Figure 3

$$J = \int_{\Gamma} \left(W_d dy - T \frac{\partial u}{\partial x} ds\right) \tag{4}$$

Γ is integration path, and W_d is deformation energy per unit of volume,

$$W_d = \frac{1}{2} \sigma_{ij} \varepsilon_{ij} \tag{5}$$

T is stress vector acting perpendicularly on contour Γ, u is deformation vector, and ds is the Γ path differential.

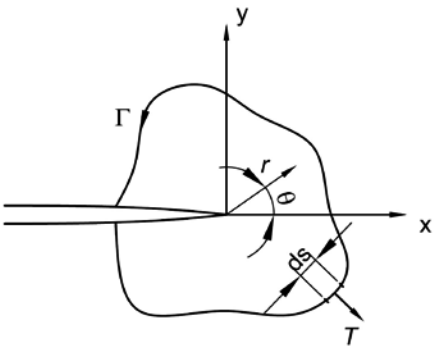

Figure 3 J integral
Slika 3. J integral

The value of the J integral was calculated by means of the Ansys programme so that its contour or Γ contour nodes were defined.

Since the specimen was modelled as linearly elastic, the value of J integral can be equalled with the elastic energy release rate G (Smith, 2003)

$$J_I = G_I \tag{6}$$

The following equation is also taken into account

$$G_I = \frac{K_I^2}{E`} \tag{7}$$

where $E`$ is an equivalent modulus of elasticity (Sih *et al*., 1965)

$$E` = \left[\frac{b_{11} b_{22}}{2}\left(\sqrt{\frac{b_{22}}{b_{11}}} + \frac{2b_{12} + b_{66}}{2b_{11}}\right)\right]^{-1/2} \tag{8}$$

and b_{ij} are compliance constants depending on the type of material. In the case of the plane-strain condition, the b_{ij} constants must be calculated from coefficients a_{ij}

$$b_{ij} = a_{ij} - \frac{a_{i3} a_{j3}}{a_{33}} \quad (i, j = 1,2,...,6) \tag{9}$$

where

$$a_{11} = \frac{1}{E_{11}},\ a_{22} = \frac{1}{E_{22}},\ a_{12} = a_{21} = -\frac{\nu_{12}}{E_{11}},\ a_{66} = \frac{1}{G_{12}} \tag{10}$$

The compliance coefficient values for the value of a_{11} were calculated from the measured modulus of elasticity, which amounted to 14 490 MPa, while the values

for other coefficients were taken from Kollmann and Cote (1984) (equation 1).

The third method of the critical stress intensity factor calculation used the differences of strain energies, from which the strain energy release rate per unit of crack propagation length was obtained. First a crack with a measured length was modelled, and then another with a longer crack. Differences in the lengths of modelled cracks ranged from 0.05mm to 0.35mm. The deformation energy of each modelled crack length was calculated by means of the programme. After that, the difference in the dW_d energies between the specimen with the longer crack and the specimen with the measured crack was calculated. The difference was divided by the difference in lengths da and the thickness of the modelled specimen b.

$$G_I = -\frac{1}{b}\frac{dW_d}{da} \tag{11}$$

Then the critical stress intensity factor was calculated considering equations 6 to 10.

The fourth method of critical stress intensity factor calculation was based on the deformation of material surrounding the crack, i.e., by the displacement of triangle element nodes as shown in Figure 4, and using the following equation (Sauoma and Sikiotis, 1986).

$$\begin{Bmatrix} K_I \\ K_I \end{Bmatrix} = [B]^{-1}[A]\sqrt{\frac{\pi}{2L_1}} \tag{12}$$

The matrix $[B]^{-1}$ is given by

$$[B]^{-1} = \begin{bmatrix} \mathrm{Re}\left\{\frac{i}{s_1 - s_2}[q_2 - q_1]\right\}\frac{1}{D} & \mathrm{Re}\left\{\frac{-i}{s_1 - s_2}[p_2 - p_1]\right\}\frac{1}{D} \\ \mathrm{Re}\left\{\frac{-i}{s_1 - s_2}[s_1 q_2 - s_2 q_1]\right\}\frac{1}{D} & \mathrm{Re}\left\{\frac{i}{s_1 - s_2}[s_1 p_2 - s_2 p_1]\right\}\frac{1}{D} \end{bmatrix} \tag{13}$$

$[D]$ is the matrix determinant

$$[D] = \det\begin{bmatrix} \mathrm{Re}\left\{\frac{i}{s_1 - s_2}[s_1 p_2 - s_2 p_1]\right\} & \mathrm{Re}\left\{\frac{i}{s_1 - s_2}[p_2 - p_1]\right\} \\ \mathrm{Re}\left\{\frac{i}{s_1 - s_2}[s_1 q_2 - s_2 q_1]\right\} & \mathrm{Re}\left\{\frac{i}{s_1 - s_2}[q_2 - q_1]\right\} \end{bmatrix} \tag{14}$$

and matrix $[A]$ is

$$[A] = \begin{bmatrix} 4u_B - u_c \\ 4v_B - v_C \end{bmatrix} \tag{15}$$

u_B and u_C are the displacements of nodes B and C in the x direction, and v_B and v_C are the displacements of nodes B and C in the y direction. L_1 is the length of triangle element, and s_1 and s_2 are complex zeros of the equation

$$a_{11}s^4 - 2a_{16}s^3 + (2a_{12} + a_{66})s^2 - 2a_{26}s + a_{22} = 0 \tag{16}$$

in the form of $s_j = \alpha_j + i\beta_j$ (j = 1,2). A zero with positive imaginary part $(\beta_j > 0)$ is appropriate for the solution,while p_j and q_j are

$$\begin{aligned} p_j &= a_{11}s_j^2 + a_{12} - a_{16}s_j \\ q_j &= a_{12}s_j + \frac{a_{22}}{s_j} - a_{26} \end{aligned} \tag{17}$$

In the case of plane-stress condition, the a_{ij} constants are compliance coefficients yielded by equation 10, and in the case of plane-strain condition by equation 9.

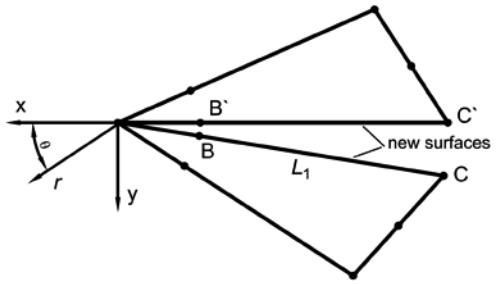

Figure 4 Triangle element with nodes
Slika 4. Elementi trokuta s čvorovima

Since the calculation takes account of the material deformation on only one side of the crack, the method can be used only for symmetric specimens with a symmetric load application. In order for the calculation to be as accurate as possible, only half of the specimen was modelled and on the lower side the programme was set a boundary condition that the specimen was symmetric. The crack tip was surrounded by two rows of 6 triangle elements each, the elements being around 0.1 mm or 1/1000 of the crack length long. The ratio between the size of the first row and the sec-

ond one was set as 1.5. The results were used to calculate the deformation of nodes in directions x and y, and to calculate the critical stress intensity factor K_{IC} for fracture mode I.

The fifth method of the critical stress intensity factor calculation used a generally known equation (Broek, 1989) applying to the CT specimen for plane-strain conditions in isotropic material

$$K_I = \frac{F}{B\sqrt{W}} f(a/W)$$

$$f(a/W) = \frac{(2+a/W)}{(1-a/W)^{3/2}}\left[0{,}886 + 4{,}64\frac{a}{W} - 13{,}32\left(\frac{a}{W}\right)^2 + 14{,}72\left(\frac{a}{W}\right)^3 - 5{,}6\left(\frac{a}{W}\right)^4\right] \quad (18)$$

where a is the crack length, W is specimen length and B specimen thickness.

The specimens moduli of elasticity E_L in a longitudinal direction were also measured. Specimens –130 mm long, 10 mm wide, and 6 mm high – were subjected to a four-point bending load on the tensile testing machine. A linear variable differential transformer (LVDT) was used to measure the specimen displacement during loading.

From the graph of the measurements of force depending on deformation, the linear regression curve coefficient in the area of linear dependence between force and deformation was determined by means of the Excel programme. The equation describing the displacement in the middle of the specimen depending on the specimen geometric data and loading force was used to calculate the modulus of elasticity E_L.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 1 indicates the measured values of the modulus of elasticity. The table shows that the specimens have an average modulus of elasticity E_L of 14 487 MPa, with standard deviation of 1 246 MPa.

Table 1 Measured modulus of elasticity in longitudinal direction E_L
Tablica 1. Izmjereni modul elastičnosti u longitudinalnom smjeru E_L

Specimen / *Uzorak*	E_L, MPa
1	14 975
2	12 442
3	15 701
4	16 694
5	13 543
6	14 874
7	13 789
8	15 293
9	13 875
10	13 684
Average / *Prosjek*	14 487
St. dev.	1 246

Figure 5 shows forces dependent on the crack mouth opening displacement of the specimen used to determine the critical stress intensity factor. The figure shows instantaneous force drop as a consequence of sudden crack propagation or an instable fracture. The figure clearly shows the linear elastic part of force dependence on mouth opening, shifting to the nonlinear part just before the crack propagates. The continuous line is a regression curve for the linear part of loading, while the inclination of the dashed line is by 5 % smaller than the continuous one. Since the intersection of a straight line with a 5 % smaller inclination and the measurements were practically equal to the maximum force, the maximum forces measured were used in the calculations.

Table 2 indicates the results of the critical stress intensity factor calculation for five different methods. The results of calculations written in bold differ insignificantly from each other. Calculations using the J integral (Figure 6) have been shown as the least sensitive to the size of elements and to the range of integration. The calculation values were around 0.496 MPa·√m, regardless of the size of basic elements, the type of elements surrounding the crack, and the distance of contour around the crack tip, up to the distance of 0.4 mm. At this distance, the integration path included two types of triangle elements and at least one type of 8-node brick element. In the case of a shorter distance, however, it was demonstrated that a satisfactory result requires at least two types of 8-node brick elements, as is the case with 1 mm large elements around the crack tip. In the case of two rows of triangle elements the accuracy of result is not satisfactory. In this case, at least one more row of 8-node brick elements is required.

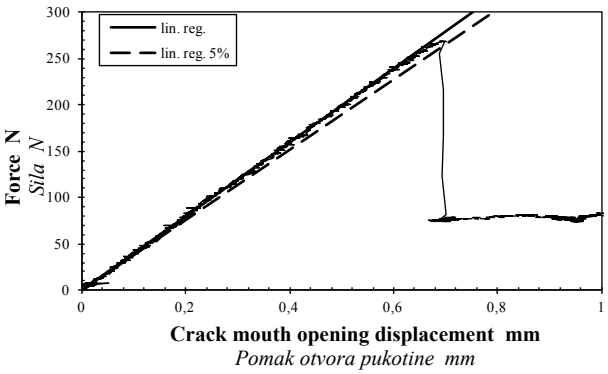

Figure 5 Force depending on crack mouth opening displacement with linear regression curves
Slika 5. Prikaz ovisnosti sile o pomaku otvora pukotine linearnom regresijskom krivuljom

Table 2 Critical stress intensity factor K_{IC} calculation; R – refinement of elements around crack tip – 8 nodes brick elements; T – triangle elements around crack tip
Tablica 2. Izračun faktora kritičnog intenziteta naprezanja K_{IC}; R – usklađivanje elemenata oko vrha pukotine – osam čvorova elementa; T – element trokuta oko vrha pukotine

	El. Size *Veličina elementa* mm	K_{IC} **(MPa√m) calculated from** / K_{IC} *(MPa√m) izračunan iz*										
		J integral (Eq. 4)				G_{IC} (Eq. 11)				Stand. (Eq. 18)	Ekst. K_I (Eq. 2)	Node displ. (Eq.12)
		dist. from crack tip, mm *Udaljenost od vrha pukotine, mm*				crack length dif., mm *Razlika duljine pukotine, mm*						
		0.2	0.4	1.6	6	0.1	0.15	0.25	0.35			
R	1	**0.497 (2el)***	**0.496 (4el)**	**0.495**	**0.495**	0.290	0.557	0.425	0.490	0.520	**0.494**	-
T		0.468 (2el)	**0.494 (3el)**	**0.495**	**0.496**	**0.495**	**0.496**	**0.497**	**0.499**		-	**0.492**
R	2	0.445 (1el)	**0.495 (2el)**	**0.495**	**0.495**	-	0.294	0.325	0.481		**0.494**	-
T		0.476 (2el)	**0.489(0.8 3el)**	**0.493**	**0.496**	0.512	0.507	0.508	0.491		-	**0.495**

* Values in brackets mean number of elements included in calculations. / *Vrijednosti u zagradama označavaju broj elemenata uključenih u izračun*.

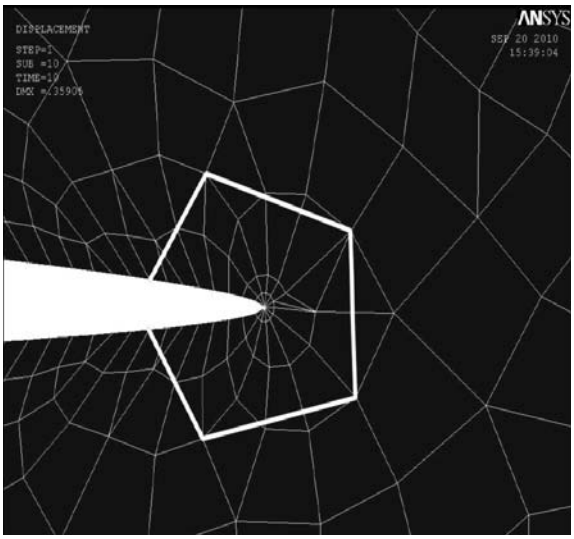

Figure 6 Meshed crack tip with *J* integral contour superimposed
Slika 6. Preklapanje mreže oko vrha pukotine s konturama *J* integrala

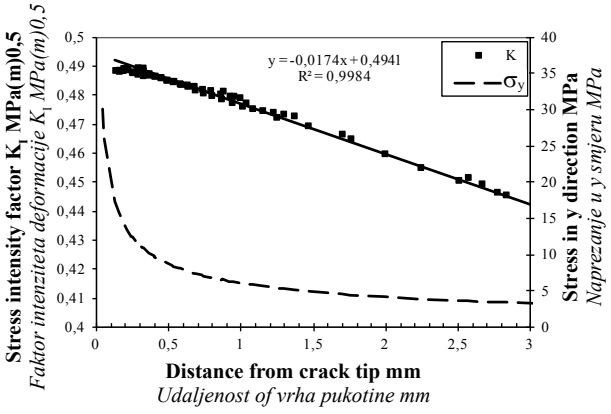

Figure 7 Stresses in y direction σ_y and stress intensity factor K_I with regression line as a consequence of distance from the crack tip
Slika 7. Prikaz ovisnosti naprezanja u y smjeru σ_y i faktora intenziteta naprezanja K_I o udaljenosti od vrha pukotine regresijskim krivuljama

Calculations based on difference of elastic deformation energy exhibit greater sensitivity to the size of elements as well as to the type of elements around the crack tip. The results are better in the case of triangle elements surrounding the tip. In the case of smaller elements, there is no deviation from the calculation using *J* integral and other two methods regardless of the size of the crack extension. When the crack is extended by 0.05 mm or 0.1% of the crack size, the results are no longer satisfactory whatever the size of the basic elements and type of elements surrounding the crack tip. In the case of 8-node brick elements where the refinement is made, the results are not satisfactory regardless of the size of elements. When elements of 2 mm in size were used and the crack was extended by 0.1mm, no calculation could be made because the elastic deformation energy decreased with an increased crack, which is contrary to other cases.

The calculation based on the stress intensity factor extrapolation at various distances of the crack tip to the distance of zero yielded equal results regardless of the size of the basic elements. The tip was surrounded only by elements with 8 nodes, since during the refinement of elements in the crack propagation line the triangle elements turned into 8-node brick elements. Stresses in the *y* direction and stress intensity factors as a consequence of the crack tip distance together with regression curve are shown in Figure 7. It clearly shows the linear dependence of the stress intensity factor on distance.

Likewise, the calculation based on the deformation of triangle element (Eq. 12) nodes was equal for both sizes of basic elements, while the triangle element size was the same in both cases, equalling 0.118 mm.

The calculation of critical stress intensity factor by a generally known equation for an isotropic CT specimen (Eq. 18) yielded about 5 % higher results. In our case, the reason for that was probably the orthotropic material, which has significantly lower modulus of elasticity in radial and in tangential direction compared to the longitudinal one, but in the equation 12 only the modulus of elasticity in longitudinal direction is used. Another reason could also be the specimen

height-to-length ratio. This is to say that the equation assumes the mentioned ratio to be 1, while in our case it was less than 1.

Since the calculation of the critical stress intensity factor by means of the *J* integral, in which the contour is sufficiently far from the tip, is satisfactory, and the calculation method simple, the *J* integral was used to calculate K_{IC} for the remaining specimens.

Table 3 shows the critical stress intensity factors calculated by means of the *J* integral. The integral contour was 6 mm away from the crack tip at the basic elements size of 2 mm and triangle elements around the crack tip. An average value of critical stress intensity factor is 0.56 MPa·√m with standard deviation of 0.047 MPa·√m, which represents less than 10 % of the mean value determined. A similar deviation can be found with the modulus of elasticity. Considering Vasić and Stanzl-Tschegg (2007), who stated the value of 0.62 MPa·√m for the RL orientation as the beech fracture toughness with a moisture content of 12 %, and the fact that fracture toughness in the TL configuration is lower than that of the RL configuration, as stated by Stanzl-Tschegg and Navi (2009), it can be ascertained that the values we obtained comply with their findings as well with Majano-Majano *et. al.* (2012). It should also be noted that the bigger specimens would probably give more representative K_{IC} values, since they are dimension dependent as reported by Stanzl-Tschegg *et. al.* (1995).

Table 3 Critical stress intensity factors K_{IC}
Tablica 3. Faktor kritičnog intenziteta naprezanja K_{IC}

Specimen *Uzorak*	K_{IC}, **MPa·√m**	**Average** *Srednja vrijednost*	**St. dev**. *Stand. devijacija*
1	0.49	0.56	0.047
2	0.63		
3	0.53		
4	0.62		
5	0.57		
6	0.58		
7	0.52		
8	0.57		
9	0.53		

4 CONCLUSION
4. ZAKLJUČAK

Comparing different methods for mode I critical stress intensity factor calculations, the *J* integral proves to be the most appropriate considering the simplicity and sensitivity to the size and shape of the elements. It was used to calculate the critical stress intensity factor for beech wood in a TL configuration, which means that the specimens were loaded in a tangential direction while the crack propagated in a longitudinal direction. The average value was 0.56 MPa·√m with a standard deviation of 0.047 MPa·√m. Comparing the results of Vasic and Stanzl-Tschegg (2007), who obtained K_{IC} of 0.62 MPa·√m in the RL configuration at 12 % wood moisture content, and the fact that the value in TL configuration is lower than the value in RL configuration, we find that the values obtained agree with research results of other authors like Majano-Majano *et al*. (2012), who stated the value for K_{IC} in TL configuration in the range from 0.44 to 0.63 MPa√m and Ozyhar *et. al.* (2012), who determined K_{IC} in TL configuration to be around 0.406. Likewise, it was found that researchers predominantly investigate the so-called 'stable fracture', which means that the crack propagates in proportion to the crack mouth opening displacement. Beech wood in the TL configuration, however, has shown to be a distinctly brittle material, since after the maximum load is achieved, the crack propagates instantaneously and at a great speed to a certain equilibrium length (Merhar and Bučar, 2012), which various authors consider to be an unstable fracture. However, the RL configuration is exhibited as a more stable one, and therefore several authors prefer to use it as a model for determining the critical stress intensity factor.

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LABORATORY FOR HYDROTHERMAL PROCESSING OF WOOD AND WOODEN MATERIALS

Testing of hydrothermal processes of wood and wooden materials

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Project and development of conventional and unconventional drying systems

Steaming chamber projects

Establishing and modification of kiln drying schedules

Consulting in selection of kiln drying technology

Introduction of drying quality standards

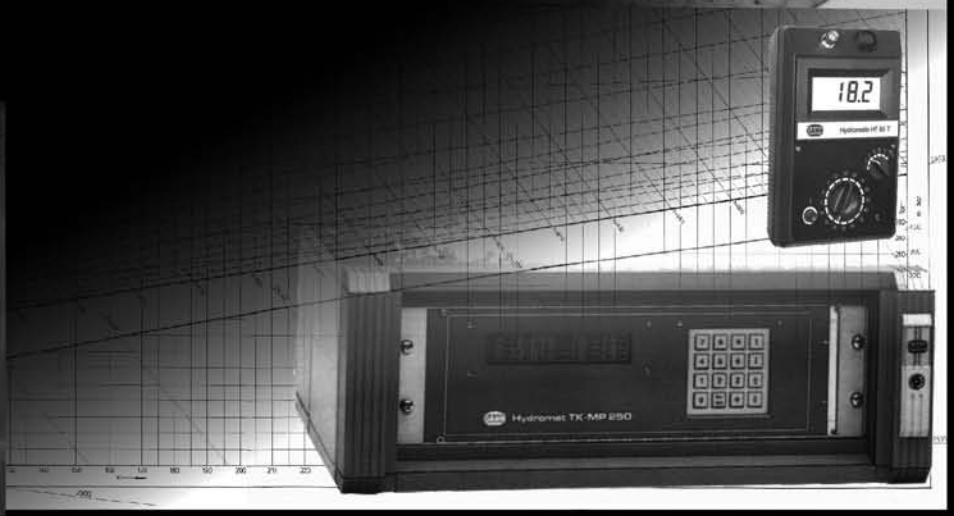
Determination of wood bending parameters

Detection and reducing of hydrothermal processes wood defects

Reducing of kiln drying time

Drying costs calculation

Kiln dryer capacity calculation



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Quantitative HPLC Analysis of Catechin in Wound-Associated Wood and Knots of Beech

Kvantitativna HPLC analiza katehina u ranjenom dijelu i kvrgama bukova drva

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ABSTRACT • *The aim of this research was to examine the content of catechin in normal and traumatic structures of beechwood by high performance liquid chromatography (HPLC). Two discs were sawn from each of six harvested trees. The first disc was taken from the lower, wounded part and the second one from the upper part of each stem. Discs containing the bases of living and dead branches were taken from the crown. Samples of wound-wood, reaction zones, sapwood, as well as living and dead knots, were sampled from discs. Samples were milled and then extracted sequentially by cyclohexane and methanol/water in a Soxhlet apparatus. A method for the separation of catechins from extracts was developed for the present chromatographic investigation. Statistical analysis did not reveal significant differences in total or hydrophilic extractives, nor in the content of catechin among the investigated trees. The content of hydrophilic extractives and catechin were significantly different among the investigated categories of wood tissues. Wound-wood and knot extracts contained the highest amount of this flava-3-ol. Reaction zones contained higher amounts of catechin than discolored wood, but less than sapwood. The extracts of discolored wood showed the lowest amounts of catechin. Sapwood samples that originated from wounded discs exhibited significantly higher contents of catechin than normal sapwood from upper discs. Accumulation of bioactive compound catechin in wound-wood, sapwood and knots is considered to be an important part of the survival strategy of living trees.*

Keywords: *catechin, liquid chromatography, wound-wood, knots, Fagus sylvatica*

SAŽETAK • *Cilj istraživanja bio je ispitati sadržaj katehina u normalnim i traumatskim strukturama bukovine primjenom tekućinske kromatografije (HPLC). Od šest bukovih stabala ispiljena su po dva diska. Prvi je disk uzet iz donjega, ranjenog dijela stable, a drugi od gornjeg dijela svakog stabla. Diskovi koji su sadržavali baze živih i mrtvih grana uzeti su od krošnje. Uzorci ranjenog dijela drva, reakcijskih zona, bjeljike, kao i živih i mrtvih kvrga, izrađeni su od pripremljenih diskova. Ispiljeni su uzorci sekvencijalno ekstrahirani cikloheksanom i smjesom metanola i vode u Soxhlet aparatu. Metoda za odvajanje katehina iz ekstrakata razvijena je za potrebe ovoga kromatografskog istraživanja. Statistička analiza dobivenih podataka nije pokazala značajne razlike između ukupnih i hidrofilnih ekstraktiva, niti u sadržaju katehina među istraživanim stablima. Sadržaj hidrofilnih ekstraktiva i katehina značajno se razlikuje u ispitivanim vrstama drvnog tkiva. Ekstraktivi iz ranjenog drva i kvrga sadržavali*

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su najveću količinu flava-3-ola. Reakcijsko drvo sadržava veće količine katehina nego drvo s diskoloracijom, ali manje nego drvo bijeljike. Ekstraktivi drva s diskoloracijom imali su najmanje količine katehina. Uzorci od drva bjeljike izrađeni od diskova ranjenog drva imali su značajno veći sadržaj katehina nego uzorci normalnog drva bjeljike izrađeni od diskova od gornjeg dijela trupca. Akumulacija bioaktivnih spojeva katehina u ranjenom drvu, drvu bjeljike i kvrgama smatra se važnim dijelom strategije preživljavanja stabala.

Ključne riječi: *katehin, tekućinska kromatografija, ranjeno drvo, kvrge, Fagus sylvatica*

1 INTRODUCTION
1. UVOD

Utilization of hardwood has been one of the main industrial and research challenges of the European wood sector in recent years. European beech (*Fagus sylvatica* L.) is an economically important tree species in the Dinaric region of south-eastern Europe. Beech wood has a favorable density and relatively homogenous structure, satisfactory workability and exceptionally good steam bending properties, which makes beechwood an all-purpose wood with a wide spectrum of applications, ranging from furniture, especially curved and turned parts of chairs, parquet, boats, toys, textile weaving shuttles, tool handles, piano parts, railway sleepers, veneer, plywood, particle and fiber boards, pulp and paper to food containers, because it does not impart taste or odor (Torelli, 1994). One of the main deficiencies of this tree species is its tendency to develop discolored wood in the central part of the tree, often called red heart, red heartwood, facultatively colored heartwood, false heartwood or red core (Bosshard, 1974; Torelli, 1984; Shigo, 1986; Sachsse, 1991; Wernsdörfer *et al.*, 2005). As opposed to normal wood, discolored beech wood is characterized by its unfavorable technological properties, including hard impregnation, problems in drying processes and veneer production and esthetic insufficiency (Koch *et al.*, 2000; Pöhler *et al.*, 2006). In addition, wood of trees from unevenly managed forests is regularly subjected to mechanical wounding, which results in a relatively predictable response of the tree. This includes the development of discoloration and eventual decay, accompanied by the formation of reaction zones, which separate compromised and sound sapwood, and the formation of wound-wood, which attempts to overgrow the wound. These compartmentalization barriers that try to block spreading of negative consequences of wounding towards intact and vital tissues, are generally described by anatomical alterations and cell necrosis accompanied with the accumulation of antimicrobial compounds and formation of polyphenol deposits (Shortle, 1979; Bauch, 1984; Shigo, 1986; Torelli *et al.*, 1994; Schwarze and Baum, 2000; Dujesiefken *et al.*, 2005; Dujesiefken and Liese, 2006; Oven *et al.*, 2008; Vek *et al.*, 2013a).

It has been recently showed by spectrophotometric analysis that the content of total phenols, flavonoids and proanthocyanidins is markedly lower in red heart than in reaction zones and wound-wood extracts (Vek *et al.*, 2013a; 2013b). It was reported that differences in the content of total phenols in reaction zones indicate differences in their formation process, differences in alterations to surrounding tissues and in the characteristics of individual trees (Vek *et al.*, 2013b). It was demonstrated that fungicidal properties on wood decaying fungi can be ascribed to extracts of wound-wood, as well as to that of healthy sapwood of beech (Vek *et al.*, 2013a). Recent chromatographic research on hydrophilic extractives of discolored and normal wood demonstrated that catechin is the dominant phenolic compound in beechwood (Baum and Schwarze, 2002; Koch *et al.*, 2003; Zule and Može, 2003; Hofmann *et al.*, 2004; 2008; Jamalirad *et al.*, 2011; 2012), but there is no information on the occurrence of catechin in wound-associated beechwood. As catechin has proven antimicrobial and fungistatic properties and it is also considered as relevant antioxidant, this flavonoid can potentially be applied in the field of wood preservatives or as technical antioxidant (Malterud *et al.*, 1985; Feucht *et al.*, 1994; Choi *et al.*, 2001; Mantani *et al.*, 2001; Baum and Schwarze, 2002; Hsu *et al.*, 2007; Yen and Chang, 2008; Rosales-Castro *et al.*, 2012).

The aim of our research was to examine the content of catechin in normal and traumatic structures of beechwood, using high performance liquid chromatography (HPLC). A chromatographic method was developed for this purpose and samples of wound-wood, reaction zones, sapwood, as well as living and dead knots, were removed from mechanically wounded trees. Knots were included because there are parallels in the function of these tissues after branch breakage (Willför *et al.*, 2003a) and wound-associated tissues.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Chemicals
2.1. Kemikalije

Methanol (HPLC grade) was provided by J.T. Baker (Deventer, Netherlands), (+)-catechin (analytical standard) and formic acid (Puriss. p.a., ~ 98 %) were purchased from Sigma-Aldrich (Steinheim, Germany), while cyclohexane (99 %) was supplied by Carlo Erba Reagents (Val de Reuil, France). Ultrapure water was produced with a Millipore water purification system A10 (Billerica, USA), which was kindly provided by the Department of Forest Ecology of the Slovenian Forestry Institute.

2.2 Material
2.2. Materijal

Samples included in the present investigation were obtained from six adult, mechanically wounded beech trees. They were selected and felled in the forest area of Kočevski Rog in southern Slovenia. Two sample discs, approximately 10 cm thick, were sawn from

each harvested tree. The first disc was taken from the lower, wounded part and the second one from the upper part of each stem. Discs containing both wound-associated tissues and abiotic discoloration were thus obtained. Furthermore, discs containing the bases of living and dead branches were taken from the crown region of individual trees. These samples will be referred to as knots (Torelli, 1990). Wood blocks of wound-wood (W), intact sapwood (S), reaction zone (RZ), discolored wood (DW) and living (LK) and dead knots (DK) were sawn from the sample discs and ground by a Retsch ZM 200 centrifugal mill (Haan, Germany), producing particles that passed through a 0.5 mm sieve (35 mesh screen). Heating of samples was prevented by applying dry ice during the milling process. The obtained wood meals were stored in a cool dark place until further processing. Sixty samples, ten per trees, were thus prepared for subsequent extraction and chromatographic analysis.

2.3 Extraction
2.3. Ekstrakcija

Wood and knot samples were extracted in two steps in a Soxhlet apparatus. Lipophilic compounds, which can have a deleterious effects on chromatographic instrumentation due to column clogging (Slanina and Glatz, 2004), were removed from 2.5 g of wood sample using 250 ml of cyclohexane for 4 hours. Hydrophilic extractives and catechin were subsequently extracted for 6 hours with 250 ml of methanol/water mixture (95:5, v/v). The extraction procedure was defined in a preliminary experiment. Total extractives and the content of hydrophilic extractives were determined gravimetrically, whereby the results were expressed in percentage of dry matter (%) and in milligrams per gram of dry wood ($mg \cdot g^{-1}$), respectively.

2.4 HPLC analysis
2.4. HPLC analiza

The chromatographic separation of catechin was performed on a Thermo Fischer Scientific Accela HPLC modular system (Waltham, USA), equipped with an Accela 600 quarter pump and Accela photodiode array detector (PDA). Methanolic extracts were filtered through Chromafil 0.45 µm polyamide filter (Macherey-Nagel, Düren, Germany) and 3 µl of each sample was directly injected into the column. A method for the separation of catechins from the extracts of wound-associated beechwood was developed for the present chromatographic investigation. Extractives were separated in an Accucore PFP column (Thermo Fischer Scientific) with particle size of 2.6 µm and dimensions of 2.1 mm × 150 mm. The column was thermostatted at 30 °C. The mobile phase consisted of water with 0.1 % of formic acid (v/v) as solvent A and methanol containing 0.1 % of formic acid as solvent B. The 10 minutes gradient from 5 to 65 % of solvent B was applied for elution of catechin, whereby the mobile phase flow rate was defined at 400 $\mu l \cdot min^{-1}$. The detection wavelength was adjusted to 275 nm and UV spectra from 200 to 400 nm were recorded for peak identification. Quantitative analysis was based on a three point calibration curve, consisting of standard solutions with mass concentration of 0.5, 5 and 50 $\mu g \cdot ml^{-1}$. Chromatograms were evaluated by ChromQuest 5.0 software. Peak identification was achieved by comparison of retention times and UV spectra of separated compounds with analytical standards. The content of catechin was expressed in mg of catechin per gram of dry sample ($mg \cdot g^{-1}$)

2.5 Statistics
2.5. Statistika

A comparison of total extractives, contents of hydrophilic extractives and content of catechin in tissues of wounded beech trees was performed by Statgraphics software. Values of measurements were first checked for normal distribution. Significant differences were then investigated by means of ANOVA at a 0.95 confidence interval. The contents of phenolic extractives in different trees and in different categories of wound-associated wood and knots were further compared by means of the multiple range test (LSD procedure).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Total extractives and content of hydrophilic extractives
3.1. Ukupni ekstraktivi i sadržaj hidrofilnih ekstraktiva

The average values for total extractives (%) and content of hydrophilic extractives (mg/g) among the investigated beech trees are presented in Table 1. Statistical analysis (ANOVA) did not reveal significant differences, either in average content of total extractives or in average content of hydrophilic extractives among the investigated beech trees. However, hydrophilic extractives were significantly different between tree No. 2 and tree No. 4 (LSD procedure) (Table 1).

Table 1 Total extractives and content of hydrophilic extractives in beech trees; average values are accompanied by standard deviations
Tablica 1. Ukupni ekstraktivi i sadržaj hidrofilnih ekstraktiva u bukovini; prosječne vrijednosti dane su sa standardnom devijacijom

Tree No. *Broj stabla*	**Total extractives,** % *Ukupni ekstraktivi, %*	**Hydrophilic extractives,** $mg \cdot g^{-1}$ *Hidrofilni ekstraktivi,* $mg \cdot g^{-1}$
1	1.82 ± 0.43^{a}	$47.47 \pm 14.46^{a, b}$
2	2.03 ± 0.54^{a}	41.33 ± 7.11^{a}
3	1.97 ± 0.52^{a}	$44.27 \pm 13.93^{a, b}$
4	1.77 ± 0.48^{a}	55.53 ± 19.73^{b}
5	1.92 ± 0.54^{a}	$47.04 \pm 12.54^{a, b}$
6	1.81 ± 0.64^{a}	$49.64 \pm 15.62^{a, b}$

$^{a - b}$ Different letters within the same column indicate statistically significant differences at a 95.0% confidence level (Fisher's least significant difference (LSD) procedure). / *Različita slova u istom stupcu označavaju statistički značajne razlike s razinom pouzdanosti od 95 % (Fisherov postupak najmanje značajne razlike, LSD)*

Average values for total extractives and average content of hydrophilic extractives obtained from wound-associated tissues and knots are given in Table 2. Total extractives showed no significant differences among categories of beechwood (ANOVA, $p = 0.0585$). However, the highest percentage of extractible compounds was distinctive for wound-wood and knot extracts, while the lowest amounts of these compounds described discolored wood. Wound-wood contained a significantly higher amount of total extractives than intact sapwood (LSD procedure). In contrast, extraction of discolored wood gave significantly less extractives than wound-wood and living knots (Table 2).

Table 2 Total extractives and content of hydrophilic extractives in wound-associated wood and knots of beech. Average values are accompanied by standard deviations.
Tablica 2. Ukupni ekstraktivi i sadržaj hidrofilnih ekstraktiva u ranjenom drvu i kvrgama bukova drva; prosječne vrijednosti dane su sa standardnom devijacijom

Category of wood *Kategorija drva*	**Total extractives, %** *Ukupni ekstraktivi, %*	**Hydrophilic extractives, mg·g^{-1}** *Hidrofilni ekstraktivi, mg·g^{-1}*
Wound-wood *ranjeno drvo*	2.24 ± 0.36^{a}	55.05 ± 20.29$^{a, d}$
Intact sapwood *zdrava bjeljika*	1.75 ± 0.44$^{b, c}$	47.22 ± 13.54$^{a, b}$
Reaction zone *reakcijsko drvo*	1.97 ± 0.44$^{a, b, c}$	42.61 ± 8.76$^{b, c}$
Discolored wood *drvo s diskoloracijom*	1.61 ± 0.67^{b}	37.94 ± 9.44^{c}
Living knot *živa kvrga*	2.14 ± 0.40$^{a, c}$	65.75 ± 5.92^{d}
Dead knot *mrtva kvrga*	2.11 ± 0.42$^{a, b, c}$	49.53 ± 17.14$^{a, b, c}$

$^{a-d}$ Different letters within the same column indicate statistically significant differences at a 95.0% confidence level (Fisher's least significant difference (LSD) procedure). / *Različita slova u istom stupcu označavaju statistički značajne razlike s razinom pouzdanosti od 95 % (Fisherov postupak najmanje značajne razlike, LSD)*

In contrast to the distribution of total extractives, a statistically significant difference is evident among different categories of the investigated wood tissues for hydrophilic extractives (ANOVA, $p = 0.0005$), ranging from 28.50 to 75.34 mg·g^{-1} (Table 2). The highest average content of hydrophilic extractives was determined for methanolic extracts of living knots. Wound-wood had significantly more hydrophilic extractives than the reaction zone. Discolored wood was the poorest in hydrophilics, whereby its content was significantly different from wound-wood, healthy sapwood and living knots. Average values for the content of hydrophilic extractives were significantly different between living and dead knots (Table 2).

3.2 Quantitative HPLC analysis of catechin
3.2. Kvantitativna HPLC analiza katehina

The average content of catechin was not significantly different among the examined beech trees (ANOVA, $p = 0.5455$). The content of catechin in the investigated trees ranged between 0.052 and 2.080 mg·g^{-1}, with the highest average value being measured in tree No. 4 (Figure 1). The high variability in the content of catechin within an individual tree (Figure 1) reflects differences among categories of wood tissues.

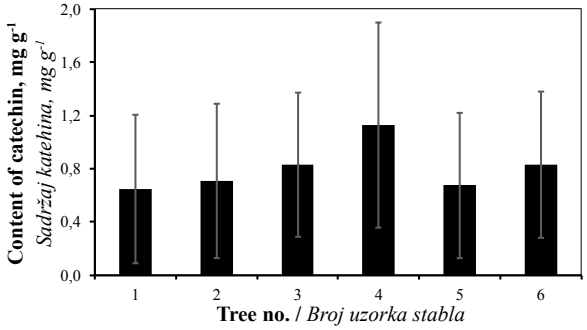

Figure 1 Average content of catechin in investigated beech trees. Error bars represent standard deviation.
Slika 1. Prosječni sadržaj katehina u istraživanim stablima bukve; na stupcima su označene standardne devijacije

The distribution of catechin among wound-associated tissues and knots of beech are given in Figure 2. Chromatograms of wound-wood, reaction zone and living knot are shown in Figure 3 to illustrate the occurrence of catechin. The average content of catechin was significantly different among different categories of wood tissues (ANOVA, $p = 0.0000$). Wound-wood and knot extracts contained the highest amount of this flavanol, while extracts of discolored wood showed the lowest amounts of catechin. Knot extracts contained significantly higher contents than sapwood, reaction zone and discolored wood. In comparison to wound-wood, extraction of dead knots resulted in a higher content of catechin. The difference between dead and living knots was not statistically significant. The amount of catechin in wound-wood was significantly higher than in sapwood, reaction zone and discolored wood. Sapwood samples contained significantly higher contents than reaction zone. The content of catechin in the reaction zone is highly variable and not significantly different from that in discolored wood (Figure 2).

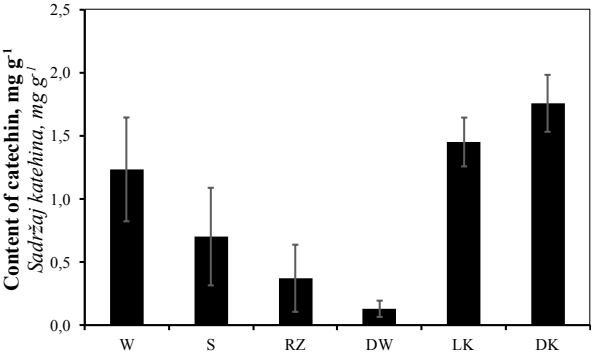

Figure 2 Content of catechin in investigated categories of beechwood. W = wound-wood, S = intact sapwood, RZ = reaction zone, DW = discolored wood, LK = living knot and DK = dead knot. Error bars represent standard deviation.
Slika 2. Sadržaj katehina u istraživanim kategorijama drva; W – ranjeno drvo, S – zdrava bjeljika, RZ – reakcijsko drvo, DW – drvo s diskoloracijom, LK – živa kvrga, DK – mrtva kvrga; na stupcima su označene standardne devijacije

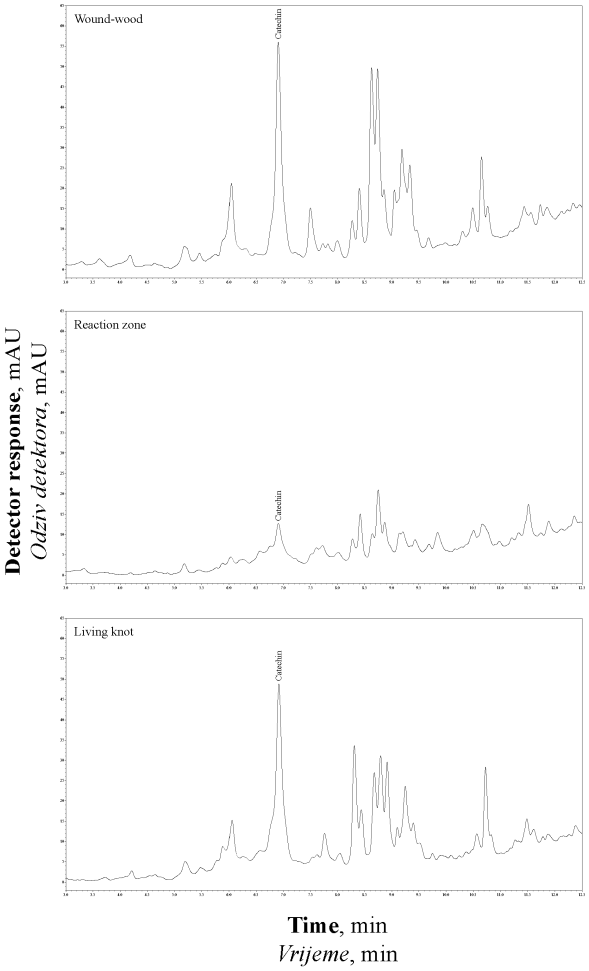

Figure 3 High performance liquid chromatograms of wound-wood, reaction zone and living knot showing the occurrence of catechin in the tissues
Slika 3. Tekućinska kromatografija ranjenog drva, reakcijskog drva i živih kvrga iz koje se vidi pojava katehina u drvnom tkivu

Variance component analysis revealed that 77.46 % of the variability in the content of catechin could be explained by the category of wood tissue, whereby 22.54 % of variability remained unexplained. As shown in Figure 4, a significant correlation between the content of catechin and hydrophilic extractives was found (R^2 = 64. 67 %, p = 0.0000).

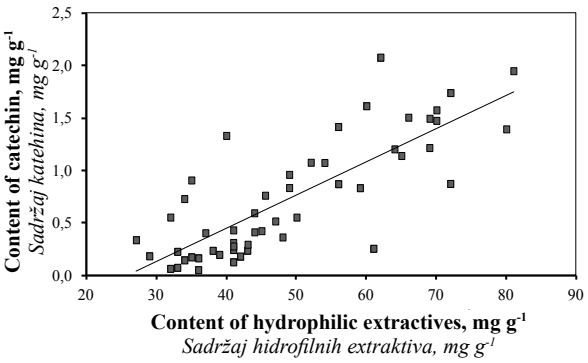

Figure 4 Correlation between the content of catechin and content of hydrophilic extractives in beech
Slika 4. Korelacija između sadržaja katehina i sadržaja hidrofilnih ekstraktiva u bukovu drvu

The content of catechin in samples taken from lower, directly wounded discs and from upper discs with discolored red heart is shown in Figure 5. Sapwood samples that originated from wounded discs had a significantly higher content of catechin than sapwood from the upper disc (ANOVA, p= 0.0005). As shown in Figure 5, differences in the content of catechin of reaction zones and discolored wood from two heights along the stem were not statistically significant.

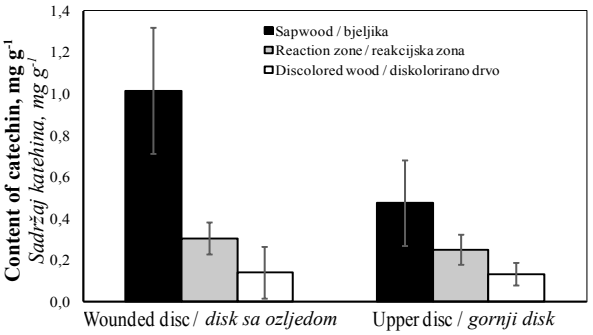

Figure 5 Content of catechin in wound-associated wood samples taken from a wounded disc and from a disc containing abiotic discoloration. Error bars represent standard deviation.
Slika 5. Sadržaj katehina u uzorcima ranjenog drva uzetima iz diska ranjenog drva i diska koji ima abiotsku diskoloraciju; na stupcima su označene standardne devijacije

Investigation of the content of both total and hydrophilic extractives in wood of selected trees confirmed the finding that *Fagus sylvatica* is a species with a relatively low amount of extractives (Rowe and Conner, 1979). Comparison of the extractive content of the examined trees revealed relatively little variation between trees from the same growing site. However, high variability in the content of hydrophilic extractives and catechin among different categories of wound associated wood tissues and knots revealed that different tissues could have different physiological functions in a living tree. It has previously been reported that sapwood of American beech (*Fagus grandifolia* Ehrh.) contains up to 4 % of extractives and discolored wood (heartwood in the original reference) contains less than 2 % of extractives (Rowe and Conner, 1979). Our results on the content of extractives in various categories of wood should also be elucidated from the methodological aspect, because the sampling procedure could have a crucial effect on the content of extractives measured in wood, irrespective of the extraction procedure and solvents used. For example, 5 to 9 times less hydrophilic extractives were measured in beech wood chips that were sequentially extracted with hexane and acetone by Soxhlet extraction (Zule and Može, 2003) than in our study.

Detailed chromatographic analysis of more polar extractives revealed that they consisted mainly of typical wood monosaccharides, whereas catechin was the predominant phenolic compound (Kubel *et al.*, 1988; Zule and Može, 2003). The distribution of catechin in different categories of wood tissues was in strong correlation with the content of hydrophilic

extractives (Figure 4). This relationship could have practical consequences as a means of relatively simple determination of catechin in wood of living trees. A relationship between the content of an individual compound and assessment of the content of a particular group of compounds has also been found for wood in other species. For instance, a strong relationship was confirmed for pinosylvin and the content of total phenols in wood extracts of pines (Venäläinen *et al.*, 2003; 2004). Our results on the distribution of catechin in sapwood, reaction zone and discolored wood of beech showed that reaction zones, which have been postulated as compartmentalization tissues, contained a higher amount of catechin than the adjacent discolored wood, but lower than sound sapwood. Our results are in accordance with the observations of Baum and Schwarze (2002). On the other hand, Hofmann *et al*. (2004) reported an abrupt change in the content of catechin, i.e., a high amount of catechin in inner sapwood and a sharp decrease beyond the color boundary. Nevertheless, our results support the suggestion of Hofmann *et al.* (2004; 2008) that catechin participates in the molecular process of red heart formation and in the formation of the chromophores of discolored wood. The relatively low amounts of catechin in discolored wood could be explained by the participation of this flavonoid in the formation of proanthocyanidins, as previously reported by some research groups (Schwarze and Baum, 2000; Baum and Schwarze, 2002). Wound-wood and especially knots exhibited a higher content of catechin than other tissues. A higher content of phenolic extractives has been found in knots of various tree species (Willfor *et al.*, 2003b; 2005; 2007). Wound-wood, which is ontogenetically young tissue, contained a higher content of catechin than sapwood in our experiment. It should be noted here that young sapwood has been shown to contain less catechin than old, inner sapwood (Hofmann *et al.*, 2004). Comparison of the catechin content in sapwood from different tree heights in our study, which also corresponds to different ages, showed that sapwood of older samples contained a higher amount of catechin. It appears that a high content of catechin in the tissue could have an important function in restricting the growth of wood decaying fungi. It has been recently demonstrated that methanolic extracts of wound-wood and sapwood inhibited the growth of wood decaying fungi, whereas extracts of reaction zones did not have an inhibitory effect (Vek *et al.*, 2013a). Extract of knots were not included in our antifungal experiment. However, the high content of catechin in both living and dead knots in beech could have an important protective function, due to its occurrence at the position in which trees, long living organisms, are exceptionally vulnerable to the ingress of pathogenic organisms after branch breakage.

4 CONCLUSIONS
4. ZAKLJUČAK

The content of catechin in wood of the investigated beech trees revealed high within-tree variation, as a result of different categories of wood tissues involved in the investigation. Our findings revealed that a high content of catechin is present in knots, wound-wood and sapwood. Wound-wood, which can be considered to be physiologically and ontogenetically young tissue, contained a higher amount of catechin than the remaining stem samples. Knots are actually the bases of branches, which are attached to stem wood in a complex way, and represent an extremely vulnerable point in the tree in case of branch breakage. The accumulation of a bioactive compound such as catechin in wound-wood, sapwood and knots is considered to be an important part of the survival strategy of trees.

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Oxidative Activation of Bagasse Fibers Surfaces in Medium Density Fiberboard Manufacturing

Oksidativna aktivacija površine vlakanaca u proizvodnji MDF ploča

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ABSTRACT • *This study presents the investigation of the effects of oxidant type (nitric acid and potassium dichromate), oxidant content (three different levels as 2, 4, and 6 percent) and urea- formaldehyde (UF) resin percentage (two levels as 5 and 7 percent) on mechanical and physical properties of interior grade medium density fiberboard made from bagasse fibers. Some panel properties were studied, such as modulus of rupture (MOR) and modulus of elasticity (MOE) in bending, compression-shear strength (C.S sth.), water absorption (WA) and thickness swelling (TS) after 2- and 24-hour immersion in cold water. In addition, the results indicated the best values for WA and TS after 2- and 24-hour immersion, and C.S. sth. was discerned at 7 percent UF resin content, together with 6 percent nitric acid. Furthermore, the greatest values for MOR and MOE were related to 7 percent UF resin content together with 4 percent nitric acid.*

Keywords: *medium density fiberboard, bagasse, oxidative activation, nitric acid, potassium dichromate*

SAŽETAK • *U studiji je istražen utjecaj vrste oksidansa (dušične kiseline i kalijeva dikromata), sadržaja oksidansa (2, 4 i 6 %) i postotnog udjela urea-formaldehidne smole (UF) (5 i 7 %) na mehanička i fizička svojstva ploča vlaknatica srednje gustoće, proizvedenih od bagasse vlakana. Analizirana su ova svojstva ploča: modul loma (MOR) i modul elastičnosti (MOE) pri savijanju, tlačno-smicajna čvrstoća (C.S sth.) te upijanje vode (WA) i debljinsko bubrenje (TS) nakon 2 i 24 sata potapanja u hladnoj vodi. Rezultati su pokazali najbolje vrijednosti za WA i TS nakon 2 i 24 sata potapanja, te za C.S sth. pri 7 %-tnom sadržaju UF smole i pri 6 % dušične kiseline. Nadalje, najveće vrijednosti za MOR i MOE zabilježene su pri 7 %-tnom sadržaju UF smole i pri 4 % dušične kiseline.*

Ključne riječi: *ploče vlaknatice srednje gustoće, bagasse, oksidativna aktivacija, dušična kiselina, kalijev dikromat*

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1 INTRODUCTION
1. UVOD

Faced with an increasing worldwide wood fiber shortage, environmental considerations, and in order to meet the future demand, the use of non-wood lignocellulosic fiber resources has been increased, and wood composites industry is showing a renewed interest in the production of panel products from agricultural residues (Chow, 1975; Odozi *et al*., 1986; Sampatharajan *et al*., 1992). Unfortunately, in Iran, similar to many developing Asian countries, deforestation and over harvesting have raised environmental awareness, which focused on the studies for using non-wood renewable resources in composite panel production. Non-wood based resources are getting more important as a raw material in the manufacture of composite panels. For countries like Iran, agricultural residues show excellent potential in composite manufacturing industries. Among them, sugarcane residue is one of the best raw materials for that purpose. Bagasse is abundant, unused, and can be obtained at a very low cost. Its lignin content is low and its open structure will facilitate liquid penetration (Zare-Hosseinabadi *et al*., 2008).

Composite panels, such as medium density fiberboard (MDF), are widely used in the construction and furniture industries (Maloney, 1996; Sellers, 2001; Reddy and Yang, 2005). A large amount of increasingly more expensive petroleum-derived adhesives are needed for their manufacture. For example, the production of medium density fiberboard requires a large volume of adhesive, which accounts for up to 20% of the production costs (Pierre-Louis *et al*., 2008). In addition, during production and end-use of MDF, particleboards, and other adhesively bonded products glued with formaldehyde-containing adhesives, such as urea-formaldehyde, formaldehyde emissions are a concern for the manufacturers and consumers (Maloney, 1996; Sellers, 2001). The stringent environmental and human health safety regulations have prompted research into reducing the amount of harmful and/or expensive adhesive components and replacing synthetic adhesives with more environmentally-friendly and safer alternatives (Widsten and Kandelbauer, 2008). One of the considerable potential techniques is the use of oxidizing chemicals to bond wood components (Johns and Woo, 1978). As early as 1939, Tischer (1939) reported on the use of oxidizing agents, such as potassium or sodium dichromate or nitric acid. He concluded that the use of an oxidant may be interpreted as leading to inter- fiber bonding (Tischer, 1939). Surface activation is today a common industrial process for many materials, e. g. in the paper, plastic, metal, wood and wood composites (Nussbaum, 1993). With an activated surface, a higher surface energy is obtained. This gives better bonding qualities in a subsequent operation. Hydrogen bonding and covalent bonding are thereby facilitated, resulting in much stronger bonding than the Van der Waal's forces possible between low energy surfaces (Nussbaum, 1993). A number of techniques are today available for achieving activated bonding (Nussbaum, 1993). Nimz (1974) reported on the use of hydrogen peroxide, a strong oxidizing agent, in mixtures with potassium ferricyanide and pulping residues to bond medium density particleboards. Stofko and Zavarin (1977) reported on the use of a wide variety of oxidants including chromates, nitrates, nitrites, peroxides, perchlorates, permangenates, ferric compounds, and persulfates. Excellent bonding is reported when such materials are dispersed throughout the mat of a high-density fiberboard furnish and hot pressed.

The objective of this study was to evaluate the effects of oxidative activation of bagasse fiber by nitric acid and potassium dichromate on resin consumption, as well as investigate some mechanical and physical properties of dry formed bagasse MDF boards.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Raw material
2.1. Sirovina

Moist depithed bagasse was collected from the MDF moist depithing plant at one of the Agro-Industrial Sites in Southwest of I. R. Iran. Industrial urea-formaldehyde resin (solid content 60 %, PH 6.8-7.1, viscosity 30-45 sec., density 1.28 $g \cdot cm^{-3}$, gel time 50- 65 sec., free formaldehyde max 2 %, pot life 5 hours, water tolerance 6 parts, storage life 4 weeks) was prepared from Tiran Shimi resin factory, I. R. Iran. The chemicals including HNO_3 (100456 nitric acid 65 %), $K_2Cr_2O_7$ (1048625 potassium dichromate), $C_2H_8N_2$ (800947 ethylene diamine) and NH_4Cl (1011430 ammonium chloride) were supplied by MERCK-schuchardt, Germany.

2.2 Bagasse steaming and defibering
2.2. Razvlaknjivanje *bagasse*

The bagasse was delivered to the Pulp and Paper Laboratory, Department of Wood and Paper Science and Technology, Faculty of Natural Resources, University of Tehran, I. R. Iran. A laboratory batch steaming system was used for cooking the bagasse. A sufficient quantity of bagasse was transferred into the steaming vessel and saturated steam was then injected. After a short presteaming time to equalize the steam pressure and temperature inside the steaming vessel, the exhaust valve was closed and steam pressure and temperature were raised up to the start point of steaming condition. The steaming time was started after reaching the target steaming temperature and continued for 5 minutes. One steaming temperature of 175 °C (p = 6 bar) was used. The cooked bagasse was discharged and defibered using a 25 cm laboratory atmospheric single disc refiner. The refined fibers were air dried to reach equilibrium moisture content under laboratory conditions and then fluffed using a hand mixer. Final drying to 1.5 % moisture content was achieved by drying at 110 °C in a laboratory tray dryer. Finally, dried fibers were stored in sealed plastic bags until used.

2.3 Experimental layout
2.3. Provedba eksperimenta

The fibers were then treated by oxidants and resinated by urea-formaldehyde resin according to full factorial experimental design with three factors and 2*3*2 levels shown in Table 1.

Table 1 Full factorial experimental design with three factors and 2*3*2 levels
Tablica 1. Dizajn eksperimenta s tri čimbenika i 2*3*2 razine

Type of oxidant *Vrsta oksidansa*	**UF resin level, %** *Razina UF smole, %*	**Oxidant level, %** *Razina oksidansa, %*	**Treatment No**. *Obrada br.*
Nitric acid *dušična kiselina*	5	2	1
		4	2
		6	3
	7	2	4
		4	5
		6	6
Potassium dichromate *kalijev dikromat*	5	2	7
		4	8
		6	9
	7	2	10
		4	11
		6	12

A three-factorial experiment with a completely randomized design was used for the analysis of variance (ANOVA) of the data, and Duncan's Multiple Range Test (DMRT) was used for differentiation and classification of the average values.

2.4 Chemical treatment
2.4. Kemijska obrada

Oxidative activation of bagasse fibers were carried out before gluing. For this purpose, each of the two different types of oxidant were used at three levels of 2, 4 and 6 percent (based on fiber dry basis). Nitric acid and potassium dichromate were diluted by distilled water and separately added to dry bagasse fibers by spraying in a laboratory rotary drum blender and then stored in sealed plastic bags for 2 hours, after homogenous mixing.

2.5 Panel manufacturing
2.5. Proizvodnja ploča

The panel characteristics and constant parameters for making MDF panels have been presented in Table 2.

Two different levels of 5 and 7 percent of urea-formaldehyde (UF) resin (based on the dry fiber content) were used. An amount of solid ammonium chloride, ethylene diamine (as a cross linking agent), and distilled water were mixed into the liquid UF resin to dilute the resin and achieve the target mat moisture content. Neither paraffin nor other water repellent additives were used. The diluted glue was sprayed onto treated fibers with consistent parameters using a laboratory rotary drum blender consisting of an internal spray nozzle. Then, the resinated fibers were manually formed into mats using a wooden frame. All the fiber mats were hot-pressed under the same hot-pressing parameters (Table 2).

Table 2 Panel manufacturing constant parameters
Tablica 2. Parametri pri proizvodnji ploča

Processing parameter *Proizvodni parametar*	**Value** *Vrijednost*
Ammonium chloride content, % UF o.d.b. *sadržaj amonijeva klorida, % UF o.d.b.*	1.5
Ethylene diamine content, % UF o.d.b. *sadržaj etilen-diamina, % UF o.d.b.*	1.5
Mat moisture content, % fiber o.d.b. *sadržaj vode u tepihu, % fiber o.d.b.*	14
Target density, $kg \cdot cm^{-3}$ *ciljana gustoća, $kg \cdot cm^{-3}$*	0.75
Dimension, mm x mm *dimenzije, mm x mm*	350x350
Nominal thickness, mm *nominalna debljina, mm*	10
Press pressure, $kg \cdot cm^{-2}$ *tlak prešanja, $kg \cdot cm^{-2}$*	35
Press closing time, $mm \cdot s^{-1}$ *brzina zatvaranja preše, $mm \cdot s^{-1}$*	4
Press temperature, °C *temperatura prešanja, °C*	175
Press time, min *vrijeme prešanja, min*	5

According to Table 1, 12 combinations, and three panels per each combination were made, which resulted in a total of 36 treated bagasse MDF panels.

2.6 Panel testing
2.6. Ispitivanje ploča

After cold stacking, to reach equilibrium moisture content, all treated MDF panels were kept in a conditioning chamber at 20±3 °C and 65±1 % *MC* for 2 weeks, in accordance with ASTM standard method (ASTM D 1037-99, 2005). The properties of density, compression-shear strength (*C.S. sth*.), modulus of rupture (*MOR*) in bending and modulus of elasticity (*MOE*) in bending in dry condition, thickness swelling (*TS*) and water absorption (*WA*) after 2 and 24-hour immersion in cold water were measured in accordance with EN standard methods (EN 310: 1993; EN 319: 1993; EN-317: 1993).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The average properties of bagasse medium density fiberboard panels have been presented in Table 3. The results of ANOVA test on the effect of different variables, including the resin percentage, oxidant type, and oxidant content on physical and mechanical properties of test panels, have been summarized in Table 4.

Table 3 Average values of the properties of bagasse MDF boards
Tablica 3. Prosječne vrijednosti svojstava MDF ploča izrađenih od *bagasse* vlakana

Treat. No.	***MC*** %	***D*** g·cm^{-3}	***MOR*** MPa	***MOE*** MPa	***C.S sth.*** MPa	***WA***, %		***TS***, %	
						2 h	24 h	2 h	24 h
1	8.1	0.70	9.7	1579	0.65	160	177	74	82
2	8.3	0.714	9.97	1513	0.73	125	137	52	58
3	8.3	0.712	9.87	1798	0.74	101	110	38	42
4	8.2	0.72	12.3	2013	0.89	94	104	42	48
5	8.1	0.709	12.7	1988	0.92	86	95	38	43
6	8.3	0.72	11.6	1896	0.93	79	86	27	30
7	8.4	0.70	10	1611	0.67	143	157	68	78
8	8.4	0.716	9.1	1465	0.67	149	163	71	84
9	8.2	0.70	8.2	1373	0.63	150	166	69	81
10	8.4	0.71	10.7	1604	0.78	123	137	52	59
11	8.1	0.71	12.3	1884	0.83	117	131	52	60
12	8.3	0.7	12.3	1884	0.82	114	131	53	61

MC – moisture content / *sadržaj vode*; D – density / *gustoća*; *MOR* – modulus of rupture / *modul loma*; MOR – modulus of elasticity / *modul elastičnosti*; *C.S sth* – compression-shear strength / *tlačno-smicajna čvrstoća*; *WA* – water absorption / *upijanje vode*; *TS* - thickness swelling / *debljinsko bubrenje*

Table 4 The results of ANOVA test on the effect of variables on MDF properties
Tablica 4. Rezultati ANOVA testa svojstava MDF ploča

Independent variable *Nezavisna varijabla*	**Dependent variable**[b] / *Zavisna varijabla*								
	MC	***D***	***MOR***	***MOE***	***C.S. sth.***	***WA***		***TS***	
						2 h	24 h	2 h	24 h
A	NS	NS	S*	S**	S**	S**	S**	S**	S**
B	NS	NS	S**	S**	S**	S**	S**	S**	S**
A×B	NS	NS	NS	NS	NS	S*	S*	NS	NS
C	NS	NS	NS	NS	NS	S**	S**	S**	S**
A×C	NS	NS	NS	NS	NS	S**	S**	S**	S**
B×C	NS	NS	NS	NS	NS	NS	NS	NS	NS
A×B×C	NS	NS	S**	S**	NS	S**	S**	NS	NS
C.V. (%)	2.14	1.85	7.53	8.19	10.72	7.78	7.60	13.67	13.07

A – oxidant type / *vrsta oksidansa*; B – resin percentage / *udjel smole*; C – oxidant level / *razina oksidansa*; [a]S* – significant at 5 percent level / *značajno na razini 5 %*; S** – significant at 1 percent level / *značajno na razini 1 %*; NS – non-significant / *nije značajno*; C.V. – coefficient of variance (standard deviation/mean) / *koeficijent varijacije (standardna devijacija/srednja vrijednost)*; [b]*MC* – moisture content / *sadržaj vode*; *D* – density / *gustoća*; *MOR* – modulus of rupture in bending / *modul loma pri savijanju*; *MOE* – modulus of elasticity in bending / *modul elastičnosti pri savijanju*; *C.S. sth.* – compression-shear strength / *tlačno-smicajna čvrstoća*; *WA* – water absorption / *upijanje vode*; *TS* – thickness swelling / *debljinsko bubrenje*; 2h – after 2-hour immersion in cold water / *nakon dva sata potapanja u hladnoj vodi*; 24 h – after 24-hour immersion in cold water / *nakon 24 sata potapanja u hladnoj vodi*

The analyses showed that nitric acid was superior to potassium dichromate. Furthermore, the physical and mechanical properties of test panels improved with increasing of resin percentage and oxidant content (Table 3 and 4). Resin percentage showed a strong effect on both physical and mechanical properties of MDF boards. The effect of resin percentage on MDF properties was significant at 99 % confidence interval ($\alpha \leq 0.01$) (Table 4). The best values were attained for 7 % UF resin. For example, the values of 11.99 MPa, 1872 MPa, and 0.861 MPa were measured for *MOR*, *MOE* and C.S. sth., respectively, and 102.16 %, 114 %, 44 % and 50 % were measured, respectively, for *WA* and *TS* after 2 and 24-hour immersion in cold water. The highest effect was observed on thickness swelling. After 2 and 24-hour immersion for 7 % UF resin TS was 71 and 70 percent, respectively, of the TS for 5 % UF resin. This is in agreement with the results of Palardy *et al*. (1989), Chow *et al*. (1996); Gomez-Bueso *et al*. (2000) and Halvarsson *et al*. (2008).

In general, the properties of wood-based particleboards and medium density fiberboards are strongly dependant on the average density and to some extent on the amount of UF resin (Suzuki and Kato, 1989; Hague *et al*., 1999; Wong *et al*., 2000; Shi *et al*., 2005). This might be ascribed to increase fiber surface wettability, fiber surface resin coverage and fiber-fiber contact point, that create cross links (interbonds) between resinated fibers, which leads to the increased forces holding the fibers followed by the increase of resin percentage and consequently also the increase of furnish moisture content (Gomez-Bueso *et al*., 2000; Halvarsson *et al*., 2008).

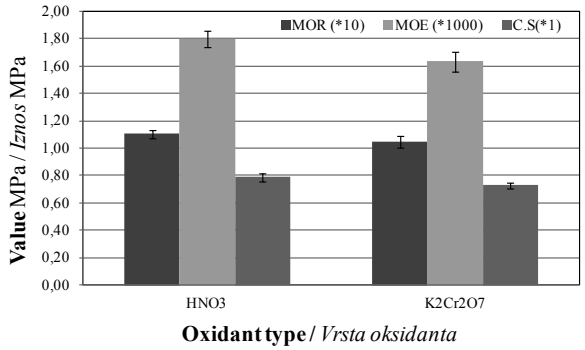

Figure 1 Effect of oxidant type on modulus of rupture (*MOR*), modulus of elasticity (*MOE*) and *C.S* strength
Slika 1. Utjecaj vrste oksidansa na modul loma (*MOR*), modul elastičnosti (*MOE*) i tlačno-smicajnu čvrstoću ploča (*C.S*)

Referring to the results in Table 4 and Figures 1 and 2, significant differences can be observed between physical and mechanical properties of two types of oxidants at 1 % level. The properties of nitric acid were better than those of potassium dichromate. The values of 11.028 MPa, 1798 MPa and 0.811 MPa were achieved for MOR, MOE and C.S. sth., respectively (Fig 1), and 107.6 %, 118 %, 45 % and 51 % for *WA* and *TS* after 2 and 24-hour immersion in cold water was achieved by nitric acid, respectively. The highest effect was observed on thickness swelling. After 2 and 24-hour immersion, *TS* for potassium dichromate was, respectively, 74 and 72 percent of that for nitric acid (Fig. 2). Nitric acid or nitrates introduce nitro-groups onto lignin or polyethylene, causing a reduction in their glass transition temperature up to 20 °C. Nitric acid may react primarily with phenolic groups, but will add nitro-groups at double bonds (Back and Danielsson, 1987). Nitric acid had a more positive effect than chromium nitrate, ferrous sulphate, or periodates (Back and Danielsson, 1987).

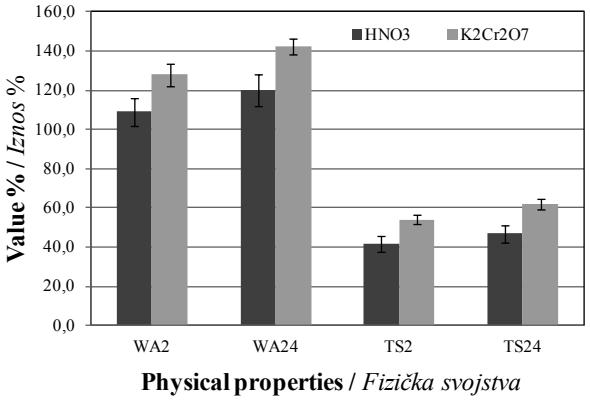

Figure 2 Effect of oxidant type on water absorption and thickness swelling after 2 and 24-hour immersion in cold water
Slika 2. Utjecaj vrste oksidansa na upijanje vode i debljinsko bubrenje ploča nakon dva i 24 sata potapanja u hladnoj vodi

It can be clearly seen from Table 4 that while all measured mechanical properties increased with the increase in oxidant content, no significant difference was shown at 95 % confidence interval ($\alpha \leq 0.05$). It is also clear that the effect of oxidant content was significantly correlated to physical properties at 99 % confidence interval ($\alpha \leq 0.01$).

Water absorption and thickness swelling decreased with increasing oxidant content from 2 to 6 percent. This is in agreement with the results of Shen (1974) and Back (1991). Moreover, the highest effect was observed on thickness swelling, as for 6 % oxidant content it was up to 20 % less than that of 2 % (Fig. 3). Rowell (1986; 1987) pointed out that modifying the cell wall polymers to make them more hydrophobic or bulking them with bonded chemicals would reduce the tendency of wood to swell and shrink by change in moisture content. This may be the reason why *WA* and *TS* were generally reduced by an increasing in oxidant content. Another reason for this may be attributed to high wettability of the oxidized fibers due to functional groups increasing, consequently good penetration of water-soluble urea-formaldehyde resin and its better performance. Also, the use of an oxidant may be interpreted as leading to inter-fiber bonding (Johns and Woo, 1978).

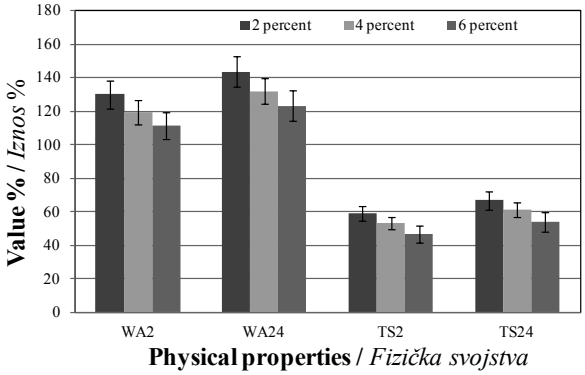

Figure 3 The influence of oxidant percentage on water absorption and thickness swelling after 2 and 24-hour immersion
Slika 3. Utjecaj udjela oksidansa na upijanje vode i debljisko bubrenje nakon dva i 24 sata potapanja u hladnoj vodi

Finally, the results showed that the effects of interaction of oxidant type, oxidant content and resin percentage on *MOR*, *MOE* and *WA* were significant at 99 % confidence interval ($\alpha \leq 0.01$) (Table 4). In addition, the highest values for *MOR* and *MOE* were related to the combination of 2 and 4 percent nitric acid along with 7 percent UF resin content (12.7 MPa and 2013 MPa, respectively) (Tables 3 and 4). The best value for *C.S.* strength was attributed to the combination of 6 percent nitric acid along with 7 percent UF resin content (0.93 MPa). The lowest values of *WA* and *TS* were also achieved for the combination of 6 percent nitric acid along with 7 percent UF resin content. The values of 79 %, 86 %, 27 % and 30 % were measured, respectively, for *WA* and *TS* after 2 and 24-hour immersion in cold water (Tables 3 and 4). Oxidative attack on lignin and especially on hemicelluloses or cellulose can also lead to some chain scission. While this process produces adequate wet strength and water swelling resistance, dry strength can be reduced (Allan and Neogi, 1971; Stenberg, 1978). One of the reasons for very high water absorption and thickness swelling might be ascribed to the fact that no water repellent additive was used. On the other hand, the natural mixture of cellu-

lose, lignin and hemicelluloses in wood material possesses a better resistance to water and water absorption than expected for annual plant materials (Halvarsson *et al*., 2009). Consequently, the fiberboard produced of annual plant materials might have even worse water-resistant properties than fiberboards made of wood material (Sauter, 1996; Markessini *et al*., 1997; Han, 2001; Mantanis and Berns, 2001; Wasylciw, 2001; Ye *et al*., 2007). The ability of water absorption into the oxidized lignocellulosic materials will also increase and contribute to a higher water sensitivity of low resin fiberboards (Halvarsson *et al*., 2009).

Even though the addition of nitric acid and potassium dichromate improved the fiberboard properties, none of the manufactured bagasse fiberboards met the European wood-based MDF standard (EN 622-5: 2006). The water swelling properties were adversely affected, so *TS* and *WA* were several times higher than specified by the MDF standard.

4 CONCLUSIONS
4. ZAKLJUČAK

According to the results, mechanical and physical properties of chemically treated bagasse MDF boards were strongly depended on resin percentage. The higher resin contents, the better mechanical and physical properties. Nitric acid showed better results than potassium dichromate, especially for thickness swelling. Furthermore, the properties of bagasse MDF boards improved with increasing oxidant content. Mechanical and physical properties of medium density fiberboards made from low resin oxidized bagasse fibers were not acceptable according to the requirements of the EN standards for MDF. Further studies should focus on methods for improving physical properties and mechanical strength of medium density fiberboards.

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Inovacije i inovativnost u „tradicionalnoj industriji“ – drvna industrija

Innovation and Innovativeness in Medium-Low Tech/Low-Tech Industries – Wood Industry

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ABSTRACT • *Krajnji cilj inovacije jest poboljšanje poslovanja, a inovacijske aktivnosti u suvremenim uvjetima poslovanja smatraju se ključnim pokretačem poslovnog uspjeha pojedinoga gospodarskog subjekta, pojedine gospodarske grane, kao i cjelokupnoga gospodarskog razvoja neke zemlje. Industrije srednjeniske i niske tehnologije, kojima pripada i drvna industrija, međutim, iznimno su važan i daleko najveći dio proizvodnog sektora zemalja članica OECD-a, pokazuju izvanrednu stabilnost te zapošljavaju visok udio stanovništva, a drvna industrija, posebno proizvodnja namještaja, uspješno je izvozno orijentirana europska gospodarska grana unutar srednjerazvijenih zemalja. Inovativnost tvrtke te inovacija kao rezultat inovativnosti mogu biti vezane za brojne vanjske i unutarnje čimbenike tvrtke, stoga je cilj ovog rada bio objasniti povezanost inovacija i inovativnosti određenih vanjskih i unutarnjih čimbenika tvrtki koji imaju/mogu imati utjecaj na razvoj inovacija i inovativnosti tvrtki, a koja je dokazana u brojnim istraživanjima velikog broja znanstvenika/autora.*

Ključne riječi: *drvna industrija, inovacije, inovativnost, tradicionalna industrija*

SAŽETAK • *In today's modern business world, development of innovations and innovation activities is considered as a key driver of business success of an individual entity, specific industry sector, as well as the overall economy of a country. However, industries of low and/or medium-low technology, where wood industry belongs, are extremely important and they represent by far the largest part of the manufacturing sector in OECD countries. They show an excellent stability and employ a high share of the population. Wood industry, especially furniture industry, is a successful export-oriented European industry. Innovative companies and innovation as a result of innovativeness can be attached to a number of internal and external company factors. Therefore, the aim of this paper was to clarify the connection between concepts of innovation and innovativeness of certain internal and external company factors that have/could have an impact on company innovativeness and innovation development, and that have been established and researched in studies of a large number of scientists / authors.*

Key words: *wood industry, innovation, innovativeness, medium-low tech/low-tech industry*

1 UVOD
1. INTRODUCTION

Inovativnost, a time i inovacije vrlo su važan pokretač gospodarskog razvoja i rasta, pri čemu je uvođenje novih ili poboljšanje postojećih proizvoda, procesa i poslovanja pretpostavka opstanka na svjetskom tržištu, ne samo razvijenih gospodarstava nego i gospodarstava u tranziciji, kakvo je hrvatsko. Inovacija nije nešto što se može ili treba uključiti i/ili isključiti kada je potrebno, odnosno kad nije potrebno. Da bi se

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inovacija učinila temeljem određene organizacijske jedinice/gospodarskog subjekta, vještine i aktivnosti vezane za inovacije treba prakticirati kontinuirano. Na taj će se način gospodarskom subjektu omogućiti prinos u korist stvaranja povjerenja, najnovijih vještina i informacija na područjima tehnologija i poslovanja, što će gospodarski subjekt učiniti inovativnijim, a time i uspješnijim u razvoju novih ili poboljšanju postojećih proizvoda, procesa i/ili poslovanja. Kao i u mnogim drugim tradicionalnim industrijama, tako i u drvnoj industriji, općenito, prevladavaju tehnologije niske složenosti, pretežno razvijene od dobavljača, a potom preuzete i prilagođene za vlastito poslovanje. U sve globaliziranijem tržištu navedena obilježja čine drvnu industriju iznimno osjetljivom. Zbog toga se, kako bi zadržali svoj položaj na tržištu, domaćemu i međunarodnomu, gospodarski subjekti unutar drvnoindustrijskog sektora sve više usmjeravaju na poduzimanje inovativnih aktivnosti koje će ih, ili koje bi ih mogle, dovesti do poboljšanja postojećih i/ili razvoja novih proizvoda, procesa i/ili poslovanja – inovacija. U posljednjih nekoliko desetljeća pojmovi *low-tech*, *medium-tech* i *high-tech* postali su sastavni dio rasprave unutar ekonomske politike.

Inovativnost tvrtke te inovacija kao rezultat inovativnosti mogu biti vezane za brojne vanjske i unutarnje čimbenike tvrtke, stoga je cilj ovog rada bio objasniti povezanost inovacija i inovativnosti određenih vanjskih i unutarnjih čimbenika tvrtki koji imaju/mogu imati utjecaj na razvoj inovacija i inovativnosti tvrtki, a koja je dokazana u brojnim istraživanjima velikog broja znanstvenika/autora.

2 INOVACIJE I INOVATIVNOST
2. INNOVATION AND INNOVATIVENESS

Prvi i iznimno važan izvor moderne inovacijske teorije jesu radovi Josefa Schumpetera (1934), koji široko i prilično općenito definira inovaciju kao povremeno uvođenje potpuno novih proizvoda/usluga ili novih kombinacija već postojećih proizvoda/usluga. Nadalje, Europska komisija (*European Commision*) (1996) definira inovaciju kao unapređenje i povećanje opsega proizvoda, usluga i povezanih tržišta; uspostavljanje novih metoda proizvodnje, nabave i distribucije; uvođenje novih promjena u menadžmentu, organizaciji i uvjetima rada zaposlenih, pri čemu je sve navedeno isključivo i moguće postići samo međusobnim interakcijama i suradnjom. Inovacije unutar gospodarskih subjekata pojavljuju se u različitim oblicima, premda je još uvijek naglasak na proizvodima pa se tako poboljšanje postojećih ili uvođenje novih proizvoda još uvijek i najčešće definiraju kao inovacija. No i razvoj inovacija vrlo je zastupljen i u procesima i u poslovanju gospodarskih subjekata te on danas u tvrtkama također ima veliko značenje (Nybakk i sur., 2009). Prema istoj skupini autora (Nybakk i sur., 2009) te prema OECD-u (*Organization for Economic Co-operation and Develoopement*) i Eurostatu (2005), s obzirom na stupanj „novoga" u proizvodu, poslovanju ili procesu, inovacije je moguće podijeliti na radikalne inovacije (*Radical Innovation*) – potpuno novi proizvod, proizvodni proces ili način poslovanja gospodarskog subjekta kojim će poslovni subjekt ostvariti bitan utjecaj na tržište i na svoju ekonomsku aktivnost na tom tržištu, i inkrementalne inovacije (*Incremental Innovation*) – poboljšavanje (dodavanje nečega) već postojećim proizvodima, proizvodnim procesima ili načinu poslovanja unutar pojedinoga gospodarskog subjekta. Prema OECD-u i Eurostatu (2005), međutim, pri podjeli inovacija prema stupnju „novoga" u proizvodu, procesu ili poslovanju, taj se stupanj promatra sa stajališta tvrtke pa ako su neki proizvod, proces ili poslovanje potpuno novi unutar gospodarskog subjekta, bez obzira na to postoji li i je li implementiran u drugim gospodarskim subjektima, takav se proizvod, proces ili poslovanje definira kao radikalna inovacija, a ako su proizvod, proces ili poslovanje poboljšani u odnosu prema prethodnom stanju unutar gospodarskog subjekta, tada se ta inovacija definira kao inkrementalna inovacija. Iznimno je važno naglasiti da je glavna značajka svih inovacija da budu implementirane – novi ili poboljšani proizvodi implementirani su u trenutku kada se uvedu na tržište, a novi ili poboljšani procesi i poslovanje implementirani su u trenutku kada počinju imati stvarnu primjenu u svakodnevnim aktivnostima tvrtke (OECD i Eurostat, 2005). Iz svega navedenoga proizlazi da je inovacija složen koncept, stoga brojni autori s različitih područja navode i definiraju različite podjele inovacija, no ovdje navedene podjele najprihvatljivije su za područje drvne industrije. Uz pojam inovacije vrlo je bitno definirati ulogu i povezanost inovativnosti tvrtke s inovacijom. Skupina autora (Nybakk i dr., 2009) ističe kako je inovacija tvrtke rezultat inovativnosti tvrtke, koja se pak definira kao karakteristika ili obilježje organizacije ili osobe koja iznosi, stvara, provodi i pretvara ideju u inovaciju, bilo proizvoda, bilo procesa i/ili poslovanja tvrtke. Biti inovativan putem razvoja novih ili poboljšanja postojećih proizvoda, procesa i/ili poslovanja može pomoći tvrtki da bolje prepozna i zadovolji želje i potrebe kupaca i tržišta te na taj način bude i uvijek ostane korak ispred vrlo oštre konkurencije (Crespell i sur., 2006).

2.1. Inovacije/inovativnost i značajke tvrtke (godine poslovanja, lokacija i veličina tvrtke)
2.1 Innovation/innovativeness and company features (years in business, location and company size)

Utjecaj starosti poslovnog subjekta na njegove inovativne aktivnosti razlikuje su od industrije do industrije, a godine njegova poslovanja jedan su od važnih čimbenika koji utječu na inovativnost tvrtke (Huergo i Jaumandreu, 2004). Utjecaj godina poslovanja na inovativnost dokazali su Frenkel i suradnici (2001) istražujući njemačke tvrtke, Huergo i Jaumandreu (2004) istražujući tvrtke španjolske industrije te Cefis i Marsili (2006) istražujući tvrtke nizozemske industrije te navodeći kako će nove tvrtke, koje poka-

zuju viši stupanj inovativnosti i zavidnu razinu razvoja, u svojim poslovnim aktivnostima težiti razvoju inovacija jer su takve tvrtke još uvijek nedovoljno poznate i nesigurne na ciljanom tržištu, time i izloženije tržišnom neuspjehu nego starije tvrtke koje su tijekom dugog niza godina poslovanja stekle i učvrstile svoj tržišni položaj. Nasuprot tome, Frenkel i sur. (2001), istražujući tvrtke izraelske industrije, došli su do suprotne spoznaje - inovativna aktivnost raste s povećanjem godina poslovanja tvrtke. Iz navedenoga je vidljivo da nema pouzdano definiranog odnosa utjecaja starosti pojedinoga poslovnog subjekta na inovativnost i razvoj inovacija.

Lokacija (mjesto), odnosno geografski prostor postali su ključni činitelji u objašnjavanju odrednica inovacija (Audretsch i Feldman, 2003). Tvrtke moraju razvijati i komercijalizirati inovacije na onim mjestima koja su za određeni tip inovacije „najprimamljivija“. Bairoch (1988) smatra kako se većina inovacija razvija u gradovima jer koncentracija osoba, različitih zanimanja i industrija stvara poslovnom subjektu povoljnu okolinu za inovativnost i razvoj inovacije, čime se ublažavaju svojstvene nesigurnosti inovativnih aktivnosti tvrtke i smanjuju nesigurnosti u razvoju inovacija. Iako se inovacije najčešće povezuju s urbanim sredinama (gradovima) koje se smatraju pravim mjestom za inovativnost poslovnog subjekta, Bryden i Refsgaard (2008) navode kako je u procesu razvoja inovacija iznimno bitno spoznati mogućnost povezivanja urbanih sredina s ruralnim područjima jer kao što tvrtka ima preduvjete za razvoj u urbanim sredinama, inovativna aktivnost i inovacija mogu se razviti i u ruralnim područjima. Isaksen je (1997) u norveškoj proizvodnoj industriji utvrdila da se u centraliziranim (gradskim) područjima više razvijaju radikalne inovacije, dok se u ruralnima i manje centraliziranim sredinama više razvijaju inkrementalne inovacije.

U studijama i istraživanjima u kojima se razmatraju odnosi veličine poslovnog subjekta i inovativne aktivnosti često se navode oprečni rezultati i zaključci. Na području istraživanja inovacija vrlo je poznata Schumpeterova hipoteza da inovativnu aktivnost poslovnih subjekata unutar različitih gospodarskih grana i industrija potiču velike tvrtke, da one često imaju bolje preduvjete za razvoj inovacija (Crespell i dr., 2006) zato što velike tvrtke pretežit dio svojih ostvarenih prihoda mogu izdvojiti za istraživanje i razvoj, što ne vrijedi za male ili srednje velike tvrtke (Laforet i Tann, 2006). Drugi autori navode drugačije zaključke – da male tvrtke u usporedbi s velikima stvaraju 2,5 puta više inovacija (Gelleman, 1982), fleksibilnije su i povezanije s kupcima, te su sposobnije predvidjeti nove tržišne uvjete i potrebe prije konkurenata (de Jong i Marsili, 2006) te da pridaju veće značenje i važnost inovacijama i inovativnosti (Jelačić i sur., 2009). Razmatrajući inovacije općenito, i ne razdvajajući ih na proizvodne, procesne i poslovne, male tvrtke više teže razvoju inovacija nego velike, premda velike tvrtke imaju više preduvjeta za njihov razvoj, npr. tehnološke mogućnosti, zapošljavanje visokoobrazovanih osoba različitih osobnih mogućnosti i vještina.

2.2. Inovacije/inovativnost i zaposlenici
2.2 Innovation/innovativnes and employees

Kao pojedinci, zaposlenici imaju sličan potencijal za inovativnost, ali primjenjuju različite pristupe u procesu stvaranja inovacija. Prepoznavši potencijal pojedinca u kombinaciji s motivacijom i poticanjem razvoja misli o inovaciji, može se očekivati da će pojedinac svojoj tvrtki ili organizacijskoj jedinici donijeti najbolje inovativnosti koje menadžment tvrtke može očekivati (Tan i Kaufmann, 2008). Da su vještine i znanja zaposlenika čimbenici koji statistički značajno utječu na inovacije, u svom su istraživanju dokazali Mohnen i Röller (2005). Iz rezultata njihove studije vidljivo je da je velikom broju tvrtki različitih industrija u raznim zemljama svijeta nedostatak visokoobrazovanoga i vještog ljudskog kadra najozbiljnija prepreka u stvaranju inovacije i razvoju inovacijskih aktivnosti jer se oni, kako navode Ostergaarad i sur. (2008), smatraju glavnim pokretačima inovacijskih aktivnosti poslovnog subjekta. Verworn i Hipp (2009) navode kako nije pravilo, iako se to može očekivati, da su one tvrtke koje u svojoj strukturi zaposlenika imaju veći udio osoba starije dobi manje inovativne ili da komercijaliziraju manji broj inovacija. Ujednačena spolna struktura povećava vjerojatnost tvrtke za inovativnošću, odnosno one tvrtke u kojima je odnos među spolovima oko 50 – 60 % prije će razviti inovativnu aktivnost nego tvrtke u kojima je 90 – 100 % zaposlenika iste spolne orijentacije (Ostergaarad i sur., 2008). Ne postoji statistički značajna razlika u inovativnim aktivnostima između muških i ženskih zaposlenika poslovnog subjekta (Damanpour i Schneider, 2006), ali u poslovnim subjektima u kojima su žene pozicionirane u višim dijelovima organizacijske strukture inovativna će se aktivnost prije realizirati nego u onim poslovnim subjektima gdje su na vodećim mjestima muškarci (Stelter, 2002). Inovativnost zaposlenika i broj inovacija među zaposlenicima smanjuje se kako se hijerarhijskom ljestvicom krećemo prema dolje (Sebora i sur., 1994). Nadalje, kvaliteta odnosa između nadređenih i podređenih članova poslovnog subjekta te davanje određenog stupnja slobode pri donošenju odluka definirani su kao bitni čimbenici koji pridonose stupnju inovativnosti i razvoju inovacija tvrtke (Scott i Bruce, 1994).

2.3. Inovacije/inovativnost, tržišni udio i izvoz
2.3 Innovation/ innovativeness, market share and export

Kada se razmatra odnos tržišnog udjela pojedine tvrtke i njezine mogućnosti za inovativnošću, tada su već tradicionalno uvriježena dva suprotna mišljenja – svima dobro poznat Joseph Schumpeter (1942) ističe kako inovativnost tvrtke raste s povećanjem tržišne koncentracije i njezina udjela, dok Arrow (1962) zaključuje suprotno – tvrtke će biti inovativnije ako se nalaze na tržištu na kojemu više različitih tvrtki ostvaruje svoj tržišni udio, ali nijedna od tvrtki nije tržišno

dominantna. Slijedeći Shumpeterove teorije, Gillbert i Newbery (1982), citirani u knjizi Jean Tirolea (1988), navode kako će tvrtke koje su već postigle tržišnu dominaciju imati veći poticaj za razvoj inovacije od tvrtki koje se sa svojom inovacijom tek probijaju na željeno tržište jer neuspjeh inovacije tržišno dominantnih tvrtki neće oslabiti njihovu profitabilnost, što ne vrijedi za tvrtke koje inovacijom pokušavaju postići tržišni uspjeh. Blundell i sur. (1999) došli su do zaključka da su visoki tržišni udio i inovacija u međusobnoj korelaciji – tvrtkama koje su inovativnije tržišni se udio povećava, dok će neuspjeh tvrtke na tržištu biti poticaj za potragu za inovacijom.

Promatrajući odnos izvoza tvrtke i njezina stupnja inovativnosti, Hirsch i Bijaoui (1985) te Cao i Hansen (2006) ističu kako tvrtke koje svoj napredak temelje na izvozu imaju preduvjet da će tendencija njihovih inovativnih aktivnosti te stupanj razvoja inovacija biti veći u usporedbi s tvrtkama koje nisu usmjerene na međunarodna tržišta ili teško ostvaruju izvoz. Nadalje, izvoz je uvelike vezan za investicijske aktivnosti tvrtke te će tvrtke izvoznice svoje poslovanje češće usmjeravati na proširenje proizvodnog programa i težiti poboljšanju svojih proizvodnih i poslovnih procesa (Alvarez i Robertson, 2004). Isti autori ističu i kako je vrlo bitno na koje tržište pojedina tvrtka izvozi jer će one tvrtke koje izvoze na tržišta svjetski razvijenih zemalja još više nastojati tom tržištu ponuditi nove, poboljšane i drukčije proizvode i/ili usluge. Analizirajući odnos tipova inovacija, Cassiman i Golovko (2007) navode kako inovacija proizvoda pojedine tvrtke u odnosu prema inovacijama u procesima proizvodnje više utječe na to da tvrtka postane izvoznik te kako uvođenje novih proizvoda povećava vjerojatnost da će tvrtka ući na inozemno tržište.

2.4. Inovacije/inovativnost, istraživanje i razvoj (IiR) i investicije
2.5. Innovation/innovativeness, research and development (R&D) and investments

Pokušaj provođenja procesa istraživanja i razvoja (IiR) za svaki je poslovni subjekt vrlo složen jer se sastoji od niza elemenata i aktivnosti koje je potrebno obuhvatiti, a sve radi pretvaranja definiranih rezultata u inovativnu aktivnost (Wang i sur., 2010), no to isključuje one aktivnosti koje ne sadržavaju element novoga, ne sadržavaju rješenje prethodne znanstvene i/ili tehnološke aktivnosti te ako je rješenje problema poznato nekomu s područja istraživane djelatnosti (OECD, 2002). Mišljenja među istraživačima i znanstvenicima o utjecaju procesa IiR na inovativnost poslovnih subjekta različita su, vjerojatno zato što je, kako je prethodno navedeno, sam proces vrlo složen te se njegov utjecaj na inovaciju također promatra kompleksno. Za proces IiR vrlo je bitan intenzitet njegova provođenja jer on utječe na razinu inovacijskog uspjeha tvrtke te čini veličinu uz pomoć koje je moguće mjeriti ulogu procesa IiR u funkciji inovacije (Zachariadis, 2003). Nadalje, trud i snaga provođenja aktivnosti IiR tvrtke može biti pokazatelj inovativne sposobnosti tvrtke (Hagedoorn i Cloodt, 2003), a vrlo je bitno da proces IiR bude konstantan jer će samo konstantno provođenje procesa dovesti do inovacije (Mansfield, 1984). Iako IiR ima važnu ulogu u inovacijskim procesima tvrtke i vrlo je važan činitelj u razvoju inovacija, mnogo inovacijskih aktivnosti ipak nije utemeljeno na aktivnostima IiR-a, nego (među ostalim) na interakciji s drugim poslovnim subjektima, istraživačkim institucijama te na organizacijskoj strukturi koja teži primjeni vanjskih znanja i spoznaja (OECD, 2005). Poslovni subjekti najčešće odluku o investiranju radi inovacijske aktivnosti donose zbog potrebe realiziranja ideje u inovaciju ili obrnuto, zbog potrebe pronalaženja izvora ideje za inovaciju (Peneder, 2008). U konačnici sam pristup procesu istraživanja i razvoja te odluka o investicijama, a sve radi poticanja inovativne aktivnosti i razvoja inovacija, ovise o vrsti industrije u kojoj se taj proces provodi, o načinu poslovanja pojedine tvrtke, o definiranim strateškim ciljevima tvrtke te o samom tipu inovacije koji tvrtka želi razviti, stoga se procesima IiR i investiranju treba pristupati s tog stajališta.

2.5. Inovacije/inovativnost te tehnološka, informatička i informacijska opremljenost
2.5 Innovation/innovativeness and technological and infomation technology equipment

Veze između informacijske i komunikacijske tehnologije (ICT) (*Information and Communication Technology*) i inovacija vrlo su jasno poznate, kao i činjenica da ulaganje u informacijsko-komunikacijsku tehnologiju i primjena računalnih aplikacija utječu na inovativnost poslovnog subjekta. Dobro definiran i uhodan informacijski sustav unutar tvrtke potiče ju na razvoj i stvaranje inovacije (Ramiller i Swanson, 2004), ali jednako tako dobro ostvarena međuorganizacijska povezanost unutar tvrtke, utemeljena na informacijskom sustavu, stvara uvjete za stalnu inovacijsku aktivnost (Malhotra i sur., 2005). Koellinger (2008) ističe kako nova tehnologija utječe na razvoj inovacija samo onda ako je primijenjena, a primjena je moguća ako je nova tehnologija integrirana u organizacijski kontekst i socijalne činitelej koji postoje u tvrtki. U većini se primjera (poslovnih subjekata) tehnološke aktivnosti najčešće temelje na računalom objedinjenoj proizvodnji (CIM) (*Computer Integrated Manufacturing*) te na sveprisutnim informatičkim alatima poput *e-maila*, Microsoft Officea te Excel/Access baza podataka (Hüsig i Kohn, 2009). Jednako tako, i upotreba interneta u inovacijama proizvoda mnogostruka je, npr. pojedinom poslovnom subjektu može pomoći u boljem razumijevanju i spoznajama o konkurentima te u stvaranju svijesti među potencijalnim kupcima o poboljšanome postojećem i/ili novom proizvodu (Bickart i Schindler, 2001).

2.6. Inovacije/inovativnost, istraživanje tržišta, tržišna orijentacija, kupci i dobavljači
2.6 Innovation/innovativeness, market reserach, market orientation, customers and suppliers

Brojne su rasprave i istraživanja o tome koliko provođenje istraživanja tržišta može utjecati na inovativnost tvrtke i razvoj inovacija među znanstvenicima,

ali su i kontradiktorne (McQuarrie, 2006). Istraživanje tržišta može biti važan alat pri donošenju odluka o razvoju inovacije, ali tvrtka koja je potencijalni inovator mora detaljno biti upoznata s tržišnim prilikama jer u suprotnome samo prikupljanje informacije, bez poznavanja tržišnih prilika, može navesti na pogrešan put i u konačnici dovesti do propasti (McQuarrie, 2006). Veryzer (2003) navodi kako poveznica između istraživanja tržišta i razvoja novog proizvoda i/ili usluge još uvijek ne postoji jer se u istraživanju tržišta i dalje primjenjuju već dobro poznate, ne nove, tzv. tradicionalne marketinške tehnike prikupljanja podataka koje potencijalnu tvrtku ne mogu dovesti do moguće radikalne inovacije. Razvoj uspješne inovacije moguće je postići bez prethodno provedenog istraživanja tržišta, dok uspješno provedeno istraživanje tržišta ne jamči inovacijski uspjeh tvrtke (McQuarrie, 2006). Nasuprot tome, provođenje istraživanja tržišta, ako je riječ o poboljšanju postojećih proizvoda/procesa/poslovanja (inkrementalnih inovacija), može imati veliku ulogu u prikupljanju podataka o potencijalnim kupcima te o njihovim trenutačnim prilikama (McQuarrie, 2006).

Mišljenja o utjecaju tržišne orijentacije na inovativnost poduzeća u literaturi su podijeljena. Gima (1996) te Laforet i Tann (2006) ističu kako tržišna orijentacija znatno utječe na inovativnost tvrtke i na stupanj tržišne orijentacije tvrtke i pozitivno je povezan s razvojem inovacija. Nadalje, orijentacija na potrošače utječe na povećanje broja radikalnih inovacija i smanjuje broj inkrementalnih inovacija (Lukas i Ferell, 2000). S druge strane, Gima (1996), citirajući Benetta i Coopera (1981), navodi kako tržišna orijentacija ne pridonosi inovativnosti i negativna je posljedica za inovacije jer dovodi do preuzimanja/kopiranja nekonkurentnih proizvoda koji već postoje na tržištu od strane konkurenata. Uspoređujući navedeno s Hrvatskom, Rajh i Božić (2005), citirani u radu Božić (2006), u zaključcima svog istraživanja navode kako je u poduzećima s jače izraženom tržišnom orijentacijom zabilježen veći udio prihoda od inovacija u ukupnom prihodu.

Kupac je bitan čimbenik koji utječe na inovativnost i kupci imaju vrlo važnu ulogu u razvoju inovacija jer njihovi vrlo sofisticiranih ukusi, želje i potrebe prisiljavaju tvrtku na neprestano stvaranje novih ili promjenu/poboljšavanje postojećih proizvoda (Laforet i Tann, 2006). Međutim, stvaranje inovacije prema osobinama kupaca može rezultirati zanimljivim proizvodom koji nitko ne želi kupiti zato što kupci ne žive kao demografske kategorije i njihovo ponašanje nije uvijek odraz njihovih potreba. Osobine kupaca poput dobi, spola, stupnja obrazovanja ili visine prihoda povezani su s potrošnjom, ali posljedično, a ne uzročno, tj. one određuju vjerojatnost hoće li neka osoba biti kupac, no nemaju veze s razlozima kupnje ili uporabe proizvoda. No, definiranje i analiza posla kupaca elementi su koji znatno smanjuju ulogu sreće ili opasnost od početnih pogrešaka na putu do razvoja inovacije (naglasak je na inovaciji proizvoda) jer se tada „oslanjamo“ na nešto što je donekle trajno (Golob, 2009). Jednako tako, i okolnosti potrošnje element su iskoristiv za inovativne aktivnosti tvrtke jer spoznaja zašto će kupac kupiti nešto u određenom trenutku omogućuje procjenu kada će pojedinac zaista kupiti inovaciju, a kada inovacija tom istom kupcu neće biti privlačna (Golob, 2009).

Osim toga, i dobavljači također mogu biti važan izvor inovacija, imaju važnu ulogu u njihovu razvoju te su bitan (sve više i nužan) činitelj koji utječe na inovativnost tvrtke (Helmsing, 1999). Uloga dobavljača u procesu razvoja inovacija tvrtke iznimno je važna jer oni kao „vanjski promatrači“ mogu nepristrano promatrati okruženje i okolnosti kupnje postojećih i/ili uvidjeti latentne probleme novih potencijalnih kupaca i otkrivena znanja kombinirati i uspoređivati sa znanjima o materijalima, tehnološkim mogućnostima proizvodnih procesa i sl. (Vercauteren, 2008). Istraživanje inovacija u EU i u Srednjoistočnoj Europi pokazalo je da se ključni izvori informacija za njihov razvoj, među ostalim, nalaze u partnerima u lancima stvaranja vrijednosti, pri čemu se naglasak stavlja na dobavljače i kupce (Radošević, 2003). Ako je međusobna interakcija (koja može biti vrlo dugotrajan i vrlo složen proces) svih sudionika u lancu stvaranja vrijednosti proizvoda i/ili usluga uspješna i ima tendenciju neprestanog poboljšavanja, tada potencijal za razvoj i komercijalizaciju inovacija raste (Vercauteren, 2008).

3. INOVACIJE/INOVATIVNOST I „TRADICIONALNA INDUSTRIJA“
3 INNOVATION/ INNOVATIVENESS AND (*MEDIUM-LOW TECH / LOW-TECH)* INDUSTRY

Polazeći od OECD-ove (1994. i 2001) klasifikacije, prerađivačku industriju na temelju tehnologije moguće je podijeliti na: 1. industriju visoke tehnologije (*high-tech industry*), 2. industriju srednjevisoke tehnologije (*medium-high tech industry*); 3. industriju srednjeniske tehnologije (*medium-low tech industry*) i 4. industriju niske tehnologije (*low-tech industry*), a ta se podjela temelji na intenzitetu odvajanja ukupno ostvarenih prihoda pojedine industrije za istraživanje i razvoj. Legler i Frietsch (2007), koristeći se također udjelom ulaganja ukupno ostvarenog prihoda različitih sektora u istraživanje i razvoj kao kriterijem, predložili su drukčiju klasifikaciju prerađivačke industrije: 1. industrije visoke tehnologije, 2. industrije srednje tehnologije i 3. industrije niske tehnologije. Postoji uvriježeno mišljenje da se društvo znanja najviše temelji na znanstvenim istraživanjima i na primjeni novih tehnologija i inovacija u području tehnološki visokorazvijenih industrija, dok se samo sekundarno značenje pridaje ulozi „tradicionalnih industrija“ (industrija srednjeniske tehnologije / niske tehnologije) među koje, uz ostale, pripada i drvna industrija (prerada drva i proizvodnja namještaja) (Hirsch-Kreinsen, 2008). Industrije niskih tehnologija po pravilu zahtijevaju nižu razinu ulaganja u istraživanje i razvoj te razvoj više temelje na primjeni znanja i tehnologija (OECD, 2005). No pojedini istraživači, Hirsch-Kreinsen i dr. (2005), von Tunzelman i Acha (2005), smatraju kako se izjednačavanje visine intenziteta/jačine

istraživanja i razvoja s visinom inovativnosti pojedine industrije ne može promatrati na razini cjelokupne industrije, već je to potrebno promatrati na razini pojedinoga gospodarskog subjekta jer unutar pojedine industrije postoje razlike između gospodarskih subjekata. Nadalje, prema glasovitoj Pavittovoj (1984) taksonomiji, industrije srednjeniskih tehnologija su one kojima prevladavaju dobavljači kao izvori inoviranja, što znači da će tvrtke unutar tih industrija većinu svojih procesa prilagođavati izvana preuzetim tehnologijama i materijalima svojih dobavljača. Tvrdnja da inovacije u tehnološki niskorazvijenim i/ili srednje niskorazvijenim industrijama ne bi trebalo promatrati kao kontradiktorne pojmove dokazali su von Tunzelmann i Acha (2005) naglašavajući kako unutar tehnološki niskorazvijenih i/ili srednje niskorazvijenih industrija postoje inovativne aktivnosti te kako navedene industrije posjeduju mogućnosti, preduvjete i uvjete za razvoj inovacija. Prema Kirner i dr. (2009), tvrtke pripadnice industrija niskih tehnologija mogu razviti i realizirati inovacije proizvodnih procesa i inovacije poslovanja gotovo jednako kao i tvrtke koje pripadaju industrijama srednjerazvijenih ili visokorazvijenih tehnologija. Inovacije proizvoda i procesa u tvrtkama za preradu drva i proizvodnju namještaja nužno ne zahtijevaju velika ulaganja u segment istraživanja i razvoja jer pripadaju industriji kojom dominiraju dobavljači čije inovativnije aktivnosti najvećim dijelom rezultiraju razvojem inkrementalnih inovacija (Sterlacchini, 1999). U takvim tvrtkama izvozne performanse također pozitivno utječu na inovativne aktivnosti i na razvoj inovacija (Sterlacchini, 1999). Robb i Xie (2003) navode da je primjena naprednih tehnologija proizvodnje, među kojima se u proizvođača namještaja ističe proizvodnja podržana računalom (CAM), usko povezana s razvojem inovacija proizvoda i inovacija poslovanja (omogućuje njihovu međusobnu povezanost). Inovativnost zaposlenika (kao pojedinca, ali i cjeline) pokazala je utjecaj na razvoj inovacija u američkim tvrtkama drvne industrije (Hovgaard i Hansen, 2004). Heanue (2008) navodi kako je među ostalim, u irskim tvrtkama koje se bave proizvodnjom namještaja vezanost za geografsku lokaciju važan element razvoja inovacija, ali i interakcije s dobavljačima, suradnicima te kupcima također podupiru inovativne aktivnosti tvrtki. U zaključcima istraživanja provedenoga u tvrtkama drvne industrije Estonije, Ukrainski i Varblane (2005) navode kako su dobavljači najznačajniji partneri u razvoju inovacija proizvodnih procesa i inovacija poslovanja, dok su kupci bitni partneri i izvori inovacija proizvoda. Inovativne mogućnosti tvrtki drvne industrije moguće je podijeliti na dva tipa – na primjenu ili stvaranje inkrementalnih inovacija i na istraživanje ili stvaranje radikalnih inovacija (Korhonen, 2006). Navedeni se tipovi međusobno dopunjuju, a pojedina tvrtka svoj napredak temelji na njihovu razvoju i pažljivom upravljanju. Crasplell i sur. (2006), istražujući sjevernoameričke tvrtke za preradu drva (piljene građe), pokazali su da strukturalni procesi razvoja proizvoda i usmjerenost na tržište i kupce unaprjeđuju njihovu inovativnost. Nadalje, Hansen i dr. (2007) zaključuju da tvrtke drvne industrije navedenu tržišnu orijentaciju razvijaju i poboljšavaju na pravilan način, samo što vrlo često nemaju definirane sustavne programe i strategije s jasno razrađenim koracima, tj. voditelji i menadžeri ne znaju kako realizirati inovativne ideje i povećati inovativnost.

4. ZAKLJUČAK
4 CONCLUSION

Zbog vrlo dinamične i promjenjive prirode tržišta gotovo je nemoguće pronaći industrijsku granu koja u svoj razvoj ne uključuje inovativnost i inovacije (kao rezultat inovativnosti), bilo neprestanu, bilo povremenu.

Starost pojedinoga poslovnog subjekta jedan je od važnih čimbenika koji utječu na inovativnost tvrtke, a posebno na razvoj novog proizvoda. Jednako tako, i lokacija tvrtke ublažava svojstvene nesigurnosti inovativnih aktivnosti tvrtke i poboljšava sposobnost tvrtke za razmjenu ideja. Nadalje, inovacijsku aktivnost i uspješnu inovaciju tvrtke moguće je realizirati samo ako svi, ali baš svi njezini zaposlenici sudjeluju u procesu inoviranja, ali uz uvjet kvalitetnog odnosa između nadređenih i podređenih članova poslovnog subjekta te davanjem određenog stupnja autonomije i slobode svakom djelatniku pri donošenju odluka. Velike će tvrtke bolju inovativnu prednost postizati na tržištima nesavršene konkurencije, dok će male tvrtke bolji rezultat inovativne aktivnosti postizati na tržištima zdrave konkurencije. Odluke o ulaganju u nove tehnologije radi povećanja mogućnosti razvoja inovacija u procesima proizvodnje vezane su za proces istraživanja i razvoja. Veze između informacijske tehnologije i inovacija vrlo su jasno poznate, kao i činjenica da ulaganje u informacijsko-komunikacijsku tehnologiju i primjena računalnih aplikacija utječu na inovativnost poslovnog subjekta. Tvrtkama koje su inovativnije tržišni se udio povećava, dok će istodobno neuspjeh tvrtke na tržištu biti poticaj za potragu za inovacijom. Tvrtke koje svoj napredak temelje na inovativnosti imaju ujedno preduvjet da tendencija njihovih izvoznih vrijednosti bude veća. U prirodi inovativnih aktivnosti jest da su vrlo često riskantne, s mnogobrojnim neizvjesnim troškovima realizacije ideja u potencijalni proizvod, proces i/ili poslovanje i rizičnim konačnim uspješnim poslovnim rezultatom. Gospodarski subjekti koji ostvaruju bliske i dobre odnose s kupcima, dobavljačima i istraživačkim institucijama te razvijaju zdrave konkurentske odnose sa svojim konkurentima imaju veću vjerojatnost za razvoj inovacija proizvoda, procesa i/ili poslovanja.

Nadalje, četiri su glavne sastavnice proizvodne snage industrije namještaja: inovacije, isporuka, fleksibilnost i vrijednost (cijena), ali je od svih njih inovacija označena kao glavni i najvažniji ključ uspjeha proizvođača namještaja. Tvrtke drvne industrije tržišnu orijentaciju razvijaju i poboljšavaju na pravilan način, samo što vrlo često nemaju definirane sustavne programe i strategije s jasno razrađenim koracima, tj.

voditelji i menadžeri ne znaju kako realizirati inovativne ideje i povećati inovativnost. Očito je da sutra nećemo poslovati ako danas poslujemo kao i jučer, a inovativnost i inovacija su kao rezultat te aktivnosti, iako ne jedini put stvaranja novih vrijednosti za potrošače, tvrtke i/ili zajednicu, zasigurno i jedan od najboljih načina opstanka na tržištu!

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International Association for Economics and Management in Wood Processing and Furniture Manufacturing WoodEMA, i.a. is international, non-political, non-profitable and open Association.

Association's goal is to promote science and results of scientific and professional work of its members, mutual scientific co-operation, as well as to support the science and professional development in the Association's field of work.

To achieve these goals the Association is working on following:

- Exchange of knowledge and researh results among members by organizing conferences and publishing articles in journals and proceedings
- Support mutual scientific cooperation among Association's members through elaboration of scientific projects
- Support the development of scientific and professional organizations in Association's fields of expertise
- Scientific and professional education by organizing scientific and professional symposiums
- Collecting and exchange of market, technological and technical data

Members from many European countries and USA invite you to join us.

All information you can get on the website or by sending e-mail to WoodEMA, i.a. general secretary.

Međunarodno znanstveno savjetovanje WoodEMA 2013

U organizaciji Katedre za proizvodni inženjering Fakulteta za menadžment, Politehnike u Czestochowi (Poljska), Asocijacije za menadžment u kvaliteti i proizvodnji iz Czestochowe te međunarodne asocijacije za ekonomiku i menadžment u preradi drva i proizvodnji namještaja WoodEMA, i.a. u Gdansku (Poljska) održano je od 29. do 31. svibnja 2013. godine 6. međunarodno znanstveno savjetovanje pod naslovom *WoodEMA 2013 – Visegrad Innovations, Innovations as the source of values in the forestry, wood processing and furniture manufacturing.* Ove je godine konferencija u Gdansku održana kao projekt Višegradskog fonda V4 pod nazivom Visegrad Small Grant No 11310223 *WoodEMA. Visegrad innovations,* s dr. sc. Renatom Statisak-Betlejewskom kao koordinatoricom projekta. Jednako tako, WoodEMA 2013 organizirana je pod pokroviteljstvom Ministarstva znanosti i visokog obrazovanja Republike Poljske, Županije Pomorskog vojvodstva, gradonačelnika Gdanska te Holdinga nacionalnih šuma i biznisa Poljske. Partneri projekta bili su Institute of Production Engineering, Faculty of Management, Czestochowa University of Technology Poljska, Jan Evangelista Purkyně University in Ústí nad Labem, Fakulta Výrobnich technologii a management Češka, Univerzita Tomáše Bati ve Zlíně Češka, Budapesti Műszaki és Gazdaságtudományi Egyetem Közlekedésmérnöki Kar - Közlekedésgazdasági Tanszék Mađarska, Technická Univerzita vo Zvolene, Drevárska Fakulta, Katedra Podnikového Hospodárstva Slovačka, Univerzita sv. Cyrila a Metoda v Tranve, Fakulta Masmedialnej Komunikacie Slovačka, Vysoka skola ekonomie a manazmentu verejnej spravy Bratislava Slovačka, Slovenská technická univerzita v Bratislave Slovačka, Alberto Di Taranto Trento Italija i WoodEMA.

Slika 1. Neke od najduljih piljenica u svijetu (46,53 m i 36,83 m) u Kešuviji
Figure 1 Some of the longest planks in the world (46,53 m i 36,83 m) in Keszubia

Za savjetovanje je na 32 rada prijavljeno 70 autora iz devet europskih zemalja, SAD-a i Indije. Savjetovanju su nazočila 43 autora.

Katarina Durkova (Slovačka) održala je predavanje o primjeni socijalnih mreža u komunikaciji drvoprerađivačkih tvrtki.

M. Moro, D. Motik, K. Šegotić i A. Pirc-Barčić (Hrvatska) u svom su se radu bavili trendovima u trgovini primarnih i sekundarnih drvnih proizvoda.

D. Motik, M. Moro, A. Pirc-Barčić i K. Liker (Hrvatska) u radu su obradili potrošnju pojedinih drvnih proizvoda na hrvatskome i inozemnom tržištu.

L. Oblak, A. Zupančič i M. Jukič (Slovenija) u svom su radu predstavili model za vrednovanje televizijskih promidžbenih poruka drvoprerađivačkih tvrtki.

A. Vedkertiova (Slovačka) predstavila je rad o korištenju informacijskom tehnologijom u komunikaciji između sveučilišta i drvnih poduzeća.

M. Zajkowska (Poljska) dala je prikaz mogućnosti povećanja konkurentnosti poduzeća drvnog sektora putem klasterskog povezivanja.

R. Novakova, A. Tomankova i E. Habinakova (Slovačka) predstavile su važnost sajmova namještaja u marketinškoj komunikaciji drvnog sektora.

A. Dijan i M. Kavran (Hrvatska) dali su prikaz promocije drvne biomase i peleta u zemljama jugoistočne Europe.

S. Borkowski i R. Stasiak-Betlejewska (Poljska) u svom su se radu bavili modelom prijenosa znanja u sustavu sveučilište – drvoprerađivačka poduzeća na poljskim primjerima.

J. Kropivšek i M. Jošt (Slovenija) dali su financijsku analizu stanja drvnog sektora Slovenije.

M. Potkany i G. Giertl (Slovačka) obradili su primjenu operativnih alata u vrednovanju investicija u proizvodnji pločastih materijala.

M. Potkany, M. Turkota i G. Giertl (Slovačka) predstavili su statističke prognoze za dodane vrijednosti u drvnoj industriji i industriji namještaja u Slovačkoj.

M. Relich (Poljska) dao je odnos između učinkovitosti i razine rizika u multi projektnoj organizaciji drvnog sektora.

R. Vlosky i D. Terrell (SAD) prikazali su proizvodnju biomase u SAD-u i njezin utjecaj na ruralne sredine u Louisiani.

H. Paluš i J. Parobek (Slovačka) prikazali su razvoj proizvodnje oblovine u Slovačkoj.

A. Kielesinska (Poljska) osvrnula se na odrednice održivog razvoja u socijalno osjetljivoj kompaniji.

A. Adamus-Matuszynska i I. Nizialek (Poljska) u svom su radu obradili strategije razvoja socijalno osjetljive kompanije u poljskoj drvnoj industriji.

S. V. Bhalerao, A. B. Borade i S. J. Deshmukh (Indija) prezentirali su mogućnost primjene Rapid Prototype Technology u izradi prototipova u preradi drva i proizvodnji namještaja Indije.

M. Bielawska (Španjolska) predstavila je ulogu institucionalne potpore inovacijama u proizvodnji namještaja, s primjerom iz španjolske industrije namještaja.

E. N. Agapova, E. N. Egorova i U. O. Kuznecova (Rusija) prikazali su utjecaje otpora zaposlenika pri uvođenju sustava upravljanja kvalitetom u drvoprerađivačke tvrtke.

P. Gejdoš (Slovačka) dao je prikaz pojedinih elemenata sustava upravljanja kvalitetom u slovačkoj proizvodnji namještaja.

J. Klementova i A. Šatanova (Slovačka) predstavile su kvalitetu usluge prijenosa informacija slovačkih sveučilišta u praksu.

N. Naprstkova i D. Kalincova (Češka) dale su prikaz testiranja materijala oštrica alata u proizvodnji drvenih greda.

M. Olkowicz i W. Szymanowski (Poljska) prikazali su područja inovacija u razvoju novih proizvoda u poljskoj proizvodnji namještaja.

J. Patalas-Maliszewska i I. Krebs (Poljska i Njemačka) predstavile su integralni koncept *business-to-business* prijenosa znanja u poduzeća.

E. Prachniar, D Prachiarova-Bohušova i R. Rybansky (Slovačka) dali su prikaz certifikacije drvoprerađivačkih poduzeća u sustavu projektnog menadžmenta.

A. Rathod i A. Kolhatkar (Indija) predstavili su bambus kao alternativu tekstilu u proizvodnji ojastučenog namještaja.

R. Ulewicz (Poljska) prikazao je mogućnost primjene Keno upitnika i istraživanju elemenata kvalitete drvenog namještaja.

E. Grzegorzewska (Poljska) dala je prikaz stanja inovativnosti u poduzećima drvnog sektora Poljske.

K. Radharth (Austrija) u svojem je radu obradila značenje inovacije utemeljene na korisnicima u malim i srednjim tvrtkama.

A. di Taranto i R. Stasiak-Betlejewska (Italija i Poljska) bavili su se istraživanjima vrednovanja kvalitete drvenih kuća s obzirom na potres i požar, pri čemu su naveli neke rezultate istraživanja provedenoga u Dolomitima.

Uz međunarodno znanstveno savjetovanje, prema ustaljenom redoslijedu, održana je i izborna generalna skupština WoodEMA asocijacije. Za novog predsjednika asocijacije u mandatnom razdoblju od 1. siječnja 2014. do 31. prosinca 2015. izabran je prof. dr. sc. Mikulaš Šupin (Slovačka), kao kandidat za predsjednika (budućeg predsjednika) imenovan je prof. dr. sc. Richard Vlosky (SAD), a za nove članove Upravnog odbora u istom mandatnom razdoblju izabrani su prof. dr. sc Darko Motik (Hrvatska), prof. dr. sc. Leon Oblak (Slovenija) i doc. dr. sc. Hubert Paluš (Slovačka). Za generalnog tajnika u svom četvrtom mandatu ponovno je izabran prof. dr. sc Denis Jelačić.

Uz ostale zaključke, u asocijaciju su primljeni novi članovi, njih dvanaest iz četiri europske zemlje (Španjolske, Mađarske, Hrvatske i Slovačke), Indije i Irana. Tako WoodEMA trenutačno ima članove s tri kontinenta, odnosno iz devet europskih zemalja (Hrvatske, Italije, Mađarske, Makedonije, Poljske, Slovačke, Slovenije, Srbije i Španjolske), SAD-a, Indije i Irana.

generalni tajnik WoodEMA, i.a.
prof. dr. sc. Denis Jelačić

Slika 2. Sudionici međunarodne znanstvene konferencije WoodEMA 2013
Figure 2 Participants of international scientific conference WoodEMA 2013

Higrokalkulator©

Iz tiska je izašao *Higrokalkulator*©, koji su izradili prof. dr. sc. Stjepan Pervan i dipl. ing. Miljenko Klarić.

Riječ je o grafičkom pomagalu koje služi za više različitih namjena u drvnoj tehnologiji.

Higrokalkulator© je vrlo koristan za područje hidrotermičke obrade drva, kao i za ostala područja drvne tehnologije. Moguće ga je primijeniti u znanosti – laboratorijskim istraživanjima, u svakodnevnom radu u struci te u nastavi sa studentima.

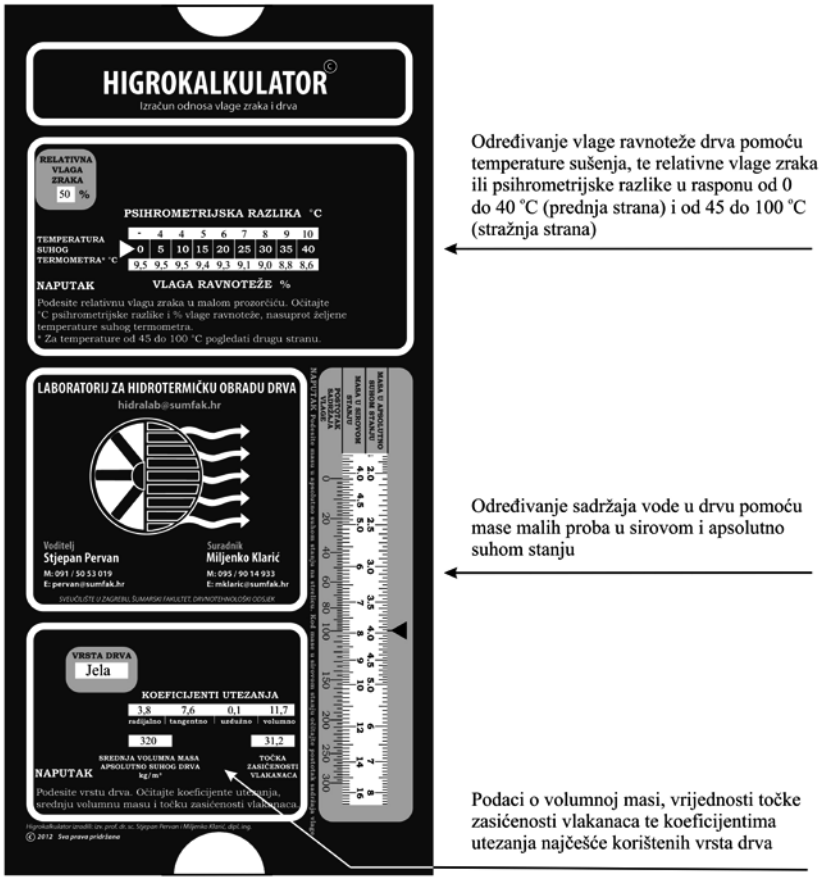
Posebna je odlika Higrokalkulatora specifičan praktičan pristup pri kojemu korisnik na najjednostavniji način ima na raspolaganju potrebne temeljne podatke za svakodnevni rad.

Veličina pomagala je 215 x 105 mm, a otisnut je na specijalnome nepoderivom papiru otpornome na habanje i vlagu.

Podaci koji se mogu očitati s *Higrokalkulatora*© skupljeni su iz velikog broja dostupnih izvora o svojstvima drva i psihrometriji zraka. Pomicanjem unutarnjeg klizača moguće je mijenjati i očitavati različite vrijednosti na otvorima za očitavanje na vanjskoj košuljici.

Podaci koje se očitava mogu se podijeliti u tri skupine:

1. određivanje vlage ravnoteže drva uz pomoć temperature sušenja (suhog termometra) te relativne vlage zraka ili psihrometrijske razlike u rasponu od 0 do 40 °C (prednja strana) i od 45 do 100 °C (stražnja strana) *Higrokalkulatora*©;
2. određivanje sadržaja vode u drvu uz pomoć mase malih proba u sirovome i apsolutno suhom stanju;
3. očitavanje podataka o volumnoj masi, vrijednosti točke zasićenosti vlakanaca te koeficijentima utezanja najčešće upotrebljavanih vrsta drva.



S obzirom na to da su navedeni podaci inače rasuti u izuzetno velikom broju različitih izvora dostupnih informacija, do sada nije napravljeno ovako jednostavno sredstvo koje bi objedinilo često tražene podatke na jasan i lako razumljiv način, te se može ustvrditi da će ovo pomagalo izuzetno dobro poslužiti znanstvenicima, studentima i stručnjacima u praksi.

Za sve dodatne informacije moguće se obratiti prof. dr. sc. Stjepanu Pervanu (tel. 01/2352 509, faks 01/ 2352-2544, e-mail: pervan@sumfak.hr).

prof. dr. sc. Stjepan Pervan

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Međunarodna asocijacija za ekonomiku i menadžment u preradi drva i proizvodnji namještaja WoodEMA, i.a. je međunarodna, nepolitička, neprofitabilna i otvorena asocijacija.

Cilj asocijacije je da promovira znanost te znanstvena i stručna dostignuća njezinih članova, omogući međusobnu znanstvenu suradnju kao i da podupre znanstveni i stručni razvoj unutar njezina područja djelovanja.

Kako bi se postigli ti ciljevi, asocijacija se bavi sljedećim aktivnostima:

- Razmjenom znanja i rezultata istraživanja među članovima organiziranjem savjetovanja i publiciranjem članaka u časopisima i zbornicima radova
- Potporom zajedničkoj znanstvenoj suradnji među članovima asocijacije kroz elaborate i znanstvene projekte
- Potporom razvoju znanstvenih i stručnih organizacija u području djelovanja asocijacije
- Znanstvenom i stručnom edukacijom organiziranjem znanstvenih i stručnih simpozija i savjetovanja
- Prikupljanjem i razmjenom tržišnih, tehnoloških i tehničkih podataka

Članovi iz mnogih Europskih zemalja i SAD pozivaju Vas da nam se pridružite.

Sve informacije možete dobiti na web stranici ili putem e-maila generalnog tajnika WoodEMA, i.a.

ABACHI

NAZIVI I NALAZIŠTE

Drvo vrste *Triplochiton scleroxylon* K. Schum. iz botaničke porodice *Sterculiaceae* potječe iz zapadne Afrike: iz Liberije, Obale Bjelokosti, Gane, Nigerije, Kameruna, Gabona, Republike Kongo. Raste zajedno s limbom (*Terminalia superba* Engl. & Diels) u tropskim kišnim šumama. Trgovački i lokalni nazivi su mu obeche (Francuska, Belgija, Velika Britanija), abachi (Njemačka, Nigerija), samba (Njemačka, Francuska, Obala Bjelokosti), wawa (Njemačka, Gana, Velika Britanija), ofa, sam (Njemačka), ayous (Francuska, Velika Britanija, Gabon, Kamerun, Kongo), aréré; obechi (Nigerija).

STABLO

Drvo vrste *Triplochiton scleroxylon* K. Schum. listača je srednje visine između 30 i 50 m. Promjer debla kreće se između 50, 120 i 180 cm, rjeđe dosegne i 200 cm. Debla su cilindrična, obično čista od grana, vrlo visoka, što omogućuje dobivanje trupaca velike tehničke dužine.

Visina do prve grane iznosi 25 do 30 m. Kora debla je glatka, a sa starenjem stabla postaje pločasta i ljušti se. Bjelkasto je sive boje, boje pijeska, a povremeno ima narančast ton. Debljina kore kreće se od 1,0 do 1,8 cm (3,0 cm). Prirodna regeneracija stabla je dobra, a podmladak iznimno dobro raste – u povoljnim uvjetima na godinu naraste i do 1,8 m u visinu.

DRVO

Makroskopska obilježja

Srž i bjeljika međusobno se jedva razlikuju po boji. Drvo je boje slonovače do boje slame, žutosmeđe, a ponekad može biti i maslinasto. Bjeljika je široka, katkada i do 15 cm. Drvo je vrlo mekano, fine i ujednačene teksture. Žica drva malo je kad ravna, premda njezina nepravilnost ne stvara probleme u preradi. Svježe je drvo vrlo neugodnog mirisa koji sušenjem nestaje. Granica goda je više-manje dobro izražena (na poprečnom presjeku katkad je uočljiva po marginalnom parenhimu i promjeni gustoće pora). Uzdužno presječene traheje istaknute su na uzdužnim presjecima. Radijalna površina drva sjaji zbog refleksije svjetlosti na većim tracima. Vrpce aksijalnog parenhima, premda vrlo guste, vidljive su na uzdužnim površinama zahvaljujući svom etažnom rasporedu. Etažnim se rasporedom *Triplochiton scleroxylon* vrlo dobro razlikuje od većine drugih svijetlih vrsta drva.

Mikroskopska obilježja

Drvo je rastresito porozno. Pore su razbacane, pretežno pojedinačne i u paru, a rjeđe u radijalnim skupinama. Promjer pora iznosi od 70...180...280 mikrometara. Gustoća pora kreće se od 1 – 3 – 10/mm^2 poprečnog presjeka. Volumni udjel pora je 3...10...22 %. U drvu postoje tile. Aksijalni je parenhim apotrahealno ljestvičast, apotrahealno marginalan, paratrahealno vazicentričan, unilateralan, konfluentan do vrpčast. Udio aksijalnog parenhima iznosi 25...30...45 %. Staničje drvnih trakova je heterogeno. Drvni traci visoki su od 4...17...40 stanica, a široki su 1 ...4... 6 stanica. Gustoća trakova je od 3 – 7 – 11/mm, a volumni udjel trakova iznosi 17...24...30 %. Vlakanca su libriformska, a raspored im je na poprečnom presjeku tangentan. Debljina stijenki vlakanaca kreće se od 1,3...3,9 do...6,5 mikrometra, a promjer lumena od 1,8...9,3...17,6 mikrometara. Dužina vlakanaca je 650...1325...2100 mikrometara. Volumni udjel vlakanaca kreće se od 15...35...46 %. U stanicama trakova i aksijalnog parenhima nalaze se kristali prizmatičnog oblika. U pojedinoj stanici nema više od jednog kristala. Stanice s kristalima normalne su veličine.

Fizikalna svojstva

Gustoća standardno suhog drva, ρ_o	250...350...520 kg/m^3
Gustoća prosušenog drva, $\rho_{12\text{-}15}$	280...380...550 kg/m^3
Gustoća sirovog drva, ρ_s	530...650 kg/m^3
Poroznost	oko 72 %
Totalno radijalno utezanje	2,2...3,3...4,2 %
Totalno tangentno utezanje	4,6...5,6...6,7 %
Totalno volumno utezanje	6,9...9,1...11,5 %

Mehanička svojstva

Čvrstoća na tlak	24...40...50,5 MPa
Čvrstoća na savijanje	30...73,5...110 MPa
Čvrstoća na vlak paralelno s vlakancima	11...49,5...79,5 MPa
Čvrstoća na vlak okomito na vlakanca	1,0...1,3...1,7 MPa
Tvrdoća prema Brinellu paralelno s vlakancima	oko 25MPa
Tvrdoća prema Brinellu okomito na vlakanca	oko 13 MPa
Modul elastičnosti	4,9...8,7 GPa

TEHNOLOŠKA SVOJSTVA

Obradivost

Drvo se lako obrađuje ručnim i strojnim alatima. Preporučuje se uporaba oštrih alata s tankim bridovima kako bi se izbjeglo čupanje i mrvljenje drva. Drvo se odlično brusi, ljušti, lijepi, pjeskari, politira i moči. Tamno močeno, upotrebljavalo se kao zamjena za drvo mahagonija. Pri spajanju se preporučuje lijepljenje premda drvo dobro drži vijke i čavle te ne puca.

Sušenje

Drvo se vrlo brzo suši, uz vrlo malo grešaka ili bez njih. To su uglavnom neznatne pukotine i blaga iskrivljenost. Trupce za sušenje treba pažljivo složiti i omogućiti dobru cirkulaciju zraka među njima. Stabilnost dimenzija je dobra, a jednom prosušeno drvo umjereno radi.

Trajnost i zaštita

Prema normi HRN 350-2: 2005, srž drva svrstava se među slabo trajna (klasa 5), teško se impregnira (klasa 3). Bjeljika je permeabilna (klasa 1). Srž i bjeljika drva nisu otporne prema napadu termita i drugih insekata poput bjeljikara i kućne strizibube. Podložne su i napadu gljiva koje uzrokuju promjenu boje i gljiva truležnica. Katkad su stabla zaražena patogenom gljivom *Botryodiploida theobromae*, koja smanjuje mehanička svojstva drva.

Uporaba

Drvo se upotrebljava za proizvodnju furnira i furnirskih ploča te ploča iverica, za obloge, unutarnje konstrukcije, za izradu namještaja i dijelova namještaja, za izradu kanua, čamaca za spašavanje, drvenih kutija. Odlično je stolarsko drvo za unutrašnje radove i nadomješta meko drvo četinjača. Trupci većih dimenzija prikladni su za masovnu proizvodnju namještaja. Cijena trupaca smatra se povoljnom.

Sirovina

Drvo na tržište dolazi u obliku trupaca i piljene građe. Trupci su obično većih dimenzija.

Napomena

Drvo može poslužiti kao zamjena za topolovinu pri izradi namještaja i panel ploča. Fina bruševina drva dobivena obradom može prouzročiti iritaciju pluća nakon duljeg izlaganja njezinu utjecaju, a u osjetljivih osoba može uzrokovati i kožnu alergiju.

Prema izvještaju međunarodne organizacija ITTO (The International Tropical Timber Organization), *Triplochiton scleroxylon* važna je sirovina za proizvodnju građe i izvoz. Zajedno s vrstama *Entandrophragma cylindricum* i *Lophira alata*, *Triplochiton scleroxylon* čini polovicu ukupno dostupne količine drvne sirovine u Kamerunu.

Vrste sličnih svojstava jesu *Didymonopanax morototoni* Decne. et Planch., *Terminalia brassii* Exell, *Ricinodendron heudelotii* Pierre, *Antiaris Africana* Engl., *A. welwitschii* Engl., *A. spp*., *Pterygota macrocarpa* K. Schum. i *P. spp.*

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prof. dr. sc. Jelena Trajković
doc. dr. sc. Bogoslav Šefc

Upute autorima

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U uvodu treba definirati problem i, koliko je moguće, predočiti granice postojećih spoznaja, tako da se čitateljima koji se ne bave područjem o kojemu je riječ omogući razumijevanje ciljeva rada.

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Svi grafikoni i tablice izrađuju se kao crno-bijeli prilozi (osim na zahtjev, uz plaćanje). Tablice i grafikoni trebaju biti na svojim mjestima u tekstu te originalnog formata u kojemu su izrađeni radi naknadnog ubacivanja hrvatskog prijevoda. Ako ne postoji mogućnost za to, potrebno je poslati originalne dokumente u formatu u kojemu su napravljeni (*excel* ili *statistica* format).

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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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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.

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Müller, D. 1977: Beitrag zur Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanslalt für Forst- und Holzwirtschaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

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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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