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DRVNA INDUSTRIJA je časopis koji objavljuje znanstvene i stručne radove te ostale priloge iz cjelokupnog područja iskorištavanja šuma, istraživanja svojstava i primjene drva, mehaničke i kemijske prerade drva, svih proizvodnih grana te trgovine drvom i drvnim proizvodima.

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DRVNA INDUSTRIJA journal contains research contributions and reviews covering the entire field of forest exploitation, wood properties and application, mechanical and chemical conversion and modification of wood, and all aspects of manufacturing and trade of wood and wood products.

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Editorial

Last year we celebrated the 70th anniversary of issuing the journal *Drvna industrija* by different activities dedicated to this important event. One of them was the organization of the scientific conference in the framework of the ICWST 2019 conference.

ICWST conference (International Conference of Wood Science and Technology) is a scientific two-day conference that takes place at the Faculty of Forestry, University of Zagreb, every year in December. Within the framework of the ICWST 2019 conference, there was a double celebration – 30th edition of the conference and 70th anniversary of the journal *Drvna industrija*, the only scientific SCI indexed journal in the field of wood science issued in Croatia.

The conference program committee selected 58 abstracts, among which 5 invited lectures, 33 oral presentations and 25 posters were found particularly interesting either by their scientific novelty, their potential for industrial applicability or by bringing out elaborated synthesis of some high impact subjects.

Among the presented papers, the editorial board of the journal *Drvna industrija* selected several high quality papers for publication in the journal, based on the relevance to the journal and the reviews of the conference abstracts. The authors were asked to prepare a full paper for the journal publication. The prepared full papers went through the regular journal review process and are finally presented to the readers of the journal *Drvna industrija*.

This issue of *Drvna industrija* contains a collection of 12 selected papers from the ICWST 2019 conference and 5 papers will be published in the issue 3/2020. The abstracts of these papers were published in the conference proceedings, while full papers are published in the journal.

The papers cover a wide range of research topics – wood anatomy, wood finishing and gluing, organization and economy of forest based industry, wood processing, wood furniture and wood-based panels, and we hope that the readers will enjoy reading these scientific novelties.

Assistant Editor-in-Chief
Assist. Prof. Josip Miklečić, PhD

Uvodnik

Prošle smo godine obilježili 70. godinu izdavanja časopisa *Drvna industrija* različitim aktivnostima posvećenim toj važnoj obljetnici. Jedna od tih aktivnosti bilo je i organiziranje znanstvenog skupa u sklopu konferencije ICWST 2019, na kojemu je održana središnja proslava 70. obljetnice časopisa.

ICWST (International Conference of Wood Science and Technology) dvodnevna je znanstvena konferencija o drvu i drvnoj tehnologiji koja se održava na Šumarskom fakultetu Sveučilišta u Zagrebu obično svake godine u prosincu. Na prošlogodišnjoj konferenciji ICWST 2019 obilježen je dvostruki jubilej – održavanje 30. ICWST-a i 70. obljetnica časopisa *Drvna industrija*, jedinoga znanstvenog časopisa u Hrvatskoj iz područja znanosti o drvu koji je indeksiran u prestižnoj bazi časopisa SCI-Expanded.

Programski je odbor ICWST-a za prezentaciju na konferenciji odabrao 58 radova, među kojima je bilo pet pozvanih predavanja, 33 usmena izlaganja i 25 postera, koji su se izdvajali bilo znanstvenim novinama, potencijalom za primjenu u industriji ili predstavljanjem elaborirane sinteze nekih vrlo važnih tema.

Među radovima koji su prezentirani na konferenciji Uredništvo časopisa *Drvna industrija* izabralo je određen broj visokokvalitetnih članaka za objavljivanje u časopisu. Radovi su odabrani na temelju zanimljivosti i relevantnosti tema te recenzija sažetaka pripremljenih za konferenciju. Od autora je zatraženo da pripreme cjelovite članke za objavljivanje u časopisu. Tako pripremljeni radovi prošli su redovni postupak recenziranja i predstavljeni su čitateljima u ovom i sljedećem broju časopisa. I na taj smo način – objavljivanjem radova u časopisu, dali doprinos obilježavanju duge povijesti časopisa *Drvna industrija*.

Ovaj broj časopisa *Drvna industrija* sadržava 12 odabranih radova s konferencije ICWST 2019, a pet radova bit će tiskano u broju 3/2020. Sažetci tih radova objavljeni su u zborniku, radovi su prezentirani na konferenciji putem usmenih priopćenja ili postera, a u časopisu su objavljeni u cijelosti.

Radovi pokrivaju širok raspon istraživačkih tema – od anatomije drva, završne obrade i lijepljenja drva, organizacije i ekonomije u drvnoj industriji do mehaničke obrade drva te izrade namještaja od drva i proizvodnje drvnih ploča. Nadamo se da će čitatelji uživati čitajući predstavljene znanstvene novosti.

Pomoćnik glavne urednice
doc. dr. sc. Josip Miklečić

Maks Merela[1], Nejc Thaler [2], Angela Balzano[1], Denis Plavčak[1]

Optimal Surface Preparation for Wood Anatomy Research of Invasive Species by Scanning Electron Microscopy

Optimalna priprema površine drva za istraživanje anatomije invazivnih vrsta drva pretražnim elektronskim mikroskopom

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ABSTRACT • *Research was done to develop the optimal method of wood surface preparation for scanning electron microscopy (SEM). Since 2018, environmental scanning electron microscope (ESEM™) FEI Quanta 250 has been installed at the Department of Wood Science and Technology in Ljubljana. We tested several methods for the pre-preparation and cutting of wood surfaces for SEM analyses. The samples had been either dried, soaked in water and frozen, impregnated with paraffin or simply moistened before cutting. We analysed wood surfaces obtained by splitting, sawing, planing, sanding and cutting on a sliding microtome with different blades. The effect of gold coating on the SEM image quality was also evaluated. Best results were obtained by cutting a pre-moistened surface on a sliding microtome with a low profile replaceable blade and gold coated afterwards. Determined methodology is technically less demanding, not time consuming and obtains results that satisfy needs for wood anatomy research at magnifications up to 12.000x. Guidelines for the optimal preparation of samples were prepared, and theoretical and practical basis for investigations of wood anatomy using SEM were provided. The method was afterwards used in analyses of invasive alien plant species – investigating their anatomical structure in the framework of the AlienPLAntSpEcies - APPLAUSE project (Urban Innovative Actions initiative). It was demonstrated that the use of the SEM opened new scope in detailed investigations of the wood structure and properties.*

Keywords*: wood anatomy; wood surface; scanning electron microscopy; SEM; invasive species; sample preparation*

SAŽETAK • *Istraživanje je provedeno kako bi se razvila optimalna metoda pripreme drvne površine za pretražnu elektronsku mikroskopiju (SEM). Od 2018. na Odsjeku za znanost i tehnologiju o drvu u Ljubljani instaliran je uređaj za pretražnu elektronsku mikroskopiju u uvjetima okoliša (ESEM™) FEI Quanta 250. Proučavali smo nekoliko metoda za pripremu i rezanje površine drva za SEM analizu. Uzorci su sušeni, potapani u vodi i smrzavani*

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[2] Author is head of development at Sivaprodukt d.o.o., Ljubljana, Slovenia.

te prije rezanja impregnirani parafinom ili samo navlaženi. Analizirali smo površine drva dobivene cijepanjem, piljenjem, blanjanjem, brušenjem i rezanjem na mikrotomu različitim oštricama. Također je proučavan utjecaj zlatnog premaza na kvalitetu SEM fotografija. Najbolji rezultati dobiveni su rezanjem prethodno navlažene površine na mikrotomu, i to zamjenjivim noževima niskog profila, nakon čega je površina drva pozlaćena. Primijenjena je metodologija tehnički manje zahtjevna, ne oduzima mnogo vremena, a dobiveni rezultati zadovoljavaju potrebe istraživanja anatomije drva pri povećanju i do 12 000 puta. Sastavljene su smjernice za optimalnu pripremu uzoraka te je postavljena teorijska i praktična osnova za istraživanje anatomije drva primjenom SEM-a. Metoda je potom primijenjena za istraživanje invazivnih biljnih vrsta – za ispitivanje njihove anatomske strukture u sklopu projekta AlienPLAntSpEcies – APPLAUSE (Urban Innovative Actions). Potvrđeno je da je upotreba SEM-a otvorila novo područje u detaljnim istraživanjima strukture i svojstava drva.

***Ključne riječi**: anatomija drva; površina drva; pretražna elektronska mikroskopija; SEM; invazivne vrste; priprema uzorka*

1 INTRODUCTION
1. UVOD

Wood is a unique natural composite made of several different cells and biopolymers that characterize its properties. Wood anatomy research is obligatory if we aim to characterize wood properties and if we want to understand wood as a raw material for various products. All relevant physical, mechanical as well as aesthetic properties of wood are reflected in its heterogeneous biological cell structure. Most commonly used method for wood anatomy investigation is bright field light microscopy (LM). For this purpose, wood needs to be cut into thin slices, stained and embedded in resin for producing permanent anatomical slides (Prislan *et al*., 2009). Anatomical structure of wood can also be revealed by several other methods that enable more or less detailed anatomical investigations. Some of research techniques also display wood structure based on detection of some other components; water in wood (in the cell wall and/or lumina) is a component that enables research by Nuclear Magnetic Resonance Imaging – MRI method. Latest devices enable MRI microscopy with spatial resolution up to 50 µm and also 3D imaging of wood structure (Merela *et al*., 2005; 2009a; Oven *et al*., 2008, 2011; Žlahtič *et al*., 2017). Wood consists of several different chemical elements and is, therefore, appropriate for Proton Induced X ray Emission (PIXE and micro-PIXE) (Merela *et al*., 2009b), where surface element distribution can also reveal wood tissue structure. Heterogeneous structure of wood is reflected in different density and this fact is exploited by the Computer Tomography that is commonly used for log scanning (detecting of internal growth anomalies, knots, rots, etc.) as well as for high resolution imaging as Micro CT (Wagner *et al*., 1989; Bucur, 2003; Mayo *et al*., 2010; Craig, 2013).

Variation of thermal conductivity inside wood tissue enables Infrared Thermal imaging. Visualization of the thermal variations of a large area of the stem in real time is well suited for spatial analysis of sap movement (Anfodillo *et al*., 1993; Niemz *et al*., 1997; Busse, 2001; Chen *et al*., 2005). Dielectric properties of wood are used in Microwave techniques imaging (Baradit *et al*., 2005; Hansson *et al*., 2005; Pastorino *et al*., 2007; Salvade *et al*., 2008; Boero *et al*., 2018), where we can distinguish areas of different density as well as different moisture content; this method is useful to detect growth defects like knots, etc.

Among all the developed methods, the Scanning Electron Microscopy (SEM) seems to be one of the most powerful techniques that enable very detailed and high magnification wood structure research. SEM uses a high energy electron beam (accelerated electrons) to produce a topographic image by scanning the surface of a sample. The electron beam, emitted by the electron source (electron gun) and collected by electromagnetic lenses in a vacuum chamber, interacts with the atoms of sample surface, providing information about the sample's surface topography, tissue orientation, chemical composition, and many other material properties (Zhou *et al*., 2006; Goldstein *et al*., 2017).

The application of SEM in wood science began long before the system became commercially available in 1965, since the wood surface and structure are well suited for this technique (Collett, 2007). The results of the first application in the ground wood pulp fiber were published by Atack and Smith (1956). After that, the potential of SEM began to be exploited in wood anatomy and investigation of wood decay observing small cubes of wood cut through the three planes (Resch and Blaschke, 1968; Findlay *et al*., 1969). In 1969, a Finnish publication (Ilvessalo-Pfäffli, 1969) demonstrated the wide-ranging surface topography capabilities of SEM showing micrographs of paper, crystals, as well as some excellent pictures of wood structure. Finally, a comprehensive atlas of three-dimensional structure of wood was presented by Meylan and Butterfield (1978a).

Despite development of techniques with other advantages, SEM remains among the most effective tools for understanding ultrastructural and developmental aspects of secondary xylem and for investigating topography and distribution of exposed features.

However, successful preparation of wooden specimens for SEM without damaging or modifying the wood surface and structure has proven rather challenging. Different protocols have been developed for wood sample preparation for SEM, which often require complex, technically demanding and time-consuming procedures (Exley *et al*., 1977; Meylan and Butterfield 1978a). Conventional protocols described in literature suggest (before cutting the wood) to soften it in a boiling mixture of glycerine and water until the wood becomes saturated and sinks in the liquid (Jansen *et al*., 1998; Collet, 2007). Treatment with hydro fluoric acid or ethylene-diamine (Carlquist, 1982) is also suggested for very hard wood species and subsequent washing for at least 12 h before sectioning (Sanderson, 1994). Often bleaching with sodium hypochlorite or house hold bleach (15 %) (60-90 min until the surface has lost color) is recommended to remove any protoplasmic debris or vessel contents from the pit chambers (Meylan and Butterfield, 1978b; Nagai *et al*., 1994; Jansen *et al*., 2000). After the sample is cut with a microtome, most common procedures consist of sample dehydration with mixture of ethanol and distilled water series (50-70-96 %) (Jansen *et al*., 1998) or with series of Methanol-Acetone-N-pentane, each series lasting for 12 hours (Thomas and Nicholas, 1966; Thomas, 2007). In the last step, different drying methods are reported including oven heating at 100 °C for 3 days and immersion of the wood samples in liquid nitrogen and freeze-drying (Jansen *et al*., 2008).

Clearly, the above-mentioned SEM protocols have some disadvantages. Besides being expensive and time consuming (duration of sample preparation at least few days), they are subject to a relatively high risk for deflecting structural changes due to chemicals and dehydration process (Hanks and Fairbrothers, 1970; Jansen *et al*., 2008).

This study aimed to develop a SEM protocol that would enable high performance analyses on a daily basis, achieving high resolution at magnifications up to 8.000x of the observed wooden traits with minimum sampling preparation. One of the aims was to check how different woodworking processes affect the final appearance of the wood surface. We analyzed wood surfaces obtained by splitting, sawing, planing and sanding. The main purpose of this research was to develop an optimal (technically not too demanding, inexpensive and not time-consuming) wood surface sample preparation for SEM analyses. Our samples for wood anatomical investigations were pre-treated in different ways and cut on a sliding microtome with two different blade types.

The developed method and protocol were afterwards used in analysis of 17 invasive alien plant species – detailed investigation of anatomical structure in the framework of the Applause project (Applause, 2019). Due to the huge amount of obtained data, in this paper we only present a selection of results referring to the following species: black locust (*Robinia pseudoacacia*), staghorn sumac (*Rhus typhina*), desert false indigo (*Amorpha fruticosa*) and red osier dogwood (*Cornus sericea*).

Black locust (*Robinia pseudoacacia*) is medium sized, suckering, deciduous tree that typically grows 12-18 m tall. The popularity of *R. pseudoacacia* as an ornamental, forestry, shelter and land reclamation species has ensured its wide introduction across many regions (Orwa et al., 2019). Native to the Allegheny Mountains, it nowadays covers much of the United States and southern Canada plus parts of Europe, Asia and South America.

The staghorn sumac (*Rhus typhina*) is a deciduous shrub or small tree growing up to 5 m. It originates from south-eastern Canada and United States, but is widely cultivated as an ornamental tree all over the world (Kossah *et al*., 2011) becoming one of the most critical invasive alien plant species.

Desert false indigo (*Amorpha fruticosa*) grows as a thornless shrub up to 6 m height. It is native in most of the United States, south-eastern Canada and northern Mexico. Because of its nice purple flowers with yellow anthers, it is cultivated as an ornamental plant so the species is present in Europe, Asia, and other continents (Wang *et al*., 1999).

Red osier dogwood (*Cornus sericea*) is native throughout northern and western North America from Alaska east to Newfoundland, south to Durango and Nuevo León in the west, and Illinois and Virginia in the east (Ashworth *et al*., 1993). It is frequently used for waterway bank erosion protection and restoration so it often spreads uncontrolled and becomes invasive.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Material selection and sample preparation
2.1. Odabir materijala i priprema uzoraka

To test all available surface preparations, we selected beech (*Fagus sylvatica*) as a reference wood species (e.g., Novak, 2018). To split the wood in radial and tangential plane, we used a sharp chisel, using a woodworking circular saw (saw blade diameter 400 mm, 96ABT pos 10° tooth at 4000 rpm) to cut the surface in all three anatomical planes. To get a planed surface (radial and tangential), we used a woodworking surface planer (with 4 blades, head diameter 120 mm and 5000 rpm). Sanding was done on woodworking belt-sanding machine with sand paper grit sequence 80/120/240 in all three wood sections (cross, radial, tangential). All final samples were prepared as 1 cm^3 cubes. Split and planed wood was observed on longitudinal sections only (as it was impossible to split wood across the axial direction), and sawn and sanded specimens on all three xylotomical planes.

A more meticulous approach was developed to perform detailed wood anatomical observations by cutting wood with microtome blades. We prepared small strictly oriented wood cubes (1 cm^3) processed with several pre-treatments before obtaining the final surface for observations.

Samples had been either dried, soaked in distilled water and frozen, or simply moistened for some seconds before cutting. One series of samples was also embedded in paraffin according to the standard procedure used for anatomical examinations of micro-cores (Prislan *et al*., 2009; Rossi *et al*., 2006; Balzano *et al*., 2018, Balzano *et al*., 2019).

Obtained samples were cut with a sliding microtome (Leica LM2010R) using either classic microtome blade (Leica) or replaceable Low Profile Microtome Blades (Leica DB80 LX) using a special blade holder – Low Profile Blade Rail Twin set (Leica). We cut 20 μm thick wood slices. When cutting with a microtome, we always trimmed wood surface for optimal

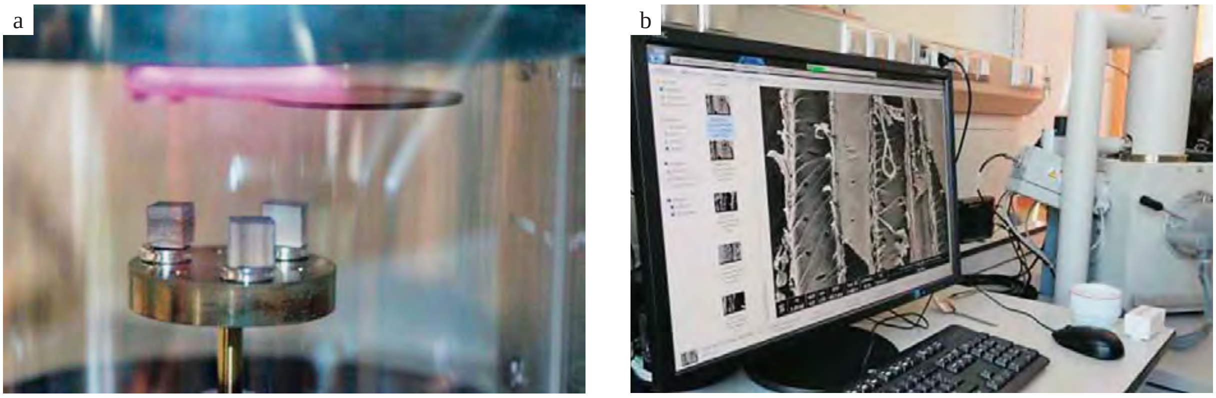

Figure 1 a) Oriented wood samples during gold coating in a Q150R ES Coating System; b) Scanning Electron Microscope (SEM) FEI QUANTA 250
Slika 1. a) Položaj uzoraka drva tijekom nanošenja pozlate parom u Q150R ES *Coating System*; b) pretražni elektronski mikroskop (SEM) FEI QUANTA 250

orientation and position and, thereafter, moved the blade to a new position to make one clear final cut with a new sharp cutting edge.

Finally, the cut samples were dried at laboratory conditions (T = 22 °C and RH = 65 %) before SEM analyses. Samples that were soaked in water and frozen were first put at T = 4 °C and RH = 65 % for 24h and afterwards dried in laboratory conditions to prevent fast drying and possible drying cracks. One series of frozen samples was freeze-dried (Telstar Lyo Quest).

The dried samples were mounted on stubs with a conductive carbon adhesive tab and part of them were coated with Au/Pd sputter-coater (Q150R ES Coating System; Quorum technologies, Laughton, UK) (Figure 1a) for 60 seconds with a constant current of 20 mA, while others remained uncoated. The thickness of gold layer deposited on the sample surface depended on the time of exposure and the sputtering current set in the system. If the layer was too thick, the surface details could be obscured. If the layer was too thin, the surface could undergo excessive charging resulting in a weak signal and low-quality images. In this way, we also checked the SEM analyses quality with and without coating.

The SEM micrographs were then taken in low voltage (5 to 10 kV) and low vacuum (50 Pa) conditions with a large field (LFD) detector in a FEI Quanta 250 SEM microscope (FEI Company, Hillsboro, Oregon, USA) (Figure 1b) at working distances between 7 and 11 mm.

The appropriate voltage depended on samples structure. High voltage beam generally resulted in a higher signal and better resolution, with the possibility of penetrating the samples surface, thus producing the signal from below the specimen's surface resulting in an unfairly information-rich image. Charging effect was also more pronounced after a few minutes at 10 kV, especially on non-coated specimens. Voltage of 5 kV was high enough to provide a high resolution image and at the same time avoid damaging the wood surface.

After SEM analyses of surfaces on all three sections (cross, radial and tangential) on beech wood, we selected technical optimal methodology for wood surface preparation. Optimal results were obtained by cutting a pre-moistened wood surface with a sliding microtome using a replaceable low-profile blade. According to this developed methodology, we finally prepared three strictly oriented cubes (1 cm^3) for each of the selected four invasive alien wood species to be analyzed for detailed anatomical structure by SEM.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Surface after processing
3.1. Površina nakon pripreme

The first part of the results presents surface appearance obtained by different woodworking processes (Figure 2). Different woodworking operations on radial and tangential plane open the wood structure so that we can recognize some wood cells (Figure 2). Figure 2a shows the surface after sanding with final sand paper grit 240. We can recognize rays, distribution of fiber with bordered pits and a vessel. Planed surface seemed to be slightly better as we can also clearly recognize individual vessel elements with intervessel pits, as well as pits between vessel and ray parenchyma (Figure 2b).

We can see that, in case of sanding the cross section, all cell lumina are filled and closed with the sanded cell wall material (Figure 2c). In this case, the penetration of impregnation or coatings cannot be as effective as cutting with circular saw (Figure 2d), where at least some of vessel lumina are still partly opened. These results are important if we aim to understand surface wood permeability before impregnation or coating. None of the described wood working operations gives a surface where it would be possible to observe wood anatomical details.

Splitting of wood in radial and tangential plane (Figure 2e and 2f) display all characteristic features of beech wood. When splitting wood, we do not cut, brush, remove or relocate cell wall matrix – splitting simply divides cells along the weakest adhesion layer and in most cases this is middle lamella. After splitting on radial section, we can clearly recognize vessel elements with opposite intervessel pits, pits between vessel and ray parenchyma. Simple perforation plates can be seen between vessel elements (Figure 2e). Among vessels, we can observe fiber with bordered or modi-

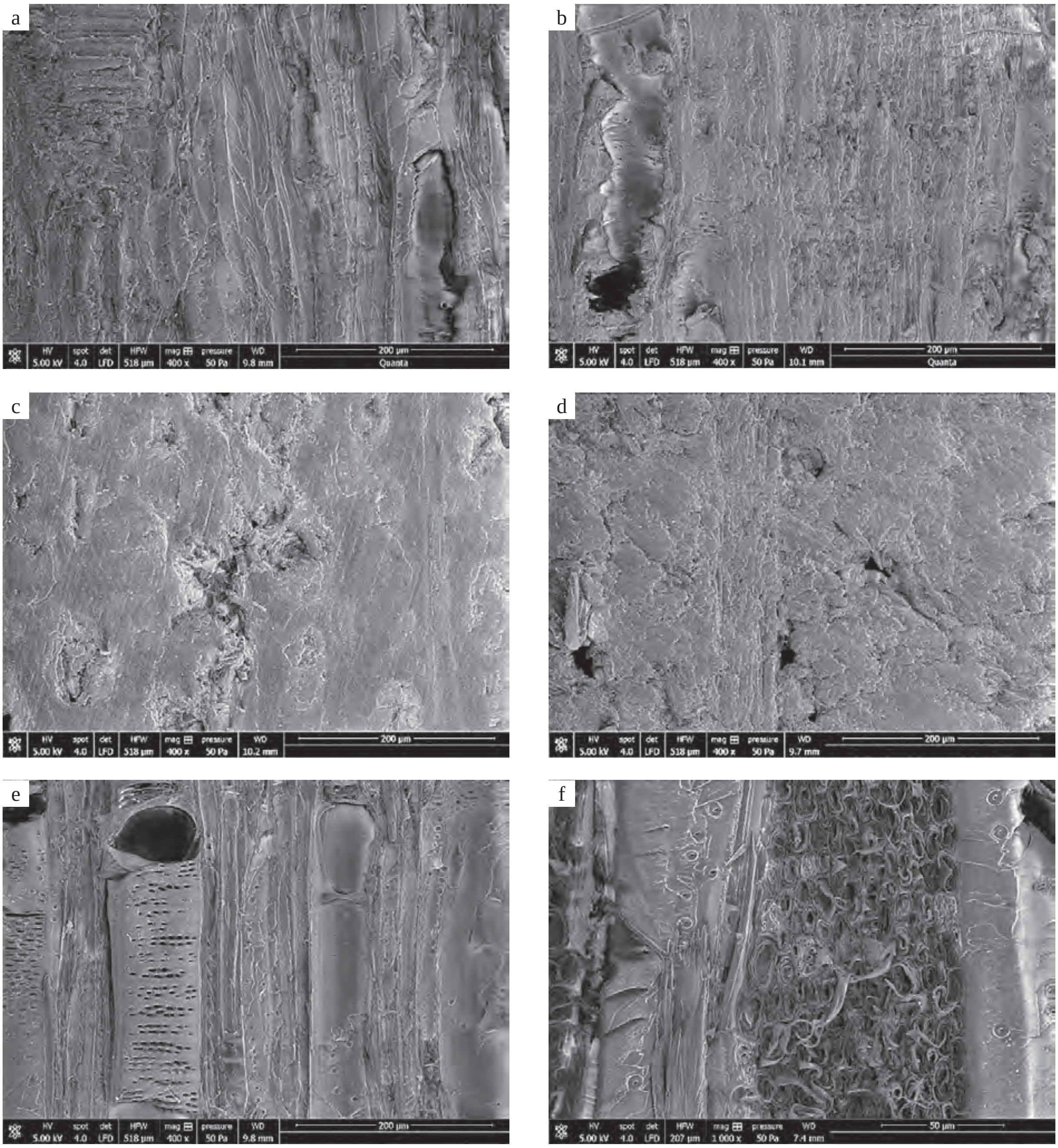

Figure 2 Beech (*Fagus sylvatica*), SEM: a) radial surface after sanding, b) radial surface after planing, c) cross surface after sanding, d) cross surface after circular cut, e) radial surface after splitting and f) tangential section after splitting
Slika 2. Bukovina (*Fagus sylvatica*), SEM: a) radijalni presjek nakon brušenja, b) radijalni presjek nakon blanjanja, c) poprečni presjek nakon brušenja, d) poprečni presjek nakon blanjanja, e) radijalni presjek nakon cijepanja, f) tangentni presjek nakon cijepanja

fied bordered pits. The same features could be recognized on split tangential section (Figure 2f), where we can also see a wide ray. Ray parenchyma cells were split by being pulled in their longitudinal direction and parts of cell walls can be seen as pulled out spiral structures – remains of cell wall matrix before crushing. We can also observe simple pits between parenchyma cells. Results showed that observation of wood structure in radial and tangential section is possible if the wood is split without any pre-treatment.

3.2 Cross section preparation
3.2. Priprema poprečnog presjeka

Due to cell orientation, the cross section surface preparation proved to be the most difficult and could only be prepared by cutting with microtome. Figure 3 presents the results of beech wood cross section cut with two different blades and subjected to several different wood pre-treatments.

In the first row, we present cutting of dried and non-pre-treated samples by solid microtome blade and replaceable low profile blade (Figure 3b). Solid blade cutting opened clear cell structure but detailed analysis revealed that cell walls of vessel elements as well as axial parenchyma and ground tissue were scraped and cell matrix was pushed partly into cell lumina (Figure 3a). Cutting with replaceable blade was better, cell walls were not scraped and cell lumina were clearer. However, since low profile replaceable blade is very thin and slim, it vibrates when cutting dry wood thus leaving marks on the surface of the specimen (Figure 3b). To avoid blade vibration during cutting (also called chattering), we prepared sample pre-treated in paraffin by the standard procedure for micro-core samples (Balzano *et al*., 2018). After the treatment, paraffin was washed from the surface by bio-clear (D-limonene) before cutting. We were able to make high quality cut, but in spite of the leaching and purification, residues of paraffin were observed in the cell lumina during the analysis, as well as on some parts of the cell wall (Figure 3c). From the samples that were immersed and soaked in water and then frozen, we obtained one of the best and clearest cross surfaces (Figure 3d). We can see that all cell walls were cut clear and that cell lumina were intact. Very similar results were obtained after cutting of pre-moistened surface (Figure 3e). Since soaking, freezing and drying after cutting proved to be time consuming and technically demanding, it was concluded that optimal surface preparation was wetting the surface with distilled water immediately before cutting (Figure 3e).

After defining optimal pre-treatment and cutting by microtome low profile replicable blade, we also tested SEM analyses of non-coated and gold coated (with different parameters) wood surface (Figure 4).

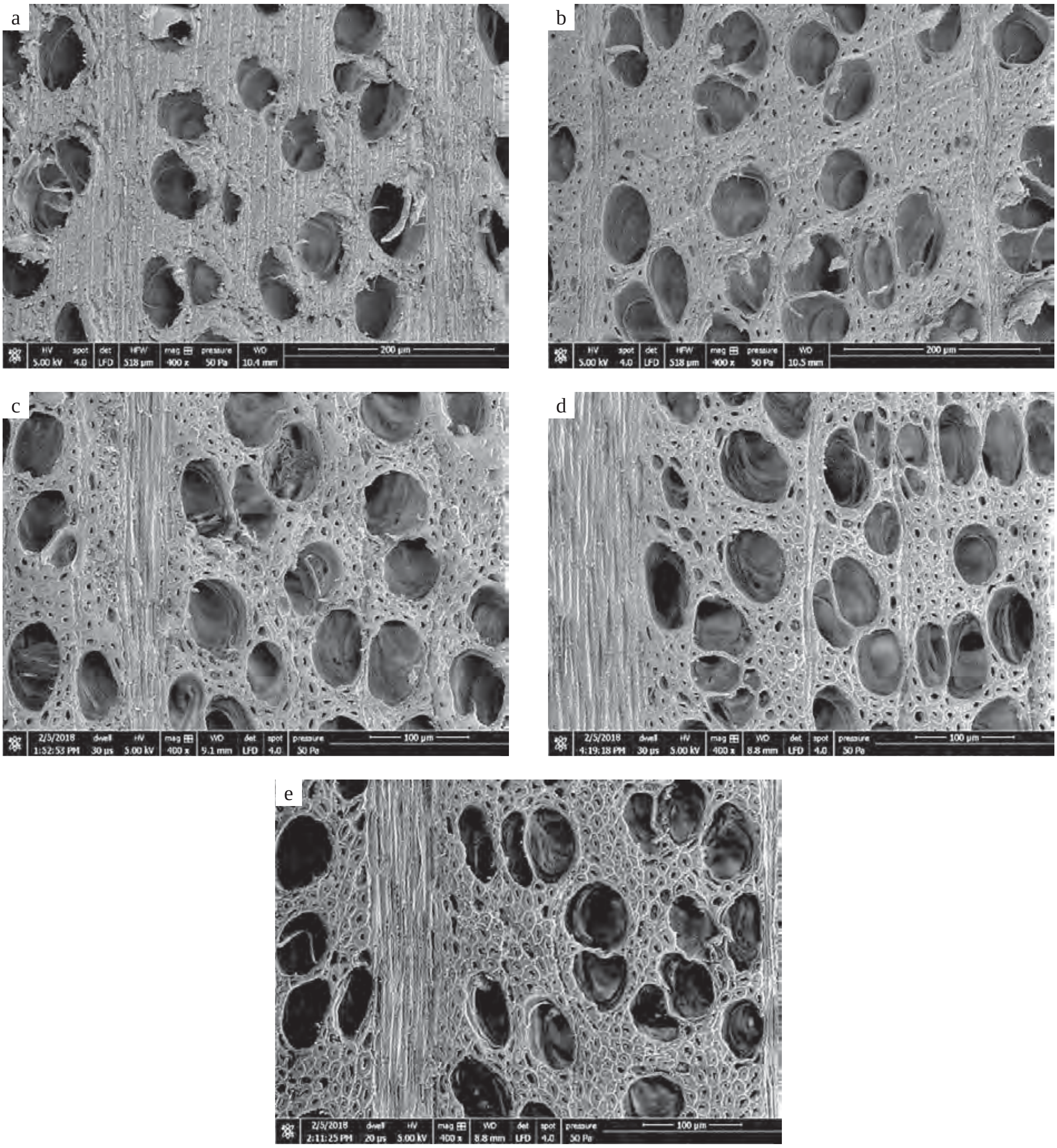

Figure 3 Beech (*Fagus sylvatica*), SEM, cross section cut on microtome: a) solid blade cut – no pre-treatment, b) replaceable blade cut – no pre-treatment, c) replaceable blade cut – wood pre-treated by paraffin, d) replaceable blade cut – wood pre-treatment by freezing and e) replaceable blade cut with a pre-moistened wood surface
Slika 3. Bukovina (*Fagus sylvatica*), SEM, poprečni presjek rezan na mikrotomu: a) čvrstim nožem – bez predtretmana, b) nožem s izmjenjivim oštricama – bez predtretmana, c) nožem s izmjenjivim oštricama – uz predtretiranje drva parafinom, d) nožem s izmjenjivim oštricama – uz predtretiranje drva zamrzavanjem, e) nožem s izmjenjivim oštricama – površina drva navlažena

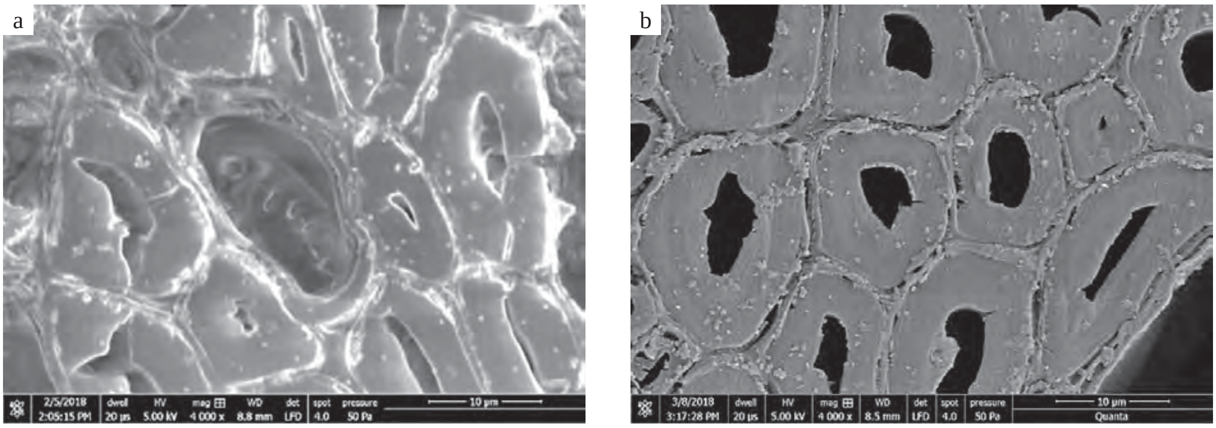

Figure 4 Beech (*Fagus sylvatica*), SEM, cross section: a) non- coated wood and b) gold coated wood surface
Slika 4. Bukovina (*Fagus sylvatica*), SEM, poprečni presjek: a) nepremazano drvo, b) pozlata parom nanesena na površinu drva

Low conductivity specimens have a limited ability of discharging electrons from the sample surface to the metal stub (and finally on the grounded parts of the microscope), resulting in the so-called charging effect (the over-lit edges of cells in Figure 4a), displayed at 4.000 × magnification. The phenomenon could be a result of poor contact between the specimen and the mount, inadequate metal coating or inadequate bulk conductivity. The coated surface gave much better results for SEM analyses, especially at higher magnifications (Figure 4b).

3.3 Wood anatomical investigation of invasive species by SEM
3.3. Istraživanje anatomije invazivnih vrsta drva uz pomoć SEM-a

The wood of invasive species was used as the main research material. In Slovenia several invasive plant species are very widespread and locally forming large stands. Since uncontrolled spreading became a serious problem, there have been many projects addressing this issue and one of them is APPLAUSE. Activities of APPLAUSE project makes it easier for the

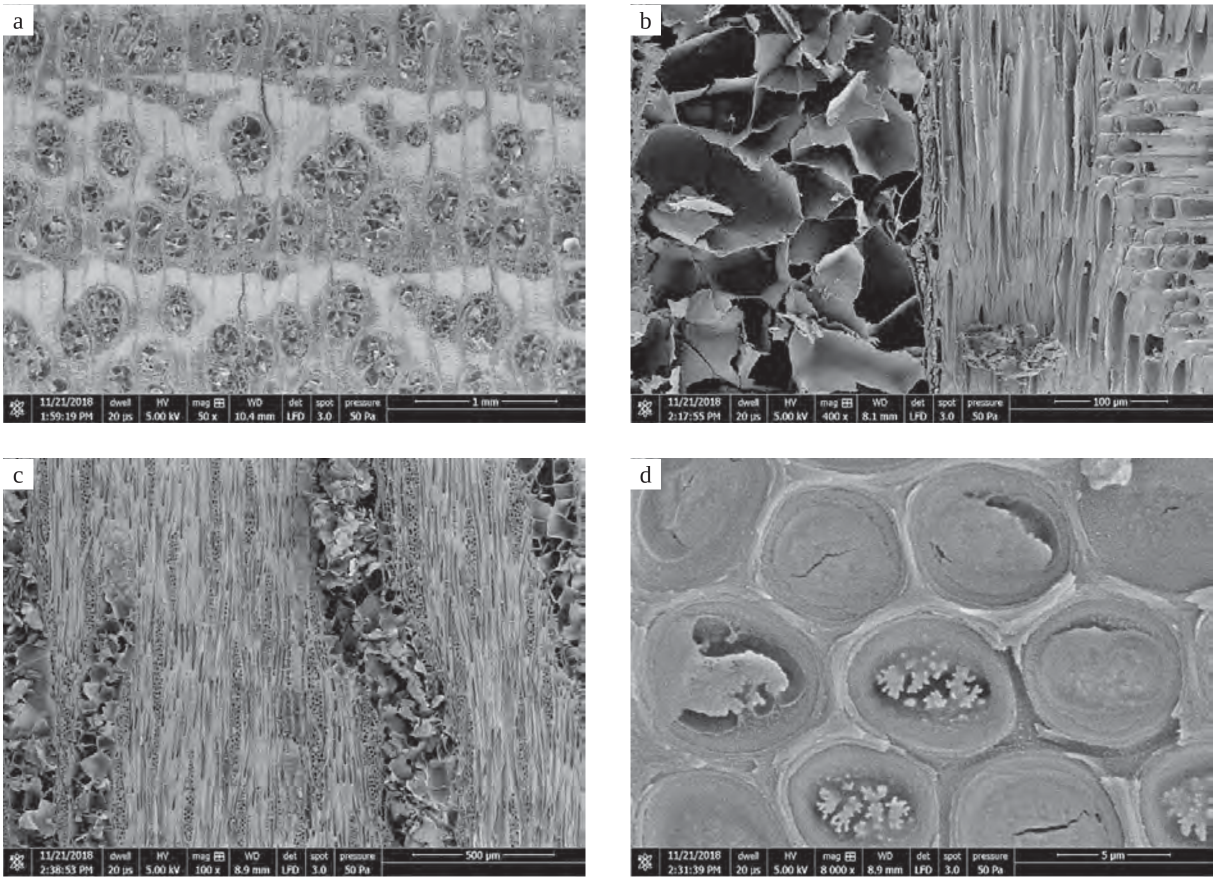

Figure 5 Black locust (*Robinia pseudoacacia*), heartwood, SEM: a) cross section, b) radial section, c, d) tangential section at various magnifications
Slika 5. Drvo bagrema (*Robinia pseudoacacia*), srž, SEM: a) poprečni presjek, b) radijalni presjek, c) i d) tangentni presjek pri različitim povećanjima

citizens to recognize invasive wood plant species and then remove and process them into useful products. Seventeen invasive wood species were identified and their properties were analyzed to find potential innovative solutions for their use. Wood anatomy research knowledge is necessary when characterizing wood properties.

One of the fastest spreading non-native invasive tree species is black locust (*Robinia pseudoacacia*), which has distinct growth rings with a ring-porous structure (Figure 5a). Earlywood as well as latewood vessels are abundantly filled with tyloses (Figure 5a-c). On SEM images, we can observe how dense and complex the structure is built from tyloses along the vessel elements. Chemical components present in the cell walls of black locust wood are crucial for its durability; tyloses present a strong barrier that obstructs the spread of fungal hyphae through the vessels. High resolution SEM images at 8000 × magnification also show vestured pits in vessel elements (Figure 5d), not often observed in *Robinia pseudoacacia*.

The staghorn sumac (*Rhus typhina*) has an interesting wood structure. On the cross section (Figure 6a), we can see the semi-to ring-porous vessel distribution. Growth rings are distinct. Vessels in latewood are grouped in radial multiples and also in clusters. Body ray cells are procumbent with one or two rows of upright square marginal cells (Figure 5b). On the tangential section, we can clearly recognize 1 to 3 seriate rays (Figure 6c) and helical thickenings in vessel elements. Figure 6d shows detailed spatial distribution of helical thickenings and intervessel pits at the 3.000 × magnification.

Desert false indigo (*Amorpha fruticosa*) cross section (Figure 7a) shows thin walled fiber from 10 to 20µm in diameter and ray parenchyma cells filled with starch grains indicating their storage function. Desert false indigo wood is semi- to ring-porous and Figure 7b shows a detail on tangential section, where we can see that vessel elements on the transition from early- to latewood – vessels are up to 80 µm long and up to 50 µm in diameter. Biseriate rays can be observed on tangential section (Figure 7c). Starch grains in axial parenchyma are 1 to 4 µm in diameter and up to 5 µm long (Figure 7 c, d).

Red osier dogwood (*Cornus sericea*) has a diffuse-porous wood, ground tissue consisting of thin to thick walled fibers and diffuse axial parenchyma (Figure 8a). Tangential section shows vessels elements with alternate intervessel pits and long scalariform perforations with 20-40 bars (Figure 8b). Observation of vessel perforations at higher magnifications (up to 12.000 ×) revealed the remnants in the scalariform perforation plate (Figure 8d and 8e). Similar structures were observed in *Illicium tashiroi* (Carlquist, 1992). The remnants in the perforation plate of red osier dogwood can be defined as extensive band-like remnants that form strands running in an axial direction.

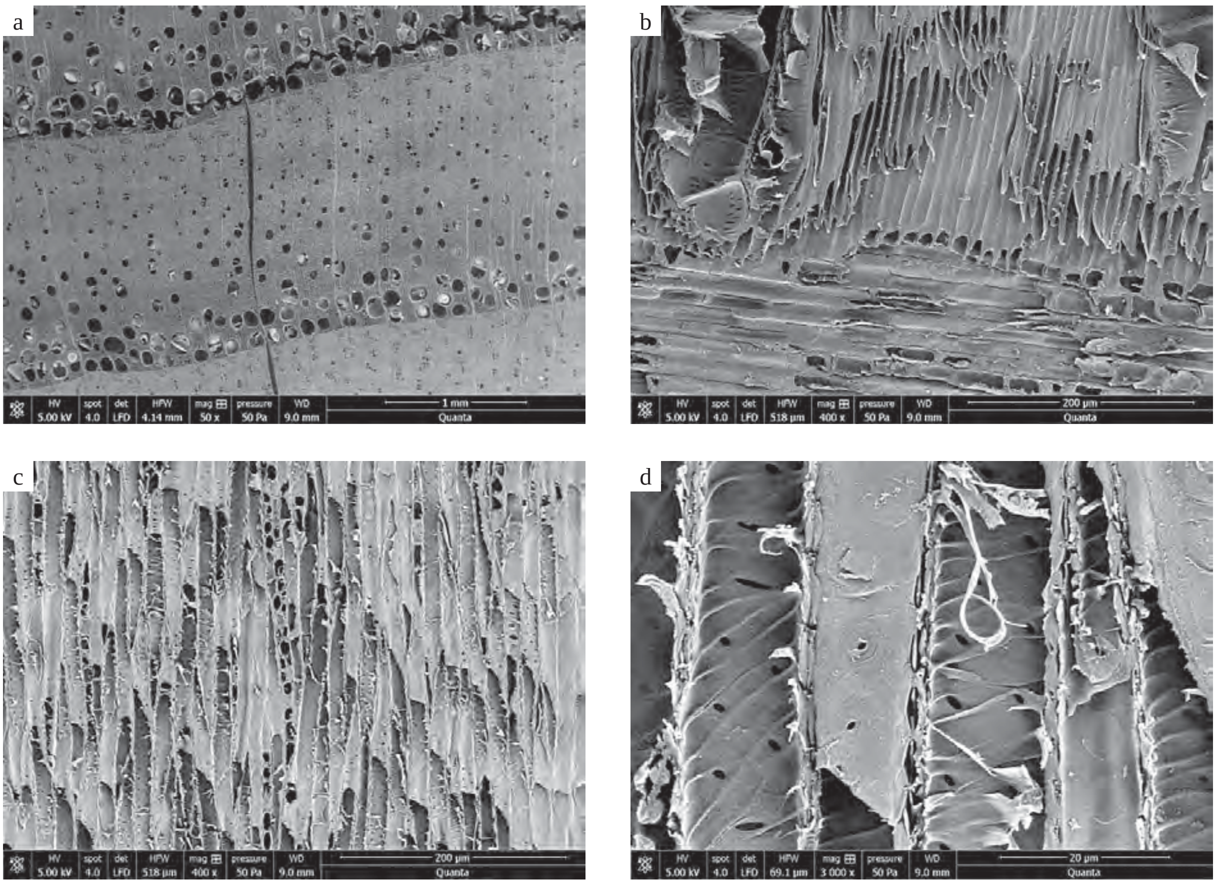

Figure 6 Saghorn sumac (*Rhus typhina*), SEM: a) cross section, b) radial section, c) tangential section and d) tangential section at larger magnification

Slika 6. Kiseli ruj (*Rhus typhina*), SEM: a) poprečni presjek, b) radijalni presjek, c) tangentni presjek, d) tangentni presjek pri većem povećanju

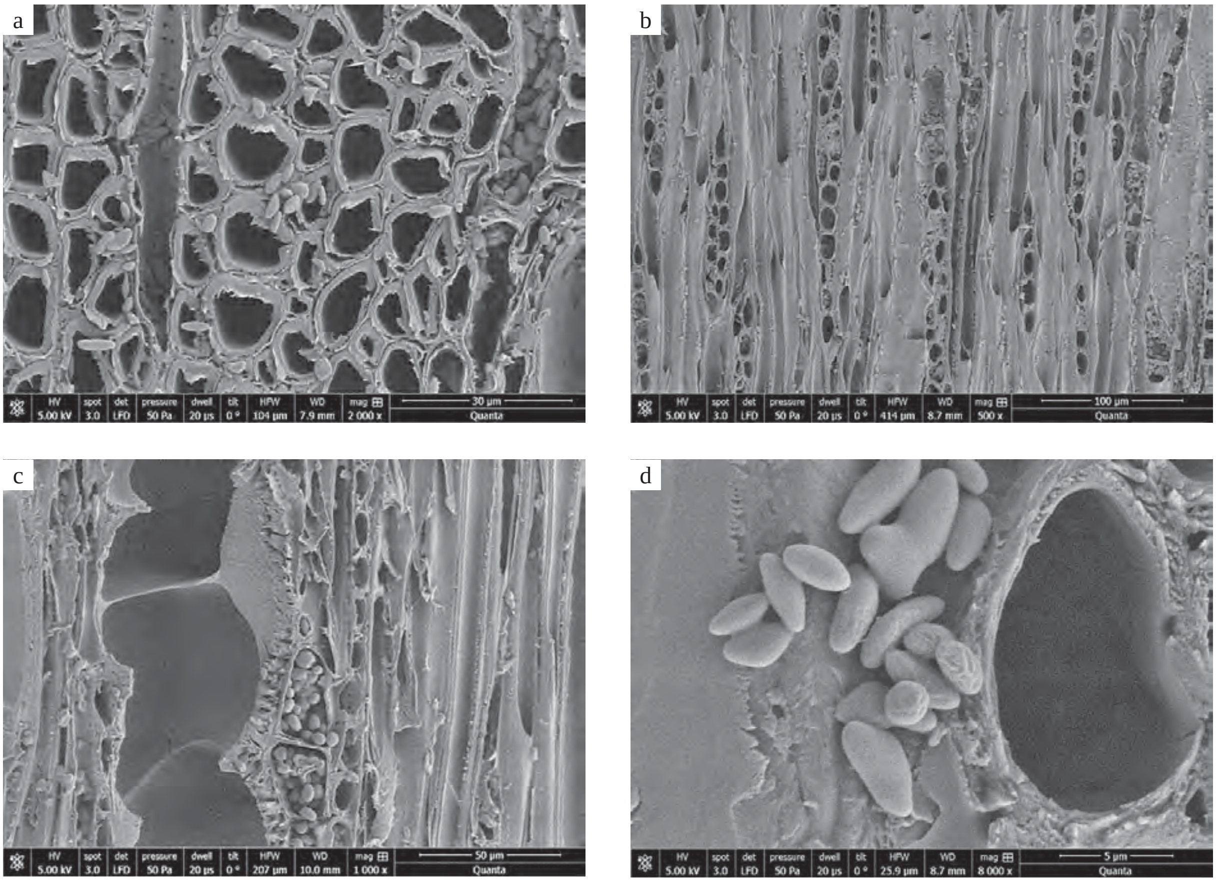

Figure 7 Desert false indigo (*Amorpha fruticosa*), SEM: a) cross section, b, c, d) tangential section at various magnifications
Slika 7. Amorfa (*Amorpha fruticosa*), SEM: a) poprečni presjek, b), c) i d) tangentni presjek pri različitim povećanjima

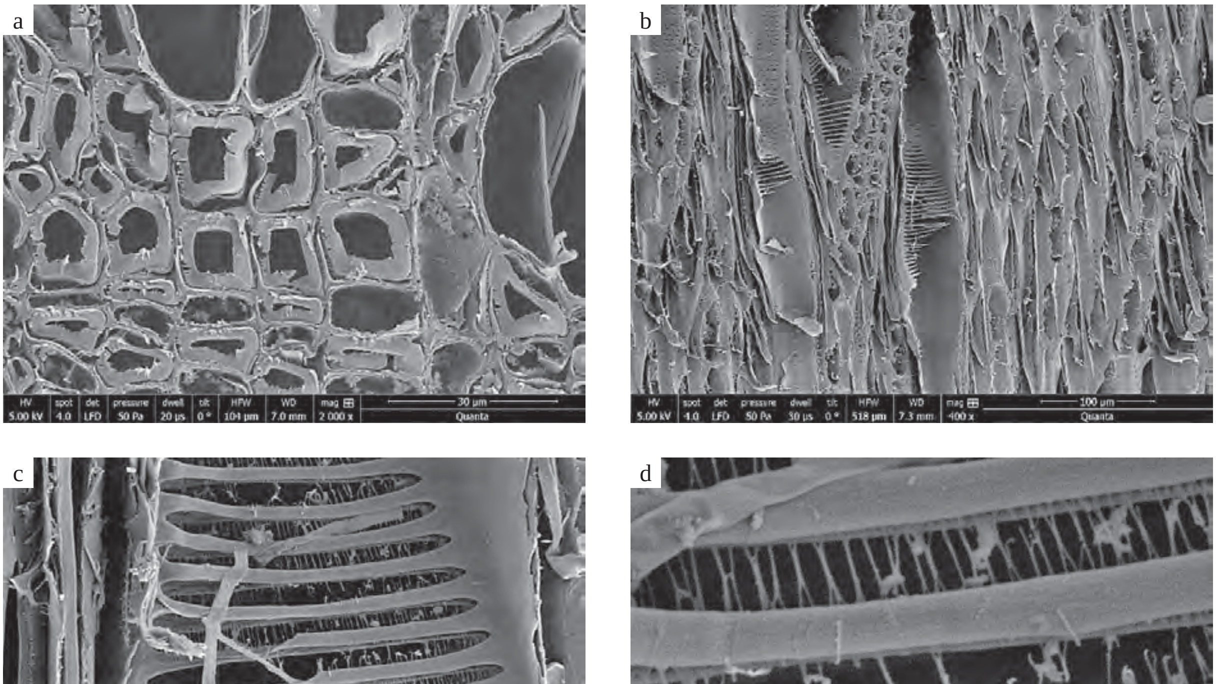

Figure 8 Red osier dogwood (*Cornus sericea*), SEM: a) cross section, b, c, d) tangential sections at various magnifications
Slika 8. Drijen (*Cornus sericea*), SEM: a) poprečni presjek, b), c) i d) tangentni presjek pri različitim povećanjima

4 CONCLUSIONS
4. ZAKLJUČAK

We optimized a method for the preparation of wooden specimens for SEM analysis. Since the method is fast and technically less demanding, it allows observation of a larger sample series on daily basis.

The best results were obtained by cutting a frozen surface using a sliding microtome with a low-profile replaceable blade followed by gold coating. However, the optimal results (considering everything from time consumption to price) were obtained by a pre-moistened surface cut on a sliding microtome with a low-profile replaceable blade followed by gold coating. We were able to prepare samples of selected invasive alien wood species for detailed SEM analyses. The developed method enabled us to observe details that can be detected only at high magnifications. High resolution images at high magnifications (up to 12.000 ×) prove that the proposed technique works for advanced wood anatomy investigations. We displayed complex structures of tyloses and vestured pits in vessels of *Robinia pseudoacacia*, spatial distribution of helical thickenings in *Rhus typhina,* starch grains in *Amorpha fruticosa* and scalariform perforations with rarely observed band-like remnants in *Cornus sericea*.

The technique is now used on a daily basis for SEM analyses at the Department of Wood Science and Technology of Biotechnical Faculty in Ljubljana.

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5 REFERENCES
5. LITERATURA

1. Anfodillo, T.; Sigalotti, G. B.; Tomasi, M.; Semenzato, P.; Valentini, R., 1993: Applications of a thermal imaging technique in the study of the ascent of sap in woody species. Plant, Cell & Environment, 16 (8): 997-1001. https://doi.org/10.1111/j.1365-3040.1993.tb00524.x.
2. Ashworth, E. N.; Stirm, V. E.; Volenec, J. J., 1993: Seasonal variations in soluble sugars and starch within woody stems of *Cornus sericea* L. Tree Physiology, 13 (4): 379-388. https://doi.org/10.1093/treephys/13.4.379.
3. Atack, D.; Smith, K. C. A., 1956: The scanning electron microscope. A new tool in fiber technology. Pulp and paper magazine of Canada (Convention issue), 57: 245-251.
4. Balzano, A.; Čufar, K.; Battipaglia, G.; Merela, M.; Prislan, P.; Aronne, G.; De Micco, V., 2018: Xylogenesis reveals the genesis and ecological signal of IADFs in *Pinus pinea* L. and *Arbutus unedo* L. Annals of botany, 121 (6): 1231-1242. https://doi.org/10.1093/aob/mcy008.
5. Balzano, A.; De Micco, V.; Merela, M.; Čufar, K., 2019: Tree-rings in Mediterranean pines-can we describe them to calendar years? Les, 68 (1): 5-14.
6. Baradit, E.; Aedo, R.; Correa, J., 2005: Knots detection in wood using microwaves. Wood Science and Technology, 40 (2): 118-123. https://doi.org/10.1007/s00226-005-0027-8.
7. Boero, F.; Fedeli, A.; Lanini, M.; Maffongelli, M.; Monleone, R.; Pastorino, M.; Randazzo, A.; Salvadè, A.; Sansalone, A., 2018: Microwave Tomography for the Inspection of Wood Materials: Imaging System and Experimental Results. IEEE Transactions on Microwave Theory and Techniques, 66 (7): 3497-3510. https://doi.org/10.1109/TMTT.2018.2804905.
8. Bucur, V., 2003: Non-destructive Characterization and Imaging of Wood. Heidelberg, Springer, 354 p.
9. Busse, G., 2001: Lock in thermography. V: Nondestructive Testing Handbook, vol. 3. Infreared and Thermal Testing. Maldague, X. (ur.). Columbus, American Society for Nondestructive Testing: 318-327.
10. Carlquist, S., 1982: The use of ethylenediamine in softening hard plant structures for paraffin sectioning. Stain technology, 57 (5): 311-317.
11. Carlquist, S., 1992: Pit Membrane Remnants in Perforation Plates of Primitive Dicotyledons and Their Significance. American Journal of Botany, 79: 660-672.
12. Chen, Z.; Gabbitas, B.; Hunt, D., 2005: A thermal imaging technique for studying crack development in wood under torsional loading. Journal of Materials Science, 40 (8): 1929-1935. https://doi.org/10.1007/s10853-005-1213-7.
13. Collett, B. M., 2007: Scanning electron microscopy: A review and report of research in wood science. Wood and Fiber Science, 2 (2): 113-133.
14. Craig, R. B., 2013: Visualizing wood anatomy in three dimensions with high-resolution X-ray micro-tomography (μCT) – a review – IAWA, 34 (4): 408-424. https://doi.org/10.1163/22941932-00000033.
15. Exley, R. R.; Meylan, B. A.; Butterfield, B. G., 1977: A technique for obtaining clean cut surfaces on wood samples prepared for the scanning electron microscope. Journal of Microscopy, 110 (1): 75-78.
16. Findlay, G. W. D.; Levy, J. F., 1969: Scanning electron microscopy as an aid to the study of wood anatomy and decay. Journal of the Institute of Wood Science, 5 (5): 57-63.
17. Goldstein, J. I.; Newbury, D. E.; Michael, J. R.; Ritchie, N. W.; Scott, J. H. J.; Joy, D. C., 2017: Scanning electron microscopy and X-ray microanalysis. Springer, 550 p.
18. Hanks, S.; Fairbrothers, D. E., 1970: Effects of preparation technique on pollen prepared for SEM observations. Taxon, 19 (6): 879-886.
19. Hansson, L.; Lundgren, N.; Antti, A. L.; Hagman, O., 2005: Micro wave penetration in wood using imaging sensor. Measurement, 38 (1): 15-20. https://doi.org/10.1016/j.measurement.2005.03.007.
20. Jansen, S.; Kitin, P.; De Pauw, H.; Idris, M.; Beeckman, H.; Smets, E., 1998: Preparation of wood specimens for transmitted light microscopy and scanning electron microscopy. Belgian Journal of Botany, 131 (1): 41-49.
21. Jansen, S.; Piesschaert, F.; Smets, E., 2000: Wood anatomy of *Elaeagnaceae*, with comments on vestured pits, helical thickenings, and systematic relationships. American Journal of Botany, 87 (1): 20-28.
22. Jansen, S.; Pletsers, A.; Sano, Y., 2008: The effect of preparation techniques on SEM-imaging of pit membranes. IAWA Journal, 29 (2): 161-178.
23. Kossah, R.; Zhang, H.; Chen W., 2011: Antimicrobial and antioxidant activities of Chinese sumac (*Rhus typhina* L.) fruit extract. Food Control, 22 (1): 128-132. https://doi.org/10.1016/j.foodcont.2010.06.002.

24. Mayo, S. C.; Chen, F.; Evans, R., 2010: Micron-scale 3D imaging of wood and plant microstructure using high-resolution X-ray phase-contrast micro tomography. Journal of Structural Biology, 171: 182-188. https://doi.org/10.1016/j.jsb.2010.04.001.
25. Merela, M.; Oven, P.; Serša, I.; Mikac, U.; 2009a: A single point NMR method for an instantaneous determination of the moisture content of wood. Holzforschung, 63 (3): 348-351. https://doi.org/10.1515/HF.2009.050.
26. Merela, M.; Pelicon P.; Vavpetič, P.; Regvar, M.; Vogel-Mikuš, K.; Serša, I.; Poličnik, H.; Pokorny, B.; Levanič, T.; Oven, P., 2009b: Application of micro-PIXE, MRI and light microscopy for research in wood science and dendroecology. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 267 (12): 2157-2162. https://doi.org/10.1016/j.nimb.2009.03.062.
27. Merela, M.; Sepe, A.; Oven, P.; Serša, I., 2005: Three-dimensional in vivo magnetic resonance microscopy of beech (*Fagus sylvatica* L.) wood. Magma, 18 (4): 171-174.
28. Meylan, B. A.; Butterfield, B. G., 1978a: Three-dimensional structure of wood. A scanning electron microscope study. Syracuse University Press.
29. Meylan, B. A.; Butterfield, B. G., 1978b: Helical orientation of the microfibrils in tracheids, fiber and vessels. Wood Science and Technology, 12 (3): 219-222.
30. Nagai, S.; Ohtani, J.; Fukazawa, K.; Wu, J., 1994: SEM observations on perforated ray cells. IAWA Journal, 15 (3): 293-300.
31. Niemz, P.; Kucera, L. J.; Flisch, A.; Blaser, E., 1997: Anwendung der Computer tomographie an Holz (Computerized tomography of wood). Holz als Roh- und Werkstoff, 55 (2): 279-280.
32. Novak, J., 2018: Priprava površin lesa za slikanje z vrstičnim elektronskim mikroskopom (*Surface preparation of wooden samples for scanning electron microscopy*), M. Sc. Thesis, Ljubljana.
33. Orwa, C.; Mutua, A.; Kindt, R.; Jamnadass R.; Anthony, S., 2009: Agroforestree Database: a tree reference and selection guide version 4.0. http://www.worldagroforestry.org/output/agroforestree-database (Accessed Jun 10, 2018).
34. Oven, P.; Merela, M.; Mikac, U.; Serša, I., 2011: Application of 3D magnetic resonance microscopy to the anatomy of woody tissues. IAWA Journal, 32 (4): 401-414.
35. Oven, P.; Merela, M.; Mikac, U.; Serša, I., 2008: 3D magnetic resonance microscopy of a wounded beech branch. Holzforschung, 62 (3): 322-328.
36. Pastorino, M.; Salvade, A.; Monleone, R.; Bartesaghi, T.; Bozza, G.; Randazzo, A., 2007: Detection of defects in woods labs by using a microwave imaging technique. In: 2007 IEEE Instrumentation & Measurement Technology Conference IMTC 2007: pp. 1-6. https://doi.org/10.1109/IMTC.2007.379332.
37. Prislan, P.; Merela, M.; Zupančič, M.; Krže, L.; Čufar, K., 2009: Use of selected light microscopy techniques to investigate wood and bark. Les, 61 (5): 222-229.
38. Resch, A.; Blaschke, R., 1968: Ueber die Anwendung des Raster-Elektronen mikroskopes in der Holzanatomie. Planta (Berl.), 78 (1): 85-88.
39. Rossi, S.; Anfodillo, T.; Menardi, R., 2006: Trephor: A new tool for sampling microcores from tree stems, IAWA Journal, 27 (1): 89-97. https://doi.org/10.1163/22941932-90000139.
40. Salvade, A.; Pastorino, M.; Monleone, R.; Randazzo, A.; Bartesaghi, T.; Bozza, G.; Poretti, S., 2008: Microwave imaging of foreign bodies inside wood trunks. In: 2008 IEEE International Workshop on Imaging Systems and Techniques, pp. 88-93. doi:10.1109/IST.2008.4659947.
41. Sanderson, J. B., 1994: Biological Microtechnique, Microscopy Handbook No. 28, Royal Microscopical Society Handbook Series. Bios Scientific Publishers, pp. 240.
42. Thomas, R. J., 2007: The ultrastructure of southern pine bordered pit membranes as revealed by specialized drying techniques. Wood and Fiber Science, 1 (2): 110-123.
43. Thomas, R. J.; Nicholas, D. D., 1966: Pit membrane structure in loblolly pine as influenced by solvent exchange drying. Forest Products Journal, 16 (3): 53-56.
44. Wagner, F. G.; Taylor, F. W.; Ladd, D. S.; McMillin, C. W.; Roder, F. L., 1989: Ultrafast CT scanning of an oak log for internal defects. Forest Products Journal, 39 (11/12): 62-64.
45. Wang, E. T.; Van Berkum, X.; Sui, H.; Beyene, D.; Chen, W. X.; Martinez-Romero, E., 1999: Diversity of rhizobia associated with *Amorpha fruticosa* isolated from Chinese soils and description of *Mesorhizobium amorphae* sp. nov. International Journal of Systematic Bacteriology, 49 (1): 51-65. https://doi.org/10.1099/00207713-49-1-51.
46. Zhou, W., Apkarian, R., Wang, Z. L. & Joy, D., 2006: Fundamentals of scanning electron microscopy (SEM). In Scanning microscopy for nanotechnology. Springer, New York, pp. 1-40.
47. Žlahtič Zupanc, M.; Mikac, U.; Serša, I.; Merela, M.; Humar, M., 2017: Distribution and penetration of tung oil in wood studied by magnetic resonance microscopy. Industrial Crops and Products, 96: 149-157. https://doi.org/10.1016/j.indcrop.2016.11.049.

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THERMODOMINUS
THERMODUX
THERMOREX
GALEKOVIĆ
Kvaliteta u tradiciji
Tvornica parketa
DUX: Gotovi lakirani masivni klasični parket
DOMINUS: Gotovi lakirani masivni klasični parket - širina 9 cm
REX: Gotovi masivni lakirani podovi - uljeni / lakirani
Termo tretirani podovi: THERMODUX, THERMODOMINUS, THERMOREX
Eksterijeri: fasade, decking
FSC
PPS Galeković | Braće Radića 199 A, 10410 Mraclin
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Enhanced Abrasion Resistance of Coated Particleboard Pre-Treated with Atmospheric Plasma

Pojačana otpornost na abraziju premazanih iverica prethodno obrađenih atmosferskom plazmom

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ABSTRACT • *This study aims to investigate the influence of atmospheric plasma treatment on the abrasion resistance of particleboards, as an example of a wood-based material, coated with a waterborne finish. The treatment of the substrate, prior to coating application, using a floating-electrode dielectric barrier discharge (FE-DBD) plasma, resulted in an enhanced abrasion resistance of the coated particleboards in comparison to the untreated ones during the abrasion test with a duration of 200 revolutions. This finding was related to lower contact angles of water and coating after treatment with plasma and greater hardness of the coating on the treated substrates. The micrographs of the sample cross sections recorded with scanning electron microscope showed differences in the amounts of remained coating on the abraded areas. Investigation with attenuated total reflection Fourier transform infrared spectroscopy revealed that treatment of the substrate with plasma did not affect the chemical composition nor the curing and structure of the later applied coating. Further studies should be performed to determine the resistance properties of such surface systems to other impacts.*

Keywords: *particleboard; plasma; coating; abrasion*

SAŽETAK • *Cilj ovog rada bio je istražiti utjecaj atmosferske plazme na otpornost iverica na abraziju, kao primjer materijala na bazi drva premazanoga vodenim premazom. Tijekom ispitivanja abrazije u trajanju od 200 ciklusa obrada iverica uz pomoć plazme (FE-DBD) prije nanošenja premaza rezultirala je poboljšanom otpornošću premazanih iverica na abraziju u usporedbi s neobrađenom ivericom. Rezultat istraživanja povezan je s nižim kontaktnim kutom vode i premaznog materijala nakon obrade iverica plazmom i s većom tvrdoćom premaza na podlozi obrađenoj plazmom. Mikrografije presjeka uzorka dobivene pretražnim elektronskim mikroskopom pokazale su razlike u količini preostalog premaza na površinama ispitanima na otpornost na habanje. Ispitivanje infracrvenom spektroskopijom uz prigušenu totalnu refleksiju pokazalo je da obrada podloge plazmom nije utjecala na kemijski sastav ni na otvrdnjavanje i strukturu kasnije nanesenog premaza. Potrebno je provesti daljnja ispitivanja kako bi se dodatno utvrdila otpornost takvih površinskih sustava.*

Ključne riječi: *iverica; plazma; premaz; abrazija*

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1 INTRODUCTION
1. UVOD

Surfaces of wood and wood-based products in interior and exterior applications are exposed to a number of physical and mechanical stresses. Protection or resistance of the wooden structure against physical and chemical influences can be obtained by surface treatment, which depends on selected coating and the type of substrate (Keskin and Tekin, 2011; Veigel *et al.*, 2014). Protection and durability of the material are important with regard to economy and manufacturing technique. Chemical and anatomical structure of wood, as well as its properties such as density, surface roughness and colour, may affect the effect of the coating. In indoor applications, the mechanical coating properties are of a prime importance, especially those like surface hardness, deformability as well as resistance to impact, friction, scratch and abrasion (Brischke *et al.*, 2019). Mechanical properties of a coating strongly depend on the binder type and the film thickness (Keskin and Tekin, 2011). Nowadays, different nanoparticles are added to the coating formulations to enhance their resistance to physical, chemical and mechanical impacts (Cristea *et al.*, 2011).

Particleboard is a wood-based panel consisting of wood or other lignocellulosic particles of various sizes, manufactured by bonding them together with a synthetic resin or binder under heat and pressure. Particleboard is used widely in the manufacture of domestic, institutional and office furniture, stair treads, cabinetry, counter tops, speakers, core for doors, signs, displays, shelving, table tops, subflooring in constructions and other industrial product application due to the smooth surface, uniform density and thickness, dimensional stability, strength, machining ability, and screw-holding capacity (Bardak *et al.*, 2011). Usually, the boards have to be overlaid (by veneers, laminates, impregnated papers, foils) or coated (application of liquid finishing materials with various finishing techniques) to meet the specific requirements of their final use. In the case of painted or overlaid boards, irregularities in the substrate, or the differences in thickness of the coating film, may have a negative impact on the adhesion of paints and overlays and hence on the quality of the final product. Uniform and flat panels provide an excellent surface for the application of coating materials, like paint, print, or varnish substances. Together forming a surface system, the performance of the coated panels is dependent on the quality of wood based panel, the type of the coating material, and a good compatibility between both (Nemli *et al.*, 2005; Rolleri and Roffael, 2010; Bardak *et al.*, 2011). As an example of the latter, a rough surface gives paints several possibilities to penetrate and create strong joins, but on the other hand, by very high roughness, an excessive volume of paint necessary to give surfaces a smooth appearance is expected (Rolleri and Roffael, 2010). Nowadays, waterborne coatings are increasingly used due to the reduced impact on the user and environment. Besides the appearance, one of the requirements of coatings for interior flooring is the ability to withstand mechanical loads like wear, erosion and abrasion (Scrinzi *et al.*, 2011; Sell and Feist, 1986).

Various methods upgrade the appearance and features of coated wooden materials, extending their lifetime and increasing their value (Nemli and Hiziroglu, 2009). Improved scratch and abrasion resistance can be induced by the use of additives such as inorganic fillers and nanoparticles (SiO_2, Al_2O_3, carbonates, silicates and sulfates of various metals) with high hardness (Bauer *et al.*, 2006; Veigel *et al.*, 2014). Furthermore, the abrasion resistance depends on the adhesive used for the panel production (Bardak *et al.*, 2011).

In applications of coatings for interior, besides proper protection properties and a suitable appearance, good resistance to impact and abrasion are expected (Rossi *et al.*, 2009; Keskin and Tekin, 2011). Concerning load bearing applications, the resistance of the material used to abrasion becomes the decisive mechanical property (Welzbacher *et al.*, 2009). Surface quality of wood composites such as particleboard is an important physical property influencing different processes, including their finishing (Istek *et al.*, 2010). There are various methods and devices to simulate the abrasion conditions of the components, and finally measure and determine the resistance of wooden materials to abrasion according to weight loss or wear through the coating after a defined time of wearing. The most useable method for the determination of abrasion resistance of various surface systems is the Taber Abraser test (Rossi *et al.*, 2005; Bauer *et al.*, 2006; Rossi *et al.*, 2009; Aytin *et al.*, 2015).

Electrical gas discharges, more commonly known as plasmas (Žigon *et al.*, 2018; Altgen *et al.*, 2019), can be used to enhance the interaction of wood and wood-based materials surfaces with applied coatings and other liquids. These plasmas can be generated in air at atmospheric pressure, presenting a cost efficient and clean technology. The effects caused by such a treatment of the substrate, via physical and chemical reactions, contribute to enhanced wettability, penetration, adhesion of the applied polymer and final properties of the formed surface system (Liston *et al.*, 1993; Wolkenhauer *et al.*, 2008; Wolkenhauer *et al.*, 2009; Wolf and Sparavigna, 2010; Altgen *et al.*, 2015; De Cademartori *et al.*, 2016; Perisse *et al.*, 2017; Reinprecht *et al.*, 2018). Generally, the basic concept for increasing the surface free energy by plasma treatment (PT) is either breaking polar bonds and leaving polar end groups, or adding polar groups to the surface (Ko *et al.*, 2018). A combination of mechanical abrasion followed by PT enhances the bonding quality (Moghadamzadeh *et al.*, 2011), but this is highly dependent on the type of plasma reactor and treatment conditions. By some plasma pre-treatments, the microstructure of treated wooden material can be altered. Coating penetration increases after exposure of the substrate to plasma. The solvent-borne as well as waterborne polyurethane coating showed deeper penetration on PT wood than on the untreated one. The ability of PT to improve coating performance on wood depends on the coating type and the effects of the treatment on the surface microstructure of wood (Haase *et al.*, 2019).

Pendulum hardness test is one of the most widely used methods for determining the coating hardness. The measured value of hardness greatly depends on the thickness of the coating; it gradually decreases with the increasing coating thickness (Sönmez *et al.*, 2011; Ma *et al.*, 2013; Gurleyen *et al.*, 2017).

Based on the cited literature and our previous research work, the aim of the present study was to investigate whether the treatment of wood-based materials surfaces with atmospheric plasma influences the abrasion resistance of a coating. For this purpose, a particleboard substrate with homogenous structure and a waterborne coating were selected as research materials. The treatment of the substrate with plasma, prior to coating application, was performed using a floating-electrode dielectric barrier discharge device (FE-DBD, Žigon *et al.*, 2019). We hypothesize that PT that increases adhesion and penetration depth of waterborne coating into wood-based materials, further leads to improved resistance of surface system to abrasion. Detailed interactions between untreated or PT substrate and coating were investigated by the measurement of water and coating droplets contact angle (CA). Besides the determination of abrasion resistance, measurements of coated surface hardness were performed, while the appearance of coated samples cross sections was studied with scanning electron microscope. In order to detect possible influence of PT on curing of the coating film, attenuated total reflection Fourier transform infrared spectroscopy was used.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Particleboard as a substrate
2.1. Iverica kao podloga

As a substrate, samples of a particleboard with dimensions of (100 × 100 × 3) mm^3 were selected. Before future processing, the samples were conditioned in a chamber with a temperature of 20 °C and relative humidity of 65 % for three weeks. After conditioning, the substrate density of 857 kg/m^3 was determined gravimetrically.

2.2 Plasma treatment of substrates surfaces and formation of coating systems
2.2. Obrada površine podloge plazmom i formiranje sustava premaza

The surface of each individual sample was treated with FE-DBD non-thermal plasma in air at atmospheric pressure, as presented in previous publications (Žigon *et al.*, 2019). For plasma ignition, an alternating high voltage (frequency 5 kHz, 15 kV peak voltage) was introduced in the insulated brass electrodes. The treated particleboard workpiece was moving with a moving rate of 2 mm/s below the electrodes, and the air discharge occurred in the gaps between the dielectrics and the samples surface (Figure 1). The distance between the dielectrics was set to 5 mm, while the distance between the dielectrics and the surface of the workpiece was about 1 mm.

The samples were coated immediately after PT process, with a black shaded commercial acrylic waterborne coating (Belinka Interier, Belinka Belles, d.o.o., Ljubljana, Slovenia), with a solid content of 34.9 %, determined according to ISO 3251 (2008). The coating with a wet film thickness of 240 μm (approximately 150 g/m^2) was manually applied with a quadruple coating applicator on the surface of control, untreated, PT samples. For reference measurements of coating hardness and ATR FT-IR spectroscopy, glass samples with applied coating were also prepared. Prior to further testing and analyses, the samples were stored in a conditioning chamber with relative humidity of 65 % at 20 °C for 21 days.

2.3 Contact angle measurements
2.3. Mjerenje kontaktnog kuta

Droplets of distilled water and coating were deposited on untreated and PT particleboard surfaces (5 samples per series) by Theta optical goniometer (Biolin Scientific Oy, Espoo, Finland), and CA measurements were made by Young-Laplace analysis using the software (OneAttension version 2.4 [r4931], Biolin Scientific, Espoo, Finland). Droplets with a volume of 5 μL were applied on 4 different places per sample, while their shape was automatically recorded and analyzed within 60 s (1.9 frames per second) after deposition.

2.4 Determination of hardness
2.4. Određivanje tvrdoće

Hardness of the untreated and coated, and PT and coated samples (5 samples per series, 5 measurements per sample) was determined by the pendulum damped oscillations test method using König pendulum tester (Model 299/300, Erichsen GmbH & Co. KG, Hemer, Germany; EN ISO 1522, 2007). The hardness value corresponded to the damping time of the pendulum oscillating on the sample surface from 6° to 3°, with respect to normal axis, measured with an electronic counter.

Figure 2 Treatment of particleboard substrate with air discharge plasma
Slika 2. Obrada iverice plazmom

2.5 Abrasion resistance tests
2.5. Ispitivanje otpornosti na abraziju

The abrasion resistance tests were performed according to the Taber Abraser method (EN 438-2, 2016) on 10 samples per series. After weighing, the specimens were mounted into the rotary platform abrasion tester (Model 503, Erichsen GmbH & Co. KG, Hemer, Germany) and abraded with rotating rubber wheels covered with sanding paper S-42 and loaded with 500 g each. The abrasion process was stopped after 10, 25, and after every further 25 revolutions up to final 200 revolutions. After each stop, the samples were weighted and scanned. A fresh sanding paper was used with every sample. A mass loss of the sample was determined according to the following equation:

$$\Delta m = \frac{m_0 - m_1}{m_0}[g] \times 100\ [\%] \quad (1)$$

Δm – samples mass loss due to abrasion (g, %)
m_0– samples mass, before abrasion (g)
m_1– samples mass, after abrasion (g)

The scans of the samples, taken during the abrasion test, were analyzed by measuring the percentage of the abraded area with the Fiji software (ImageJ 1.46d, Bethesda, Maryland, USA) by grey value set to 80 (ranging from 0 - total white to 255 - total black) (Schindelin *et al.*, 2012; Altgen *et al.*, 2019).

2.6 Scanning electron microscopy (SEM) investigations
2.6. Istraživanje pretražnim elektronskim mikroskopom (SEM)

The cross sections of the untreated and PT samples in the region of abrasion were analyzed with SEM FEI Quanta 250 (FEI, Hillsboro, Oregon, USA). Before the start of observation, the surfaces were evened by microtome. Possible differences in the microstructure between untreated and PT substrates were analyzed with a large field (LFD) and circular backscattered (CBD) detector. The dry film thickness of the coating and its penetration depth were measured on 20 spots of the cross sections as well. The micrographs were taken at 100× and 500× magnification in a low vacuum (50 Pa), the electron source voltage of 10.0 kV, at a working distance of 10 mm, and the spot size of 3.0. During the capture of the image, the time of the beam transition through the sample was 45 μs.

2.7 Attenuated total reflection Fourier transform infrared (ATR FT-IR) spectroscopy
2.7. Pojačana infracrvena spektroskopija uz prigušenu totalnu refleksiju (ATR FT-IR)

ATR FT-IR spectroscopic measurements of the dry coating film on glass, untreated and PT particleboard were performed using a Perkin Elmer Spectrum Two spectrometer (PerkinElmer Inc., Waltham, Massachusetts, USA), with a $LiTaO_3$ detector in the absorbance mode. The spectra were measured on 5 different spots (16 scans per spot) of the coated samples, at a wavelength range from 600 cm^{-1} to 4000 cm^{-1} and at a resolution of 0.5 cm^{-1}. For later comparison, ATR FT-IR spectra were also recorded on coated glass samples.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Contact angles of liquids on untreated and PT substrates
3.1. Kontaktni kutovi tekućina na neobrađenim podlogama i podlogama obrađenim plazmom

Average values of apparent CA of water and coating droplets during the first 60 s after application are depicted in Figure 2. On the right side, the photos of the droplets immediately after deposition are shown. The surface of the particleboard treated in this study turned out to be less prone to interact with water, but the values are in agreement with findings in the literature (Baharoğlu *et al.*, 2012; Sandak *et al.*, 2015), since the measured CA of water droplets were above 100°. This might be related to relatively high density of the substrate, applied higher temperature during pressing in the production of boards and consequently physical-chemical modifications of the surface, presence of the adhesive and other possible water repellent constituents on its surface. Treatment of the surface with plasma lowered the CA of water by about 15°, making the surface more hydrophilic. However, CA of applied coating droplets was lower in comparison to water CA. Here, the influence of PT to make the surface more susceptible to coating was less pronounced, but obvious (about 5° lower CA). Wolkenhauer and co-authors (2008) found an enhanced absorbency of a waterborne formulation (i.e. polyvinyl acetate adhesive) into particleboard surfaces treated with atmospheric DBD plasma. According to their findings, the reason for that could be the enhanced hydrophilicity of the surface treated with the formulation containing waterborne polymer.

3.2 Surface hardness
3.2. Tvrdoća površine

The pendulum hardness test is based on the principle that the harder the measured surface, the greater the oscillation time of the pendulum. The amplitude of the pendulum oscillation decreases gradually because of the damping during the pendulum hardness test. The pendulum hardness of the coating is greatly related to its dry film thickness (Ma *et al.*, 2013). There were no significant differences in the average thickness of the dry coating film (about 45 μm), measured on untreated and PT sample with SEM at different spots. From the results shown in Figure 3, it can be seen that a coating film applied on a glass plate (thickness film about 65 μm) had a very low oscillation time, meaning high damping of the pendulum due to the elastic deformations of the film. The coatings applied on untreated substrates exhibited slightly lower average oscillation time (about 1 s) than a coating applied on PT substrate. However, the increase in film hardness of 4 % for the PT substrate as compared to the one on untreated substrate is not significant due to the relatively low statistics. It is thus not possible to deduce any influence on the bulk hardness by PT prior to coating application. Therefore, further investigations are required to determine possible alternations of the curing process of this coating due to PT.

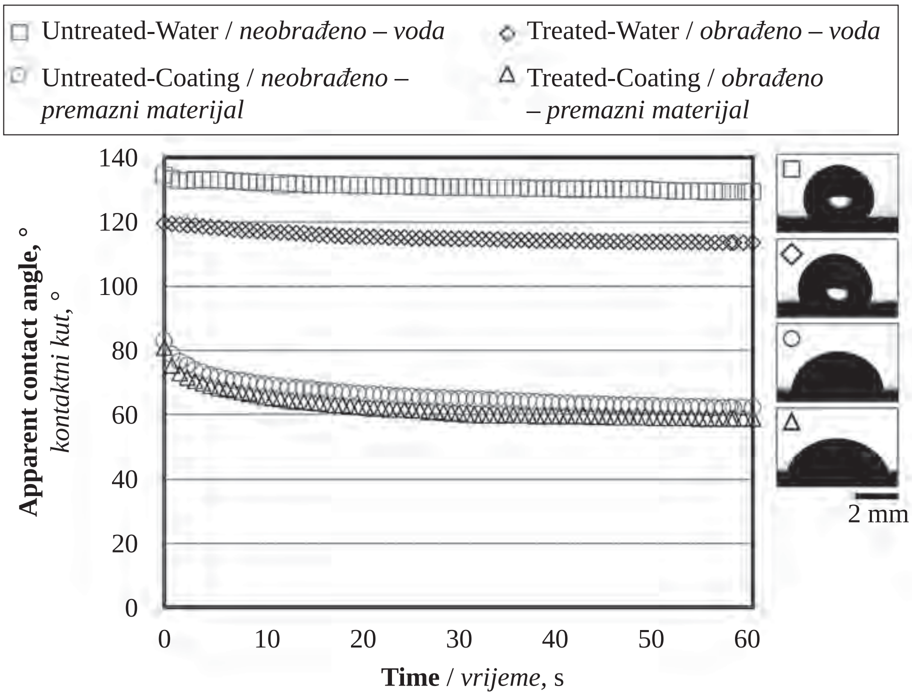

Figure 2 Apparent contact angles of water and coating droplets applied on untreated and PT substrates surfaces. On the right side, photos of droplets immediately after deposition are shown
Slika 2. Kontaktni kut vode i premaznog materijala nanesenoga na neobrađenu i plazmom obrađenu podlogu (na desnoj su strani fotografije kapi neposredno nakon nanošenja na podlogu)

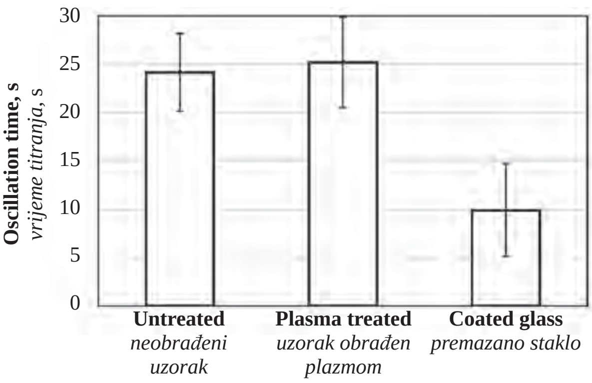

Figure 3 Pendulum oscillation times of waterborne acrylic coating films applied on untreated and PT particleboard substrate, and on glass
Slika 3. Vrijeme titranja njihala filma vodenoga poliakrilatnog premaza nanesenoga na neobrađenu i plazmom obrađenu površinu uzorka te na staklo

3.3 Resistance to abrasion
3.3. Otpornost na abraziju

Figures of representative samples, taken during the abrasion test after a certain number of revolutions are shown in Table 1. Visual differences between untreated samples and PT samples are summarized in Figure 4, showing detected pixels by grey value set to 80. The differences in the amount of abraded coating were shown already after the first 25 revolutions. After 100 revolutions, the differences reached the maximum (about 6 %), and at the final amount of revolutions, the surface system with untreated substrate was completely abraded, while at PT ones, some coating still remained.

The mass losses during the abrasion test of the samples are in agreement with other results shown in this paragraph (Figure 5). The absolute mass losses with respect to the masses of the whole samples are

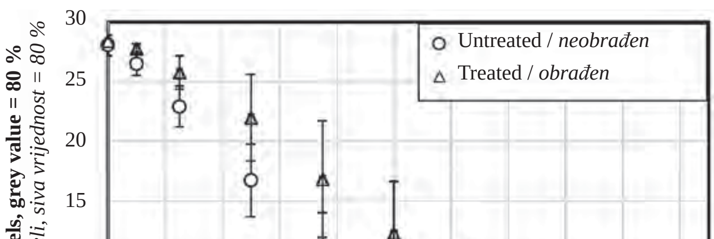

Figure 4 Detected pixels as percentage of remained coating on abraded area during abrasion resistance test on untreated or PT substrates
Slika 4. Detektirani pikseli kao postotak preostalog premaza na istrošenom području tijekom ispitivanja otpornosti na abraziju na neobrađenim i plazmom obrađenim podlogama

Table 1 Appearance of representative samples after a specific number of revolutions in abrasion resistance test. Left side of images is shown as processed with Fiji software for grey value analysis
Tablica 1. Izgled reprezentativnih uzoraka nakon određenog broja ciklusa ispitivanja otpornosti na abraziju. Lijeva strana fotografija obrađena je *Fiji* softverom za analizu sive vrijednosti.

Sample Type *Vrsta uzorka*	**Number of revolutions, appearance** *Broj okretaja, izgled*				
	0	10	25	50	75
Untreated *neobrađen*					
Plasma treated *obrađen plazmom*					
	100	125	150	175	200
Untreated *neobrađen*					
Plasma treated *obrađen plazmom*					

lower than 1 %, but expected, since only a part of the coating was removed, and at the end of the tests a part of the substrate was removed as well. The results showed that on the samples, treated with plasma prior to coating process, less material was removed. From the results of visual estimation and detected mass losses, it can be concluded that increased abrasion resistance of PT samples is related to a greater hardness of the coating film applied on such a substrate.

3.4 SEM micrographs
3.4. SEM mikrografije

Figure 6 shows micrographs of samples cross sections detected with LFD and CBD detectors. The micrographs were captured in the region comprising non-abraded (central) part of the samples surface and part with abraded surface.

On the abraded area of an untreated sample (Figure 6a) no coating is present, whereas at the PT sample after 200 revolutions some coating still remained on the surface (Figure 6b). The reason for that could be a greater hardness of the coating film and/or deeper penetration of the coating by treated substrate. However, due to compressed structure of the cells, it was hard to estimate the coating penetration depth and make constructive conclusions about the latter between untreated and PT samples.

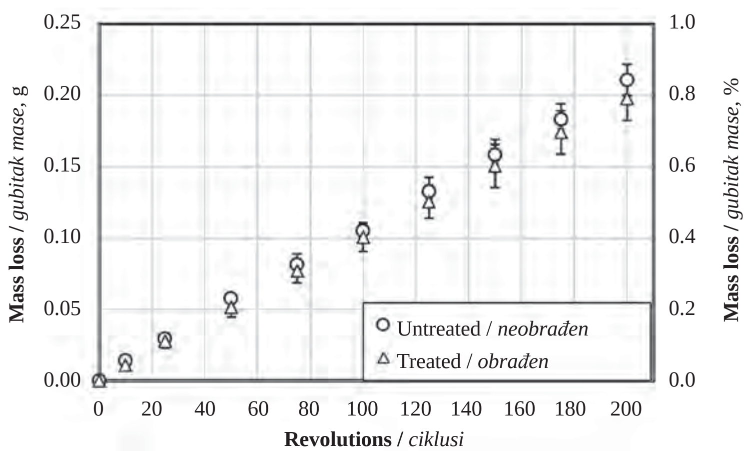

Figure 5 Absolute mass loss of surface systems during abrasion resistance test with respect to mass of the whole sample, previously untreated or treated with plasma
Slika 5. Apsolutni gubitak mase površinskih sustava, prethodno neobrađenih i obrađenih plazmom, tijekom ispitivanja otpornosti na abraziju u odnosu prema masi cijelog uzorka

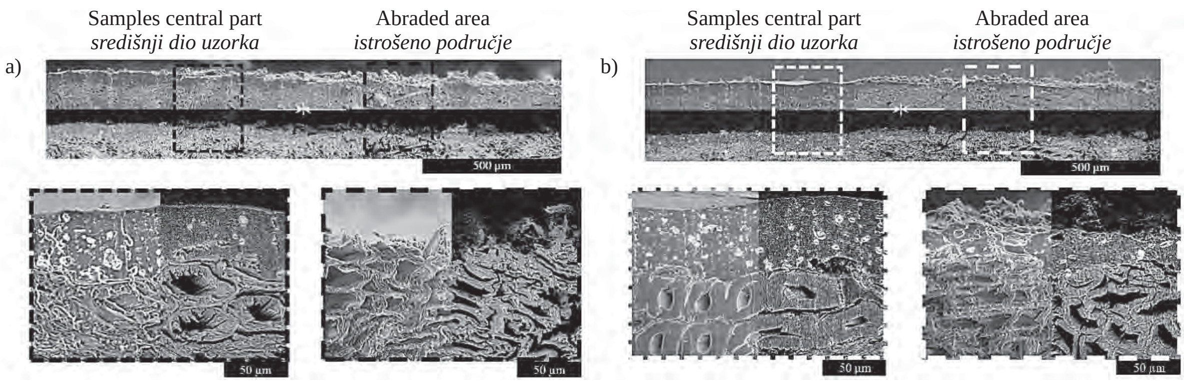

Figure 6 SEM micrographs of samples after abrasion resistance test: a) untreated substrate, b) substrate treated with plasma
Slika 6. SEM mikrografije uzoraka nakon ispitivanja otpornosti na abraziju: a) neobrađena podloga, b) podloga obrađena plazmom

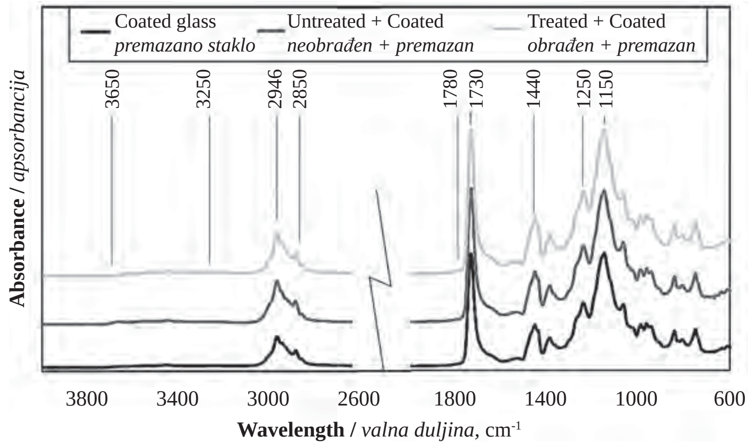

Figure 7 ATR-FTIR spectra of waterborne acrylic coating films, applied on glass, and untreated and PT particleboard substrate
Slika 7. ATR-FTIR spektar filma poliakrilatnog premaza nanesenoga na staklo i na neobrađenu i plazmom obrađenu ivericu

3.5 ATR FT-IR spectra
3.5. ATR FT-IR spektri

Infrared spectroscopy is a sensitive and reliable technique, which permits to quantify the chemical changes of the chemical structure of polymer materials. Figure 7 shows the infrared spectra of waterborne acrylic coating films, applied on glass, and untreated and PT particleboard substrate. Some IR characteristic bands of functional groups, such as O–H (3650 and 3250 cm^{-1}), alkane C–H (2946 and 2850 cm^{-1}), carboxylic acid CO (1780, 1730 and 1440 cm^{-1}), ester C–O– (1730 and 1250 cm^{-1}) and aliphatic ether (1150 cm^{-1}), are marked (Scalarone *et al.*, 2007; Nguyen *et al.*, 2016). By comparing the main peaks of all three spectra, it can be seen that no changes between them were detected. Therefore, the higher hardness of the coating film due to prior PT of the substrate could not be explained by this technique.

4 CONCLUSIONS
4. ZAKLJUČAK

Particleboards were successfully treated using FE-DBD plasma in air at atmospheric pressure, yielding an increased abrasion resistance of waterborne coating according to both visual estimation and mass losses after a specific number of revolutions. The reason for such behavior could be related to greater hardness (oscillation time 1 s or 4 % longer) of the surface system with PT substrates and enhanced wettability of the substrate with both water (CA lower for about 15°) and coating (CA lower for about 5°). Similar to visual estimation of abraded coating in the abrasion test, the investigation of the cross section structures on microscopic level showed the differences in the amounts of coating remained on the abraded areas. Investigations with ATR-FTIR revealed that PT did not have effects on chemical composition of the coating film, which could be the reason for higher hardness detected on these samples.

For a better understanding of the properties of such surface systems, further studies should be performed to investigate the influence of PT, prior to coating application, on their resistance to other impacts.

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5 REFERENCES
5. LITERATURA

1. Altgen, D.; Bellmann, M.; Wascher, R.; Viöl, W.; Mai, C., 2015: Enhancing mechanical properties of particleboards using plasma treated wood particles. European Journal of Wood and Wood Products, 73: 219-223. https://doi.org/10.1007/s00107-015-0879-z.
2. Altgen, D.; Grigsby, W.; Altgen, M.; Rautkari, L.; Mai, C., 2019: Analyzing the UF resin distribution in particleboards by confocal laser microscopy. Composites, Part A, 125: 105529. https://doi.org/10.1016/j.compositesa.2019.105529.
3. Aytin, A.; Korkut, S.; As, N.; Ünsal, Ö.; Gündüz, G., 2015: Effect of Heat Treatment of Wild Cherry Wood on Abrasion Resistance and Withdrawal Capacity of Screws. Drvna industrija, 66 (4): 297-303. https://doi.org/10.5552/drind.2015.1440.
4. Baharoğlu, M.; Nemli, G.; Sarı, B.; Bardak, S.; Ayrılmış, N., 2012: The influence of moisture content of raw material on the physical and mechanical properties, surface roughness, wettability, and formaldehyde emission of particleboard composite. Composites, Part B, 43 (5): 2448-2451. https://doi.org/10.1016/j.compositesb.2011.10.020.
5. Bardak, S.; Sarı, B.; Nemli, G.; Kırcı, H.; Baharoğlu, M., 2011: The effect of décor paper properties and adhesive type on some properties of particleboard. International Journal of Adhesion and Adhesives, 31: 412-415. https://doi.org/10.1016/j.ijadhadh.2011.02.008.
6. Bauer, F.; Flyunt, R.; Czihal, K.; Buchmeiser, R. M.; Langguth, H.; Mehnert, R., 2006: Nano/micro particle hybrid composites for scratch and abrasion resistant polyacrylate coatings. Macromolecular Materials and Engineering, 291: 493-498. https://doi.org/10.1002/mame.200600034.
7. Brischke, C.; Ziegeler, N.; Bollmus, S., 2019: Abrasion resistance of thermally and chemically modified timber. Drvna idustrija, 70 (1): 71-76. https://doi.org/10.5552/drvind.2019.1813.
8. Cristea, M. V.; Riedl, B.; Blanchet, P., 2011: Effect of addition of nanosized UV absorbers on the physico-mechanical and thermal properties of an exterior waterborne stain for wood. Progress in Organic Coatings, 72: 755-762. https://doi.org/10.1016/j.porgcoat.2011.08.007.
9. De Cademartori, P. H. G.; De Carvalho, A. R.; Marangoni, P. R. D.; Berton, M. A. C.; Blanchet, P.; De Muniz, G. I. B.; Magalhães, W. L. E., 2016: Adhesion performance and film formation of acrylic emulsion coating on medium density fibreboard treated with Ar plasma. International Journal of Adhesion and Adhesives, 70: 322-328. https://doi.org/10.1016/j.ijadhadh.2016.08.002.
10. Gurleyen, L.; Ayata, U.; Esteves, B.; Cakicier, N., 2017: Effects of heat treatment on the adhesion Strength, pendulum hardness, surface roughness, color and glossiness of scots pine laminated parquet with two different types of UV varnish application. Maderas. Ciencia y tecnología 19 (2): 213-224. https://doi.org/10.4067/s0718-221x2017005000019.
11. Haase, G. J.; Leung, H. L.; Evans, D. P., 2019: Plasma pre-treatments to improve the weather resistance of polyurethane coating on black spruce wood. Coatings, 9 (1). https://doi.org/10.3390/coatings9010008.
12. Istek, A.; Aydemir, D.; Aksu, S., 2010: The effect of décor paper and resin type on the physical, mechanical, and surface quality properties of particleboards coated with impregnated décor papers. BioResources, 5 (2): 1074-1083.
13. Keskin, H.; Tekin, A., 2011: Abrasion resistances of cellulosic, synthetic, polyurethane, waterborne and acid-hardening varnishes used woods. Construction and Building Materials, 25: 638-643. https://doi.org/10.1016/j.conbuildmat.2010.07.028.
14. Ko, C.-L.; Kuo, Y.-L.; Lee W.-J.; Sheng, H.-J.; Guo, J.-Y., 2018: The enhanced abrasion resistance of an anti-fingerprint coating on chrome-plated brass substrate by integrating sputtering and atmospheric pressure plasma jet technologies. Applied Surface Science, 448: 88-94. https://doi.org/10.1016/j.apsusc.2018.04.075.
15. Liston, E. M.; Martinu, L.; Wertheimer, M. R., 1993: Plasma surface modification of polymers for improved adhesion: a critical review. Journal of Adhesion Science and Technology, 7 (10): 1091-1127.
16. Ma, X.; Qiao, Z.; Huang, Z.; Jing, X., 2013: The dependence of pendulum hardness on the thickness of acrylic coating. Journal of Coatings Technology and Research, 10 (3) 433-439. https://doi.org/10.1007/s11998-013-9477-3.
17. Moghadamzadeh, H.; Rahimi, H.; Asadollahzadeh, M.; Hemmati, R. A., 2011: Surface treatment of wood polymer composites for adhesive bonding. International Journal of Adhesion and Adhesives, 31: 816-821.
18. Nemli, G.; Örs, Y.; Kalaycıoğlu, H., 2005: The choosing of suitable decorative surface coating material types for interior end use applications of particleboard. Construction and Building Materials, 19: 307-312. https://doi.org/10.1016/j.conbuildmat.2004.07.015.
19. Nemli, G.; Hiziroglu, S., 2009: Effect of press parameters on scratch and abrasion resistance of overlaid particleboard panels. Journal of Composite Materials, 43 (13): 1413-1420. https://doi.org/10.1177/0021998308103416.
20. Nguyen, T. V.; Nguyen-Tri, P.; Nguyen, T. D.; El Aidani, R.; Trinh, V. T.; Decker, C., 2016: Accelerated degradation of water borne acrylic nanocomposites used in outdoor protective coatings. Polymer Degradation and Stability, 128: 65-76. https://doi.org/10.1016/j.polymdegradstab.2016.03.002.
21. Perisse, F.; Menecier, S.; Duffour, E.; Vacher, D.; Monier, G.; Destrebecq, J.-F.; Czarniak, P.; Górski, J.; Wilkowski, J., 2017: MDF treatment with a Dielectric Barrier Discharge (DBD) torch. International Journal of Adhesion and Adhesives, 79: 18-22. https://doi.org/10.1016/j.ijadhadh.2017.09.006.
22. Reinprecht, L.; Tiňo, R.; Šomšák, M., 2018: Adhesion of coatings to plasma modified wood at accelerated weathering. In: European Conference on Wood Modification 2018 (ECWM9), Creemers, J.; Houben, T.; Tjeerdsma, B.; Militz, H.; Junge, B.; Gootjes, J. Arnhem (eds.), The Netherlands (On-line Proceedings), 205-209.
23. Rolleri, A.; Roffael, E., 2010: Influence of the surface roughness of particleboards and their performance towards coating. Maderas ciencia y tecnologia, 12 (2): 143-148.https://doi.org/10.4067/s0718-221x2010000200009.
24. Rossi, S.; Deflorian, F.; Fontanari, L.; Cambruzzi, A.; Bonora, P. L., 2005: Electrochemical measurements to evaluate the damage due to abrasion on organic protective system. Progress in Organic Coatings, 52: 288-297. https://doi.org/10.1016/j.porgcoat.2004.09.005.
25. Rossi, S.; Deflorian, F.; Scrinzi, E., 2009: Comparison of different abrasion mechanisms on aesthetic properties of organic coatings. Wear, 267: 1574-1580. https://doi.org/10.1016/j.wear.2009.06.021.
26. Sandak, J.; Sandak, A.; Hiziroglu, S.; Bosak, S., 2015: Surface characterization of particleboard panels manu-

factured from eastern redcedar using a multi-sensor approach. International Panel Products Symposium, At Llandudno, North Wales, UK: 27-37.
27. Scalarone, D.; Lazzari, M.; Castelvetro, V.; Chiantore, O., 2007: Surface monitoring of surfactant phase separation and stability in waterborne acrylic coatings. Chemistry of Materials, 19: 6107-6113. https://doi.org/10.1021/cm0714077.
28. Schindelin, J.; Arganda-Carreras, I.; Frise, E.; Kaynig, V.; Longair, M.; Pietzsch, T.; Preibisch, S.; Rueden, C.; Saalfeld, S.; Schmid, B.; Tinevez, J.-Y.; White, J. D.; Hartenstein, V.; Eliceiri, K.; Tomancak, P.; Cardona, A., 2012: Fiji – an Open Source platform for biological image analysis. Nat. Methods 9(7): 676-682.
29. Scrinzi, E.; Rossi, S.; Deflorian, F.; Zanella, C., 2011: Evaluation of aesthetic durability of waterborne polyurethane coatings applied on wood for interior applications. Progress in Organic Coatings, 72: 81-87. https://doi.org/10.1016/j.porgcoat.2011.03.013.
30. Sell, J.; Feist, W. C., 1986: Role of density in the erosion of wood during weathering. For. Prod. J., 36 (3): 57-60.
31. Sönmez, A.; Budakçı, M.; Pelit, H., 2011: The effect of the moisture content of wood on the layer performance of water-borne varnishes. BioResources, 6 (3), 3166-3178.
32. Veigel, S.; Grüll, G.; Pinkl, S.; Obersriebnig, M.; Müller, U.; Gindl-Altmutter, W., 2014: Improving the mechanical resistance of waterborne wood coatings by adding cellulose nanofibers. Reactive and Functional Polymers, 85: 214-220. https://doi.org/10.1016/j.reactfunctpolym.2014.07.020.
33. Welzbacher, C.; Brischke, C.; Rapp, A.; Koch, S.; Hofer, S., 2009: Performance of thermally modified timber (TMT) in outdoor application – durability, abrasion and optical appearance. Drvna industrija, 60 (2): 75-82.
34. Wolf, R.; Sparavigna, A. C., 2010: Role of plasma surface treatments on wetting and adhesion. Engineering, 2: 397-402. https://doi.org/10.4236/eng.2010.26052.
35. Wolkenhauer, A.; Militz, H.; Viöl, W., 2008: Increased PVA-glue adhesion on particle board and fibre board by plasma treatment. Holz als Roh- und Werkstoff, 66: 143-145. https://doi.org/10.1007/s00107-007-0217-1.
36. Wolkenhauer, A.; Avramidis, G.; Hauswald, E.; Loose, S.; Viöl, W.; Militz, H., 2009: Investigations on the drying behaviour of adhesives on plasma-treated wood materials. Wood Research, 54 (1): 59-66.
37. Žigon, J.; Petrič, M.; Dahle, S., 2018: Dielectric barrier discharge (DBD) plasma pretreatment of lignocellulosic materials in air at atmospheric pressure for their improved wettability: a literature review. Holzforschung, 72 (11): 979-991. https://doi.org/10.1515/hf-2017-0207.
38. Žigon, J.; Petrič, M.; Dahle, S., 2019: Artificially aged spruce and beech wood surfaces reactivated using FE-DBD atmospheric plasma. Holzforschung, 73 (12): 1069-1081. https://doi.org/10.1515/hf-2019-0005.
39. ***EN 438-2, 2016: High-pressure decorative laminates (HPL) – Sheets based on thermosetting resins (usually called laminates), Part 2: Determination of properties.
40. ***EN ISO 1522, 2007: Paints and varnishes – Pendulum damping test.
41. ***ISO 3251, 2008: Paints, varnishes and plastics – Determination of non-volatile-matter content.

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Digital Development of Slovenian Wood Industry

Digitalni razvoj slovenske drvne industrije

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ABSTRACT • *The research examined the digital development of the Slovenian wood industry, especially the implementation of the concept of Industry 4.0 into practice. Within this, the implementation of specific technological pillars was studied, with the emphasis on smart factories and smart, innovative products. In the empirical part of the research, we prepared a survey and interviewed selected managers and entrepreneurs. We compared answers regarding sub-sectors, the size of the companies and the level of digitalization. The general results show that around half of the surveyed companies are already implementing the Industry 4.0 concept into their businesses, while the rest are beginners when speaking about digitalization. The biggest obstacles to the implementation of the concept are the high investments in equipment and the lack of financial support from the state. The lack of digital competencies, which is especially prevalent among older workers, is another major barrier that businesses face. Only 30 % of the surveyed companies are engaged in the production of smart products. We can conclude that digitalization in the Slovenian wood industry is still at a relatively low level, but with the latest strategic orientations at both the state and business level, this situation will certainly improve in the near future.*

Keywords: *Digitalization; Industry 4.0; Internet of Things; Wood-industry; Slovenia*

SAŽETAK • *U radu je predočeno istraživanje digitalnog razvoja slovenske drvne industrije, posebice istraživanje primjene koncepta Industrija 4.0 u praksi. Unutar toga proučavana je primjena specifičnih tehnoloških stupova s naglaskom na pametne tvornice i pametne, inovativne proizvode. U empirijskom dijelu istraživanja pripremili smo anketu i intervjuirali odabrane menadžere i poduzetnike. Usporedili smo odgovore koji se odnose na podsektore, veličinu poduzeća i razinu digitalizacije. Opći rezultati pokazuju da približno polovica anketiranih tvrtki u poslovanju već primjenjuje koncept Industrija 4.0, dok su ostale tvrtke početnici u digitalizaciji. Najveće su prepreke provedbi koncepta velika ulaganja u opremu i izostanak državne financijske potpore. Nedostatak digitalnih kompetencija, koji je osobito vidljiv među starijim radnicima, dodatna je velika prepreka s kojom se tvrtke suočavaju. Samo 30 % anketiranih tvrtki bavi se proizvodnjom pametnih proizvoda. Može se zaključiti da je digitalizacija u slovenskoj drvnoj industriji još uvijek na relativno niskoj razini, ali s najnovijim strateškim orijentacijama i na državnoj i na poslovnoj razini ta će se situacija u skoroj budućnosti sigurno poboljšati.*

Ključne riječi: *digitalizacija; Industrija 4.0; internet stvari; drvna industrija; Slovenija*

1 INTRODUCTION
1. UVOD

Digital development is an important aspect of the development of society as a whole, and of all (business) entities operating within them. Globalization and the rapid development of information and communication technologies (ICT) are causing major changes in modern societies. The so-called information society, also called the knowledge society or even digital society, is establishing what Keidanren (2016) calls a smart society. The development of a digital society provides

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many opportunities for progress, but also many challenges. A digital single market in Europe, one of the top ten priorities of the European Commission, would create the right environment, both formally and technologically, for the effective development of digital society at the European level and in all Member States (European Commission, 2016).

Research shows that the state of digitization of European society is poor, as half of the EU population still lacks basic digital literacy and competencies (European Commission, 2019). This and major technological advances in the field of digitalization require concrete actions at the level of economic policies. At the EU level, one of the most important actions in the digitization of society is the Smart Specialization Strategy (S3) (European Commission, 2018). In Slovenia, the implementation of this concept is an important part of the country's economic policy, which is also reflected in the smart specialization strategy platform for directing development investments in areas where Slovenia has a critical mass of capacities, knowledge, and competencies, and where innovation potential is highly expressed (Republic of Slovenia, 2019).

As an important part of industrial development, significant changes are expected in the whole economy and each company in the field of digitalization, which is one of the Key Enabling Technologies at the EU level (Commission of the European Communities, 2009). Despite the high importance of digitization and in spite of the economic growth of Slovenia in recent years (Kmet Zupančič, 2019), as many as 82 % of Slovenian companies have a low digital index (which measures the intensity of the use of ICT in doing business), and within manufacturing companies the situation is even worse (Zupan, 2018; Statistical Office, 2018).

The concept of "Industry 4.0" symbolizes the beginning of the fourth industrial revolution (Lasi *et al*., 2014). It was presented as a strategic initiative to increase German competitiveness in the manufacturing industry, with the aim of transforming industrial production by digitizing and harnessing the potential of new technologies (Herakovich, 2016). It represents the modern technological trends of automation and creates the so-called cyber-physical systems, while technologically it is reflected in the Internet of Things (IoT) and cloud computing solutions (Xu *et al*., 2018). Industry 4.0 is changing the way companies operate, and requires major investments in new technologies if they are to remain competitive in the market. New strategies and advantages are required to face international competitors, which, among other, include new business models, improvement of productivity, innovations and cooperation in terms of technology, outsourcing and supply chain (Paluš *et al*., 2015). In case of environmentally sensitive markets, the competitiveness is influenced by factors related to the origin of wood material from sustainable and renewable sources (Paluš *et al*. 2019). Companies need to decide how and where to invest in new technologies, and which ones can best meet their needs. Without a full understanding of the changes and opportunities that Industry 4.0 can provide, companies are at risk of great loss (Cotteleer and Sniderman, 2017). An important notion that we are facing in Industry 4.0, and closely related to it, is the IoT. This is reflected at the level of smart cities, smart factories, smart homes, and smart products. However, with the improvement of wireless communications, smartphones and sensor network technologies, more and more networked things and smart devices are being integrated into IoT (Xu *et al*., 2014). Within the technological pillars and trends of the concept of Industry 4.0, it is expected that blockchain, digital twins, quantum computing, augmented analytics and artificial intelligence will drive disruption and new business models (Panetta, 2018).

The term "smart factory" is not yet dominant, as there are several other terms that are also used for the same idea, such as the u-factory or ubiquitous factory, the Factory of Things, the real-time factory, and the intelligent factory of the future (Hozdić, 2015). Movrin (2017) argues that a smart factory connects the human, product, process, and business to a holistic system and contains the following components: smart products, smart equipment, smart people, smart conceptualized processes and smart management. In this context, two important terms appear, namely smart products and smart people. Smart products are able to perform calculations, store data and communicate with the environment. Not only do these products provide their identity, but they also describe their characteristics, status, and history, and are able to provide information about their life cycle (Schmidt *et al*., 2015). Even in the timber industry, this concept is not entirely new. For example, IKEA has been involved in the manufacture of various pieces of smart furniture and smart homes for several years. Besides wardrobes with smart lighting and other single smart furniture solutions, Ikea is launching a new robotic furniture system called Rognan for people who live in small spaces; the large storage unit, controlled by a touchpad, can slide across a room to divide it into two living spaces, and contains a bed, desk, and a couch. (Lee, 2019). Some Slovenian wood industry companies have already started developing intelligent furniture (Alples, 2016). Digital competencies, which relate to the confident and critical use of a full range of digital information and communication technologies and solve underlying problems, are essential in the context of "smart people" (Carretero Gomez *et al*, 2017). However, the digital literacy of employees in Slovenian companies is at a relatively low level, so companies will in the future be forced to provide the training needed to acquire the digital competencies required by certain jobs (Kropivšek, 2018).

The research was focused on an examination of the understanding of the concept of Industry 4.0 and its implementation in the Slovenian wood industry. We also studied the implementation of specific technological pillars into practice, with the emphasis on smart factories and smart, innovative products. The objective of the research was to measure the degree of digitalization, to define the challenges and obstacles that companies encountered before or during the digitalization process and to measure the impact of information and communication technologies on business in the next three years. Beside this, the importance of digitization activities in the strategic plans of companies was established, and the share of revenue that companies intend to invest in digitization over the next years was measured. Within this, one of the goals of the research was to calculate the correlation between the level of digitalization and the share of revenue that companies intend to invest in it over the next three years. We also intended to evaluate the "factory of the future" elements that companies already use or plan to use at their factory in the next three years. Finally, we were interested in whether there are differences between companies from different sub-sectors and between companies of different sizes.

2 METHODS
2. METODE

In the empirical part of the research, we prepared a survey and interviewed selected managers and entrepreneurs. The questionnaire included topics like the challenges of digitalization, strategic directions, digital competencies, data analytics, smart products, and smart factories. The questionnaire consisted of 21 questions; three of these were demographic and most of the others asked for Likert-type scale responses. More in detail, the questions in the questionnaire were about the Industry 4.0 potential, the degree of digitalization, challenges and obstacles that companies encountered before or during the digitalization process, impact of information and communication technologies on business in the next three years, the importance of digitization activities in the strategic plans of companies for their investments in the next three years, the share of revenue that companies intend to invest in digitization over the next three years and the "factory of the future" elements that companies use in their factory or plan to use in the next three years. The survey process took place from 18^{th} of November 2018 to 25^{th} of February 2019 in digital format on the 1ka web portal (1ka, 2019). The target population of the survey was as follows: companies operating in sub-sectors C16 (wood processing) and C31 (manufacture of furniture) in Slovenia (NACE, 2019), members of the Chamber of Commerce and Industry of Slovenia and the Chamber of Craft and Small Business of Slovenia. Invitations to complete the questionnaire were sent by those two institutions to their members. Since the exact number of members and their addresses are a business secret that was not disclosed to us, we only assume that the population size was about 1000 companies. We received answers from 131 companies. Forty-one companies answered only demographic questions, 44 companies partly completed the questionnaire (they answered the first few questions), and the rest 46 companies answered all the questions in the survey. The statistical software SPSS 25.0 was used for data analysis, and the results are presented in this work. We presented the results of the Likert-scale questions using a diverging stacked bar chart, which is especially suitable for the presentation of this type of data (Robbins and Heiberger, 2011). The Fisher's Exact Test was used to compare the results regarding sub-sectors and the size of the companies. Spearman's rank correlation coefficient was used as a nonparametric measure of dependence between the size of the companies and the challenges of digitalization, the level of digitalization and the production of smart products, and the level of digitalization and the share of revenue that companies intend to invest in it over the next three years.

In the second part of the study, we interviewed managers and entrepreneurs of three wood industry companies of different sizes (two of them were mid-size and one of them small company) with a long tradition and a clear orientation into the future. The interviews were conducted in July 2019.

3 RESULTS
3. REZULTATI

Among the companies that participated in the survey and answered all the questions (46 companies), more than half (54 %) were micro size, 30 % were small and 16 % mid-size / big companies. The proportions were also similar for the first few questions from the survey that more respondents answered. The mix of companies by size in the survey is comparable to that seen in the Slovenian wood industry, where micro and small companies prevail (Kropivšek *et al*, 2019). The proportions of respondent companies operating in sub-sectors C16 and C31 are similar (about 45 %), while 10 % of companies selected "Other" as their main activity (carpentry, roofing, sales, installation of furniture, etc).

The question about the degree of digitalization was answered by 90 companies; 54 were micro companies, 27 small and nine mid-size or big. The red colour in Figure 1 indicates companies that are not prepared or are just preparing for digitalization. Half of the companies (50 %) are complete beginners in the introduction of the concept of Industry 4.0 into their business. One-quarter of companies (23 %) know about digitalization and are preparing to launch it. Only one small company has a clear digitalization plan. The blue colour presents companies that have already started the process of digitalization. Eight percent of the companies have started their first digitalization activities, 17 % of companies are already digitized to some extent, and only one company is fully digitized. Although the term Industry 4.0 has been known since 2011, implementation of the concept in Slovenian wood companies is quite low. We can conclude that the level of digitalization is the lowest in micro companies, followed by small companies, while as many as 67 % of mid-size and big companies are digitalized to some extent. The level of digitalization differs significantly among the different sizes of companies (p=0.026, Fisher exact test). The level of digitalization differs significantly among sub-sectors as well (p=0.037, Fisher exact test), especially between C31 and other, where C31 is better, while between C31 and C16 sub-sectors there are no differences.

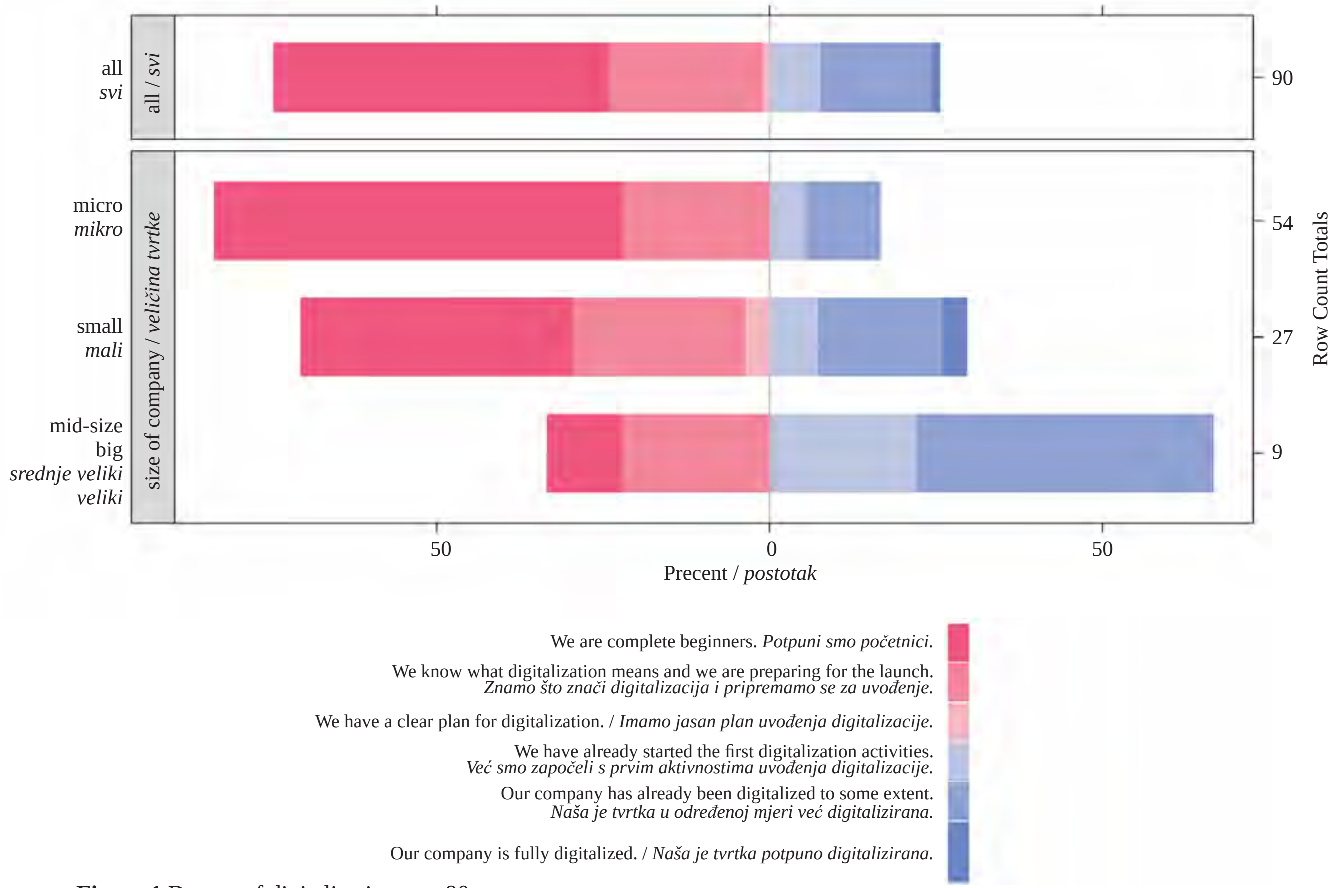

Figure 1 Degree of digitalization, *n* = 90
Slika 1. Stupanj digitalizacije tvrtki, *n* = 90

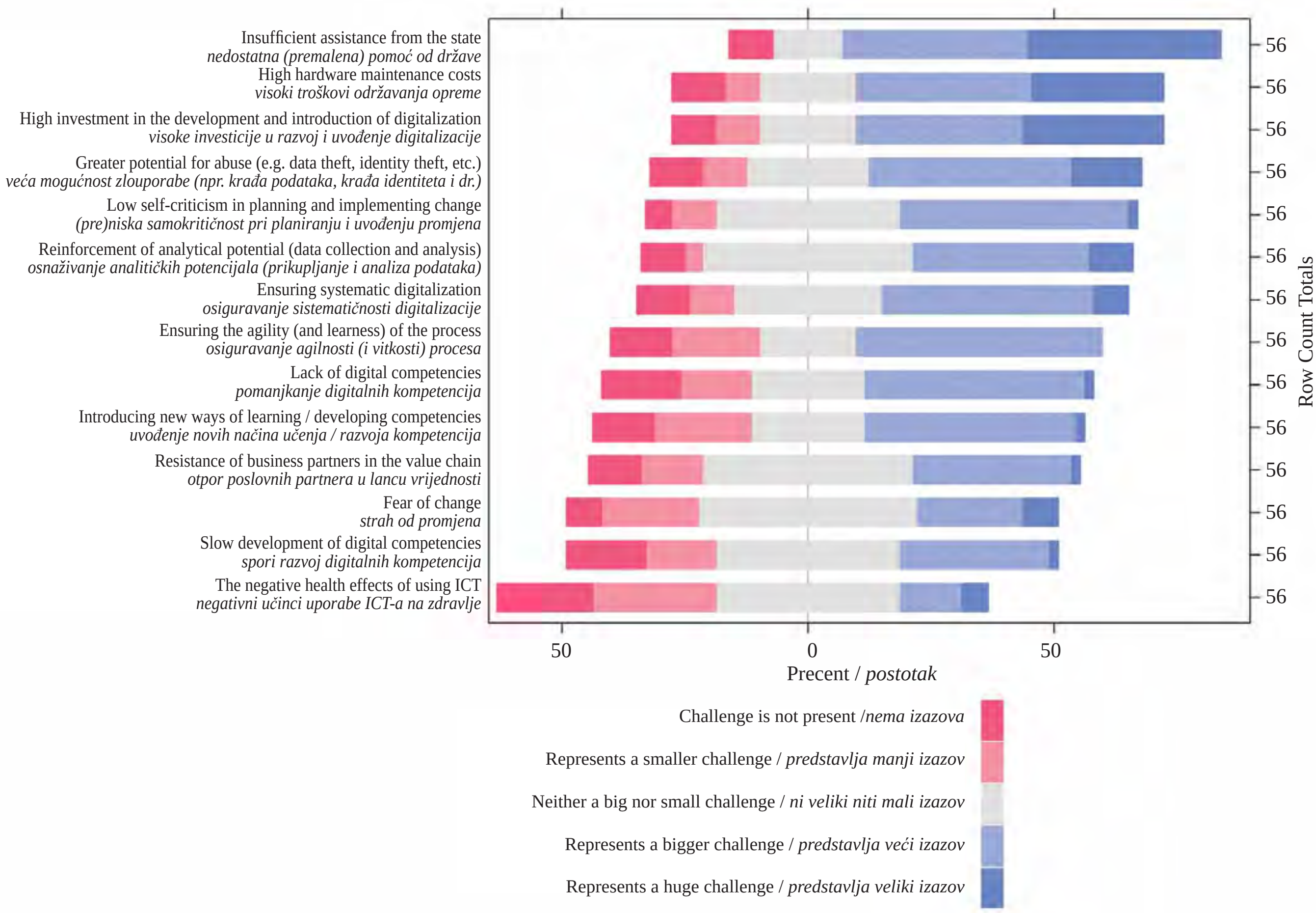

Figure 2 Challenges and obstacles that companies encountered before or during the digitalization process, *n* = 56
Slika 2. Izazovi i prepreke s kojima se tvrtke susreću prije i tijekom procesa digitalizacije, *n* = 56

The biggest challenge in the digitalization process is *Insufficient assistance from the state*, with 78 % of the surveyed companies considering it as a big or a very big challenge. *High hardware maintenance costs*, *High investments in the development and introduction of digitalization* and a *Greater potential for abuse* also represent significant obstacles. According to the respondents, the least important challenge is the negative health effects of using ICT, because 20 % of respondents do not face this problem at all, and 26 % believe that it is only a small obstacle for their company. It is interesting that the *Resistance of business partners in the value chain*, *Fear of change* and *Slow development of digital competencies* appear to be relatively small challenges for the companies. On average, small companies face the biggest challenges with regard to digitalization, while for mid-size and big companies the problems are smaller. Statistically significant differences among different sizes of companies were found only for the challenge of a *Greater potential for abuse* (p=0.002, Fisher exact test). The correlation between the size of the companies and the challenge *Greater potential for abuse* was negative (Spearman correlation coefficient=–0.350, p=0.008). The size of the various challenges and obstacles does not differ significantly among sub-sectors.

Figure 3 shows that, according to the respondents, cloud computing (37 %), smart applications and analytics (30 %) and conversational platforms (28 %) currently have the most impact on their business. In contrast, artificial intelligence (8 %), digital twins (8 %), immersive experience (10 %) and blockchain (12 %), have the least impact on the business. In addition to the technologies that already have an impact, most respondents stated that smart things, event-driven computing and artificial intelligence will have a significant impact in the future. However, a large proportion of companies (41 %) believe that artificial intelligence does not and will not affect their business in the future. Similarly, a high proportion of companies believe that their business will not be affected by immersive experience (31 %) and blockchain (31 %). Cloud computing was expected to have or will have an impact on most companies in the future, as data storage offers security and makes it easier to share data with others. Also, the use of smart applications and conversational platforms is almost inevitable in today's world. According to the respondents, smart things do not have a big impact on their business yet, but they expect this to grow in the future. This is understandable, since smart things, factories and cities cause changes in the environment and market, and are a trend that is changing both society and business. Almost half of the companies believe that artificial intelligence does not and will not affect their business in the future. One of the important reasons for this opinion is the very high investment required to implement artificial intelligence.

A third of the surveyed companies (30 %) are engaged in the production of smart products. Most of them (23 %) manufacture other furniture, 14 % manufacture chairs and tables, 11 % interior constructions and cabinets, 9 % exterior constructions and artistic products,

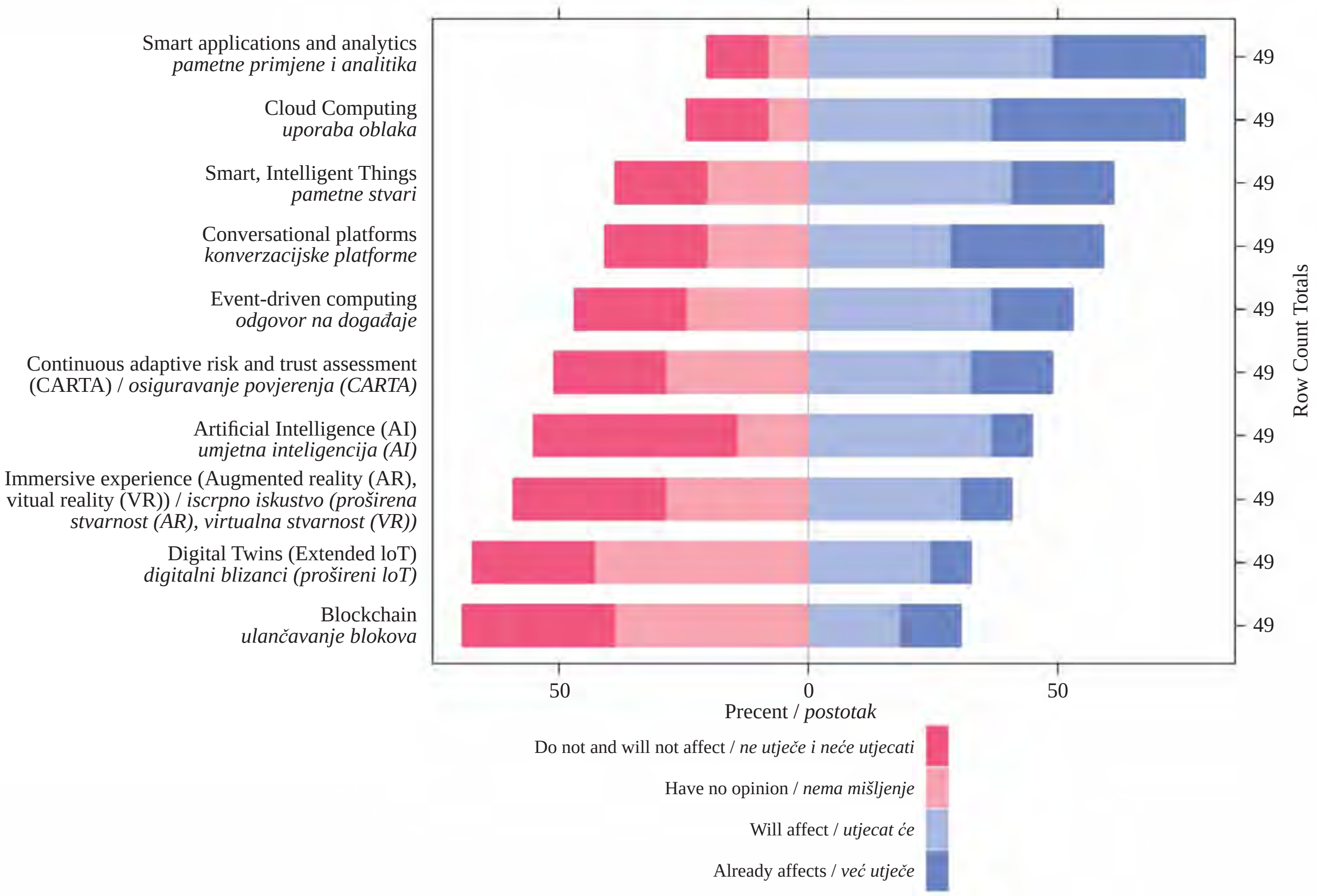

Figure 3 Impact of information and communication technologies on business in the next three years, n = 49
Slika 3. Utjecaj informacijsko-komunikacijskih tehnologija na poslovanje u sljedeće tri godine, n = 49

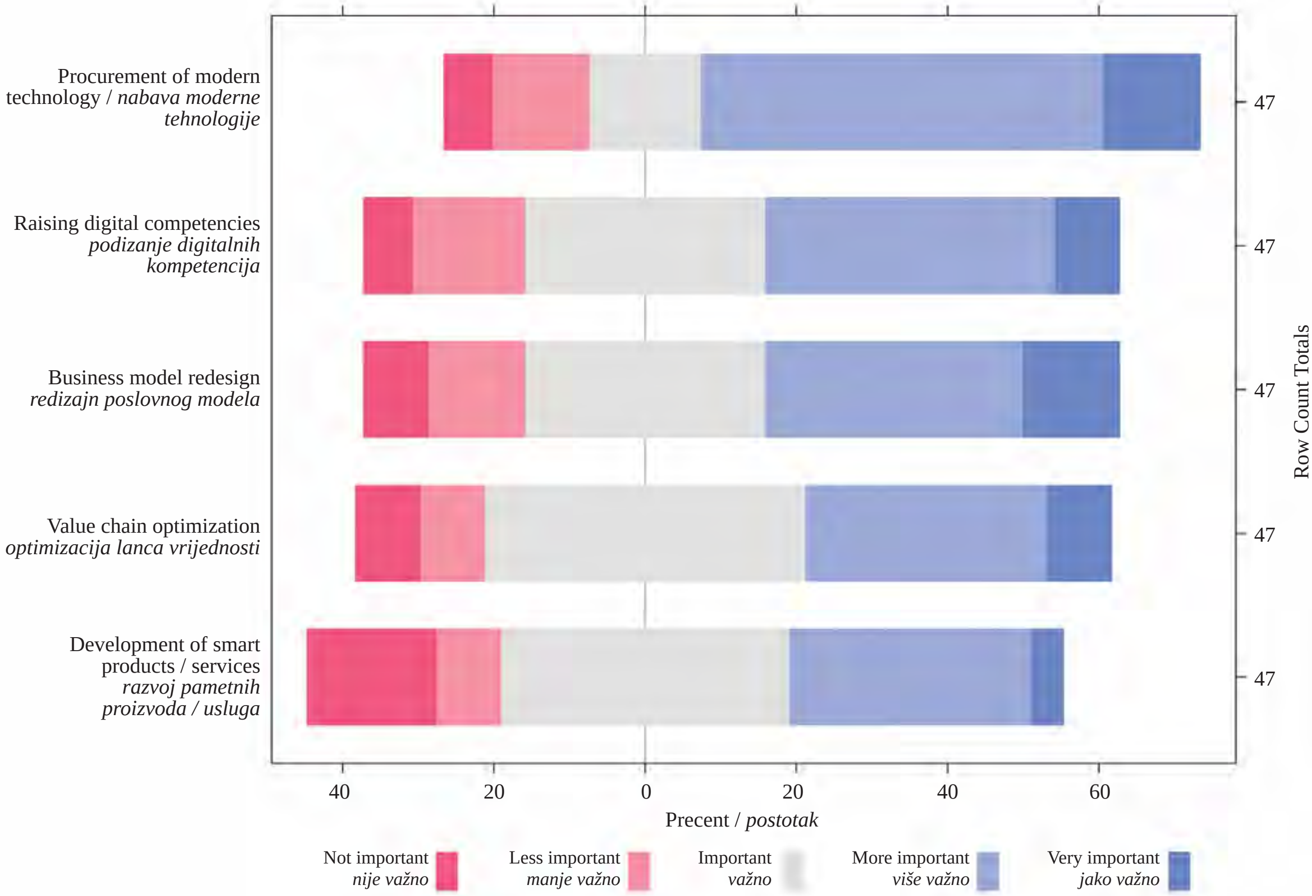

Figure 4 Importance of digitalization activities in strategic plans of companies for their investments in the next three years, *n* = 47
Slika 4. Važnost digitalizacijskih aktivnosti u strateškim planovima poduzeća za njihova ulaganja tijekom sljedeće tri godine, *n* = 47

while 3 % produce packaging, wooden fancy goods, sports tools and wooden toys. The results are as expected, as smart furniture has only become a trend in the last few years. In the next few years the manufacturing of smart products is expected to grow, because the primary goal of smart products is not just to make life easier for their users, but also to send feedback to manufacturers, enabling them to continually improve and upgrade their products. The differences in the proportions of companies that manufacture smart products among the various sizes of companies and sub-sectors are not significant. We were interested in whether those companies on a higher level of digitalization manufacture smart products more often, but the correlation is insignificant (Spearman correlation coefficient=0.147, p=0.135).

Figure 4 shows that, according to the respondents, the most important digitalization activity in their strategic plans is the *Procurement of modern technology*, because 65 % of respondents estimate that this is important or very important for their investments over the next three years. *Raising digital competencies* and *Business model redesign* are the second most important, followed by *Value chain optimization*. According to the respondents, the *Development of smart products or services* is the least important activity.

Most of the surveyed companies (89 %) (Figure 5) intend to invest a certain share of revenues in the digitization of their business in the next three years. Eleven percent of companies do not intend to invest in digitalization, while 48 % intend to invest up to 2 %, 30 % of companies up to 5 %, and 11 % of companies above 5 %. The differences between the sizes of companies and subsectors are not significant. Figure 6 shows the correlation between the rate of digitization and the share of revenue that companies intend to invest in this over the next three years. The numbers in the circles and the sizes of circles indicate how many companies fall into a given category. The results show that the correlation is positive, and that more digitalized companies intend to invest more in digitization in the future. The positive correlation between the level of the digitalization and the share of revenue that companies intend to invest in digitization over the next three years is also confirmed by the Spearman correlation coefficient (0.502, p<0.001).

Figure 7 shows that the companies in Slovenia rarely use the elements of the factories of the future. However, more use is anticipated within the next few years. Twenty-eight percent of the surveyed companies already use advanced materials, and 15 % use advanced sensors. The share of companies that use advanced sensors differs significantly among different sizes of companies (p=0.014, Fisher exact test). Among mid-sized / big companies, almost half indicate that they use advanced sensors. None of the companies use smart plasma systems, and only 7 % use 3D printing. The difference in the use of 3D printing among different sizes of companies is significant (p=0.021, Fisher exact test). Among the other elements of the factory of the future mentioned in the survey, only intelligent guidance systems (11 %) are used by more than 10 % of the compa-

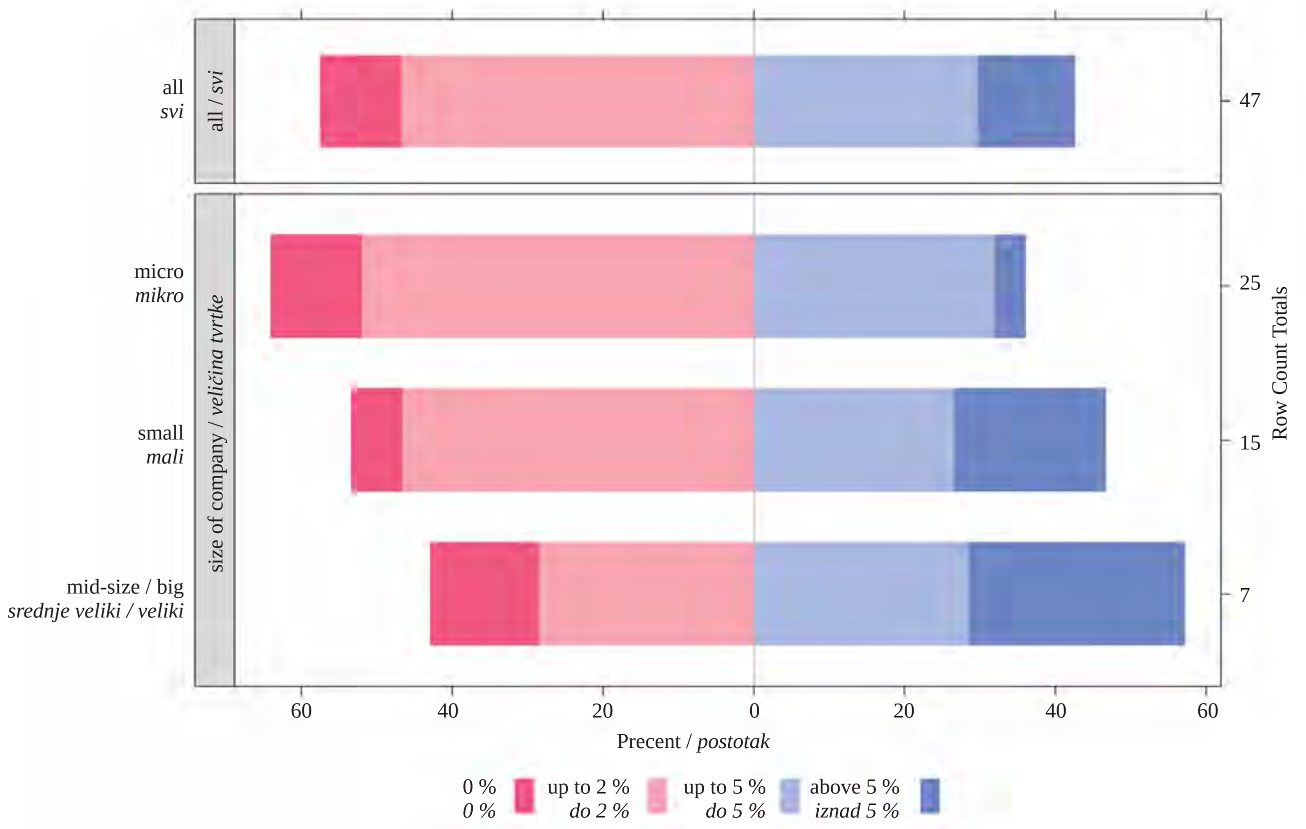

Figure 5 Share of revenue that companies intend to invest in digitization over the next three years, *n* = 47
Slika 5. Udio prihoda koji tvrtke namjeravaju uložiti u digitalizaciju tijekom sljedeće tri godine, *n* = 47

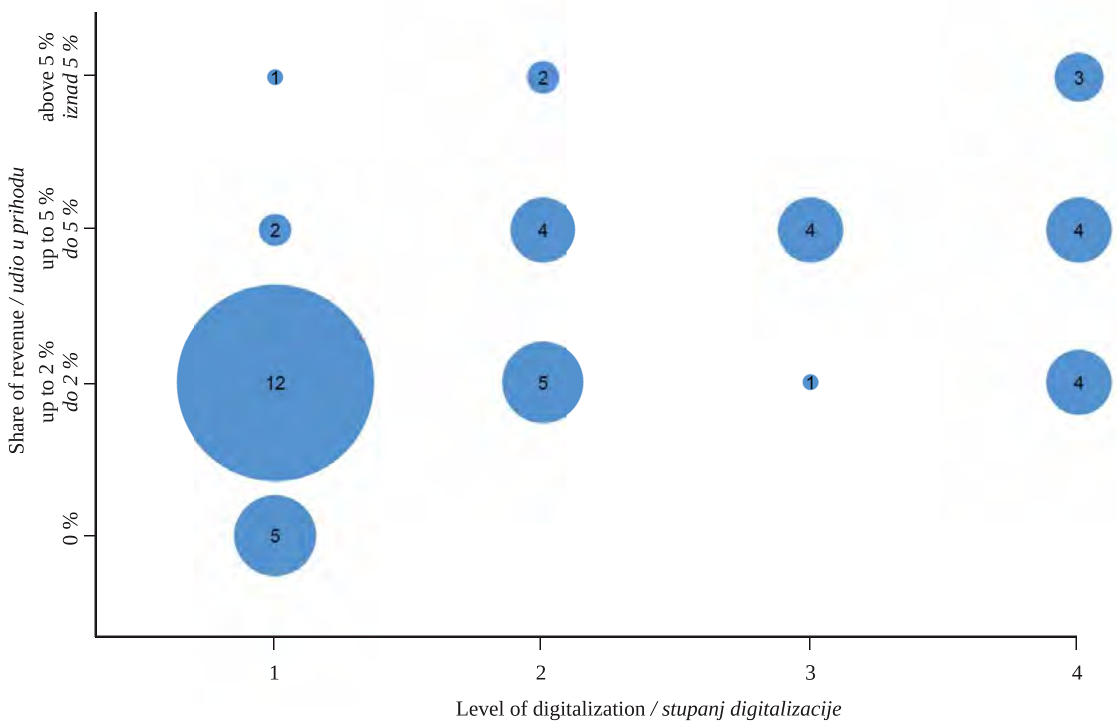

Figure 6 Correlation between the level of digitalization and share of revenue that companies intend to invest in it over the next three years, *n* = 47. Numbers in circles represent the number of companies in the groups (Legend of the *x*-axis: 1 – We are complete beginners, 2 – We know what digitalization means and we are preparing for the launch, 3 – We have already started the first digitalization activities, 4 – Our company has already been digitalized to some extent)
Slika 6. Korelacija razine digitalizacije i udjela prihoda koji tvrtke namjeravaju uložiti u digitalizaciju tijekom sljedeće tri godine, *n* = 47; brojevi u krugovima označavaju broj tvrtki u skupinama (legenda osi *x*: 1 – *potpuni smo početnici*, 2 – *znamo što znači digitalizacija i pripremamo se za njezino uvođenje*, 3 – *već smo započeli prve digitalizacijske aktivnosti*, 4 – *naša je tvrtka već donekle digitalizirana*)

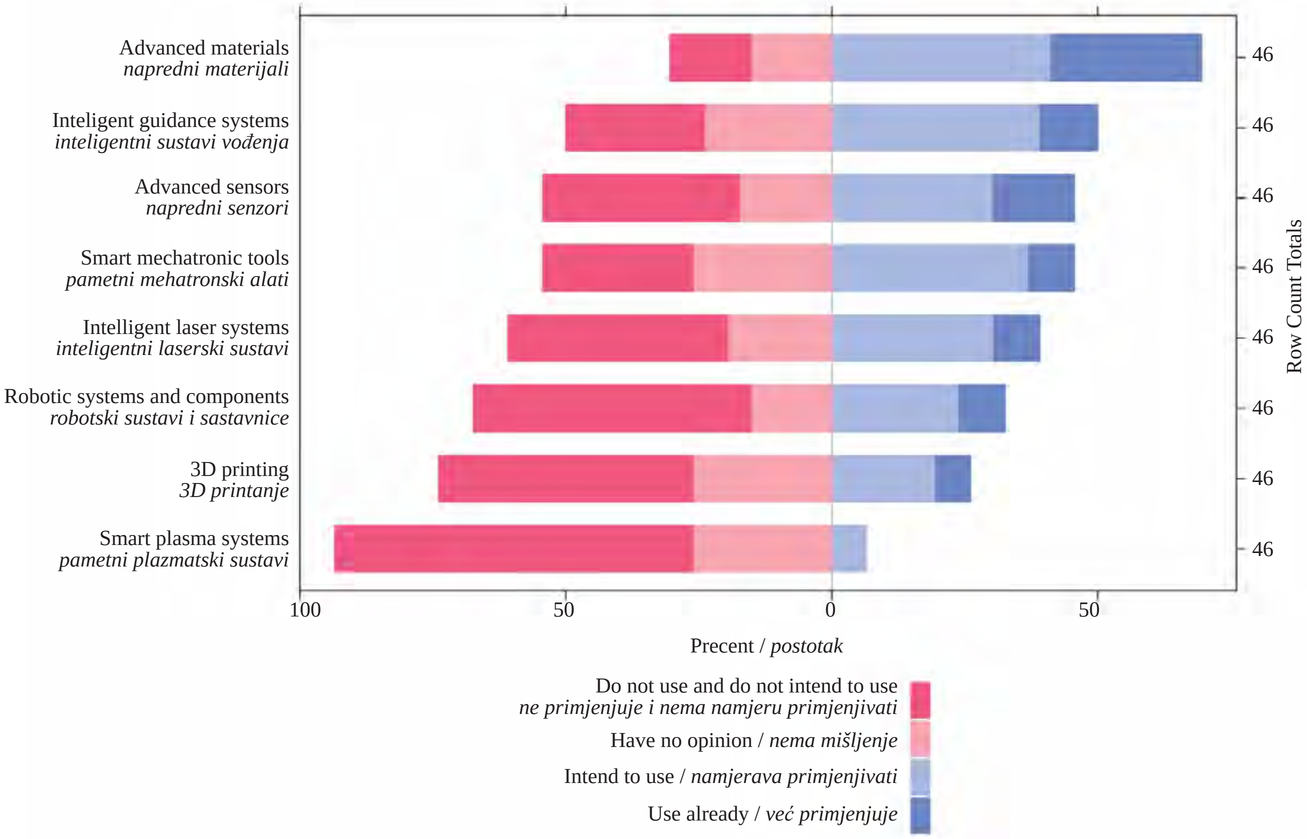

Figure 7 The "factory of the future" elements that companies use at their factory or plan to use in the next three years, *n* = 46
Slika 7. Elementi „tvornice budućnosti“ što ih tvrtke primjenjuju u svojoj tvornici ili ih planiraju uvesti tijekom sljedeće tri godine, *n* = 46

nies. Robotic systems and components are only used by micro and mid-size / big companies, and not by small companies, which indicates that the difference among different sizes of companies is statistically significant (p=0.029, Fisher exact test). Advanced materials (41 %), intelligent guidance systems (39 %) and smart mechatronic tools (37 %) are elements of the factory of future that are currently not used but a large number of companies intend to use them in the next three years.

4 DISCUSSION
4. RASPRAVA

Digitalization is changing the way companies do business and is closely linked to investments in modern (digital) technology, its development, and use. This is also strongly linked to the development of the competencies of employees who use and develop these technologies. This is especially true for technology-based companies, which include wood-industry (manufacturing) companies operating in the C16 and C31 sub-sectors. More than 80 % of the sample of companies surveyed in this research were micro and small enterprises, and this proportion is representative of the wood industry in Slovenia. Since digitalization requires significant investment on the one hand and demands great flexibility to meet this adaptation/change on the other, we were interested in whether there are any differences between different sizes of companies in this context.

Half of the surveyed companies are already implementing the concept of Industry 4.0, as a fundamental concept of digitalization of manufacturing companies, into their businesses, while the rest are beginners in terms of digitalization. Comparing the rate of digitization by the size of companies, we found out that the worst situation is among micro-companies, while it is better in mid-size and large companies, where up to two-thirds of enterprises are already digitized. This confirms that the size of enterprises affects the degree of digitization. The correlation between business efficiency and performance, where C16 is better than C31 (Kropivšek *et al.*, 2019; Kropivšek *et al.*, 2017), and the degree of digitization could not be confirmed. However, we have confirmed that more successful companies are more aware of the importance of digitalization for the success of their current and, above all, future business, and therefore invest more in it. There is a positive correlation between the degree of digitalization and share of revenue that companies intend to invest in it over the next three years, which means that the more digitalized companies intend to invest even more in this in the future than the less developed ones. This is the result of a higher level of awareness of the importance of digitalization in ensuring the success of the business in the digital age, and earlier positive experiences of the results of digitization. This was also confirmed by the interviewees.

The biggest obstacles to the implementation of the concept of digitalization in business are high investments for the equipment and lack of financial support from the state. On average, small businesses face the biggest challenges, while medium and large companies face smaller challenges in the digitalization process. As expected, for smaller companies the amount of any investment and high maintenance costs are far more important than for larger ones, but, on the other hand, it is surprising that practically all challenges related to people (resistance to change, lack of competencies, etc.) are seen as less problematic. There were no significant differences in this regard among companies of different sizes. One of the major challenges is the lack of digital competencies among older workers, which was especially highlighted in the interviews. This, as well as an awareness that new knowledge and digital competencies will be necessary for the further development of companies, led the surveyed companies to see as very important an increase in digital competencies of employees in the strategic plans of companies for their investments in the next three years. This is especially true for medium-sized and large companies, which have a greater proportion of older employees, and these are more aware of the importance of digitalization to business success. While implementing the concept of Industry 4.0, the surveyed companies ranked as the most important the following digital competencies (from the DigComp model (Carretero Gomez *et al.*, 2017)): information literacy, understanding and ensuring digital security, and communication/collaboration using modern ICT. These findings are in line with the fundamental guidelines for the development of an information society in Europe (European Commission, 2016).

For the surveyed companies, investing in modern, digital technology and developing digitalized business models, in addition to raising digital competencies, represent the most important activities in their strategic investment plans. In the context of investing in ICT, companies evaluate as the most important investing in cloud computing and conversation platforms, smart app and smart things development, as they are seen as already influencing, or soon will influence, the operation of the companies in the near future. In particular, this refers to investing in smart things (IoT), which does not yet have a major impact on the operations of the surveyed companies but is becoming increasingly important globally. Companies expect the IoT to have a major impact on their business performance in the future, notably the development of smart products and the implementation of (more) elements of a smart factory into their operations. We found that only about a third of the surveyed companies are currently engaged in the development and manufacture of smart products, which is rather low considering their importance. The more digitalized companies are making smart products more often, but the correlation is insignificant. We also looked at the implementation of smart factory elements, which are applied (on average) in less than 15 % of the surveyed companies. Within the elements of smart factories, advanced materials and sensor technologies stand out in particular. Among other elements of the factory of the future, only intelligent management systems are used by more than 10 % of companies. Advanced materials, intelligent guidance systems, and smart mechatronic tools are also elements that are planned to be used by a large number of surveyed companies over the next three years, but are not currently in use.

As part of the Smart Specialization Strategy projects that have been ongoing in Slovenia and Europe since 2015 (STA, 2015), companies see the greatest potential in creating international connections and globalization, followed by improving (digital) competencies, developing new (smart) materials and products, and encouraging investment in technology, including digital infrastructure. In all these elements, companies see great potential. Considering the number of projects carried out under the Smart Specialization Strategy of Slovenia and strategic research and innovation partnerships (SRIP) (Republic of Slovenia, 2019), within which many wood industry companies are active members, most of such potential has already been realized, or is still in the process of becoming so. One of the most successful priority areas and partnerships within this strategy is the "smart building and home with timber chain", where companies have developed many new systems, materials, and products; progress has also been made in the field of wood science (SRIP, 2019).

5 CONCLUSION
5. ZAKLJUČAK

The results of this study show that digitalization in the Slovenian wood industry is still at a relatively low level, but there are significant differences between companies. The size of a company is a factor that greatly influences the degree of digitalization, and the related firm plans for the near future. Awareness of the importance of digitalization and past experience of digitalization appear to be the most important reasons for further development of such technology and approaches within a company. It is also of particular importance to provide a digital infrastructure and implement the modern elements of a smart factory, develop smart products and raise employees' digital competencies. The latter is extremely important in terms of the efficient use of modern technologies and further development of companies in this field. For further development, the preparation of a digital strategy is a key document at both the national level (Republic of Slovenia, 2016) and at the level of companies, where the assistance of the state is very important. To this end, in 2019, companies are eligible to (co)-finance the preparation of digital strategies through vouchers (Digital Innovation Hub Slovenia, 2019), which eliminates one of the major obstacles that companies have highlighted in the research. With a clearly outlined strategy and its implementation, the situation with regard to the digitalization of wood-industry companies will also improve. In further research, it would be highly welcome to investigate in more detail the preparation of digital strategies in wood companies, and above all to compare their implementation with companies in other sectors.

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6 REFERENCES
6. LITERATURA

1. Carretero Gomez, S.; Vuorikari, R.; Punie, Y., 2017: DigComp 2.1: The Digital Competence Framework for Citizens with eight proficiency levels and examples of use. Publications Office of the European Union. DOI: http://dx.doi.org/10.2760/38842.
2. Cotteleer, M.; Sniderman, B., 2017: Forces of change: Industry 4.0. Deloitte Insights. https://www2.deloitte.com/insights/us/en/focus/industry-4-0/overview.html?nc=1#what is-industry-4 [25.6.2019)].
3. Herakovič, N., 2016: Nekateri tehnološki izzivi Industrije 4.0. Ventil, 22 (1): 10-16.
4. Hozdić, E., 2015: Smart factory for industry 4.0: A review. International Journal of Modern Manufacturing Technologies, 7 (1): 31.
5. Keidanren, 2016: Toward realization of the new economy and society. http://www.keidanren.or.jp/en/policy/2016/029_outline.pdf. [20.9.2019].
6. Kmet Zupančič, R., 2019: Development Report 2019. The Institute of Macroeconomic Analysis and Development of the Republic of Slovenia IMAD, Ljubljana. http://www.umar.gov.si/en/slovenias-development/ [10.10.2019].
7. Kropivšek, J.; Milavec, I.; Likar, B., 2017: Analiza poslovanja slovenske lesne panoge. Les/Wood, 66 (2): 47-56. https://doi.org/10.26614/les-wood.2017.v66n02a05.
8. Kropivšek, J., 2018: Konceptualni model digitalizacije izobraževanja: Primer visokošolskega izobraževanja v lesarstvu v Sloveniji. Les/Wood, 67 (2): 63-74. https://doi.org/10.26614/les-wood.2018.v67n02a06.
9. Kropivšek, J.; Perić, I.; Pirc Barčić, A.; Grošelj, P.; Motik, D.; Jošt, M., 2019: A Comparative Evaluation of Operational Efficiency of Wood Industry Using Data Envelopment Analysis and Malmquist Productivity Index: the Cases of Slovenia and Croatia. Drvna industrija, 70 (3): 287-298. https://doi.org/10.5552/drvind.2019.1937.
10. Lasi, H.; Fettke, P.; Kemper, H. G.; Feld, T.; Hoffmann, M., 2014: Industry 4.0. Business & Information Systems Engineering, 6: 239-242. https://doi.org/10.1007/s12599-014-0334-4.
11. Lee, D., 2019: Ikea is introducing robotic furniture for people who live in small spaces. https://www.theverge.com/2019/6/4/18652178/ikea-rognan-robot-murphy-bed-furniture-ori-living-democratic-design-days [5. 8. 2019].
12. Movrin, P., 2017: Pametna tovarna na ključ za globalni trg. glas gospodarstva, november 2017, p. 45.
13. Panetta, K., 2018: Gartner Top 10 Strategic Technology Trends for 2019. Gartner. https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology--trends-for-2019/ [21.9.2019].
14. Paluš, H.; Parobek, J.; Liker, B., 2015: Trade Performance and Competitiveness of the Slovak Wood Processing Industry within the Visegrad Group Countries. Drvna industrija, 66 (3): 195-203. https://doi.org/10.5552/drind.2015.1431.
15. Paluš, H.; Parobek, J.; Dzian, M.; Šimo-Svrček, S.; Krahulcová, M., 2019: How companies in the wood supply chain perceive the forest certification. Acta Facultatis Xylologiae Zvolen, 61(1): 155-165. https://doi.org/10.17423/afx.2019.61.1.15.
16. Robbins, N. B.; Heiberger, R. M., 2011: Plotting Likert and other rating scales. In: Proceedings of the 2011 Joint Statistical Meeting, pp. 1058-1066.
17. Schmidt, R., Möhring, M.; Härting, R.-C.; Reichstein, C.; Neumaier, P.; Jozinović, P., 2015: Industry 4.0 – Potentials for Creating Smart Products: Empirical Research results. Business Information Systems, 18th International Conference, BIS 2015, Poznań, Poland, pp. 16-27.
18. Zupan, G., 2018: Digitalni indeks slovenskih podjetij. Uporabna Informatika, 4: 11. https://uporabna-informatika.si/index.php/ui/article/view/5. [20.9.2019].
19. Xu, L. D., He, W.; Li, S., 2014: Internet of Things in Industries: A Survey. IEEE Transactions on Industrial Informatics, 10/4: pp. 2233-2243.
20. Xu, L. D.; Xu, E.; Li, L., 2018: Industry 4.0: state of the art and future trends. International Journal of Production Research, 56 (8): 1-22.
21. *** 1ka, 2019: Integrated support for survey process. https://www.1ka.si/d/sl [26.3.2019].
22. *** Alples, 2016: Alples partner v projektu "Akustično pametno pohištvo". https://www.alples.si/sl/stories/rc31-partner-v-projektu-pametno-akusticno-pohistvo/ [27.7.2019].
23. *** Commission of the European Communities, 2019: Key Enabling Technologies. https://ec.europa.eu/growth/industry/policy/key-enabling-technologies_en [20.9.2019.
24. *** Digital innovation hub Slovenia, 2019: Digitalna strategija. https://dihslovenia.si/smernice/digitalne-strategije/ [10.10.2019].
25. *** European Commission, 2016: The European Union explained: A digital single market in Europe - Bringing down barriers to unlock online opportunities. https://publications.europa.eu/en/publication-detail/-/publication/01368318-4e3d-11e6-89bd-01aa75ed71a1/language-en [20.9.2019].
26. *** European Commission, 2018: Smart specialization platform. http://s3platform.jrc.ec.europa.eu/ [20.9.2019].
27. *** European Commission, 2019: The Digital Economy and Society Index (DESI). URL: https://ec.europa.eu/digital-single-market/en/desi [23.9.2019].
28. *** Republic of Slovenia, 2016: Digitalna Slovenija 2020 – Strategija razvoja informacijske družbe do leta 2020. https://www.gov.si/assets/ministrstva/MJU/DI/7df0f756bc/Strategija-razvoja-ID.pdf [10.10.2019].
29. *** Republic of Slovenia, 2019: Izvajanje Slovenske strategije pametne specializacije. https://www.gov.si/zbirke/projekti-in-programi/izvajanje-slovenske-strategije-pametne-specializacije/ [10.9.2019].
30. *** SRIP, 2019: Pametne stavbe in dom z lesno verigo. https://www.teces.si/sl/srip-psidl/fokusna-podrocja-srip#Les [12.10.2019].
31. ***STA, 2015: Smart Specialisation Strategy Adopted. http://www.sloveniatimes.com/smart-specialisation-strategy-adopted [15.10.2019].
32. *** Statistical Office, Republic of Slovenia, 2018: The rate of digitization of enterprises with at least 10 persons employed in 2018. https://www.stat.si/StatWeb/en/News/Index/7812 [14.10.2019].

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Changes in Customer Preferences for Furniture in Slovenia

Promjene sklonosti kupaca namještaja u Sloveniji

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ABSTRACT • *In the last decade, the Slovenian furniture industry market has experienced a number of changes, especially with the arrival of new retailers on the market. The situation is such that furniture manufacturers and retailers are still trying to determine the best ways to adjust to new customer demands. A well known thing is that customer satisfaction is the key component for the success of the business. In order for companies to be more successful, it is important to get better insight into customers'needs and wants. In line with this, the purpose of this study, which compare the surveys conducted in 2010 and 2019, was to observe and analyse changes in the preferences of customers for furniture: materials, attributes, and styles when deciding on new furniture in Slovenia. The results of this research showed that customers' preferences for furniture materials have changed in the last decade. Similarly, the factors that influence their purchase decisions when buying interior and exterior furniture have changed as well. It was found that wood was widely preferred as a furniture material among the respondents in both years studied.*

Keywords: *wooden furniture; customer preferences; survey; Slovenian market*

SAŽETAK • *U posljednjem desetljeću slovensko je tržište namještaja doživjelo mnoge promjene, posebice ulaskom stranih trgovaca. Stoga proizvođači namještaja i trgovci i dalje pokušavaju odrediti najbolje načine prilagodbe novim zahtjevima kupaca. Općenito je poznato da je zadovoljstvo kupaca ključna komponenta za uspjeh poslovanja. Kako bi tvrtke bile uspješne, važno je imati što bolji uvid u potrebe i želje kupaca. U skladu s tim, cilj ovog istraživanja, koje uspoređuju ankete provedene 2010. i 2019., bila je usporedba i analiza promjena sklonosti kupaca pri odabiru i kupnji namještaja, i to u smislu materijala, svojstava i stila. Rezultati provedenog istraživanja pokazali su da su se sklonosti ispitanika u odabiru materijala namještaja u posljednjem desetljeću promijenile. Osim toga, promijenili su se i činitelji koji utječu na njihove odluke pri kupnji namještaja za vanjsku ili unutarnju upotrebu. Ispitivanja su pokazala da je drvo 2010. bio vrlo poželjan materijal za izradu namještaj, a to je i danas.*

Ključne riječi: *namještaj od drva; sklonosti kupaca; anketa; slovensko tržište*

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1 INTRODUCTION
1. UVOD

The benefits derived from wood are the key factors in the competition between wood and non-wood products. A wood product is composed of various attributes, and the consumers' choice is guided by their quality. With regard to the product, the main challenge is to get consumers' attention, catch their preferences and buying habits. The aim of this study was thus to better understand consumer preferences and buying habits with regard to furniture and to observe the changes in the preferences of Slovenian costumers.

An important body of literature focuses on consumer preferences in furniture markets and the competition between wood and non-wood products. The typical characteristics consumers assign to wood materials have been studied by several researchers (Pakarinen and Asikainen, 2001; Bowe and Bumgardner, 2004; Scholz and Decker, 2007; Kaputa *et al*., 2018). Attempts have also been made to map how the properties of wood are related to preferences (Nyrud *et al*., 2008). The effects of background and profession on preferences have also been investigated (Marchal and Mothe, 1994; Roos and Nyrud, 2008). However, a study of how wood as a material is perceived and characterised in relation to alternative wood-based materials, such as panels and wood-based composites, remains to be conducted. Jonsson *et al.* (2008) identified the attributes and associations that people use to describe different types of wood materials, and explored how they relate to preferences.

The wood used for furniture production has a strong impact on consumer's preferences for the product as a whole. Costa *et al*. (2011) confirmed that the quality levels of wood product attributes are endogenous variables, and depend on the level of information a consumer has in the buying decision process. According to Scholz and Decker (2007), the wood species used in manufacturing not only affects the material appearance, but also the preferences for seemingly unrelated attributes, like style and design. An Sheng Lee (2010) found that the features of furniture product designs and consumer satisfaction have positive correlations in a Taiwanese sample. The feature of functional design mostly influences consumers' satisfaction when making decisions to buy furniture products. Bumgardner *et al*. (2007) evaluated consumer preferences for six domestic wood species. Similar research by Nichols and Bumgardner (2007) evaluated how age, gender and income influence consumer preferences for the species used in household furniture products, and they found that age and income were statistically significant in this context (with a stronger effect of age), while gender was not significant.

Numerous studies have measured consumer attitudes toward wooden furniture. Buehlmann and Shuler (2009) analysed the development and opportunities in the US furniture market. Later on, Buehlmann cooperated with Lihra and Graf (2012) and they measured, via a choice-based conjoint analysis, the value that US consumers assign to the availability of customisation when buying furniture. They found that, roughly 50 % of consumers' product choice is driven by price, 20 % by product customisation, 20 % by delivery time, and 10 % by the time needed to customise the product. Ponder (2013) compared and determined the extent to which attitudes and behaviour towards home furniture have changed over a five-year period. In Finland, Pakarinen and Asikainen (2001) examined the use of wood as a material for furniture, aiming to highlight the important attributes that consumers consider when selecting a piece of furniture. Based on their results, quality and design were ranked as the most important attributes. Troian (2011) defined the factors that influence consumers' choice of a product and analysed the furniture preferences in Italy and in different cultural environments. She concluded that, despite the fact of high-speed globalization, consumers from different geographical zones do vary their behaviour in the different cultural contexts. This could create a barrier to rapid entry in foreign markets. Thus, furniture manufacturers have to deal with a deeper understanding of local cultures and their influence upon purchase behaviour.

Other studies have measured consumer attitudes towards eco-labelled forest products (Forsyth *et al.*, 1999; Ozanne and Smith, 1996; Ozanne and Vlosky, 1997; Vlosky *et al.*, 1999). Generally, these studies found that consumers hold favourable attitudes to certified products, and would like to purchase them. They are willing to pay more and they prefer certified to uncertified forest products. However, for most respondents, product attributes other than eco-labelling are more important when forming preferences (for example, price). Research done by Teisl (2003) found that consumer demand and willingness to pay for certified products are contingent on the information provided on an ecolabel. Consumers prefer ecolabels with detailed information about the environmental benefits associated with eco-labelled products.

The issue of the consumer preferences for furniture was also the subject of several studies in Slovakia and Croatia (Kaputa and Supin, 2010; Kaputa, 2013; Kaputa *et al*., 2018). In addition, several authors (Oblak and Jost, 2011; Palus *et al*., 2014; Palus and Mat'ova, 2009) have dealt with the awareness of end-users about the labels used by forest certification schemes, which allow to track the origin of wood. Several conclusions can be drawn from these earlier studies: the most relevant purchase decision factors are quality, price and design of furniture. The most preferred is modern style furniture. The decision to buy a certain piece of furniture most frequently arises in a store, followed by when using a catalogue or the internet, and is mostly based on a compromise between the man and woman in a household (Kaputa and Supin, 2010). Over 40 % of respondents are aware of the existence of labelled products, either spontaneously or when prompted, but only 5 % of them understand the exact or approximate meaning of the labels. Most of consumers, who are aware of labels and also read them, are between the ages of 41-60 and represent either middle or higher income classes (Palus *et al*., 2014).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The questionnaire was developed based on previous research results and using the existing literature. The first survey, held in November 2010, was implemented during the furniture fair Ambient in Ljubljana. There were 300 surveyed respondents and the results have not been published. The second survey was done in April 2019 using a web platform (www.1ka.si). There were 128 valid filled-in questionnaires, out of 218 clicks on the page where the survey was published. A link to the electronic version of the questionnaire was distributed by students and researchers using social networks and e-mail addresses. Thus, a non-probability snowball sampling method was used to spread the questionnaire. Nonprobability sampling, used to cover as many respondents as possible, could also be called purposive sampling, as Dillon *et al.* (1990) stated, because certain segments of the target population were intentionally overrepresented in the sample (such as age categories – any respondents under 18 years old).

The questionnaire consisted of two parts, where the first part dealt with demographic characteristics such as gender, achieved education level (primary school, high school, and university), and the age categories.

The questions in the second part were concerned with a decision-making process when purchasing furniture, and specific consumer preferences for:

- material: solid wood, wood composites, plastic, metal, glass, and combination of materials (requested for both – interior and exterior furniture)
- furniture attributes (price, manufacturing quality, design, environmental attributes, country of origin, warranty, colour, brand, and safety), and
- furniture styles (rustic, modern, futuristic, and retro).

The respondents answered using a Likert-type scale, based on the observation in Churchill (1979) that no single item is likely to provide a perfect representation of the general idea. The scales revealed the level of agreement with various statements: 1 (definitely no), 2 (somewhat no), 3 (neither yes nor no/indifferent), 4 (somewhat yes), and 5 (definitely yes). For interpretation purposes of the frequency analysis results, we combined the answers "Definitely Yes" and "Somewhat Yes" into one indicating a positive attitude towards a certain kind of material. The same approach was applied in case of the answers "Definitely No" and "Somewhat No", which indicated a negative attitude. The indifferent attitude stayed as it was.

The statistical software SPSS PASW Statistics 18 and STATISTICA 12 for MS Windows were used for the data analyses, as well as Microsoft Excel. First, frequency analysis and cross-tabulation were used to determine the basic relationships among the answers. Pearson's chi-squared test of independence (at an $\alpha = 0.05$ significance level) was used to assess the significance of the frequency differences among the demographic characteristics.

The null hypothesis was stated to test the statistical significance of differences in preferences between the two surveys (at a 95 % confidence interval). A nonparametric Mann-Whitney U test for two independent samples was employed, since the test of normality revealed that the data were not normally distributed.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Demographic analyses of samples
3.1. Demografska analiza uzoraka

First, the significance of differences between the samples of the two surveyed years was analysed. There are no statistically significant differences in frequencies (Pearson's chi-square test at $\alpha = 0.05$ significance level) between the respondents from the two years in terms of gender. On other hand, there are significant differences between the samples of respondents regarding the frequencies of achieved education ($\chi^2 = 58.670$; $p < 0.05$) as well as between the frequencies of the compared age categories ($\chi^2 = 25.613$; $p < 0.05$). Both samples contain a high share of respondents of a young age – between 18 and 30 years old (over 40 % in 2010 and over 33 % in 2019). In 2019, the sample was composed of respondents with a higher share of older age categories and with a higher level of education, where fewer had finished high school and more completed bachelor's and postgraduate degrees.

3.2 Consumer preferences regarding furniture material
3.2. Sklonosti kupaca u smislu odabira materijala za namještaj

As shown in Table 1, the consumer preferences regarding the material for interior furniture did not change in the scope of the observed years, except for furniture made of plastic. On the other hand, compared preferences for exterior furniture were only similar in case of furniture made of glass. All the other preferences for the exterior furniture material were significantly different at $\alpha = 0.05$ significance level between the observed years.

The marginal answers are clear from Figure 1, which introduces especially high shares of the 'definitely' positive attitudes towards interior furniture made of solid wood (reaching almost 60 % of respondents in both years) and high shares of the 'definitely' negative attitudes towards interior furniture made of plastic (ranging from around 33 % in 2010 up to 46 % in 2019).

Overall, the most preferred material for interior furniture was solid wood, as stated by 74 % of the respondents in 2010 and 81 % in 2019 (Figure 1). The second option is wood composite, followed by a combination of materials, glass, metal and finally plastic. The biggest fall in preferences (and statistically significant: Mann-Whitney $U = 15424.0$, $p = 0.001$) between 2010 and 2019 was observed in case of plastic. This fact could be related to an anti-plastic campaign in the EU and worldwide (Barrett, 2019).

Table 1 Mann-Whitney U test of consumer preferences regarding furniture material
Tablica 1. Mann-Whitneyjev U-test sklonosti kupaca u odabiru materijala za namještaj

	Furniture material *Materijal za namještaj*	**Mann-Whitney U** *Mann-Whitneyjev U-test*	**Asymp. sig. (2-tailed)** *Asimptotska značajnost (dvosmjerni test)*
Furniture for interior use *Namještaj za unutarnju uporabu*	Wood (solid) / *masivno drvo*	18313.0	0.397
	Wood composite / *drvni kompozit*	18153.0	0.351
	Plastic / *plastika*	15424.0	**0.001**
	Metal / *metal*	17475.0	0.127
	Glass / *staklo*	17155.0	0.070
	Combination of materials *kombinacija materijala*	19142.5	0.959
Furniture for exterior use *Namještaj za vanjsku uporabu*	Wood (solid) / *masivno drvo*	15398.0	**0.000**
	Wood composite / *drvni kompozit*	14060.5	**0.000**
	Plastic / *plastika*	14671.5	**0.000**
	Metal / *metal*	15404.0	**0.001**
	Glass / *staklo*	18832.5	0.747
	Combination of materials *kombinacija materijala*	16933.5	**0.046**

Statistical significance at 0.05 level / *statistička značajnost na razini od 0,05*
n = 300 participants in 2010 and *n* = 128 participants in 2019 / *n = 300 ispitanika u 2010.; n = 128 ispitanika u 2019.*

The results showed that solid wood was the most preferred material for exterior furniture (preferred by 60 % of respondents), although it scores 20 % less in 2019 mostly due to the risen share of indifferent attitudes (Figure 2). The second highest ranked material for exterior furniture was a combination of materials, which gained 10 % from 2010 to 2019 (from 45 % up to 55 %). This might be related to the development of "new" combinations of materials in the last decade. In contrast, traditional wood composites are not so suitable for exterior use, and this was recognised by the respondents as more than 50 % of them expressed a negative attitude to this material.

Metal became more favourable within the sample of respondents in 2019, where a considerably higher share expressed a positive attitude, while at the same time the share of negative attitude dropped by a similar rate (around 10 %) – similar as in the case of furniture made of plastic material. Preferences for furniture made of glass have maintained the same attitudes.

3.3 Furniture attributes
3.3. Obilježja namještaja

As expected, the most important furniture attribute (of all analysed) is manufacturing quality, as almost all the respondents in 2019 (97 %) marked quality as a factor influencing their purchase decision (Figure 3). The design of products has become more important for customers over the years, as the share of respondents with a positive attitude increased from 71 % up to 91 %, and it is the second most important attribute in 2019. In general, the high shares of positive (more than

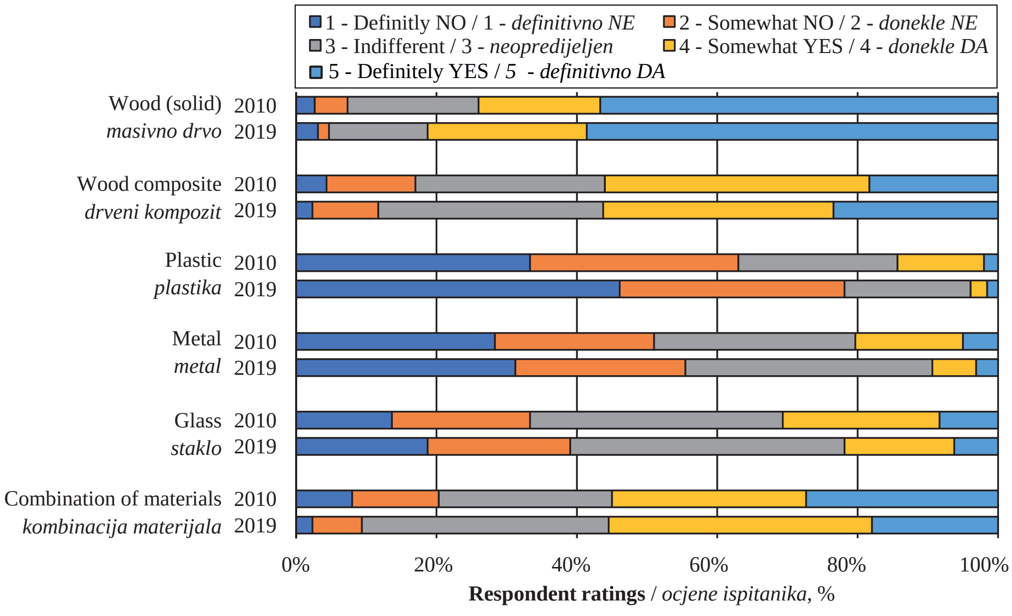

Figure 1 Preferences towards the material used for furniture for interior use
Slika 1. Sklonosti potrošača materijalima za izradu namještaja u interijeru

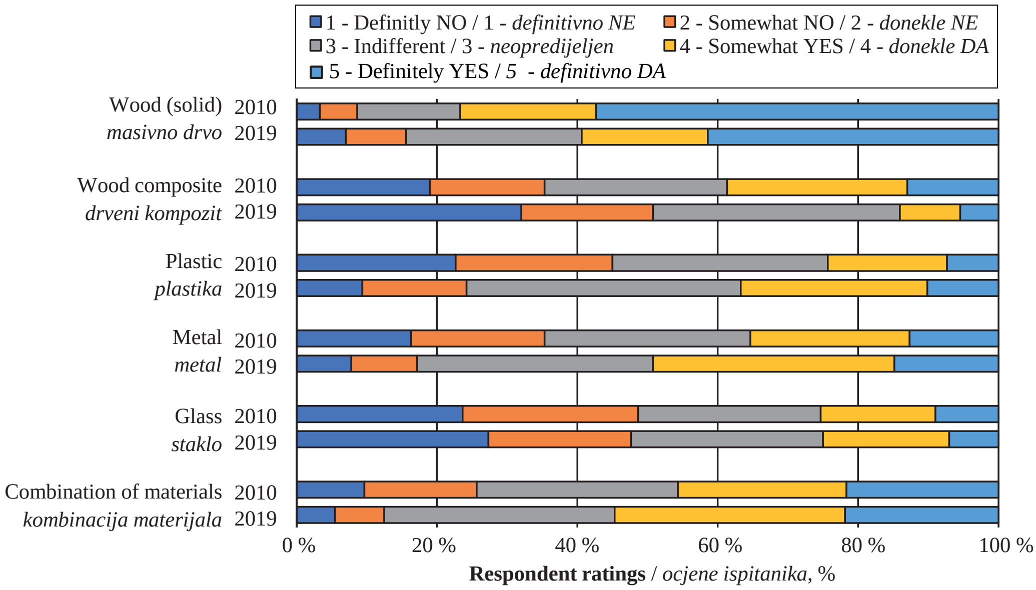

Figure 2 Preferences towards the material used for furniture for exterior use (2010 vs 2019)
Slika 2. Sklonosti potrošača materijalima za izradu namještaja u eksterijeru (usporedba: 2010. i 2019.)

70 %) attitudes for quality, design, colour, price and safety indicated that these factors are of a great importance among respondents. Similar findings were reported in previous studies carried out in Slovenia (Oblak *et al*., 2017, 2009), where the authors found that quality and design were the most relevant factors in purchase decisions. Quality was also recognised as the most important factor in other regions – Croatia and Slovakia (Motik *et al*., 2004).

The lowest importance was observed in case of country of origin and brand. Moreover, in 2019, preferences for brand even dropped (compared to 2010) at the level of around 20 %, while negative attitudes increased. On the other hand, the share of respondents whose purchase decision is influenced by environmental attributes and safety increased considerably from 2010 to 2019 up to the level of 54 % (environmental attributes) and over 72 % (safety), respectively, and simultaneously, the share of respondents who are not influenced by these factors decreased.

Respondents were also asked about their preferences for furniture style. The most preferred style in both years was modern style, with 72 % of positive attitudes in 2010 and 66 % in 2019 (the change was statistically significant: Mann-Whitney U = 16675.5, p = 0.023). According to Kaputa *et al*. (2018), the modern

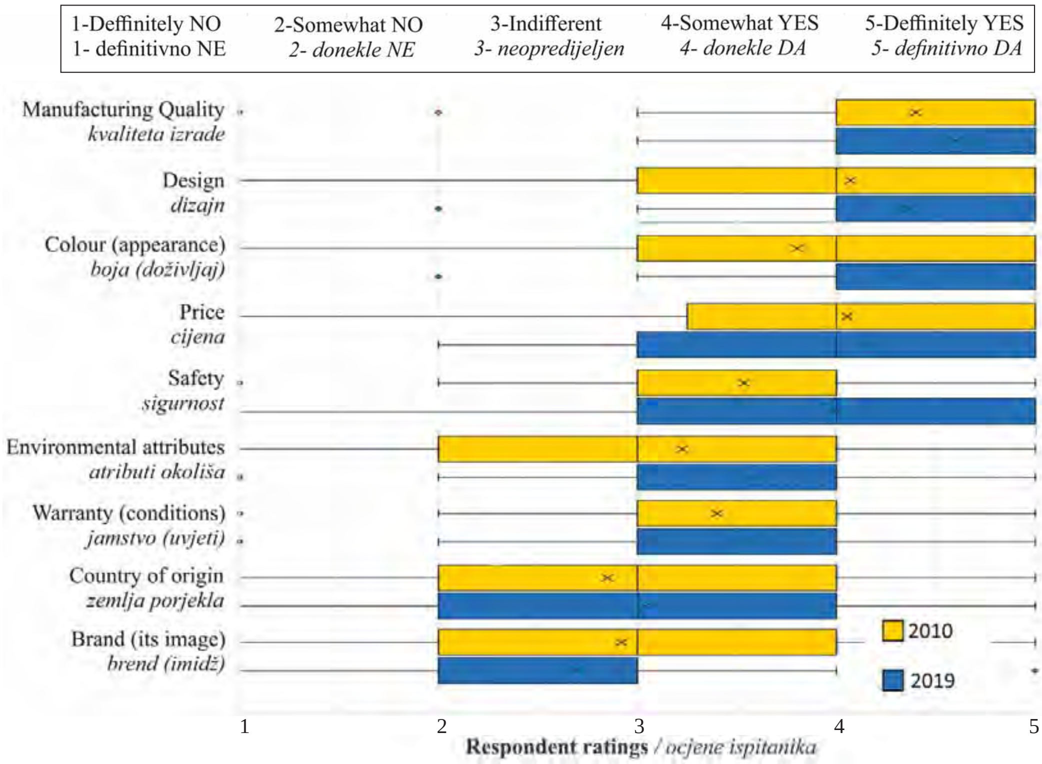

Figure 3 Factors influencing purchase decision to buy furniture (2010 vs 2019)
Slika 3. Činitelji koji utječu na odluku o kupnji namještaja (usporedba: 2010. i 2019.)

style furniture is also a first choice for the majority of consumers in Slovakia and Croatia. We observed a decrease in the preference for the futuristic style, with just 11 % of positive attitudes and 58 % of negative ones in 2019. Other preferences (for rustic and retro style) has not changed over time and stayed around 30 %.

3.4 Source of information when deciding to buy a piece of furniture
3.4. Izvori informacija pri odluci o kupnji namještaja

Figure 4 introduces distribution of consumers' responses about ways how or where a purchase decision is made. The results show that a store is the most frequent place. Moreover, the share of consumers whose decision to buy a piece of furniture is made in a store increased (statistically significant: Mann-Whitney U = 15251.5, p = 0.004) by 17 % between the years observed, since 59 % of respondents marked this option in 2010 and up to 76 % in 2019. The increase in the use of the internet as a source was also statistically significant (Mann-Whitney U = 16701.5, p = 0.028 – increased by 9 %) and in 2019 it even reached the level of decisions made in stores in 2010 (Figure 4). Internet became the most popular source of information in all fields, but results indicated that costumers still want to see and touch furniture before making a purchase decision. Oblak *et al*. (2009) and Perić *et al*. (2015) also reported that furniture stores were the most preferred source of information in Slovenia and Croatia.

The importance of fairs and exhibitions fell from 40 % in 2010 to 30 % in 2019 (the change was statistically significant; Mann-Whitney U = 15861.0, p = 0.003). Such decrease in popularity is also reflected in the decline of the number of furniture companies that were present at the main furniture fair in Slovenia – Ambient in Ljubljana. In 2010, 83 furniture companies were present at the fair, while in 2018 this number fell to 23 (GR, 2018). The importance of offline advertisements (TV, radio or print) also decreased. Offline advertisement seems to be the least important, as less than 20 % of consumers marked it as relevant for their purchase decision.

In addition, we found out that 84 % of the decisions to purchase furniture in 2019 were based on a compromise between both partners living in a household. Women most likely decide about design and colour, while men decide about the quality. Just 10 % stated that only the female partner decides, while only 6 % said only the male partner does. Based on these findings, we suggest that manufacturers and sellers should aim their marketing communication at women with emphasis on design and colour attributes of furniture.

4 CONCLUSIONS
4. ZAKLJUČAK

The results of this study show that customer preferences changed in the years studied - 2010 and 2019. The most preferred material for interior and exterior furniture is solid wood, and over time it has gained some popularity for interior use and lost some for exterior use. For inside use, the second and the third most preferred materials for furniture were wood composites and a combination of materials, with similar preferences in both years observed, while other materials were less popular. On the other hand, combination of materials was the second preferred in case of exterior furniture, while wood composites were the least favoured. All the examined furniture attributes gained in importance with regard to purchase decisions from 2010 to 2019, except for the price, where no change was observed. The most important factor was the quality of the product, followed by design and colour, while country of origin and brand were the factors with the smallest impact on purchase decisions.

Findings about the least importance of a brand are interesting since many companies are keen to build

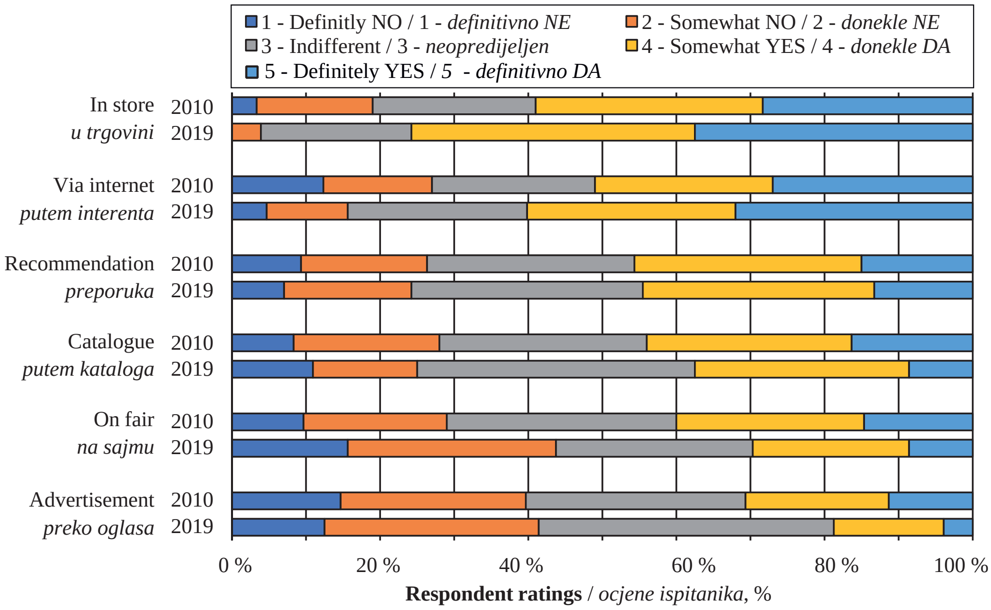

Figure 4 The ways how/where purchase decision to buy a piece of furniture is made (2010 vs 2019)
Slika 4. Kako i gdje kupci donose odluke o kupnji namještaja (usporedba: 2010. i 2019.)

their image via branding as a major marketing strategy. The same finding about a brand also comes from the study revealing consumers' preferences for furniture in Slovakia and Croatia (Kaputa *et al*., 2018). It is a challenge for further research to reveal if this is a phenomenon of the regional furniture market or it is caused by overall change of consumers' preferences. Considering also the fact of increasing importance of factors such as environmental attributes, we would like to introduce here the statement of John Grant (2012) that post-brand period has arrived.

It was found that a store is the most frequent place where a purchase decision is made. The second most frequent option is that such decision is made online (via internet). Tools of an offline advertisement (e.g. TV or newspapers) were the least important promotional channels for furniture.

The limitation of this study is the used sampling technique (snowball sampling) in both investigated years. In that case, the samples did not represent the population and thus the results cannot describe the entire population. The next limitation is the demographic composition of the samples with an unusually high share of young people (in both 2010 and 2019). Further, there are significant differences between the two samples of respondents regarding their education and age categories.

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5 REFERENCES
5. LITERATURA

1. Lee, A. S., 2010: A Study on Predicting Consumers' Satisfaction Based on the Features of Furniture Product Designs. International Journal of Organizational Innovation 2, 138-160.
2. Barrett, A., 2019: WWF Launch Anti-Plastic Campaign. Bioplastics News (online). https://bioplasticsnews.com/2019/06/14/wwf-launch-anti-plastic-campaign/ (Accessed Sep. 17, 2019).
3. Bowe, S. A.; Bumgardner, M. S., 2004: Species selection in secondary wood products: Perspectives from different consumers. Wood and Fiber Science, 36: 319-328.
4. Buehlmann, U.; Schuler, A., 2009: The U.S. household furniture industry: Status and opportunities. Forest Products Journal 59.
5. Bumgardner, M.; Nicholls, D.; Donovan, G., 2007: Effects of species information and furniture price on consumer preferences for selected woods. Wood and Fiber Science, 39 (1): 71-81.
6. Costa, S.; Garcia, S.; Ibanez, L., 2011: Do Taste and Quality Perception Influence Consumer Preferences for Wood? An Econometric Model with Latent Variables. Forest science, 57 (2): 89-101. https://doi.org/10.1093/forestscience/57.2.89.
7. Dillon, W. R., 1990: Marketing research in a marketing environment, 2nd edition. Homewood, IL: Irwin.
8. Forsyth, K.; Haley, D.; Kozak, R., 1999: Will consumers pay more for certified wood products. Journal of Forestry, 97: 18-22.
9. ***GR, 2018. Sejemski katalog 2018. (online). http://www.pohistveni-sejem.si/za-obiskovalce/2796. http://www.pohistveni-sejem.si/za-obiskovalce/2796 (Accessed Sep. 21, 2019).
10. Grant, J., 2012: The Green Marketing Manifesto (online). https://www.wiley.com/en-si/The+Green+Marketing+Manifesto-p-9780470687314 (Accessed Mar. 30, 2020).
11. Jonsson, O.; Lindberg, S.; Roos, A.; Hugosson, M.; Lindström, M., 2008: Consumer Perceptions and Preferences on Solid Wood, Wood-Based Panels, and Composites: A Repertory Grid Study. Wood and Fiber Science, 40: 663-678.
12. Kaputa, V., 2013: Trh a environmentálne atribúty výrobkov z dreva. Technical University in Zvolen.
13. Kaputa, V.; Pirc Barčić, A.; Maťová, H.; Motik, D., 2018: Consumer Preferences for Wooden Furniture in Croatia and Slovakia. BioResources, 13: 6280-6299. http://dx.doi.org/10.15376/biores.13.3.6280-6299.
14. Kaputa, V.; Supin, M., 2010: Consumer preferences for furniture. In: Proceeding of International Conference WoodEMA. Vyhne, Slovakia, pp. 81-90.
15. Lihra, T.; Buehlmann, U.; Graf, R., 2012: Customer preferences for customized household furniture. Journal of Forest Economics, 18: 94-112. http://dx.doi.org/10.1016/j.jfe.2011.11.001.
16. Marchal, R.; Mothe, F., 1994: Appreciation of Oak Wood (*Quercus robur* L, *Quercus-petraea* Liebl) for the French Consumer and Wood Professionals. Annales Des Sciences Forestieres, 51: 213-231. http://dx.doi.org/10.1051/forest:19940302.
17. Motik, D.; Kusá, A.; Jazbec, A.; Jelačić, D., 2004: Comparison of furniture demand in Croatia and Slovakia. Forest Products Journal, 54: 85-89.
18. Nicholls, D.; Bumgardner, M., 2007: Evaluating selected demographic factors related to consumer preferences for furniture from commercial and from underutilized species. Forest Products Journal, 57 (12): 79-82.
19. Nyrud, A. Q.; Roos, A.; Rødbotten, M., 2008: Product attributes affecting consumer preference for residential deck materials, Canadian Journal of Forest Research, 38 (6): 1385-1396. https://doi.org/10.1139/X07-188.
20. Oblak, L.; Barčić, A. P.; Klarić, K.; Kuzman, M. K.; Grošelj, P., 2017: Evaluation of Factors in Buying Decision Process of Furniture Consumers by Applying AHP Method. Drvna industrija, 68: 37-43. http://dx.doi.org/10.5552/drind.2017.1625.
21. Oblak, L.; Jost, M., 2011: Methodology for Studying the Ecological Quality of Furniture. Drvna industrija, 62: 171-176. http://dx.doi.org/10.5552/drind.2011.1038.
22. Oblak, L.; Kropivšek, J.; Hrovatin, J.; Zupancic, A., 2009: Analiza vplivov na nakupno odločanje pri nakupu pohištva. Les/Wood, 61: 291-296.
23. Ozanne, L. K.; Smith, P. M., 1996: Consumer segments for environmentally marketed wooden household furniture. Wood and Fiber Science, 28: 461-477.
24. Ozanne, L. K.; Vlosky, R. P., 1997: Willingness to pay for environmentally certified wood products: A consumer perspective. Forest Products Journal, 47: 39-48.
25. Pakarinen, T. J.; Asikainen, A. T., 2001: Consumer segments for wooden household furniture. Holz als Roh- und Werkstoff, 59: 217-227. http://dx.doi.org/10.1007/s001070100187.

26. Palus, H.; Mat'ova, H., 2009: End-user awareness of environmentally appropriate wood products in Slovakia. In: Proceeding of International Conference WoodEMA, University of Zagreb, Faculty of Forestry, Šibenik, Croatia, pp. 111-116.
27. Palus, H.; Parobek, J.; Kaputa, V., 2014: The role of forest certification in the european timber regulation. In: Proceedings of Scientific Papers, Position and Role of the Forest Based Sector in the Green Economy, pp. 111-117.
28. Perić, I.; Grladinović, T.; Greger, K.; Kropivšek, J., 2015: Sources of Competitiveness for Furniture Manufacturing Firms: A Review of Literature and Research Issues. In: Proceeding of International conference on wood science and technology, University of Zagreb, Faculty of Forestry, Zagreb, Croatia, pp. 179-185.
29. Ponder, N., 2013: Consumer Attitudes and Buying Behavior for Home Furniture. Mississippi State University: College of Business (online). http://www.ffi.msstate.edu/pdf/consumer_attitudes.pdf (Accessed Sep. 21, 2019).
30. Roos, A.; Nyrud, A. Q., 2008: Preferences for pressure-treated wooden deck materials. Wood and Fiber Science, 40: 436-447.
31. Scholz, S. W.; Decker, R., 2007: Measuring the impact of wood species on consumer preferences for wooden furniture by means of the Analytic Hierarchy Process. Forest Products Journal, 57: 23-28.
32. Teisl, M., 2003: Eco-labeled forest products: Are consumers not listening, or are producers not communicating? Orono: University of Maine, Department of Resource Economics and Policy.
33. Troian, D., 2011: The consumer perception of design. Case study furniture sector. Trento: University of Trento.
34. Vlosky, R. P.; Ozanne, L. K.; Fontenot, R. J., 1999: A conceptual model of US consumer willingness-to-pay for environmentally certified wood products. Journal of Consumer Marketing, 16: 122-136. http://dx.doi.org/10.1108/07363769910260498.

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Engineering the Properties of Eco-Friendly Medium Density Fibreboards Bonded with Lignosulfonate Adhesive

Dizajniranje svojstava ekološki prihvatljivih ploča vlaknatica srednje gustoće proizvedenih uporabom lignosulfonatnog ljepila

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ABSTRACT • *Free formaldehyde emissions from wood-based panels, especially in indoor applications, pose serious risks to human health at certain concentrations. Prolonged exposure to formaldehyde can cause adverse health effects including eye, nose and throat irritation, other respiratory symptoms and cancer. As a consequence, new formaldehyde emission limits for composite wood products were established in Europe, USA and Japan. This, together with the stricter environmental legislation are the main driving factors for shifting the scientific and industrial interest from the traditional formaldehyde-based synthetic resins to the new bio-based adhesives for production of eco-friendly wood-based panels. The lignin-based products are one of the most prospective ecological alternatives to the traditional formaldehyde resins. The main interest in lignin is due to its phenolic structure with several favourable properties for the formulation of wood adhesives such as high hydrophobicity and low polydispersity.*
The present article is aimed at studying the possibilities for using lignosulfonate as an adhesive for the production of eco-friendly MDF. Regression models describing the impact of lignosulfonate concentration and hot pressing temperature on the exploitation properties of MDF panels were developed. The individual and combined impact of both factors was analysed in order to determine the optimal exploitation properties of the panels.

Keywords: *eco-friendly MDF; lignosulfonate; physical and mechanical properties; bio-based adhesives; wood-based panels*

SAŽETAK • *Emisija slobodnog formaldehida iz ploča na bazi drva, posebice primijenjenih u unutarnjim prostorima, u određenim je koncentracijama ozbiljan rizik za zdravlje ljudi. Dulja izloženost formaldehidu može uzrokovati znatne zdravstvene probleme, uključujući iritaciju očiju, nosa i grla, druge respiratorne simptome i rak. Stoga su u Europi, SAD-u i Japanu određene nove granice emisije formaldehida za kompozitne proizvode od drva. To je, zajedno sa strožim zakonodavstvom o okolišu, bio glavni poticaj za prebacivanje znanstvenoga i industrijskog fokusa s tradicionalnih sintetičkih smola temeljenih na formaldehidu na nova prirodna ljepila za proizvodnju ekološki prihvatljivih ploča na bazi drva. Proizvodi na bazi lignina jedna su od najperspektivnijih ekoloških alter-*

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nativa tradicionalnim formaldehidnim smolama. Glavni razlog zanimanja za lignin jest njegova fenolna struktura s nekoliko povoljnih svojstava za formulaciju ljepila za drvo poput visoke hidrofobnosti i niske polidisperznosti. Cilj ovog rada jest proučavanje mogućnosti uporabe lignosulfonata kao ljepila za proizvodnju ekološki prihvatljivih ploča vlaknatica srednje gustoće (MDF ploča). Razvijeni su regresijski modeli koji opisuju utjecaj koncentracije lignosulfonata i temperature prešanja na svojstva MDF ploča. Analiziran je pojedinačni i kombinirani utjecaj obaju elemenata kako bi se odredila optimalna svojstva ploča.

Ključne riječi: *ekološki prihvatljive MDF ploče; lignosulfonat; fizička i mehanička svojstva; prirodna ljepila; ploče na bazi drva*

1 INTRODUCTION
1. UVOD

The production of medium density fibreboards (MDF) is one of wood-based industries with the fastest growth rate. Production in the European Panel Federation member countries grew by 2 % in 2016 to 12 million m^3 and in the broader European subregion it grew by 2.6 %, to 17.5 million m^3 (FAO 2017, European Panel Federation 2017). One of the main technical barriers and disadvantages associated with this production is the free formaldehyde emission that poses serious risks to human health at certain concentrations (Carvalho *et al.*, 2012; Mantanis *et al.*, 2018). This problem has been extensively studied in the recent years (Athanasossiadou *et al.*, 2009; Pizzi, 2016) and one of the most advanced solutions is the use of formaldehyde-free bio-based adhesives, which do not significantly increase the production costs of wood-based panels and at the same time maintain their exploitation properties (Nordström *et al.*, 2017, Pizzi, 2003; Pizzi, 2006; El Mansouri *et al.*, 2007; Sepahvand *et al*., 2018; Hemmilä *et al*., 2017).

The lignin-based products, including lignosulfonates, are one of the most prospective ecological alternatives to the traditional formaldehyde adhesive systems, used in the wood panel industry (Shimatani *et al.*, 1994; El Mansouri *et al*., 2007; Nordström *et al*., 2017; Pizzi, 2016; Yotov *et al*., 2017). Lignosulfonates have good bonding properties when applied to wood fibres; the main barrier for their wide industrial application is the worsened water resistance of fabricated panels (Dimitrescu *et al*., 2009). This issue can be partially resolved by adding lignosulfonates to other adhesive systems (Nasir *et al*., 2014; Savov *et al*., 2017; Hemmilä *et al*., 2019) or by modifying the parameters for the production of panels (Antov *et al*., 2019; Savov *et al*., 2019).

Analytical study on engineering the properties of eco-friendly MDF panels produced in laboratory conditions using lignosulfonates as adhesives is presented in this article. Two main factors were studied – the concentration of adding lignosulfonate in the wood-fibre mass and hot pressing temperature.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In order to design the properties of eco-friendly MDF, panels were produced at three different lignosulfonate concentrations – 20 %, 30 % and 40 %, and three hot pressing temperatures – 200 ºC, 210 ºC and 220 ºC. The panels were produced with a thickness of 6 mm and a density of 850 kg/m^3. The experimental plan is presented in Table 1.

Table 1 Experimental plan
Tablica 1. Plan istraživanja

No.	**MDF panel density *ρ*, kg/m³** *Gustoća MDF ploča ρ*, kg/m³	**Lignosulfonate concentration *K*, %** *Koncentracija lignosulfata K*, %	**Hot pressing temperature *T*, ºC** *Temperatura prešanja T*, °C
1	850	20	200
2	850	20	210
3	850	20	220
4	850	30	200
5	850	30	210
6	850	30	220
7	850	40	200
8	850	40	210
9	850	40	220

Factory-produced wood-fibre mass with the following composition – common beech (*Fagus sylvatica* L.) – 57 %), European oak (*Quercus robur* L.) – 35 %, and white poplar (*Populus alba* L.) – 8 %, was used for the purpose of the study. The mass was dried to 11 % water content. The pulp freeness, determined by the Schopper-Riegler method, was 11° ShR. The bulk density of the mass was 29 kg/m^3. The calcium lignosulfonate content was 15 % and had the following characteristics: calcium - up to 6 %; reduced sugars – 7 %; ash content – 14 %; dry content – 93 %; acidic factor in 10 % solution - pH = 4.3 ± 0.8; bulk density - 550 kg/m^3.

Wood fibres were mixed with the lignosulfonate and paraffin for 50 s in a high-speed glue blender (850 min^{-1}). The hot pressing was performed on a laboratory press type PMC ST 100, Italy. The applied pressing regime of MDF was as follows: in the first stage, the pressure was increased for 20 s to 3.0 MPa and maintained for 20 % of the whole pressing cycle, then the pressure was evenly decreased for 10 s to 1.2 MPa and maintained for a duration of 30 % of the whole pressing cycle; the third (last) pressing period was carried out at the pressure of 0.6 MPa for 50 % of the whole cycle. The pressing factor was 90 s/mm^1. The physical and mechanical properties of the obtained MDF panels were determined in accordance with the requirements of the respective EN standards (EN 310; EN 317; EN 319; EN 322 and EN 323). The mechanical properties of MDF panels were determined on a universal testing machine Zwick/Roell Z010.

On this basis the following regression equation in a coded form was derived:

$$\hat{Y} = B_0 + B_1 \cdot X_1 + B_2 \cdot X_2 + B_{12} \cdot X_1 \cdot X_2 + + B_{11} \cdot X_1^2 + B_{22} \cdot X_2^2 \qquad (1)$$

where $\hat{Y}$ is the predicted value of the respective MDF output parameter, X_1 is the lignosulfonate concentration in a coded form and X_2 is the hot pressing temperature in a coded form.

A standard methodology was used to determine the adequacy of the model by calculating the Fisher criterion and comparing it with the table values. Variance relation $F_{calc} = \frac{S_y^2}{S_\varepsilon^2}$ was calculated, where S_y^2 is the residual variance and S_ε^2 is the variance of random disturbance determined on the basis of the variance under the null experiment (at 30 % lignosulfonate concentration and 210 ºC hot pressing temperature). The testing was carried out on 8 test samples for each parameter and variational and statistical processing of the results was made to test the adequacy of the model, encoded by the following formula:

$$\tilde{X}_i = X_i \cdot \Delta_i + X_{i0} \qquad (2)$$

where $\tilde{X}_i$ is the natural meaning of the factor, Δ_i is the variation interval and X_{i0} is the variation interval median.

The accuracy of the applied model was determined by the multiple correlation coefficient.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The summarised results of the exploitation properties of the laboratory produced MDF panels at different lignosulfonate concentrations and hot pressing temperature are presented in Table 2.

Data about the tests in the null experiment are presented in Table 3.

All derived equations correspond to the critical value F (0.005; 3; 7) = 4.35, and the values for the respective models are: for the water absorption – 2.37; for the swelling in thickness – 3.17; for the bending strength – 3.85; for the modulus of elasticity in bending – 3.02; and for the internal bond strength – 4.21.

The coded form of the regression equation for the water absorption of MDF panels is:

$$\hat{A} = 57.20 - 5.02 \cdot X_1 - 1.63 \cdot X_2 + + 2.35 \cdot X_1^2 + 0.2 \cdot X_2^2, \% \qquad (3)$$

where X_1 is the lignosulfonate concentration and X_2 is the hot pressing temperature in coded form. The equation is characterised by the coefficient of determination $R^2 = 0.96$.

From Eq. 3, it can be concluded that the effect of lignosulfonate concentration was significantly stronger in the studied range. The impact of the factor at the variation range from 20 to 40 % was about 2.6 greater than the effect of hot pressing temperature within the

Table 2 Results of physical and mechanical properties of eco-friendly MDF panels
Tablica 2. Rezultati ispitivanja fizičkih i mehaničkih svojstava ekološki prihvatljivih MDF ploča

Panel No. *Broj ploče*	**Density ρ, kg/m³** *Gustoća ρ,* kg/m³	**Water absorption *A*, %** *Upijanje vode A,* %	**Swelling in thickness G_t, %** *Bubrenje* G_t, %	**Bending strength f_m, N/mm²** *Čvrstoća na savijanje* f_m, N/mm²	**Modulus of elasticity in bending E_m, N/mm²** *Modul elastičnosti pri savijanju* E_m, N/mm²	**Internal bond strength f_t, N/mm²** *Čvrstoća na raslojavanje* f_t, N/mm²
1.	855±7	74.8±2.7	24.1±1.0	22.75±0.4	2894±97	0.62±0.005
2.	841±9	64.8±1.9	23.0±0.6	20.89±0.7	2655±130	0.66±0.025
3.	831±8	62.5±1.8	22.0±0.7	24.79±0.6	3308±130	0.68±0.026
4.	849±5	58.3±1.7	21.8±0.8	32.08±0.4	3734±115	0.70±0.009
5.	847±7	57.8±2.3	19.8±0.6	30.54±1.0	3853±188	0.71±0.026
6.	856±8	55.5±2.4	19.5±0.5	30.58±1.1	3956±129	0.71±0.029
7.	842±8	56.5±2.7	20.8±1.0	30.33±1.3	3676±85	0,74±0.015
8.	854±5	53.7±2.5	19.6±0.4	32.08±0.8	3440±92	0,72±0.011
9.	854±5	53.4±1.9	18.5±0.8	26.61±0.8	3613±96	0,64±0.027

Table 3 Initial panel property values
Tablica 3. Početne vrijednosti svojstava ploče

Sample No. *Broj uzorka* / **Properties** *Svojstva*	1	2	3	4	5	6	7	8
Water absorption *A*, % / *upijanje vode A*, %	55.67	47.48	60.45	57.22	53.11	43.51	55.24	54.78
Swelling in thickness G_t, % / *bubrenje* G_t, %	19.93	14.77	16.48	17.07	20.69	18.28	20.58	20.38
Bending strength f_m, N/mm² *čvrstoća na savijanje* f_m, N/mm²	24.5	28.2	26.1	26.8	28.2	22.1	28.4	28.60
Modulus of elasticity E_m, N/mm² *modul elastičnosti pri savijanju* E_m, N/mm²	3650	3550	3390	3680	3560	3150	3940	3980
Internal bond strength f_t, N/mm² *čvrstoća na raslojavanje* f_t, N/mm²	0.828	0.679	0.615	0.674	0.677	0.699	0.811	0.737

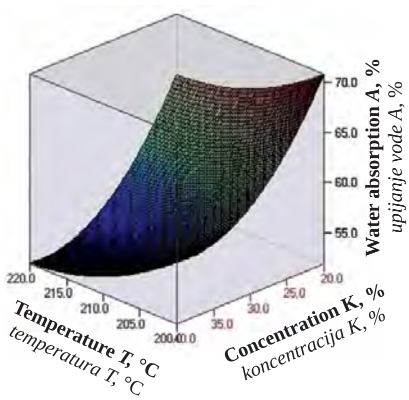

Figure 1 Variation of water absorption of eco-friendly MDF panels depending on lignosulfonate concentration and hot pressing temperature
Slika 1. Varijacije upijanja vode ekološki prihvatljivih MDF ploča ovisno o koncentraciji lignosulfonata i temperaturi prešanja

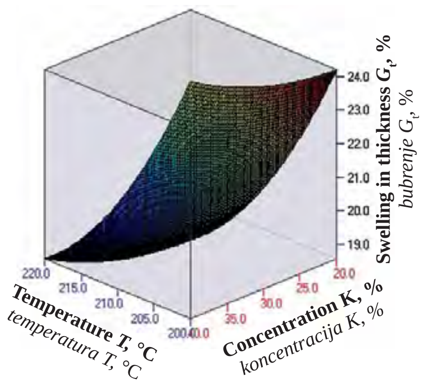

Figure 2 Variation of swelling in thickness of eco-friendly MDF panels depending on lignosulfonate concentration and hot pressing temperature
Slika 2. Varijacije bubrenja ekološki prihvatljivih MDF ploča ovisno o koncentraciji lignosulfonata i temperaturi prešanja

range from 200 to 220 ºC. This can be attributed to the selected relatively high hot pressing temperatures above 200 ºC. Therefore, water absorption can be better designed by varying the concentration of adding lignosulfonate in the wood-fibre mass. The graphic representation of this dependence after encoding the equation is presented in Figure 1.

It can be concluded that an improvement in water resistance (decreased water absorption) was determined when lignosulfonate concentration was increased from 20 % to 40 % and hot pressing temperature was increased from 200 ºC to 220 ºC, respectively. The water absorption values were significantly improved when the lignosulfonate concentration was increased from 20 % to 35 % and the hot pressing temperature – from 200 ºC to 210 ºC.

The coded form of the regression equation for the swelling in thickness of the laboratory produced MDF panels is:

$$\hat{G}_t = 20.10 - 1.79 \cdot X_1 - 1.21 \cdot X_2 + 0.09 X_1 \cdot X_2 + \\ + 1.05 \cdot X_1^2 + 0.41 \cdot X_2^2, \% \qquad (4)$$

where X_1 is the lignosulfonate concentration and X_2 is the hot pressing temperature in coded form. The equation is characterised by a coefficient of determination $R^2 = 0.95$.

Decreased swelling in thickness of MDF panels was determined with increasing the concentration of lignosulfonate solution and hot pressing temperature. Again, lignosulfonate concentration was the more significant factor in the studied variation range. However, the effects of both studied factors were comparable. Strong quadratic dependence was determined between the swelling in thickness of MDF panels and lignosulfonate concentration.

The variation of swelling in thickness of MDF panels depending on lignosulfonate concentration and hot pressing temperature is presented in Figure 2.

The analysis of the obtained results of this property is similar to the water absorption of the panels. Significantly greater relative improvement was determined with increasing the lignosulfonate concentration up to 35 % and less with increasing the concentration from 35 % to 40 %. Regarding the hot pressing temperature, the relatively greater improvement was determined with increasing the temperature up to 210 ºC.

The coded form of the regression equation for the bending strength is as follows:

$$\hat{f}_m = 31.54 + 4.15 \cdot X_1 + 0.2 \cdot X_2 - 2.52 X_1 \cdot X_2 - \\ - 5.54 \cdot X_1^2 - 0.07 \cdot X_2^2, \text{ N·mm}^{-2} \qquad (4)$$

where X_1 is the lignosulfonate concentration and X_2 is the hot pressing temperature in coded form. The coefficient of determination of Eq. 4 is $R^2 = 0.90$.

The effect of lignosulfonate concentration on this property was significantly greater than the effect of hot pressing temperature. The quadratic dependence between the lignosulfonate concentration and bending strength of the panels was strongly pronounced. A strong impact of the interaction of both studied factors on bending strength values was determined in comparison with the water absorption and swelling in thickness of the laboratory produced MDF panels. In other words, processes of destruction of wood components occur at the relatively higher hot pressing temperature and lignosulfonate concentration and low moisture content of the pressed material, which results in increased panel brittleness.

The graphical representation of the dependence of bending strength on lignosulfonate concentration and hot pressing temperature after encoding Eq. 4 is given in Figure 3.

Improvement of bending strength values was determined with increasing the lignosulfonate concentration from 20 % to 30 % and increasing the hot pressing temperature from 200 ºC to 220 ºC. Further increase of hot pressing temperature and lignosulfonate concentration above 30 % resulted in deterioration of the studied property. This deterioration was even more strongly pronounced at concentrations above 35 %.

To achieve the EN 622-5 standard requirement of 27 N/mm² for MDF panels with general application in humid environment, the lignosulfonate concentration should be at least 25 %.

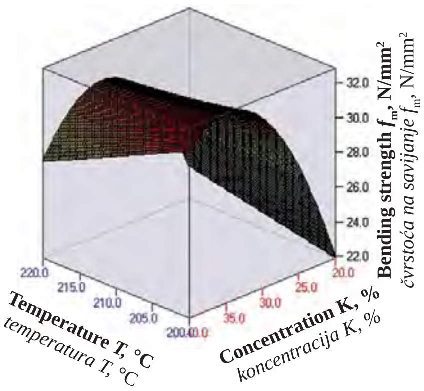

Figure 3 Variation of bending strength of eco-friendly MDF panels depending on lignosulfonate concentration and hot pressing temperature
Slika 3. Varijacije čvrstoće na savijanje ekološki prihvatljivih MDF ploča ovisno o koncentraciji lignosulfonata i temperaturi prešanja

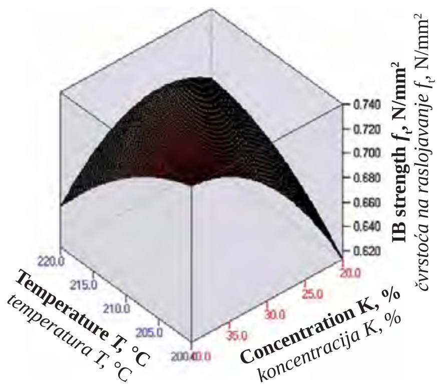

Figure 5 Variation of internal bond strength of eco-friendly MDF panels depending on lignosulfonate concentration and hot pressing temperature
Slika 5. Varijacije čvrstoće na raslojavanje ekološki prihvatljivih MDF ploča ovisno o koncentraciji lignosulfonata i temperaturi prešanja

The regression equation regarding the modulus of elasticity of MDF panels is as follows:

$$\hat{E}_m = 3753 + 385 \cdot X_1 + 168 \cdot X_2 - 228 X_1 \cdot X_2 - 656 \cdot X_1^2 + 141 \cdot X_2^2, \text{ N·mm}^{-2} \quad (5)$$

where X_1 is the lignosulfonate concentration and X_2 is the hot pressing temperature in coded form. The coefficient of determination of equation (5) is $R^2 = 0.97$.

Similar to the bending strength, the modulus of elasticity in bending was more dependent on lignosulfonate concentration compared to the hot pressing temperature, i.e. the concentration factor is more appropriate for engineering the respective MDF property. The interaction of the studied factors resulted in decreased values of the modulus of elasticity in bending. The graphic representation of the dependence of the modulus of elasticity in bending on the lignosulfonate concentration and hot pressing temperature, after encoding Eq. 5, is presented in Figure 4.

Improvement of the modulus of elasticity in bending was determined with increasing the hot pressing temperature and lignosulfonate concentration up to 35 %. Further increase of temperature and concentration resulted in decreased values of the studied property. This can also be explained by the occurring destruction of some wood components under the impact of the increased lignosulfonate concentration, hot pressing temperature and pressing duration.

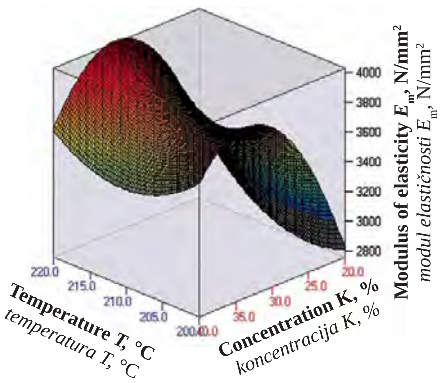

Figure 4 Variation of modulus of elasticity in bending of eco-friendly MDF panels depending on lignosulfonate concentration and hot pressing temperature
Slika 4. Varijacije modula elastičnosti pri savijanju ekološki prihvatljivih MDF ploča ovisno o koncentraciji lignosulfonata i temperaturi prešanja

The regression equation of the internal bond strength of the panels is as follows:

$$\hat{f}_t = 0.705 + 0.033 \cdot X_1 + 0.005 \cdot X_2 - 0.014 \cdot X_1 \cdot X_2 - 0.013 \cdot X_1^2 + 0.002 \cdot X_2^2, \text{ N·mm}^{-2} \quad (6)$$

where X_1 is the lignosulfonate concentration and X_2 is the hot pressing temperature in coded form. The coefficient of determination of Eq. 5 is $R^2 = 0.98$.

Separately, the studied factors had positive impact on the internal bond strength of MDF panels. Once again, the negative effect of their interaction was reported. The graphic representation of the dependence of the internal bond strength on the lignosulfonate concentration and hot pressing temperature, after encoding Eq. 6, is presented in Figure 5.

Improvement of internal bond strength values was determined at lignosulfonate concentration of up to 35 % and increase of the hot pressing temperature up to 220 ºC. Further increase of hot pressing temperature resulted in decreased values of the studied property.

4 CONCLUSIONS
4. ZAKLJUČAK

The use of lignosulfonate as an adhesive is a perspective approach for producing eco-friendly MDF panels without harmful free-formaldehyde emissions. The exploitation properties of MDF panels can be successfully engineered by varying the lignosulfonate concentration from 20 % to 40 % and hot pressing temperature from 200 ºC to 220 ºC. The concentration of adding lignosulfonate solution to wood-fibre mass has a stronger impact on the panel properties within the determined variation range in comparison with the hot pressing temperature. This can be explained by the relatively high (more than 200 ºC) hot pressing temperature and increased press time. For this reason, a deterioration of the strength properties of the panels is observed with increasing the hot pressing temperature at lignosulfonate concentrations above 35 %. Decreasing the concentration below 30 % is not justified since this does not lead to additional utilisation of the lignosulfonate hydroxyl groups but requires increasing the hot pressing temperatures.

Despite the significant positive results achieved in the production of lignosulfonate-based MDF panels, there are some considerable drawbacks that should be noted, e.g. the difficulties in activating lignosulfonates and their binding to wood fibres, as well as the required substantial increase of pressing temperature and extended pressing time. The latter outlines the future trends of extensive research in the field of MDF production on the basis of lignosulfonate adhesives.

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5 REFERENCES
5. LITERATURA

1. Antov, P.; Valchev, I.; Savov, V., 2019: Experimental and Statistical Modeling of the Exploitation Properties of Eco-friendly MDF through Variation of Lignosulfonate Concentration and Hot Pressing Temperature. In: Proceedings of the 2nd International Congress of Biorefinery of Lignocellulosic Materials (IWBLCM2019), pp. 104-109.
2. Athanassiadou, E.; Tsiantzi, S.; Markessini, C., 2009: Producing Panels with Formaldehyde Emission at Wood Levels. European Network of Bioadhesion Expertise (ENBA), pp.16.
3. Carvalho, L.; Magalhães F.; Ferra, J., 2012: Formaldehyde Emissions from Wood-Based Panels – Testing Methods and Industrial Perspectives. In Chemistry, Applications and Role in Polymerization. Cheng, C.; Lin, L. (eds.). Nova Science Publishers, Inc: Hauppauge, NY.
4. Dumitrescu, L.; Manciulea, I.; Patachia, S.; Perniu, D., 2009: Wood Adhesives Based on Lignocellulosic Materials. Annals of DAAAM for 2009 & Proceedings of the 20th International DAAAM, Vienna, Austria, pp. 289-290.
5. El Mansouri, N. E.; Pizzi, A.; Salvado, J., 2007: Lignin-based wood panel adhesives without formaldehyde. Holz als Roh- und Werkstoff, 65: 65-70. https://doi.org/10.1007/s00107-006-0130-z.
6. Hemmilä, V.; Adamopoulos, S.; Karlsson, O.; Kumar, A., 2017: Development of sustainable bio-adhesives for engineered wood panels – a review. RSC Advances, 7 (61): 38604-38630.
7. Hemmilä, H.; Adamopolus, St.; Hosseinpourpia, R.; Ahmed, Sh. A., 2019: Ammonium Lignosulfonate Adhesives for Particleboards with pMDI and Furfuryl Alcohol as Crosslinkers. Polymers, 11: 1633. https://doi.org/10.3390/polym11101633.
8. Mantanis, G. I.; Athanassiadou, E. T.; Barbu, M. C.; Wijnendaele, K., 2018: Adhesive systems used in the European particleboard, MDF and OSB industries. Wood Material Science & Engineering, 13 (2): 104-116. https://doi.org/10.1080/17480272.2017.1396622.
9. Nasir, M.; Gupta, A.; Beg, M.; Chua, G. K.; Kumar, A., 2014: Physical and mechanical properties of Medium Density Fiberboard using soy-lignin adhesives. Journal of Tropical Forest Science, 1: 41-49.
10. Nordström, E.; Demircan, D.; Fogelström, L.; Khabbaz, F.; Malmström, E., 2017: Green binders for wood adhesives. Interhopen Books, pp. 71. https://doi.org/10.5772/intechopen.72072.
11. Pizzi, A., 2003: Wood Adhesives Chemistry and Technology. Marcel Dekker, Inc., New York.
12. Pizzi, A., 2016: Wood products and green chemistry. Annals of Forest Science, 73: 185-203. https://doi.org/10.1007/s13595-014-0448-3.
13. Pizzi, A., 2006: Recent developments in eco-efficient bio-based adhesives for wood bonding: opportunities and issues. Journal of Adhesion Science and Technology, 20 (8): 829-846. https://doi.org/10.1163/156856106777638635.
14. Savov, V.; Mihajlova, J., 2017: Influence of the content of lignosulfonate on physical properties of medium density fiberboard. International Conference Wood Science and Engineering in the Third Millennium – ICWSE, pp. 348-352.
15. Savov, V.; Valchev, I.; Antov, P., 2019: Processing factors for production of eco-friendly medium density fibreboards based on lignosulfonate adhesives. In: Proceedings of the 2nd International Congress of Biorefinery of Lignocellulosic Materials, pp. 165-169.
16. Sepahvand, S.; Doosthosseini, K.; Pirayesh, H.; Maryan, B. K., 2018: Supplementation of Natural Tannins as an Alternative to Formaldehyde in Urea and Melamine Formaldehyde Resins used in MDF Production. Drvna industrija, 69 (3): 215-221. https://doi.org/10.5552/drind.2018.1726.
17. Shimatani, K.; Sono, Y.; Sasaya, T., 1994: Preparation of moderate-temperature setting adhesives from softwood kraft lignin, part 2. Effect of some factors on strength properties and characteristics of lignin-based adhesives. Holzforschung, 48: 337-342. https://doi.org/10.1515/hfsg.1994.48.4.337.
18. Yotov, N.; Valchev, I.; Petrin, St.; Savov, V., 2017: Lignosulphonate and waste technical hydrolysis lignin as adhesives for eco-friendly fiberboard. Bulgarian Chemical Communications, 49: 92-97.
19. ***EN 310, 1999: Wood-based panels – Determination of modulus of elasticity in bending and of bending strength.
20. ***EN 316, 2009: Wood fibre boards – Definition, classification and symbols.
21. ***EN 317, 1998: Particleboards and fibreboards – Determination of swelling in thickness after immersion in water.
22. ***EN 322, 1998: Wood-based panels – Determination of moisture content.
23. ***EN 323, 2001: Wood-based panels – Determination of density.
24. ***EN 622-5, 2010: Fibreboards – Specifications, part 5: Requirements for dry process boards.
25. ***European Panel Federation, 2017: Annual report 2016/2017, www.europanels.org (Accessed April 10, 2019).
26. ***Forest products statistics, 2017, http://www.fao.org/forestry/statistics (Accessed April 10, 2019).

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The Influence of Wood Modification on Transfer Function of a Violin Bridge

Utjecaj modifikacije drva na prijenosnu funkciju mosta za violinu

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ABSTRACT • *The violin bridge is an important component of a violin since it transmits the excitation forces from the string to the violin body. Depending on its structure, at a certain frequency spectrum, the bridge acts as a damper or amplifier of excitation forces, which depends on its transfer function. In the study, transfer functions in the range from 400 Hz to 7000 Hz in vertical directions of 3 bridges were measured. The bridges were made from maple wood and supplied by different manufacturers. The bridges were then thermally modified, and the transfer functions were measured again. To determine the influence of thermal modification on material properties, a sample of maple wood was also modified together with the bridges, and the modulus of elasticity and shear modulus before and after the modification were measured. Using Ansys software, a bridge was modelled by the finite element method, by which natural frequencies and transfer functions before and after the modification were calculated. It can be confirmed from the research that wood modification influences the bridge transfer function and that the finite element method can be used to determine the dynamic properties of the bridge by knowing the wood material properties and, therefore, to predetermine the transfer function of the violin bridge before its production.*

Keywords: *violin bridge; excitation; transfer function; finite element method; Ansys; wood modification*

SAŽETAK • *Most na violini važan je dio toga glazbala jer prenosi pobudne sile iz žica u tijelo violine. Ovisno o svojoj strukturi, most na određenome frekvencijskom spektru djeluje kao prigušivač ili kao pojačalo pobudnih sila, što ovisi o njegovoj prijenosnoj funkciji. U istraživanju su mjerene prijenosne funkcije u rasponu od 400 do 7000 Hz u okomitim smjerovima na tri mosta. Mostove od javorova drva izradili su različitih proizvođači. Naknadno su mostovi toplinski modificirani i ponovo su izmjerene njihove funkcije prijenosa. Da bi se utvrdio utjecaj toplinske modifikacije na svojstva materijala, zajedno s mostovima modificiran je i uzorak javorova drva te su izmjereni modul elastičnosti i modul smicanja prije i nakon modifikacije. Uz upotrebu softvera Ansys most je modeliran metodom konačnih elemenata, kojom su izračunane prirodne frekvencije i funkcije prijenosa prije i nakon modifikacije. Na temelju istraživanja može se potvrditi da modifikacija drva utječe na funkciju prijenosa mosta i da se metodom konačnih elemenata mogu odrediti dinamička svojstva mosta ako su poznata svojstva drvnog materijala. Prema tome, prijenosna funkcija mosta violine može se odrediti unaprijed, prije njegove izrade.*

Ključne riječi: *most za violinu; pobuda; prijenosna funkcija; metoda konačnih elemenata; Ansys; modifikacija drva*

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1 INTRODUCTION
1. UVOD

A violin is a musical instrument that has been known for centuries. The first violins were developed in Italy in the 16th and 17th centuries (Rossing, 2010) and reached a peak in the eighteen century in the hands of masters such as Antonio Stradivarius and Giuseppe Guarneri del Gesu of Cremona. Since then, many researchers have been involved in violin research. Some have explored the functioning of violins as a whole (Bissinger, 2008; Matsutani, 2018; Tai *et al.*, 2018; Woodhouse, 2014), while others have studied the influence of various materials from which a violin is made and their surface treatment (Aditanoyo *et al.*, 2017; Setragno *et al*., 2017), as well as the influence of damping and strings on the composition of the sound (Bissinger, 2004; Ravina, 2017).

A violin consists of several different components, whereby the bridge is definitely one of the more important parts. Its job is to transfer the excitation forces from the string to the top of the violin. When a violin player excites a string with a bow, it starts to oscillate at a frequency that depends on the string and can range from a few hundred to several thousand Hz. In addition to the basic frequency, the string also oscillates with higher frequencies, called harmonic frequencies, which are integer multiples of the basic frequency. Depending on the structure, the violin bridge can thus act as a filter, by which at a certain frequency range the excitation forces can be transferred to the body of the violin, in some regions even amplified, while suppressed in another frequency range. Both frequency ranges can be identified by a transfer function, which can be measured from the bridge or calculated using various approaches. The importance of the bridge and its dynamic properties is also evidenced by numerous studies that have been done by various researchers, who have investigated both its shape and the material from which the bridge is made (Bissinger, 2006; Dujourdy *et al.*, 2019; Gough, 2018; Jansson *et al.*, 2016; Kabała *et al.*, 2018; Matsutani, 2017; Woodhouse, 2005; Zhang *et al.*, 2013). One of the approaches for improving the relevant properties of wood without the use of toxic chemicals is wood modification. There are several modifications available on an industrial scale. One of the most frequently used techniques is thermal modification. Based on the data of Welzbacher and Scheiding (2011), between 250,000 and 300,000 m^3 of thermally modified wood is produced annually in Europe.

The purpose of the research was thus to study the influence of thermal modification of wood on the dynamic properties of a violin bridge and to determine their transfer function.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Three bridges made from maple wood were taken (Figure 1). Bridges No. 1 and No. 2 were made by Aubert and bridge No. 3 was made by the Teller company. Bridge No. 2 was partially designed and adapted for use on a specific violin.

The violin bridges were clamped on a Kistler dynamometer type 9272 (Figure 2) and the transfer functions of the bridges were measured in the vertical direction. The bridges were excited on the upper side of the bridge with a harmonic force in the frequency range from 400 to 7000 Hz, in 3 Hz steps by Tira TV51120 exciter. The excitation was gradual from minimum to maximum frequency, whereby each excitation frequency was paused for 150 ms for a steady state response to be established. The excitation force was measured with a Bruel & Kjaser type 8200 piezo force transducer, which was inserted between the bridge and the exciter, and the response of the transmitted force was measured with a Kistler dynamometer. Both force signals were captured with a sampling frequency of 100 kHz using a NI USB 6361 measuring card and LAbVIEW software, which was also used for the transfer function calculation. The transfer function of the experimental system was also measured, so that the Kistler dynamometer was directly excited, and the transfer function calculated from the measured excitation and response forces.

Bridge No. 1 was then modelled with Solidworks software, and a modal analysis was performed using finite element methods with Ansys software, whereby the natural frequencies of the bridge were calculated. The modulus of elasticity, shear modulus and Poisson ratios were taken from the literature (Kollmann, 1975) and adjusted relatively so that the calculated natural frequency of the main mode was in agreement with the natural frequency obtained from the measured transfer function. Material density and damping ratios, however, were determined from measurements of the mass and volume of the bridge, and from the measured transfer function, respectively, using the bandwidth method (Maia and Silva, 1998)

Figure 1 Tested violin bridges
Slika 1. Ispitivani mostovi za violinu

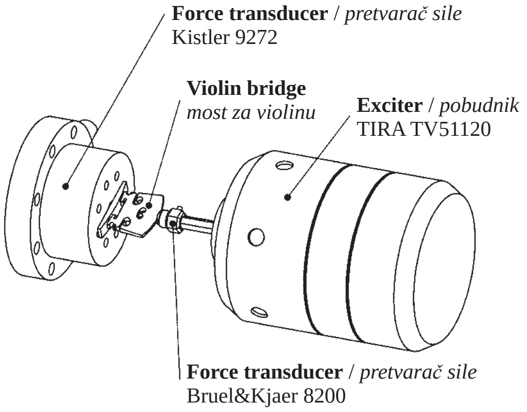

Figure 2 Testing of violin bridges
Slika 2. Ispitivanje mostova za violinu

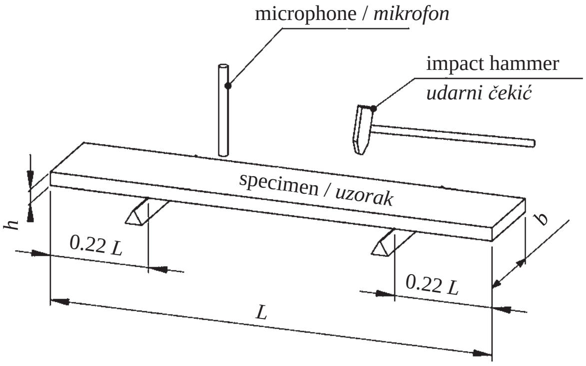

Figure 5 Experimental system for modulus of elasticity and shear modulus determination
Slika 5. Eksperimentalni sustav za određivanje modula elastičnosti i modula smicanja

$$\xi = \frac{1}{2}(r_2 - r_1) \tag{1}$$

where r_2 and r_1 represent the ratios between the excitation and natural frequencies at the amplitude values of the transfer function which are by $\sqrt{2}$ lower than the maximum value for a given vibration mode, as shown in Figure 3.

Using the finite element method, a harmonic analysis was also performed, by which the transfer function was calculated. The clamped bridge was excited with a force of 1 N at different frequencies from 400 to 7000 Hz, in steps of 10 Hz, on 1/4 length of the bridge, so that asymmetric modes were also excited (Figure 4).

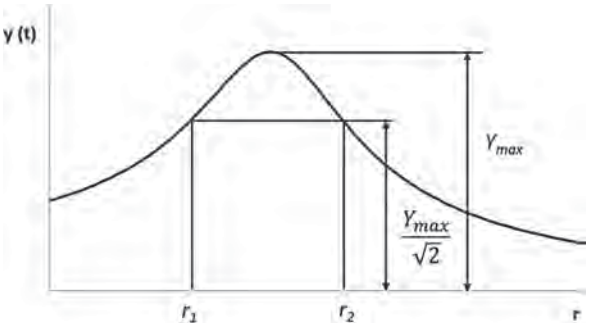

Figure 3 Damping ratio determination from transfer function using bandwidth method
Slika 3. Određivanje omjera prigušivanja iz funkcije prijenosa primjenom metode propusnosti

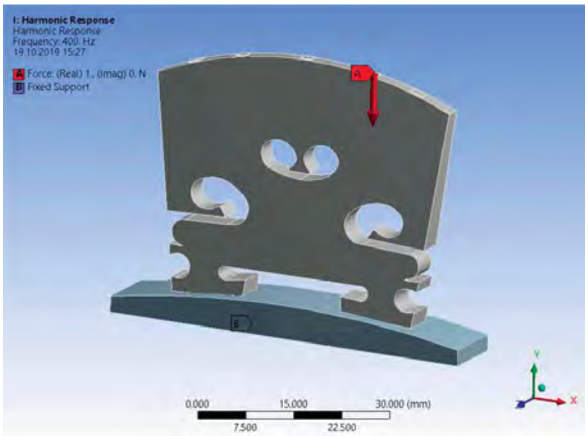

Figure 4 Finite element harmonic analysis setup
Slika 4. Postavljanje harmonične analize konačnih elemenata

In order to determine the effect of thermal modification on the material properties, a maple board with no visible defects and uniform growth was taken. From the board, 4 specimens with dimensions 300 mm × 80 mm × 8 mm and 160 mm × 25 mm × 8 mm in L × R × T and R × L × T directions, respectively, were cut and modified by the same procedure as the bridges.

Prior to the modification, the elastic modulus in longitudinal and radial directions and the shear modulus were measured, the samples being freely supported at distances of 0.22 L and 0.77 L, and excited with a hammer (Figure 5) to vibrate freely at their natural frequencies.

The vibration of the samples was measured using a Bruel & Kjaer Typ 4939 microphone, NI USB 6361 measuring card and LabVIEW software, with a sampling rate of 100 kHz. An FFT (Fast Fourier Transform) was made from the time signal and the natural frequencies f_n for the various vibration modes were determined from the frequency spectrum. Modulus of elasticity E and shear modulus G were calculated using linear regression of the equation (Brancheriau and Bailleres, 2002)

$$\begin{aligned}
&\frac{E}{\rho} - \frac{E}{KG}\left[QF_2(m)4\pi^2\frac{AL^4 f_n^2}{IP_n}\right] = \\
&= 4\pi^2\frac{AL^4 f_n^2}{IP_n}\left[1 + QF_1(m)\right] \\
&Q = \frac{I}{AL^2} \\
&F_1(m) = \theta^2(m) + 6\theta(m) \\
&F_2(m) = \theta^2(m) - 2\theta(m) \\
&\theta(m) = m\frac{\tan(m)\tanh(m)}{\tan(m) - \tanh(m)} \\
&m = \sqrt[4]{P_n} = (2n+1)\frac{\pi}{2}, n \in N
\end{aligned} \tag{2}$$

where K is a constant that depends on the geometry of the cross-section (for rectangular, $K = 5/6$), I is the moment of inertia, A is the cross-sectional area of the beam, f_n is the n-th natural frequency. Parameters m, $F_1(m)$ and $F_2(m)$ are calculated on the basis of index n for the n-th natural frequency.

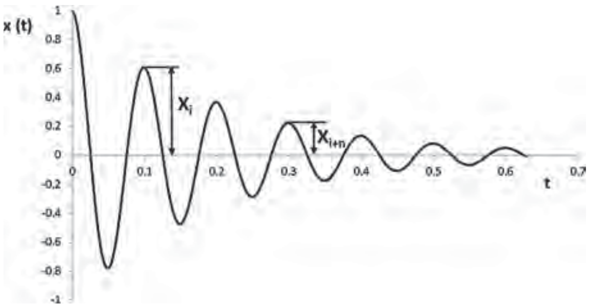

Figure 6 Determination of parameters needed for calculation of a logarithmic decrement of an underdamped system from a transient response
Slika 6. Određivanje parametara potrebnih za proračun logaritamske dekretacije prigušenog sustava iz prolaznog odziva

From the time recordings of specimen vibration, the material damping ratio ξ was also determined by means of logarithmic decrement (Maia and Silva, 1998)

$$\delta_n = \ln\frac{X_i}{X_{i+n}} = \frac{2n\pi\xi}{\sqrt{1-\xi^2}} \quad (3)$$

where X_i and X_{i+n} are the amplitudes at locations *i* and *i+n*, respectively, as shown in Figure 6.

The bridges and maple specimens were then thermally modified. Thermal modification was performed according to the Silvapro® commercial procedure (Rep *et al.*, 2012). Samples were thermally modified at 195 °C. Prior to modification, samples were wrapped in Al foil to limit oxidation processes of wood. Al foil considerably slows down oxygen diffusion and consequently prevents unwanted polymer degradation. This solution proved to be effective for thermal modification of smaller specimens. Results are comparable to modification in an anoxic atmosphere. The time of modification at the target temperature was 3 hours and mass loss of the samples after modification was determined gravimetrically. After modification, samples were stored in the laboratory for a week (23 °C; 65 %). After conditioning, both the transfer functions of the bridges and the material properties of the maple specimens were determined again. From the data, the influence of the thermal modification, in terms of the modification coefficient of wood properties, was calculated for the modulus of elasticity, shear modulus, density and damping ratios. Taking into account the changes due to the modification, modal and harmonic finite element analysis with the finite element method was performed again, and a comparison between the measured and calculated transfer functions of the bridges was made.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 1 shows the average values of the measured properties of maple specimens before and after modification. The modulus of elasticity in the longitudinal and radial directions increased by an average of 3.5 % and 5 %, respectively, while shear modules increased by 1.2 % and 17 %. The latter value is relatively large compared to other values and this may be due to measurement error. In contrast to the elastic properties, the density decreased by 3 %, and the damping ratios in longitudinal and radial directions by 15 %. Table 2 shows the properties of the material that were used in the modelling of the bridge by the finite element method, together with the correction factors obtained from Table 1. To calculate the change in all three values of the shear modulus, a single factor of 1.012 obtained from a comparison of the shear modulus of G_{LT} was used, since the factor of 1.169 obtained from parallel samples seemed to be somewhat large and unrealistic when compared to the G_{RT} module. Table 2 also shows the material density for bridge No. 1 and a damping factor of 0.029 and 0.016 for the unmodified and modified bridge, respectively, which are significantly higher than the damping values obtained from the maple samples, where the damping factors in longitudinal samples for unmodified and modified wood amounted to 0.0081 and 0.0069, respectively, and for radial samples to 0.013 and 0.011, respectively.

The measured transfer functions of the violin bridges are shown in Figures 7 to 9. The figures clearly

Table 1 Average modulus of elasticity, shear modulus, density and damping factors for unmodified and modified maple wood
Tablica 1. Prosječni modul elastičnosti, modul smicanja, gustoća i čimbenici prigušenja nemodificiranoga i modificiranog javorova drva

	Maple unmodified *Nemodificirana javorovina*	**Maple modified** *Modificirana javorovina*	**Modified / unmodified** *Modificirano / nemodificirano*
E_L, MPa	13264	13727	1.035
E_R, MPa	1832	1923	1.050
G_{TL}, MPa	1117	1130	1.012
G_{RT}, MPa	346	405	1.169
r, kg/m^3	592	574	0.970
ξ_L	0.0081	0.0069	0.851
ξ_R	0.0130	0.0111	0.853

Table 2 Modulus of elasticity, shear modulus, density and damping factors for unmodified and modified maple wood used in the finite element method calculation for bridge No. 1
Tablica 2. Modul elastičnosti, modul smicanja, gustoća i čimbenici prigušenja nemodificiranoga i modificiranog javorova drva korišteni u proračunu metodom konačnih elemenata za most br. 1

	Unmodified *Nemodificirano*	**Modified** *Modificirano*
E_L, MPa	8300	8590
E_R, MPa	1262	1324
E_T, MPa	730	767
G_{LR}, MPa	1013	1024
G_{RT}, MPa	249	252
G_{TL}, MPa	913	924
ξ	0.029	0.016
ρ, kg/m^3	560	520

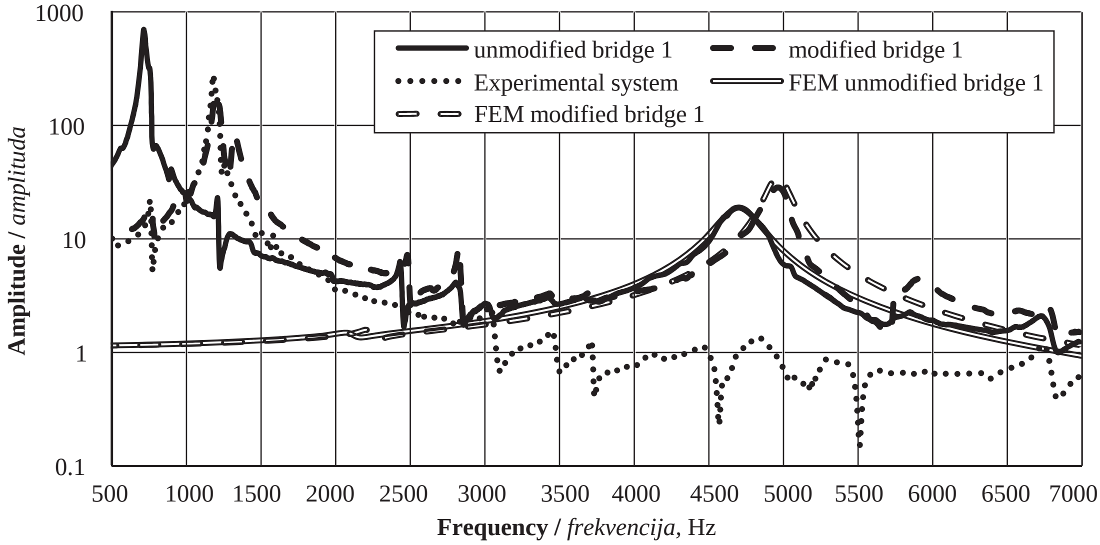

Figure 7 Measured and calculated transfer functions for violin bridge No. 1
Slika 7. Izmjerene i izračunane vrijednosti prijenosne funkcije mosta za violinu br. 1

show an increase of amplitude in the resonant frequency found for bridge No. 1 at 4720 Hz and increases with modification to 4950 Hz. At bridge No. 2, which is already partly shaped and adapted for the violin, the resonant frequency increased from 3760 Hz to 3970 Hz, as well as for bridge No. 3, where the resonant frequency increased from 4880 Hz to 5090 Hz. In addition to the increase in the resonant frequencies, the images also show an increase in the amplitude of the modified bridges, which coincides with a decrease in the damping. In addition to an amplitude increase at the mentioned frequencies, the amplitudes of the transfer functions are also increased at frequencies from 500 to 1500 Hz, which are due to the transfer function of the experimental system, and therefore should not be taken into account. The images show that the experimental system has the first resonant frequency with the highest vibration amplitude at 1180 Hz, and additional resonant frequencies at higher values but with significantly smaller amplitudes.

To get the representative vibration modes, only bridge No. 1 was modelled with the finite element method, using the data from Table 2. Figure 10 shows the vibration modes of bridge No. 1 together with the associated natural frequencies. The most important vibration modes for a violin are #3, known as the “rocking” mode, and vibration mode #6, known as the “bouncing” mode, where the calculated natural frequency for unmodified and modified bridges amounted to 4705 Hz and 4960 Hz, respectively. In addition to the modal analysis, a harmonic analysis was performed, by which a transfer function was calculated for bridge No. 1, whose values are shown in Figure 7. Very good agreement between the measured and calculated transfer functions can be seen between 3000 Hz and 7000 Hz for both unmodified and modified bridges, which deteriorates at frequencies below 3000 Hz, since the measured transfer function has higher values due to the influence of the experimental system. If the measured transfer function of the bridge were to be correct-

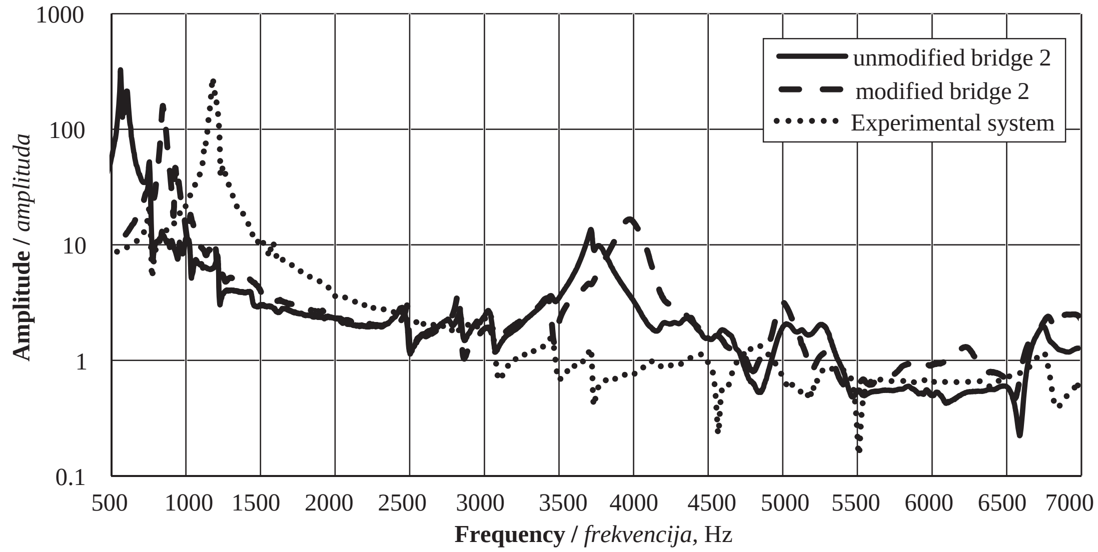

Figure 8 Measured transfer functions for violin bridge No. 2
Slika 8. Izmjerene vrijednosti prijenosne funkcije mosta za violinu br. 2

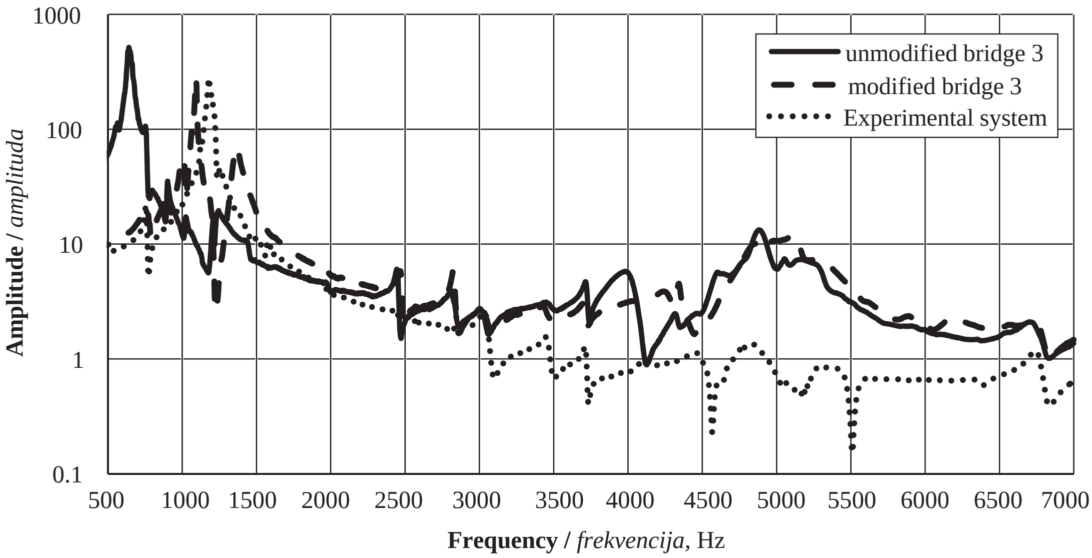

Figure 9 Measured transfer functions for violin bridge No. 3
Slika 9. Izmjerene vrijednosti prijenosne funkcije mosta za violinu br. 3

ed considering the experimental system transfer function, the agreement would be better at lower frequencies, too. The calculated transfer function of the bridge, in addition to a pronounced increase in amplitudes at 4720 Hz and 4950 Hz, also has a slight increase in amplitudes at frequencies of 2060 Hz and 2200 Hz, which are the natural frequencies of the rocking oscillation mode, and, due to its low vibration amplitude, are not evident in the measured transfer functions.

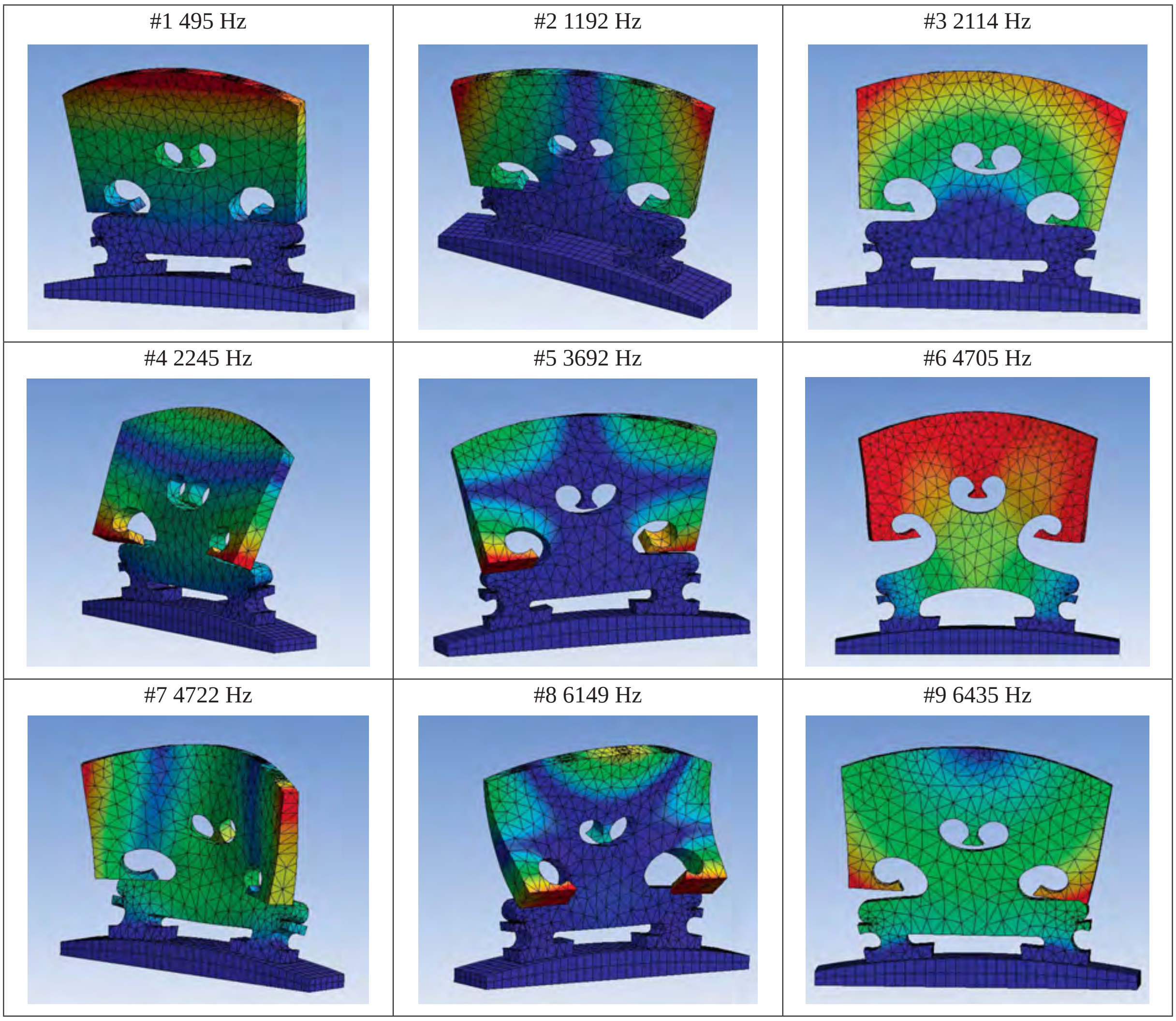

Figure 10 Vibration modes and corresponding natural frequencies of unmodified violin bridge No. 1
Slika 10. Načini vibracija i odgovarajuće prirodne frekvencije nemodificiranog mosta za violinu br. 1

4 CONCLUSIONS
4. ZAKLJUČAK

From the analysis of the violin bridges, whereby the transfer functions were measured and calculated, it can be confirmed that thermal modification of wood affects the transfer function of violin bridges. Since the modulus of elasticity and shear modulus increase and the density decreases with modification, the natural frequencies increase accordingly, which means that the frequency range of the forces transferred by the bridge from the strings to the violin body increases. In addition, the modification also reduces the damping factors of the material, which helps to increase the amplitudes at the resonant frequencies of the bridges. The research thus confirmed that thermal modification is reasonable when the transmitted frequency range is to be increased and bridge damping is to be minimized. It is also reasonable to use the finite element method to calculate the transfer function and the natural frequencies of the bridge, since the study showed very good agreement between the calculated and measured values.

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5 REFERENCES
5. LITERATURA

1. Aditanoyo, T.; Prasetiyo, I.; Putra, I. B. A., 2017: Study on Vibro-acoustics Characteristics of Bamboo-based Violin. Procedia Engineering, 170: 286-292. https://doi.org/10.1016/j.proeng.2017.03.029.
2. Bissinger, G., 2004: The role of radiation damping in violin sound. Acoustics Research Letters Online-Arlo, 5 (3): 82-87. https://doi.org/10.1121/1.1675811.
3. Bissinger, G., 2006: The violin bridge as filter. Journal of the Acoustical Society of America, 120 (1): 482-491. https://doi.org/10.1121/1.2207576.
4. Bissinger, G., 2008: Structural acoustics of good and bad violins. Journal of the Acoustical Society of America, 124(3): 1764-1773. https://doi.org/10.1121/1.2956478.
5. Brancheriau, L.; Bailleres, H., 2002: Natural vibration analysis of clear wooden beams: a theoretical review. Wood Science and Technology, 36: 347-365. https://doi.org/10.1007/s00226-002-0143-7.
6. Dujourdy, H.; Ablitzer, F.; Cabaret, J.; Gautier, F., 2019: Force measurements at the bridge of a string instrument from acceleration measurements on the soundboard. Proceedings of the 26th International Congress on Sound and Vibration, ICSV 2019.
7. Gough, C., 2018: The violin bridge-island input filter. Journal of the Acoustical Society of America, 143 (1): 1-12. https://doi.org/10.1121/1.5019474.
8. Jansson, E. V.; Barczewski, R.; Kabała, A., 2016: On the violin bridge hill – Comparison of experimental testing and FEM. Vibrations in Physical Systems, 27: 151-160.
9. Kabała, A.; Niewczyk, B.; Gapiński, B., 2018: Violin bridge vibrations – FEM. Vibrations in Physical Systems, 29: 1-7.
10. Kollmann, F. F. P., 1975: Principles of wood science and technology. Berlin, Heidelberg, New York, Springer-Verlag.
11. Maia, N. M. M.; Silva, J. M. M., 1998: Theoretical and experimental modal analysis. Hertfordshire, Research Studies Press.
12. Matsutani, A., 2017: Photoelastic observation of violin bridge. Toraibarojisuto/Journal of Japanese Society of Tribologists, 62 (10): 617-622. https://doi.org/10.1143/JJAP.41.6291.
13. Matsutani, A., 2018: Experimental demonstration on air cavity mode of violin using holed sheets of paper. Physics Education, 53 (2): 1-6.
14. Ravina, E., 2017: Low-cost experimental assessment of forces in the contact bridge-soundboard of stringed musical instruments. Mechanisms and Machine Science, 47: 459-466. https://doi.org/10.1007/978-3-319-48375-7_49.
15. Rep, G.; Pohleven, F.; Košmerl, S., 2012: Development of the industrial kiln for thermal wood modification by a procedure with an initial vacuum and commercialisation of modified Silvapro wood. In: Proceedings of 6th European conference on wood modification. Jones, D.; Militz, H.; Petrič, M.; Pohleven, F.; Humar, M.; Pavlič, M. (eds.). Biotechnical Faculty, Ljubljna, Slovenia, pp. 13-20.
16. Rossing, T. D., 2010: The science of string instruments. New York, Springer
17. Setragno, F.; Zanoni, M.; Antonacci, F.; Rovetta, T.; Invernizzi, C., 2017: Feature-based analysis of the impact of ground coat and varnish on violin tone qualities. Acta Acustica united with Acustica, 103 (1): 80-93. https://doi.org/10.3813/AAA.919035.
18. Tai, H. C.; Shen, Y. P.; Lin, J. H.; Chung, D. T., 2018: Acoustic evolution of old Italian violins from Amati to Stradivari. Proceedings of the National Academy of Sciences of the United States of America, 115 (23): 5926-5931. https://doi.org/10.1073/pnas.1800666115.
19. Welzbacher, C. R.; Scheiding, W., 2011: Implementation of a Quality Assurance System for thermally modified timber (TMT) by the Association of Central European TMT-Producers. The International Research Group on Wood Protection, IRG/WP 11-40558 Stockholm, Sweden.
20. Woodhouse, J., 2014: The acoustics of the violin: a review. Reports on Progress in Physics, 77 (11): 1-42. https://doi.org/10.1088/0034-4885/77/11/115901.
21. Woodhouse, J., 2005: On the ”bridge hill” of the violin. Acta Acustica united with Acustica, 91 (1): 155-165.
22. Zhang, C. Z.; Zhang, G. M.; Ye, B. Y.; Liang, L. D., 2013: Violin Bridge Mobility Analysis under In-Plane Excitation. Sensors, 13 (11): 15290-15306. https://doi.org/10.3390/s131115290.

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Characterisation and Modelling of Drying Kinetics of Thin Ash and Oak Wood Lamellas Dried with Infrared Radiation and Hot Air

Karakterizacija i modeliranje kinetike sušenja tankih lamela drva jasena i hrasta infracrvenim zračenjem i vrućim zrakom

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ABSTRACT • *Infrared and hot air drying characteristics of thin ash (Fraxinus excelsior L.) and oak (Quercus robur L.) wood lamellas were experimentally determined using an infrared and hot air laboratory device. Drying curves of 2 mm thick lamellas were established in the temperature range between 60 °C and 90 °C, and fitted by Fick's diffusion model. Drying efficiency, drying rate and effective diffusivity have been estimated and compared between the used drying techniques. Moisture ratio exponentially decayed with duration of the process at all used temperatures. Effective diffusivity was greater in ash than oak wood, and it was not significantly influenced by the drying technique. The increased bound water diffusivity with increased drying temperature that caused shortening of the drying process was confirmed in both wood species. Similar activation energy was determined with both wood species, lower when the IR drying technique was used.*

Key words: *wood drying kinetics; hot air drying; infrared drying; moisture diffusion*

SAŽETAK • *Obilježja infracrvenog sušenja i sušenja vrućim zrakom tankih lamela drva jasena (Fraxinus excelsior L.) i drva hrasta (Quercus robur L.) utvrđene su eksperimentalno uz pomoć laboratorijskih uređaja za infracrveno sušenje i sušenje vrućim zrakom. Krivulje sušenja lamela debljine 2 mm utvrđene su u rasponu temperatura između 60 i 90 °C te su prilagođene Fickovu difuzijskome modelu. Učinkovitost i brzina sušenja te efektivna difuznost procijenjene su i uspoređene unutar primijenjenih tehnika sušenja. Omjer sadržaja vode eksponencijalno se smanjuje s trajanjem procesa pri svim temperaturama primijenjenima u eksperimentu. Efektivna je difuznost drva jasena bila veća nego drva hrasta, a tehnike sušenja nisu znatnije utjecale na nju. Za obje vrste drva potvrđena je veća difuznost vezane vode s povećanjem temperature sušenja, što je uzrokovalo skraćenje procesa sušenja. Slična je energija aktivacije utvrđena za obje vrste drva, a niža je zabilježena pri IC tehnikama sušenja.*

Ključne riječi: *kinetika sušenja drva; sušenje vrućim zrakom; infracrveno sušenje; difuzija vlage*

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1 INTRODUCTION
1. UVOD

Wood is industrially most often dried on the convective heat transport phenomenon, which is energy intensive and relatively slow process, as it relies on heat conduction from the circumference towards to the interior of the board (Keey *et al*., 2000). For the most part of the process, moisture from wood is removed by diffusion, where the opposite moisture gradient, comparing to temperature gradient, is present for the mass transfer to the wood surface.

In order to improve the heat transfer to wood, other ways of heating the material have been explored for some time. Efficient energy transfer throughout the volume, even at greater thicknesses, was confirmed for example by dielectric radio-frequency heating (Torgovnikov, 1993) and also by microwaves (Perre and Turner, 1999; Turner and Farguson, 1995). The use of infrared radiation has proven to be an even simpler way of heating wood, however with some limitations. The latter heating techniquet was found to be limited in penetration depth (Dupleix *et al*., 2012b; Zavarin *et al*., 1990) and dependent on surface characteristics of wood (De Santo, 2007) and wood moisture content – it is more efficient when wood holds free water (Kollmann and Cote, 1968).

The laboratory and pilot studies confirmed that infrared heating is a promising alternative to soaking of wood in hot water prior to veneer peeling (Dupleix *et al*., 2012a), and the green wood surface can be heated up to the depth of several millimetres. It has been also demonstrated that even living trees are heated via IR radiation (Potter and Andressen, 2010). Related to wood drying, studies report on evolution of specific temperature and moisture profiles, when wood is exposed to infrared radiation (Cserta *et al*., 2012). The latter study specifically reports on the stagnation of lower temperature in the core of drying boards due to wood drying by osmotic effect. The evaporation of the internal moisture in this case was brought by a partial vacuum, as a result of local disappearance of liquid water. The same research group performed successfully the pilot drying process of Norway spruce exposed to IR irradiation (Cserta *et al*., 2011). The movement of moisture, presented as dilute aqueous solution, was described in this case as semipermeable membrane process. The intensification of sawn wood drying using IR radiation is also reported for hardwood species, but only at moisture content (MC) above fibre saturation point (Pinchewska and Kompanets, 2013). The transport of bound water by IR radiation, for example, has been studied in the drying of wood chips, where expectedly greater diffusivity was determined at the higher temperature used (Sridhar and Madhu, 2015).

This paper analyses the drying kinetics of predried thin wood lamellae, dried in normal temperature range (≤ 90 °C) to low MC by applying classical hot air convective drying and infrared-heating-drying principle. We hypothesize that the heat transfer to the wood structure is more efficient at IR drying, which might improve the bound water mass transfer at equal boundary conditions.

2 MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Sampling
2.1. Uzorkovanje

Predried (MC_i = 12 %) radially oriented lamellae (n = 10) of ash (*Fraxinus excelsior* L.) and oak wood (*Quercus robur* L.) 5 mm thick, were obtained from local wood flooring manufacturer by random selection from the production process. The density of ash wood was 620 kg/m^3 (coef. of variation CV = 3.6 %) and for oak wood it was 605 kg/m^3 (CV = 1.2 %). The lamellae were then conditioned in normal climate (T = 20 °C, RH = 65 %) for 2 weeks, and afterwards planed to the thickness of 2 mm. The thickness of the lamellae was reduced in order to have as short a drying process as possible with minimal lateral transport of moisture through the edges of the

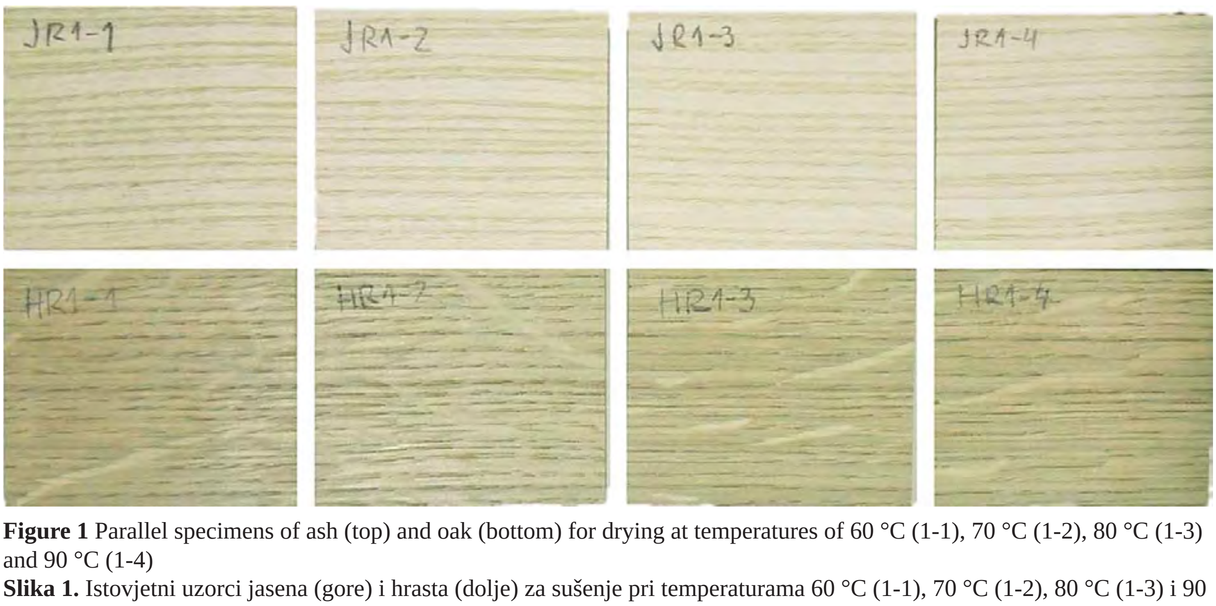

Figure 1 Parallel specimens of ash (top) and oak (bottom) for drying at temperatures of 60 °C (1-1), 70 °C (1-2), 80 °C (1-3) and 90 °C (1-4)
Slika 1. Istovjetni uzorci jasena (gore) i hrasta (dolje) za sušenje pri temperaturama 60 °C (1-1), 70 °C (1-2), 80 °C (1-3) i 90 °C (1-4)

Figure 2 IR drying (left) and hot air drying experimental set-up (right)
Slika 2. IC sušenje (lijevo) i eksperimentalna komora za sušenje vrućim zrakom (desno)

test specimens. Finally, the lamellae were cut into 4 parallel test specimens of nominal dimensions 60 by 50 by 2 mm (length × width × thickness) (Figure 1).

2.2 Experimental set-up and procedure
2.2. Postavljanje eksperimenta i procedure

2.2.1 Drying with infrared radiation
2.2.1. Sušenje infracrvenim zračenjem

Infrared (IR) drying was performed in a laboratory IR-thermogravimetric moisture analyser Kern DBS 60-3. The dimensions of the dryer are typical 0.15 by 0.15 by 0.1 m with the above positioned electric IR heater and parabolic mirror. The test specimens were laid on a thin profiled metal mesh and on a weighing stand so that the nearest hot surfaces from the wood was only 20-30 mm. The IR heater (halogen glass heater, 400 W, λ = 1.5 to 8 μm) maintained the constant temperature during each drying trial (T_1 = 60 °C, T_2 = 70 °C, T_3 = 80 °C, T_4 = 90 °C; ΔT = ± 0.5 °C, PID-control), and the mass (Δm = ± 0.001 g) of the specimen was continuously captured at 1-minute intervals by NI LabView software (Figure 2).

2.2.2 Hot air drying
2.2.2. Sušenje vrućim zrakom

Hot air drying was carried out in a laboratory dryer (Kambič SP-210) with typical dimensions of 0.6 by 0.7 by 0.6 m. The specimen carrier was placed in the middle of the chamber, and it was hung on a precise laboratory balance (Tehtnica Exacta 300 EB) placed on the dryer outside. With the axial fan mounted on the back of the dryer, we maintained constant air movement (v = 1 m/s) at 4 individual drying temperatures: T_1 = 60 °C, T_2 = 70 °C, T_3 = 80 °C, T_4 = 90 °C. The mass (Δm = ± 0.001 g) of the specimens was continuously captured at 1-minute intervals by NI LabView software (Figure 2). We ended the process with both drying techniques, i.e. IR and hot air, when the change in mass between two successive measurements was less than 0.1 % of the initial mass of the specimen.

2.3 Analysing of drying kinetics
2.3. Analiza kinetike sušenja

The determined weight of test specimens at the beginning (m_i), during (m_t) and at the end of the drying process (m_e), when equilibrium was reached, was used to determine the dimensions less mass change, i.e. moisture ratio (MR, Eq. 1).

$$MR = \frac{m_t - m_e}{m_i - m_e} \tag{1}$$

The theoretical Fick's model of mass transfer was used afterwards to analyse the kinetics of both IR and hot air drying. The model assumes that diffusivity is the sole physical mechanism responsible for the transfer of water to the wood surface. Relation between the moisture ratio and the effective diffusion coefficient was given by Crank (Crank, 1976) and this could be used for slab geometry by making an assumption that the initial moisture is uniformly distributed in the specimen. This relation was reduced to Eq. 2 assuming that the wood specimen is homogeneous, mass transfer through the wood is controlled by bound water and water vapour diffusion and effect of shrinkage is negligible.

$$MR = \frac{8}{\pi^2} exp\left[\frac{-\pi^2 \cdot D_{eff} \cdot t}{4 \cdot L^2}\right] = \frac{8}{\pi^2} exp\left[\frac{-\cdot t}{\tau}\right] \tag{2}$$

Where L is the half thickness of the wood specimen (m), D_{eff} is the effective diffusion coefficient in m^2/s and t is the drying time in seconds. By plotting *ln* (MR) versus drying time, D_{eff} was determined from the slope (k) of the line, which is expected to increase with the increasing of the drying temperature. The reciprocal value of the slope k is defined as well the time constant τ. It is a characteristic time of the response of the first order system (FOS; Eq. 2) and equals the time when 2/3 of the total response of the system is realized. According to the 1st order system theory, 99.9 % of the response, which equals the total drying time, is achieved at 5 times the characteristic time τ (Bučar, 2007).

Finally, the activation energy was estimated using Arrhenius equation (Eq. 3). In this respect, we used plot of ln (D_{eff}) versus reciprocal of absolute drying temperature (1/T) for both tested drying techniques. From the slope of the line, activation energy E_a (kJ/mol) was calculated, and from the intercept, pre-exponential factor (D_0) was calculated (gas constant R = 8.314 J·mol^{-1}·K^{-1}).

$$D_{eff} = D_0 exp\left[\frac{-E_a}{R \cdot T}\right] \qquad (3)$$

2.4 Determination of IR transmittance and IR absorbance
2.4. Određivanje IC transmisije i IC apsorbancije

The penetration depth of IR radiation into the wood structure was checked using a FTIR spectroscope (Perkin Elmer Spectrum One). For this purpose, we made microtome slices in the radial-longitudinal plane of the wood on the sliding microtome (Leica SM2010R) of the two species studied. Transmission FTIR spectra were recorded on microtomic slices 10 to 100 microns thick (ΔL = 10 μm). We transformed transmission spectra into absorbance spectra and calculated mean IR transmittance / IR absorbance in the range from 4000 to 400 cm^{-1} (2.5 to 25 μm).

2.5 Determination of IR-emissivity
2.5. Određivanje IC emisivnosti

A polyvinyl chloride material (3M) with known emissivity in the spectral range 7.5-13 μm (LWIR) was applied to the surface of all specimens. Thermograms were recorded with FLIR I60 thermographic camera at 50 °C, and emissivity of wood in LWIR spectral range was determined with FLIR software. The measurement parameters were as follows: air temperature 21 °C, air relative humidity 52 %, reflected apparent temperature 20.9 °C, distance of objects surface from the lens was 120 mm, angle of measurement in relation to the object normal was 15°, and airflow and dotted reflections were inhibited. Eighteen measurements were conducted for each wood species.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Drying kinetics
3.1. Kinetika sušenja

Fick's law of diffusion described well drying kinetics of ash and oak with both used techniques in the studied temperature range (0.83 ≤ R^2 ≤ 0.96).

In the case of IR drying, the fastest process expectedly took place at the highest used temperature (90 °C) and was 2 times faster in ash than in oak (τ_{ash} = 7.3 min, τ_{oak} = 14.7 min). Lowering of drying temperature significantly decreased the drying rate of both wood species tested. The slowest response was achieved with IR drying at 60 °C, where the calculated (Eq. 2) characteristic drying time was 28.7 min for ash, and 49.0 min for oak. As different drying temperatures were used, mean final – equilibrium wood moisture content (MC_e) also varied from 1.1 % at 60 °C to 0.1 % at 90 °C (Figure 3).

The hot air drying of ash went about as fast as or slightly slower than infrared drying of this wood species. The lowest characteristic time was determined for drying at 90 °C (τ_{90} = 8.6 min), lower for drying at 80 °C (τ_{80} = 12.4 min) and 70 °C (τ_{70} = 23.5 min), and the lowest for drying at 60 °C (τ_{60} = 32.1 min) (Figure 4). Hot air drying of oak was even slightly faster (Δτ =

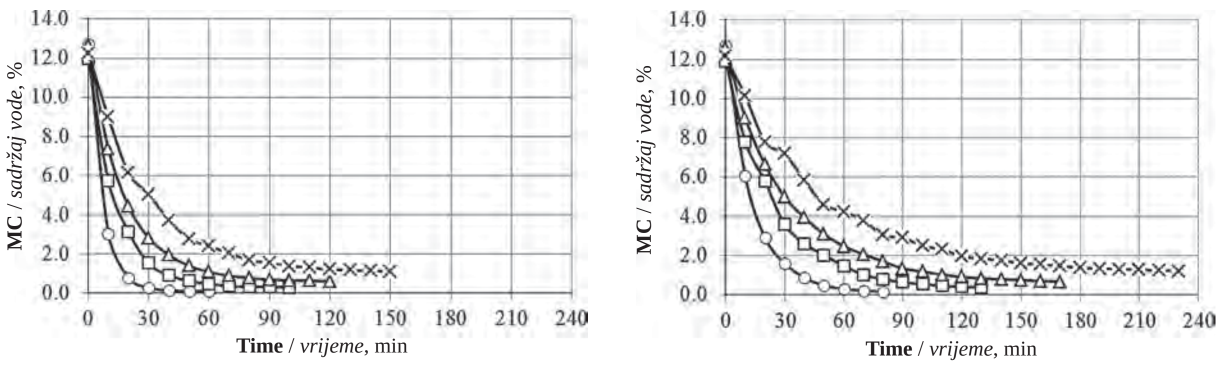

Figure 3 Kinetics of infrared drying of ash (left) and oak wood (right) at temperature between 60 °C and 90 °C (× 60 °C, Δ 70 °C, □ 80 °C, ○ 90 °C).
Slika 3. Kinetika infracrvenog sušenja jasena (lijevo) i hrasta (desno) pri temperaturama između 60 i 90 °C (× 60 °C, Δ 70 °C, □ 80 °C, ○ 90 °C).

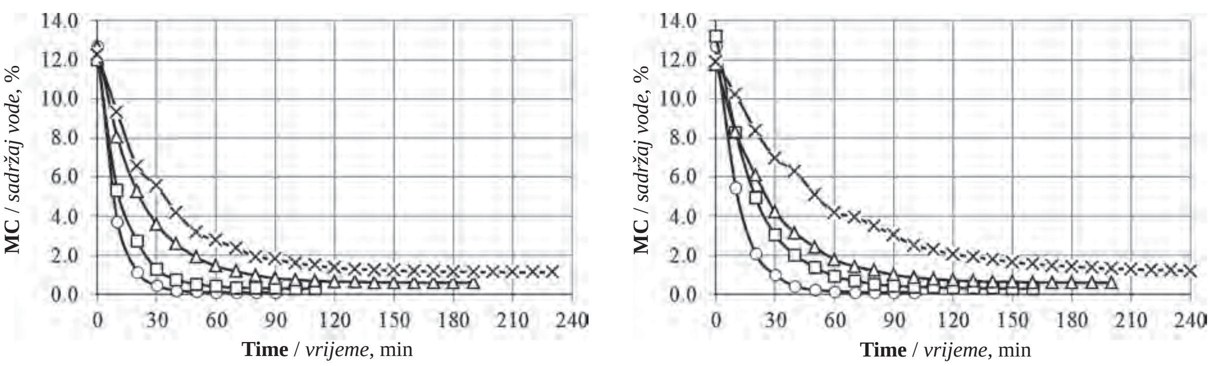

Figure 4 Kinetics of hot air drying of ash (left) and oak wood (right) at temperature between 60 °C and 90 °C (× 60 °C, Δ 70 °C, □ 80 °C, ○ 90 °C)
Slika 4. Kinetika sušenja vrućim zrakom jasena (lijevo) i hrasta (desno) pri temperaturama između 60 i 90 °C (× 60 °C, Δ 70 °C, □ 80 °C, ○ 90 °C)

Table 1 Effective diffusion coefficient (D_{eff}) as a function of temperature at infrared and hot air drying of ash and oak wood (*CV* – coef. of variation)
Tablica 1. Koeficijent efektivne difuznosti (D_{eff}) kao funkcija temperature pri infracrvenom sušenju *i sušenj*u vrućim zrakom drva jasena i hrasta (*CV* – koef. varijacije)

T °C	**Ash** / *Jasen*				**Oak** / *Hrast*			
	Infrared /*Infracrveno*		**Hot air** / *Vrući zrak*		**Infrared** / *Infracrveno*		**Hot air**/ *Vrući zrak*	
	D_{eff} ($\cdot 10^{-9}$)	*CV*	D_{eff} ($\cdot 10^{-9}$)	*CV*	D_{eff} ($\cdot 10^{-9}$)	*CV*	D_{eff} ($\cdot 10^{-9}$)	*CV*
	m^2/s	%	m^2/s	%	m^2/s	%	m^2/s	%
60	0.29	6.8	0.27	8.4	0.17	3.1	0.17	13.0
70	0.43	3.6	0.36	5.7	0.25	7.4	0.29	8.6
80	0.60	6.1	0.68	13.5	0.34	6.3	0.41	8.2
90	0.91	5.2	1.01	10.5	0.55	4.6	0.75	9.4

-12.5 %) compared to IR drying of this wood species. The minimum characteristic time was also measured for drying at the highest temperature (τ_{90} = 11.3 min), lower for drying at 80 °C (τ_{80} = 20.3 min) and 70 °C (τ_{70} = 26.9 min), and the lowest for drying at 60 °C (τ_{60} = 50.5 min).

Small and insignificant differences in the kinetics of the drying processes in the tested drying techniques were also reflected in the calculated effective diffusion coefficients according to Eq. 2. When drying ash wood, the lowest diffusion coefficients were measured from $0.27 \cdot 10^{-9}$ to $0.29 \cdot 10^{-9}$ m^2/s at 60 °C and the highest from $0.91 \cdot 10^{-9}$ to $1.01 \cdot 10^{-9}$ m^2/s at 90 °C (Table 1). The diffusion coefficients measured in the drying of oak wood were significantly smaller compared to ash, despite the higher density of the latter (ρ_{ash} = 620 kg/m^3; ρ_{oak} = 605 kg/m^3). For drying of oak wood, a diffusion coefficient of $0.17 \cdot 10^{-9}$ m^2/s was measured at 60 °C for both drying techniques, and maximum values of $0.55 \cdot 10^{-9}$ to $0.75 \cdot 10^{-9}$ m^2/s were measured at 90 °C. Generally, the calculated values of the diffusion coefficients in transverse direction of these two tested wood species are comparable with literature data (Siau, 1984).

From the Arrhenius equation (Eq. 3) and Arrhenius plot (Figure 5), activation energy (E_a) was found to be between 37.8 to 46.3 kJ/mol for ash and between 38.1 to 48.3 kJ/mol for oak, where lower values were found at infrared drying for both tested wood species. The pre-exponential factor (D_0) was determined as $2.47 \cdot 10^{-4}$ m^2/s and $4.54 \cdot 10^{-3}$ m^2/s for infrared and hot air drying of ash; the values of $1.57 \cdot 10^{-4}$ m^2/s and $5.37 \cdot 10^{-4}$ m^2/s were determined for infrared and hot air drying of oak. The calculated activation energy value for bound water and water vapour diffusion in ash and oak wood is comparable to the literature data (Siau, 1984; Stamm, 1964).

Since the activation energy equals the minimum energy requirement that must be met for diffusion to occur at the studied temperature interval (60 to 90 °C), lower measured E_a at infrared drying actually means better utilization of the energy input for water vapour transport in both wood species. Nevertheless, this difference in activation energy between the two processes may also be due to differences in the temperature of the subjects. For IR drying, a higher temperature in the middle of the test pieces is expected, and thus a positive correlation of temperature and moisture gradients. However, the differences between the drying techniques are small and the D_{eff} deviations between techniques vary at some temperatures (Table 1).

3.2 Transmission and absorption of infrared radiation in wood
3.2. Transmisija i apsorpcija infracrvenog zračenja u drvu

For both wood species, FTIR spectra were determined with a typical finger print range between 2.5 and 10 µm. Better transmission was determined in the higher wavelength range, in particular between 12 and 15 µm, and above 20 µm. Expectedly, better FTIR spectra (greater difference between valleys and peaks) were determined at thinner microtome slices of both wood species (Figure 6).

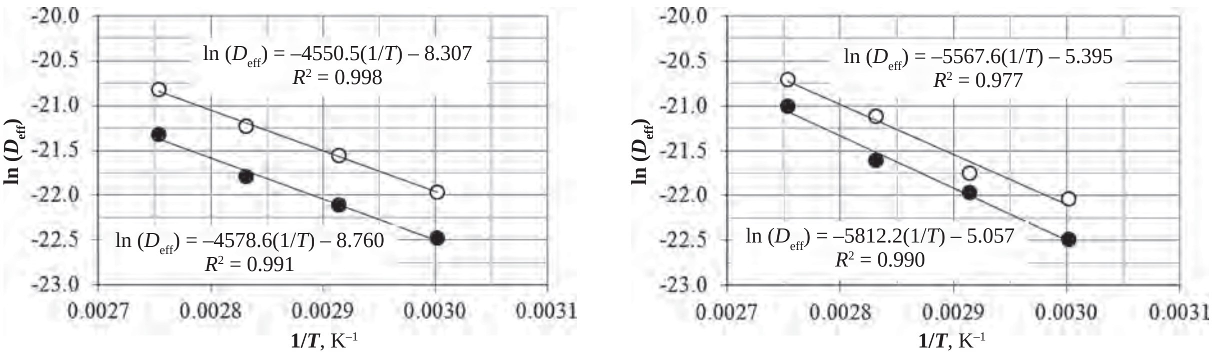

Figure 5 Relation between the reciprocal of absolute temperature and effective diffusion coefficient at infrared (left) and hot air drying (right) of wood (○-ash, ●-oak)
Slika 5. Odnos između recipročne apsolutne temperature i koeficijenta efektivne difuznosti drva pri infracrvenom sušenju (lijevo) i sušenju vrućim zrakom (desno) (○ – jasen, ●hrast)

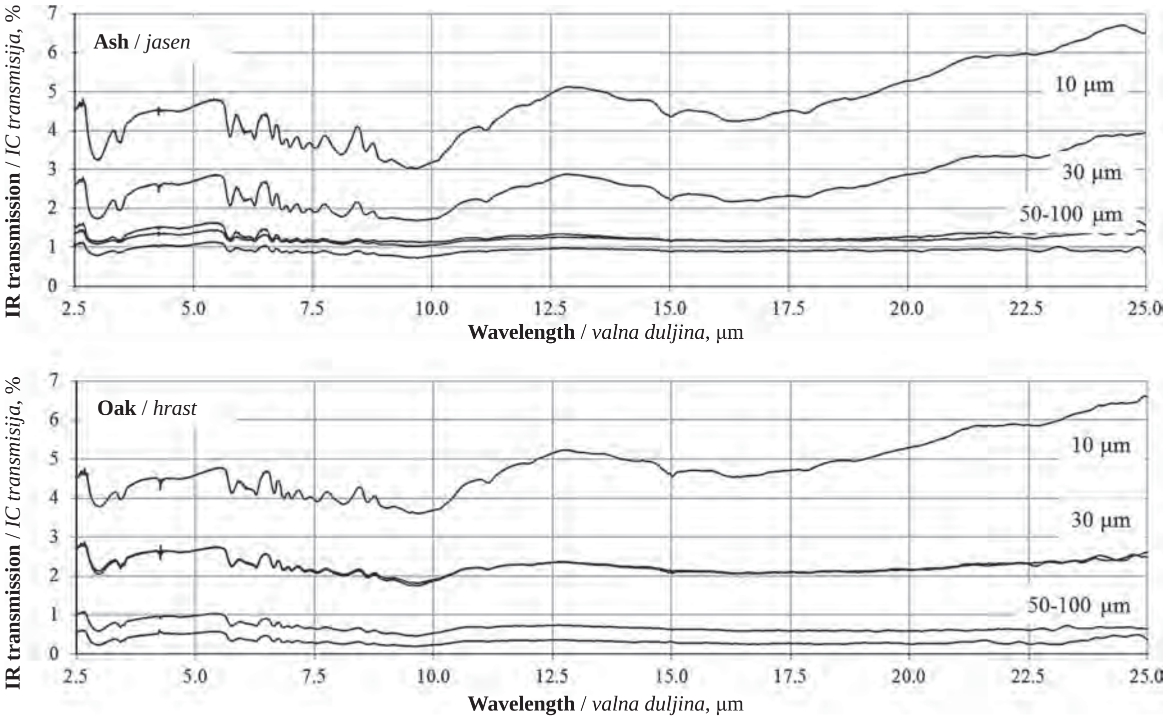

Figure 6 Transmission FTIR spectra of ash (above) and oak (below) microtome slice of different thickness (10 to 100 *µm*)
Slika 6. Transmisija FTIR spektra jasena (gore) i hrasta (dolje) mikrotomskih preparata različitih debljina (od 10 do 100 µm)

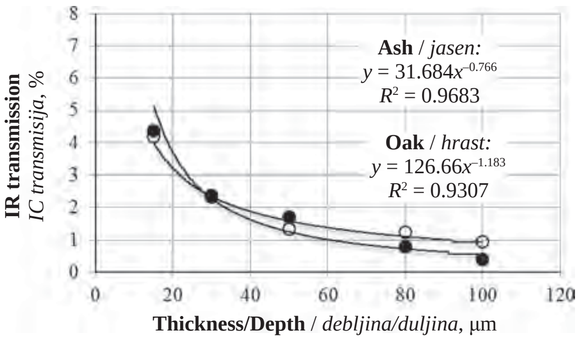

Figure 7 Relation between thickness/depth of ash (○) and oak (●) wood and average infrared transmission.
Figure 7. Odnos između omjera debljine/dubine drva jasena (○) i hrasta (●) i prosječne infracrvene transmisije

Expectedly, it turns out that the average IR transmissivity in the transmitted wavelength range (2.5 to 25 µm) significantly decreases with increasing microtome slice thickness of both wood species (Figure 7). The found trend, i.e. logarithmic decay of intensity of transmitted IR beam with path length, obeys the Beer-Lambert law. The Beer-Lambert law implies that both type (structure) and the concentration (density) of the molecules are important in the process of radiation absorption (Parker, 1971). However, an insignificant difference in IR absorption between the two wood species has been confirmed.

Other studies, like ours, mention the possibility of penetrating IR radiation up to 100 µm (Makoviny and Zemiar, 2004), or even to a maximum of 134 µm (Zavarin *et al.*, 1991). The latter study also reports on minor influence of wood density and fibre orientation on energy absorption and penetration depth in wood.

3.3 Wood and emissivity of infrared light
3.3. Drvo i emisivnost infracrvenog zračenja

No significant difference was found between IR emissivity of ash and oak samples (*Table 2*). Since the emissivity of a surface is its ability to absorb (and emit) energy of radiation, the more absorbent a surface is, the higher is its emissivity. It has been reported that wet wood absorbs more IR energy than dry wood and that ε increases with *MC* up to the fibre saturation point (FSP), at which point it reaches the IR emissivity of water (ε_{water} = 0.93) (Kollmann and Cote, 1968).

Reflectance of IR light is found to be related with the surface roughness (Jones *et al.*, 2008). However, there is some controversy about the effect of surface roughness. Some studies highlighted that rougher the

Table 2 IR emissivity (*ε*) of ash and oak wood samples with descriptive statistics (*N* – number of measurements; *Mean* – arithmetic mean; *SD* – standard deviation; *95 CI* – 95 % confidence interval of the mean; *Med* – median; IQR – interquartile range; *CV* – coefficient of variation)
Tablica 2. IC emisivnost (*ε*) uzoraka drva jasena i hrasta s deskriptivnom statistikom (*N* – broj mjerenja; *Mean* – aritmetička sredina; *SD* – standardna devijacija; *95 CI* – 95-postotni interval pouzdanosti aritmetičke sredine; *Med* – medijan; *IQR* – interkvartilni raspon; *CV* – koeficijent varijacije)

	N	Mean	SD	95 CI	Med	IQR	Min	Max	CV
Ash / *Jasen*	18	0.920	0.011	0.0086 – 0.0171	0.923	0.014	0.894	0.936	1.239
Oak / *Hrast*	18	0.906	0.012	0.0093 – 0.0185	0.909	0.015	0.876	0.926	1.365

wood surface, the greater the reflection and less the IR absorption due to increased light scattering (Bennett and Porteus, 1961; De Santo, 2007). The opposite was also found (Zavarin *et al*., 1990; 1991). It was also reported that the effect of surface roughness on absorbance differs according to the wavelength (Tsuchikawa *et al*., 1996).

4 CONCLUSIONS
4. ZAKLJUČCI

1. Fick's law of diffusion describes well the kinetics of infrared and hot air drying of ash and oak lamellas between 60 °C and 90 °C. The calculated diffusion coefficient increased with used temperature and obeyed the Arrhenius law.
2. The diffusion of bound water and water vapour, despite greater wood density, was found to be better in ash than in oak wood, which improves the drying kinetics.
3. The use of infrared radiation did not affect significantly the drying kinetics in low wood MC range. Calculated transport coefficients of ash and oak wood, when compared to conventional hot air drying of tested species, were similar. Slightly lower activation energy for transport of bound water in wood was found at IR drying.
4. The average IR transmittance wavelength range (2.5 to 25 μm) significantly decreases with increasing wood thickness, obeying the Beer-Lambert law. IR radiation reaches ash- and oak wood depth of approx. 100 μm.

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5 REFERENCES
5. LITERATURA

1. Bennett, H. E. J.; Porteus, J. O., 1961: Relation between surface roughness and specular reflection at normal incidence. Journal of Optical Society of America, 51: 123.
2. Bučar, B., 2007: Internal and external moisture transport resistance during non-stationary adsorption of moisture into wood. Zbornik gozdarstva in lesarstva, 84: 17-21.
3. Crank, J., 1976: The Mathematics of Diffusion, vol 2, Oxford University Press, Oxford.
4. Cserta, E.; Hegedus, G.; Nemeth, R., 2011: Dryng process in Norway spruce wood exposed to infrared radiation. BioResources, 6 (4): 4181-4189.
5. Cserta, E.; Hegedus, G.; Nemeth, R., 2012: Evolution of temperature and moisture profiles of wood exposed to infrared radiation. BioResources, 7 (4): 5304-5311.
6. De Santo, J. A., 2007: Overview of rough surface scattering. Light Scattering and Nanoscale Surface Roughness. Nanostructure Science and Technology, Springer, New York.
7. Dupleix, A.; Ahmedou, S. A. O.; Bleron, L.; Rossi, F.; Hughes, M., 2012a: Rational production of veneer by IR-heating of green wood during peeling. Holzforschung, 67: 53-58.
8. Dupleix, A.; De Sousa Meneses, D. M. H. R. M., 2012b: Mid infrared absorption properties of green wood. Wood Science and Technology, 47 (6): 1231-1241.
9. Jones, P. D.; Schimleck, L. R.; Daniels, R. F.; Clark, A.; Purnell, R. C., 2008: Comparison of Pinus taeda L. whole-tree wood property calibration using diffuse reflectance near infrared spectra obtained using a variety of sampling options. Wood Science and Technology, 42 (5): 358-400.
10. Keey, R. B.; Langrish, T. A. G.; Walker, J. C. F., 2000: Kiln-drying of lumber. Springer, Hedelberg.
11. Kollmann, F.; Cote, W. A., 1968: Principles of Wood Science and Technology: Solid Wood, vol 1. Springer-Verlag, Berlin.
12. Makoviny, L.; Zemiar, J., 2004: Heating of wood surface layers by infrared and microwave radiation. Wood Research, 49 (4): 33-40.
13. Parker, F. S., 1971: Quantitative Analysis. In: Parker F. S. (ed.), Application of Infrared Spectroscopy in Biochemistry, Biology and Medicine. Springer, Boston, pp. 80-83.
14. Perre, P.; Turner, I. W., 1999: The use of numerical simulation as a cognitive tool for studying the microwave drying of softwood in an over-sized waveguide. Wood Science and Technology, 33: 445-464.
15. Pinchewska, O.; Kompanets, S., 2013: Hardwood drying intensification. Annals of Warsaw University of Life Sciences, 84: 32-35.
16. Potter, B. E.; Andressen, J. A., 2010: A finite-difference model of temperatures and heat flow within a tree stem. Revue Canadienne de Recherche Forestiere, 32: 548-555.
17. Siau, J. F., 1984: Transport processes in wood. Springer-Verlag, Berlin.
18. Sridhar, D.; Madhu, G. M., 2015: Drying Kinetics and Mathematical Modeling of Casuarina Equisetifolia Wood Chips at Various Temperatures. Periodica Polytechnica Chemical Engineering, 59 (4): 288-295.
19. Stamm, A. J., 1964: Wood and cellulose science. Ronald Press, New York.
20. Torgovnikov, G., 1993: Dielectric Properties of Wood and Wood-based Materials. Springer Series in Wood Science. Springer, Haidelberg.
21. Tsuchikawa, S.; Hayashi, K.; Tsutsumi, S., 1996: Nondestructive measurement of the subsurface structure of biological material having cellular structure by using near-infrared spectroscopy. Applied Spectroscopy, 50 (9): 1117-1124.
22. Turner, I. W.; Farguson, W. J., 1995: A study of the power density distribution generated during combined microwave and convective drying of softwood. Drying Technology, 13: 1411-1430.
23. Zavarin, E.; Cool, L. G.; Jones, S. G., 1990: Analysis of solid wood surfaces by Diffuse Reflectance Infrared Fourier-Transform (DRIFT) spectroscopy. Journal of Chemistry Technology, 10 (4): 495-513.
24. Zavarin, E.; Cool, L. G.; Jones, S. G., 1991: Analysis of solid wood surfaces by internal-reflection fourier-transform infrared-spectroscopy. Journal of Wood Chemistry and Technology, 11 (1): 41-56.

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Physical Properties of Juvenile Wood of Two Paulownia Hybrids

Fizička svojstva juvenilnog drva dvaju hibrida paulovnije

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ABSTRACT • *There is a growing trend in the world of planting fast growing species (rotations 5 to 10 years). Their primary purpose is the production of wood fibers and biomass, but they certainly represent the potential in making solid wood products as well. One of the fast-growing species is Paulownia sp., a species of extremely fast growing wood. Plantation breeding of Paulownia sp. in Croatia is increasing, although there is a little knowledge about the technical properties of Paulownia wood and its end use is questionable. This paper presents preliminary results of some physical properties of juvenile wood of two Paulownia hybrids planted in the area near the town of Glina in the Republic of Croatia. One hybrid is 9501 ((Paulownia fortunei × Paulownia elongata) × (Paulownia fortunei × Paulownia tomentosa)) and the other hybrid is Shan Tong (Paulownia fortunei × Paulownia tomentosa). The aim of this study was to investigate physical properties of juvenile wood of two Paulownia hybrids from one site in Croatia, to determine differences in physical properties of wood between two hybrids and to evaluate the correlation between density and shrinkages of each hybrid. Significant differences in oven dry density, basic density and density at maximum MC, between the two hybrids were determined. There is no statistically significant difference in longitudinal, radial, tangential and volumetric shrinkages between the two hybrids.*

Keywords: *hybrid 9501; hybrid Shan Tong; juvenile wood; Paulownia wood; physical properties*

SAŽETAK • *U današnje je vrijeme zamjetan sve češći trend sadnje brzorastućih vrsta drveća (ophodnje od 5 do 10 godina). Te su vrste primarno namijenjene proizvodnji drvnih vlakana i biomase, ali svakako je vidljiv i njihov potencijal u proizvodima od cjelovitog drva. Jedna od brzorastućih vrsta je Paulownia sp., koju odlikuje izrazito brz rast. Iako se malo zna o tehničkim svojstvima drva paulovnije, a njegova je krajnja upotreba upitna, u Hrvatskoj je u porastu plantažni uzgoj paulovnije. U ovom su radu prikazani preliminarni rezultati istraživanja nekih fizičkih svojstava juvenilnog drva hibrida paulovnije s lokaliteta u blizini grada Gline u Hrvatskoj. Prvi je hibrid 9501 ((Paulownia fortunei × Paulownia elongata) × (Paulownia fortunei × Paulownia tomentosa)), a drugi Shan Tong (Paulownia fortunei × Paulownia tomentosa). Cilj rada bio je istražiti fizička svojstva juvenilnog drva hibrida paulovnije s lokaliteta u Hrvatskoj, utvrditi razlike u fizičkim svojstvima drva tih hibrida te odrediti međusobni odnos gustoće i utezanja unutar hibrida. Utvrđene su značajne razlike u gustoći drva u apsolutno suhom stanju, u nominalnoj gustoći i gustoći pri maksimalnom sadržaju vode između tih dvaju hibrida. Među hibridima nisu utvrđene statistički značajne razlike u longitudinalnome, radijalnome, tangentnome ni volumnom utezanju.*

Ključne riječi: hibrid 9501; hibrid Shan Tong; juvenilno drvo; drvo paulovnije; fizička svojstva

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1 INTRODUCTION
1. UVOD

The trend of increasing demand for wood raw material is becoming of great global concern. The answer to this would be to plant more fast growing trees of different species, in order to conserve native forests and to ensure adequate supplies of wood. *Paulownia* sp. is an example of very adaptable genus requiring minimal management after the first few years (El-Showk, 2003). It has been cultivated throughout Asia for centuries, with China having the longest history (Ates *et al*., 2008).

Paulownia wood is considered to be extremely fast growing, especially in the juvenile phase of growth. Under optimal conditions, *Paulownia* sp. trees can produce useful timber within five to six years, measuring 30-40 cm in diameter after ten years (Olson and Carpenter, 1982; Zhao-Hua *et al*., 1986). It is widely used for various purposes, with excellent prospects for pulp and biomass (Vilotić *et al.*, 2015; Icka *et al.*, 2016; Vusić *et al.*, 2018). However, as a solid wood, it is suggested to be used in products that are not subject to great loads during exploitation (Šoškić *et al.*, 2003) and not for structural purposes (Koman *et al*., 2017).

Due to its high adaptability, new markets are developing rapidly for plantation grown *Paulownia* sp. in many countries. In Croatia, the most commonly propagated are *Paulownia* hybrids Shan Tong and 9501. Currently, there are no Paulownia hybrid trees with known origin older than four years in Croatia. Drvodelić (2018) investigated their propagation by root cuttings, where the difference in rooting percentage between two hybrids depended on the cutting thickness and drying procedure. However, technical properties of hybrids 9501 and Shan Tong have not been investigated so far in Croatia. In addition, there are limited data on technical properties of wood of different *Paulownia* species (Ayhildiz and Kol, 2010; Kiaei, 2013; San *et al*., 2016; Komán *et al*., 2017).

Therefore, data on properties of *Paulown*ia hybrid wood grown on the territory of the Republic of Croatia are needed. This information could determine whether *Paulownia* sp. is profitable for cultivation and use as a raw material for industrial purposes.

The aim of this study was to investigate physical properties of *Paulownia* hybrids 9501 and Shang Tong juvenile wood from one site in the Republic of Croatia, to determine differences in physical properties of wood between two hybrids and to evaluate the correlation between density and shrinkages of each hybrid.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

For the purpose of this research, two 4-year old *Paulownia* hybrids were taken from the area near the town of Glina in Croatia. One hybrid is 9501 ((*Paulownia fortunei* × *Paulownia elongata*) × (*Paulownia fortunei* × *Paulownia tomentosa*)) and the other hybrid is Shan Tong (*Paulownia fortunei* × *Paulownia tomentosa*). Five test trees of each hybrid were taken from the experimental stand. All trees were chosen as representative of the stand according to HRN ISO 3129:2015.

Four disks were cut at breast height (1.3 m), upwards to the crown, from each tree. Disks were approximately 5 cm thick and 10 cm in diameter. Maximum number of test samples were cut from each disk, according to HRN ISO 3129:2015.

Physical properties determined in this study were density in absolutely dry condition, basic density and density at maximum moisture content (HRN ISO 13061-2:2015); longitudinal, radial and tangential shrinkage (ISO 13061-13:2016); volumetric shrinkage (ISO 13061-14:2016) and maximum moisture content (HRN ISO 13061-1:2015).

Statistical analysis of data and their comparison were carried out in Statistica 8. Data were analyzed and presented as the minimum, mean and maximum values, as well as standard deviation. The analysis of variance (ANOVA) was used to determine whether there are any statistically significant differences between the means of investigated wood properties of two *Paulownia* hybrids. Duncan's multiple range test (DMRT) was applied to test statistical significance at $\alpha = 0.05$ level. The simple linear regression model was used to analyze the relationship between density and shrinkage.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Statistical values of Paulownia hybrids 9501 and Shan Tong juvenile wood, as well as the summary of analysis of variance (ANOVA) for oven dry density, basic density, density at maximum moisture content (MC), longitudinal, radial, tangential, and volumetric shrinkage are shown in Table 1, Table 3, Figure 1 and Figure 2.

Physical properties of wood, especially wood density and dimensional stability, are important factors affecting wood quality (Ištok *et al.*, 2016). Mean oven dry density of hybrid 9501 is 249 kg/m^3 and of hybrid Shan Tong is 237 kg/m^3 (Table 1). The analysis of variance (ANOVA) indicated that there is significant difference in oven dry density between the two hybrids (Table 3). However, these differences in mean values amounted only to about 6%. The values are similar to the findings on *Paulownia elongata*, 240 kg/m^3 (Šoškić *et al*., 2003); *Paulownia tomentosa*, 276 kg/m^3 (Komán *et al*., 2017); *Paulownia fortunei*, 274 kg/m^3 (Šoškić *et al*., 2017) and 261 kg/m^3 (Kiaei, 2013).

For hybrid 9501, the mean value of longitudinal shrinkage is 0.30 %, radial shrinkage 2.35 %, tangential shrinkage 4.95 % and volumetric shrinkage 7.62 % (Table 1). For hybrid Shan Tong, the mean value of longitudinal shrinkage is 0.35 %, radial shrinkage 2.47 %, tangential shrinkage 5.30 % and volumetric shrinkage 7.81 % (Table 1). The analysis of variance (ANOVA) indicated that there is no significant difference in shrinkages between the two hybrids (Table 3). Very high variability of longitudinal shrinkage is present. This could be explained by low age of investigated trees, closely to juve-

Table 1 Descriptive statistical analysis of physical properties between Paulownia hybrids 9501 and Shan Tong
Tablica 1. Deskriptivna statistička analiza fizičkih svojstava hibrida paulovnije 9501 i Shan Tong

Property *Svojstvo*	**Hybrid** *Hibrid*	**Number of samples** *Broj uzoraka*	**Mean**[a] *Srednja vrijednost*[a]	**Standard deviation** *Standardna devijacija*	**Min**	**Max**
Oven dry density *gustoća u apsolutno suhom stanju*	9501	34	0.249 a	0.016	0.221	0.295
	Shan Tong	34	0.237 b	0.019	0.201	0.277
Basic density / *nominalna gustoća*	9501	34	0.233 a	0.014	0.208	0.272
	Shan Tong	34	0.220 b	0.017	0.187	0.252
Density at maximum MC *gustoća pri maksimalnom sadržaju vode*	9501	34	0.719 a	0.078	0.600	0.917
	Shan Tong	34	0.669 b	0.063	0.562	0.850
Longitudinal shrinkage *longitudinalno utezanje*	9501	34	0.30 a	0.202	0.04	0.74
	Shan Tong	34	0.35 a	0.332	0.04	1.20
Radial shrinkage / *radijalno utezanje*	9501	34	2.35 a	0.489	1.61	3.42
	Shan Tong	34	2.47 a	0.631	1.67	4.69
Tangential shrinkage / *tangentno utezanje*	9501	34	4.95 a	0.643	4.05	6.26
	Shan Tong	34	5.30 a	0.969	3.80	8.02
Volumetric shrinkage / *volumno utezanje*	9501	34	7.62 a	0.966	6.07	9.38
	Shan Tong	34	7.81 a	1.409	5.13	11.21
Maximum MC / *maksimalni sadržaj vode*	9501	34	208 a	19.432	172	253

[a] Rresults with different letters have a significant difference with the Duncan's test. / *Rezultati s različitim slovima statistički se značajno razlikuju prema Duncanovu testu.*

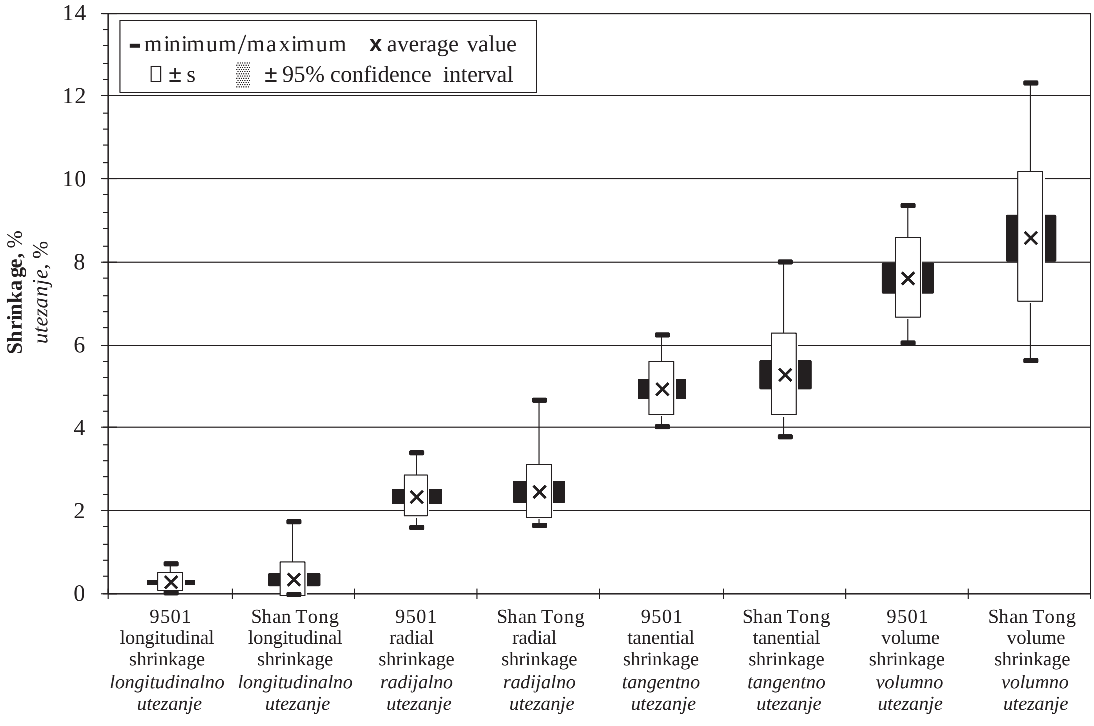

Figure 1 Statistical analyses of longitudinal, radial, tangential and volume shrinkage, between two paulownia hybrids
Slika 1. Statistička analiza longitudinalnoga, radijalnoga, tangentnoga i volumnog utezanja, dvaju hibrida paulovnije

Table 2 Comparison of shrinkage values with references
Tablica 2. Usporedba vrijednosti utezanja s rezultatima iz literature

Property *Svojstvo*	**Hybrid 9501 (our research)** *Hybrid 9501 (vlastito istraživanje)*	**Hybrid Shan Tong (our research)** *Hybrid Shan Tong (vlastito istraživanje)*	***P. elongata*** **(Šoškić *et al.*, 2003)**	***P. fortunei*** **(Šoškić *et al.*, 2003)**	***P. tomentosa*** **(Kiaei, 2013)**	***P. fortunei*** **(Komán *et al.*, 2017)**
Radial shrinkage / *radijalno utezanje*	2.35	2.47	2.49	2.54	-	2.20
Tangential shrinkage / *tangentno utezanje*	4.95	5.30	4.74	4.79	-	3.89
Volumetric shrinkage / *volumno utezanje*	7.62	7.81	8.31	8.35	7.54	6.94

Table 3 Analysis of variance (ANOVA) results for physical properties between Paulownia hybrids 9051 and Shan Tong juvenile wood
Tablica 3. Analiza varijance (ANOVA) fizičkih svojstava juvenilnog drva hibrida paulovnije 9051 i Shan Tong

Property *Svojstvo*	**Effect** *Varijabilnost*	**Sum of squares** *Suma kvadrata*	**Degree of freedom** *Stupnjevi slobode*	**Mean square** *Varijanca*	F	p
Oven dry density *gustoća u apsolutno suhom stanju*	Between Groups / *između grupa*	0.003	1	0.003	8.41	0.005
	Within Groups / *unutar grupa*	0.020	66	0.000		
	Total / *ukupno*	0.023	67			
Basic density *nominalna gustoća*	Between Groups / *između grupa*	0.003	1	0.003	12.67	0.000
	Within Groups / *unutar grupa*	0.015	66	0.000		
	Total / *ukupno*	0.018	67			
Density at maximum MC *gustoća pri maksimalnom sadržaju vode*	Between Groups / *između grupa*	0.043	1	0.043	8.649	0.005
	Within Groups / *unutar grupa*	0.329	66	0.005		
	Total / *ukupno*	0.372	67			
Longitudinal shrinkage *longitudinalno utezanje*	Between Groups / *između grupa*	0.513	1	0.051	0.678	0.413
	Within Groups / *unutar grupa*	4.990	66	0.076		
	Total / *ukupno*	5.503	67			
Radial shrinkage *radijalno utezanje*	Between Groups / *između grupa*	0.262	1	0.262	0.822	0.368
	Within Groups / *unutar grupa*	21.028	66	0.319		
	Total / *ukupno*	21.290	67			
Tangential shrinkage *tangentno utezanje*	Between Groups / *između grupa*	2.038	1	2.038	3.014	0.087
	Within Groups / *unutar grupa*	44.634	66	0.676		
	Total / *ukupno*	46.672	67			
Volumetric shrinkage *volumno utezanje*	Between Groups / *između grupa*	4.244	1	4.244	2.722	0.103
	Within Groups / *unutar grupa*	102.903	66	1.559		
	Total / *ukupno*	107.147	67			
Maximum MC *maksimalni sadržaj vode*	Between Groups / *između grupa*	233.0	1	233.0	0.628	0.430
	Within Groups / *unutar grupa*	24491.0	66	0.781		
	Total / *ukupno*	24724.0	67			

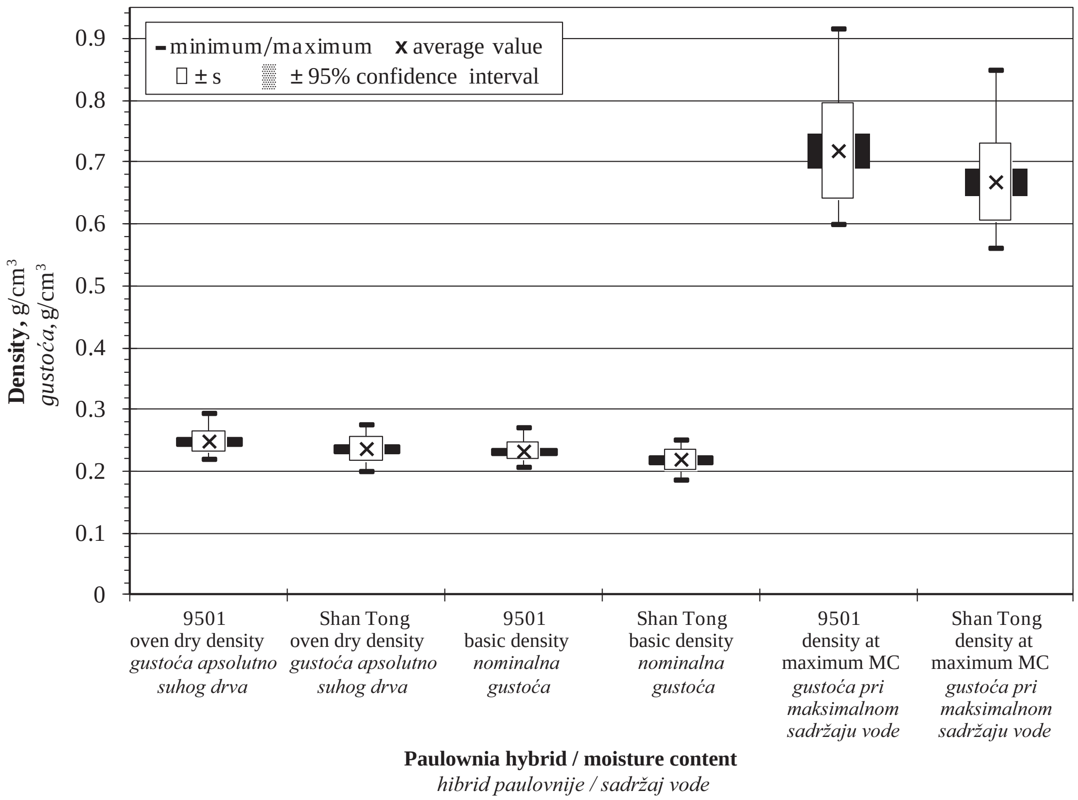

Figure 2 Statistical analyses of oven dry density, basic density and density at maximum MC, between two paulownia hybrids
Slika 2. Statistička analiza gustoće u apsolutno suhom stanju, nominalne gustoće i gustoće pri maksimalnom sadržaju vode, dvaju hibrida paulovnije

Table 4 Relationship between oven dry density and shrinkage of Paulownia hybrids 9051 and Shan Tong juvenile wood
Tablica 4. Odnos između gustoće i utezanja juvenilnog drva hibrida paulovnije 9501 i Shan Tong

	R	**Equation** / *Jednadžba*	*F*[a]	*p*
Relationship between oven dry density and shrinkage (9501) *Odnos između gustoće u apsolutno suhom stanju i utezanja (9501)*				
Longitudinal shrinkage / *longitudinalno utezanje*	0.02		0.113 [NS]	0.916
Radial shrinkage / *radijalno utezanje*	0.4635		8.751 *	0.006
Tangential shrinkage / *tangentno utezanje*	0.3073		3.334[NS]	0.077
Volumetric shrinkage / *volumno utezanje*	0.5014		10.745*	0.003
Relationship between oven dry density and shrinkage (Shan Tong) *Odnos između gustoće u apsolutno suhom stanju i utezanja (9501)*				
Longitudinal shrinkage / *longitudinalno utezanje*	0.0980		0.311[NS]	0.581
Radial shrinkage / *radijalno utezanje*	0.3468		4.375*	0.045
Tangential shrinkage / *tangentno utezanje*	0.3045		3.268[NS]	0.080
Volumetric shrinkage / *volumno utezanje*	0.3183		3.609[NS]	0.067

*significant at level < 0.05 / *značajno pri < 0,05*
[NS]not significant / *nije značajno*

nility of wood. Irregularity and large variations in longitudinal shrinkage were reported by many authors (Welch, 1932 and 1934; Kelsey, 1963; Hann, 1969; Skaar, 1988). Based on the work of Harris and Meylan (1965), the major cause of the variation in longitudinal shrinkage is varying microfibril angle.

Table 2 shows the comparison of investigated values of shrinkage with other authors.

In this study, regression equations between oven dry density and shrinkage, as well as, statistical significance between two properties are shown in Table 4. The relationship between oven dry density and shrinkage is statistically significant only for radial and tangential shrinkage of hybrid 9501 and radial shrinkage of hybrid Shan Tong. Negative correlation between oven dry density and longitudinal shrinkage in both hybrids was determined. Radial, tangential and volumetric shrinkage showed positive correlation with oven dry density. Measured shrinkages showed weak correlation coefficient with oven dry density, except radial and volumetric shrinkage of hybrid 9501. Similar results were reported by Šoškić *et al*. (2003) for *Paulownia elongata* and *Paulownia fortunei* wood.

4 CONCLUSIONS
4. ZAKLJUČAK

Preliminary result of juvenile wood of two *Paulownia* hybrids showed statistically significant differences between mean values of some investigated physical properties.

Significant differences in oven dry density, basic density and density at maximum MC, between hybrid 9501 and hybrid Shan Tong were determined. However, these differences in mean values of densities amounted only to about 6 %.

There is no statistically significant difference in longitudinal, radial, tangential and volumetric shrinkages between the two hybrids.

Radial, tangential and volumetric shrinkage values of both investigated hybrids are similar to references for some *Paulownia* wood species.

Both hybrids should be investigated after five to ten years when they reach larger diameters.

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5 REFERENCES
5. LITERATURA

1. Ates, S.; Ni, Y.; Akgul, M.; Tozluoglu, A., 2008: Characterization and evaluation of Paulownia elongata as a raw material for paper production. African Journal of Biotechnology, 7.
2. Akyildiz, M. H.; Kol, H. S., 2010: Some technological properties and uses of paulownia *(Paulownia tomentosa Steud.)* wood. Journal of Environmental Biology, 31 (3): 351-355.
3. Drvodelić, D., 2018: Propagation of Paulownia by root cuttings. Šumarski list, 5-6: 297-307. https://doi.org/10.31298/sl.142.5-6.2.
4. El-Showk, S., 2003: The Paulownia Tree. An Alternative for Sustainable Forestry, http://cropdevelopment.org/docs/PaulowniaBooklet.pdf (Accessed Oct 1, 2019).
5. Harris, J. M.; Meylan, B. A., 1965: The influence of microfibril angle on longitudinal and tangential shrinkage in Pinus radiata. Holzforschung, 19 (5):144-153.
6. Hann, R. A., 1969: Longitudinal shrinkage in seven species of wood. U.S.D.A. forest service research note. Madison, Wisconson.
7. Icka, P.; Damo, R.; Icka, E., 2016: Paulownia tomentosa, a fast growing timber. The annals of Valahia. University of Targoviste, Trgoviste, Romania. https://doi.org/10.1515/agr-2016-0003.
8. Ištok, I.; Sedlar, T.; Šefc, B.; Sinković, T.; Perković, T., 2016: Physical Properties of Wood in Poplar Clones ’I-214’ and ’S1-8’. Drvna industrija, 67 (2), 163-170. https://doi.org/10.5552/drind.2016.1604.
9. Kelsey, K. E., 1963: The shrinkage-moisture content relationship for wood with special reference to longitudinal shrinkage. Australia. C.S.I. RO. Div. Forest Prod. Proj. T.P. 8, Prog. Rep. No. 2, 18 pp., Melbourne.

10. Kiaei, M., 2013: Technological properties of Iranian cultivated paulownia wood *(Paulownia fortunei)*. Cellulose Chemistry and Technology, 47 (9-10): 735-743.
11. Komán, S.; Feher, S.; Vityi, A., 2017: Physical and mechanical properties of Paulownia tomentosa wood planted in Hungaria. Wood Research, 62 (2): 335-340.
12. Olson, J.; Carpenter, S. B., 1982: Specific gravity, fiber length and extractive content of young paulownia. Wood and Fiber Science, 17 (4): 428-438.
13. San, H. P.; Long, L. K.; Zhang, C. Z.; Hui, T. C.; Seng, W. Y.; Lin, F. S.; Hun, A. T.; Fong, W. K., 2016: Anatomical Features, Fiber Morphological, Physical and Mechanical Properties of Three Years Old New Hybrid Paulownia: Green Paulownia. Research Journal of Forestry, 10: 30-35. https://doi.org/10.3923/rjf.2016.30.35.
14. Skaar, C., 1988: Wood-water relations. In: T. E. Timell (ed.), Springer Series in Wood Science. Springer-Verlag, Berlin, Heidelberg.
15. Šoškić, B.; Lovrić, A.; Vukovojac, B., 2003: The research of some physical properties of wood Paulownia elongata and Paulownia fortuneii. Glasnik Šumarskog fakulteta, Beograd, 87, pp. 211-221.
16. Welch, M. B., 1932: The longitudinal variation of timber during seasoning. Journal and proceedings of the Royal SOC. New South Wales, 66: 492-497.
17. Welch, M. B., 1934: The longitudinal variation of timber during seasoning. Journal and proceedings of the Royal SOC. New South Wales, 68: 249-254.
18. Vilotić, D.; Popović, J.; Mitrović, S.; Šijačić-Nikolić, M.; Ocokoljić, M.; Novović, J.; Veselinović, M., 2015: Dimensions of Mechanical Fibres in Paulownia elongata S. Y. Hu Wood from Different Habitats. Drvna industrija, 66 (3): 229-234. https://doi.org/10.5552/drind.2015.1365.
19. Vusić, D.; Migalić, M.; Zečić, Ž.; Trkmić, M.; Bešlić, A.; Drvodelić, D., 2018: Fuel properties of Paulownia biomass. Proceedings of Natural resources, green technology and sustainable development. Zagreb, Croatia, 5-8 6. 2018, pp. 126-130.
20. Zhao-Hua, Z.; Ching-Ju, C.; Xin-Yu, L.; Yao Gao, X., 1986: Paulownia in China: Cultivation and Utilization. Asian Network for Biological Sciences and International Development Research Centre, Beijing, China.
21. *** HRN ISO 3129, 2015: Drvo – Metode uzorkovanja i opći zahtjevi za ispitivanje fizikalnih i mehaničkih svojstava na manjim uzorcima masivnog drva
22. *** HRN ISO 13061-1, 2015: Fizikalna i mehanička svojstva drva – Metode ispitivanja za manje uzorke masivnog drva, 1. dio: Određivanje sadržaja vode za provođenje ispitivanja fizikalnih i mehaničkih svojstava.
23. *** HRN ISO 13061-2, 2015: Fizikalna i mehanička svojstva drva – Metode ispitivanja za manje uzorke masivnog drva, 2. dio: Određivanje gustoće za provođenje ispitivanja fizikalnih i mehaničkih svojstava.
24. *** ISO 13061-13, 2016: Physical and mechanical properties of wood – Test methods for small clear wood specimens, Part 13: Determination of radial and tangential shrinkage.
25. *** ISO 13061-14, 2016: Physical and mechanical properties of wood – Test methods for small clear wood specimens, Part 14: Determination of volumetric shrinkage.

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Thermal Degradation of Bonding Strength of Aspen Plywood

Toplinska degradacija čvrstoće lijepljenja ploče od uslojenog drva jasike

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ABSTRACT • *The objective of this research was to study the effect of exposure time on the bonding strength of aspen plywood at elevated temperatures. The plywood samples were manufactured under laboratory conditions using two types of adhesive: urea-formaldehyde (UF) and phenol-formaldehyde (PF). The plywood samples were tested after exposure to three different temperatures (150 °C, 200 °C and 250 °C) and three exposure time levels (1, 2 and 3 hours) at each temperature. Additionally, a set of control samples was tested at room temperature. The quality of bonding was assessed by shear strength test in compliance with the requirements of the standard EN 314-1. The mass and density losses as well as colour changes of the plywood samples were also determined. The findings of this study indicated that exposure of plywood panels to elevated temperature caused significant degradation of their bonding strength. PF plywood samples lost 63.2 % of their initial strength after 3 h of exposure at 250 °C, while UF samples lost 65.9 % of their initial strength already after 3 h of exposure at the temperature of 200 °C. Statistical regression-based models were also developed for predicting the loss of plywood bonding strength as functions of mass and density losses and total colour difference. As the mass/density losses or total colour difference of panels increased, the losses in bonding strength increased too.*

Keywords: *plywood; heat treatment; bonding strength; mass loss; density loss; colour change*

SAŽETAK • *Cilj ovog istraživanja bio je ispitati utjecaj vremena izlaganja toplini na čvrstoću lijepljenja ploča od uslojenog drva jasike. Uzorci ploča od uslojenog drva proizvedeni su u laboratorijskim uvjetima uporabom dvije vrste ljepila: urea-formaldehidnog (UF) i fenol-formaldehidnog (PF) ljepila. Uzorci ploča od uslojenog drva ispitani su nakon izlaganja različitim temperaturama (150 °C, 200 °C i 250 °C) tijekom različitog vremena izlaganja (1, 2 i 3 sata). Usto, skupina kontrolnih uzoraka ispitana je pri sobnoj temperaturi. Kvaliteta lijepljenja ocijenjena je testom smične čvrstoće u skladu sa zahtjevima norme EN 314-1. Također, određeni su gubitci mase i smanjenje gustoće, kao i promjena boje uzoraka ploča od uslojenog drva. Rezultati ove studije pokazali su da izlaganje ploča od uslojenog drva povišenoj temperaturi uzrokuje znatno smanjenje njihove čvrstoće lijepljenja. Uzorci ploča od uslojenog drva zalijepljeni PF ljepilom izgubili su 63,2 % svoje početne čvrstoće nakon tri sata izlaganja na 250 °C, dok su uzorci ploča od uslojenog drva zalijepljeni UF ljepilom izgubili 65,9 % početne čvrstoće već nakon tri sata izloženosti temperaturi 200 °C. Nadalje, razvijeni su statistički regresijski modeli za predviđanje gubitka čvrstoće lijepljenja ploča od uslojenog drva kao funkcije gubitka mase, smanjenja gustoće i ukupne razlike u boji. Kako se povećavao gubitak mase, smanjivala gustoća ili povećavala ukupna razlika u boji ploča, tako su se povećavali i gubitci čvrstoće lijepljenja.*

Ključne riječi: *ploča od uslojenog drva; toplinsko tretiranje; čvrstoća lijepljenja; gubitak mase; smanjenje gustoće; promjena boje*

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1 INTRODUCTION
1. UVOD

Global plywood production and consumption are increasing (FAO 2018). Plywood is widely used in various industries, in particular in construction. Due to its high physical and mechanical properties, plywood is used in construction side by side with solid wood. In Ukraine, birch and alder are used mainly for plywood production while aspen is much less used. One of the reasons for the lack of use of aspen in the production of plywood is the lack of information on the behaviour of such plywood when exposed to high temperatures. The increasing use of plywood in construction requires knowledge of the behaviour of plywood in different environmental conditions. In particular, structural members made using plywood can be subjected to high temperatures. Therefore, knowledge of the properties of plywood under high temperature is extremely important.

The performance of solid wood or wood-based composites, such as particleboard, flakeboard, waferboard, and oriented strandboard (OSB) at or after exposure to elevated temperatures has been well studied (Suchsland and Enlow 1968; Hsu *et al*., 1989; Zhang *et al*., 1997; Bekhta *et al*., 2003; Ohlmeyer and Lukowsky 2004; Del Menezzi and Tomaselli 2006, Bekhta and Marutzky 2007; Okino *et al*., 2007). These studies generally reported that the post heat treatment improved dimensional stability and enhanced durability and fungal resistance of materials, while decreasing the mechanical properties of the composites. The performance of plywood panels at or after exposure to elevated temperatures is less studied. Some authors (Sinha *et al*., 2011b; Zhou *et al*., 2012; Lunguleasa *et al*., 2018) found that the bending strength of plywood panels decreased with the increase of the heat treatment temperature and exposure time. Sinha *et al*., (2011a) also proposed regression models to predict the loss of plywood strength as a function of temperature and duration of heat treatment. Candan *et al*., (2012) showed that (a) increasing the severity of thermal treatment of plywood panels resulted in smoother surfaces; (b) the wettability properties of the treated panels were lower than those of the untreated panels; (c) the treated panels exhibited more hydrophobic characteristics for outdoor application.

Shear strength is one of the main parameters of plywood panels by which their quality of bonding is evaluated. An extensive literature search did not reveal any information about the effects of elevated temperatures on adhesive bonding performance of interior aspen plywood. The objective of this research was to investigate the effects of heat-treatment on the adhesive bonding strength of the plywood panels made using different types of adhesive.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, an aspen (*Populus tremula* L.) rotaty cut wood veneer was used. The thickness of the veneer was 1.5 mm, and the moisture content of veneer sheets was 6-8 %.

The plywood panels had been bonded using commercial urea-formaldehyde (UF) KFC-0.1-MYY and phenol formaldehyde (PF) Vatex-244 resins. We chose UF and PF resins because these adhesives are most commonly used for the manufacture of plywood (UF is interior-type resin, while PF is a more heat-resistant, exterior-type resin). UF and PF adhesives had the following parameters, respectively: solid content 66 % and 46 %, dynamic viscosity 379.3 and 213.7 MPa·s, gel time 55 s (at 100 °C) and 120 s (at 150 °C), free formaldehyde content not more than 0.15 and 0.1 %, hydrogen ion concentration (pH) 8.6 and 12. UF adhesive solution used in the manufacturing was composed of 100 parts of UF resin by weight, 15 parts of wheat flour by weight, and 4 parts of 15 % concentrated NH_4Cl by weight. The PF resin was used for plywood panel manufacturing without any filler or additive.

Plywood panels of 300 mm × 300 mm were made in an electrically heated hydraulic laboratory press. The specific pressing pressure of 1.8 MPa and temperature of 130 °C were used, and 6 min pressing time (during the last 30 s of the press cycle the pressure was continuously reduced to 0 MPa). In this study, we applied the same pressing temperature of 130 °C, as well as the same pressing modes to both adhesives, only to be able to compare the properties of UF and PF plywood panels made under the same conditions, knowing that the same pressing modes for these two adhesives may affect, to some extent, the final properties of the panels. The adhesive spreads were 120 and 130 g/m^2 based on wet mass for UF and PF adhesive, respectively. The adhesive was applied onto one side of every uneven ply. The plies were assembled perpendicularly to each other (veneer sheets were laid up tight/loose) to form plywood of five plies. Adhesive was applied on the veneer surface with a hand roller spreader. After pressing, the plywood panels were subjected to conditioning for 5 days, after which all panels were cut to extract test samples according to the standard requirements. Three plywood panels were made for each experimental condition and control.

The heat treatment of the test samples was performed in a laboratory temperature controlled ventilated oven SNOL 67/350 (AB "Utenos Elektrotechnika", Lithuania) with ±1 °C sensitivity under atmospheric pressure. All samples were heat treated at a temperature of 150 °C, 200 °C and 250 °C during 1, 2 and 3 hours at each temperature in the presence of air. Once the samples were taken out of the oven, they were cooled to room temperature before testing. Thereafter, the dimensions and weights of the plywood samples were measured to calculate the density of the plywood panels according to the standard EN 323:1993. Moreover, after heat treatment and cooling, the mass and density losses were determined and colour parameters were estimated. Then, bonding strength test was carried out according to the relevant standard (EN 314-1:2003). The bonding strength was determined by adhesive layer near the middle of the sample, i.e. at the second layer of glue. The quality of bonding was assessed in compliance with the requirements of this standard, pre-treatment according to point 5.1.1 (interior conditions): samples immersion for 24-h in water at a temperature of 20±3 °C. Fifteen samples were used for each variant of bonding strength mechanical testing. Additionally, a set of control samples was tested at room temperature.

The colour measurements of all specimens were recorded on the surface of plywood samples before and after thermal treatment with a colorimeter Minolta Croma-Meter CR-300. The *CIEL*a*b** colour system was used, where L^* describes the lightness, a^* and b^* describe the chromatic coordinates on the green-red and blue-yellow axis, respectively. From the $L^*a^*b^*$ values, the colour uniformity was calculated as a difference in the lightness (ΔL^*) and chromaticity parameters (Δa^* and Δb^*) between heat-treated and un-treated plywood samples. In addition, hue angle (h), saturation (C^*) and total colour difference (ΔE) were calculated too. On the hue circle, h = 0° denotes redness and h = 90° denotes yellowness. Saturation C^*, corresponding to the distance between the colour and the centre of the chromaticity plane, is a measure of colour intensity. For each specimen, 10 random measurements of surface colour were taken.

The analysis of variance (ANOVA) was conducted to study the effect of the heat treatment temperature and exposure time on the properties of plywood samples at the 0.95 confidence interval.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Mass and density losses of heat-treated plywood samples
3.1. Gubitak mase i smanjenje gustoće toplinski tretiranih uzoraka ploča od uslojenog drva

Table 1 shows the mass and density losses of the plywood samples bonded with UF and PF adhesives under different conditions of heat treatment. The mass and density losses of the UF-bonded samples are slightly greater than the mass and density losses of the PF-bonded samples. As can be seen from Table 1, the increase in mass and density losses of the samples with increasing temperature and duration of heat treatment is typical (characteristic) of heated plywood samples. Particularly dramatic loss of mass and density of the samples is observed under heat treatment at 250 °C for 3 hours. At the temperature of 250 °C, the mass and density losses for both UF- and PF-bonded plywood samples exceeded 20 %. At the temperature of 150 °C for treatment time of 1-3 hours, the mass and density losses averaged 7.6-8.1 % and 4.0-7.8 % for UF- and PF-bonded plywood samples, respectively. These losses are obviously connected with the evaporation of moisture from the plywood samples. With the increase of the heat treatment temperature up to 200 °C, the mass and density losses continued to increase. The highest mass losses of 33.1 % and 36.6 % were observed for PF and UF samples at 250 °C/3 h heat treatment. At high treatment temperature, the significant mass loss is caused by the release of various by-products during degradation of wood hemicellulose (Bekhta and Niemz, 2003; Poncsak *et al.*, 2006).

The highest density losses of 25.0 % and 27.7 % were observed for PF and UF samples at 250 °C/3 h heat treatment. Besides, the density of plywood samples decreases more with increasing temperature at the same treatment time than with increasing the duration of treatment at a certain temperature. With increasing processing time, the plywood samples lost more mass and consequently their density decreased.

Similarly, applying heat treatment to OSB panels, some researchers (Del Menezzi and Tomaselli, 2006; Mendes *et al.*, 2013) have established that, with the increase in treatment temperature and duration, the panels lost more mass, and finally, their density reduced. Lunguleasa *et al.* (2018) also observed that the mass loss of beech plywood panels increased whereas bending strength decreased with the increase of heat treatment duration and temperature.

3.2 Colour changes of plywood samples
3.2. Promjene boje uzoraka ploča od uslojenog drva

It is possible to use colour to evaluate the strength of heated plywood panels. Therefore, as a degradation indicator, colour changes were measured. The colour pa-

Table 1 Mass and density losses of aspen plywood samples depending on the type of adhesive and treatment temperature and time
Tablica 1. Gubitak mase i smanjenje gustoće uzoraka ploča od uslojenog drva jasike ovisno o vrsti ljepila, temperaturi i vremenu izlaganja

Temperature of treatment, °C *Temperatura tretiranja, °C*	**Time of treatment, h** *Vrijeme izlaganja,* h	**Mass losses, %** *Gubitak mase, %*		**Density losses, %** *Smanjenje gustoće, %*	
		PF	**UF**	**PF**	**UF**
150	1	7.64	7.90	4.37	7.33
	2	7.96	8.07	6.66	7.61
	3	7.67	8.12	4.04	7.76
200	1	9.71	8.77	10.09	5.93
	2	11.58	9.94	13.45	6.09
	3	13.03	10.26	13.06	11.32
250	1	22.50	27.64	15.23	21.98
	2	30.17	29.69	22.76	23.81
	3	33.09	36.60	25.04	27.69

rameters L^*, a^*, b^*, h, C^* and the differences of ΔL, Δa, Δb, ΔC, and ΔE are presented in Tables 2 and 3. The heat treatment provides a darkening of the surface of the plywood panels. The degree of colour change of the samples depends on the temperature to which the samples were subjected. At 150 °C, the changes in colour were slight. This is because the major change in the material was caused by the loss of water and volatile organic compounds that lead to physical changes. The darkening of the surfaces of the samples increased gradually, depending on the change in the treatment temperature ranging from 150 to 250 °C. Colour changes are significant at higher temperatures, mainly due to the transformation of carbohydrates, phenols and other extracts from the middle to the outside of the sample during the evaporation of moisture (Zhang *et al.*, 2013). Other authors (Hsu *et al.*, 1989; Del Menezzi and Tomaselli, 2006) have also observed such panel darkening when working with panel heat treatment.

Heat treatment of plywood samples reduces lightness of colour L^* and chromatic coordinates a^* and b^*. These parameters could be used as a factor for determining the level of the treatment of samples. The values of total colour difference are very high and proportional to the temperature applied (Table 3). The highest values of total colour difference were observed at the temperature of 250 °C, namely 56.4 % and 61.0 % for PF and UF bonded samples, respectively. Total colour difference is slightly higher for UF-bonded samples than for PF-bonded samples. At the highest treatment temperature of 250 °C, the colour of the samples changed from light to black, namely the lightness L^* of the samples decreased by 65.2 % and 67.6 % for the PF- and UF-bonded samples, respectively. At the same treatment conditions, the saturation C^* of the samples decreased by 73.0 % and 80.3 %, respectively, for the samples glued with PF and UF.

Colour changes, as well as mass loss of the plywood samples during heat treatment, are mainly caused by the chemical changes in the wood components, in particular by the degradation of hemicelluloses. This is confirmed by the close relationship between these parameters. We found a good correlation between mass loss and total colour difference (Fig. 1). The greater the mass loss, the stronger the colour changes and, conversely, the greater the colour changes, the greater the mass loss (Fig. 1). The finding of previous researches (Yildiz *et al.*, 2006; Nazerian *et al.*, 2011) also showed that heat treatment causes important degradations of the material and significant mass loss, resulting in a decrease of the hemicellulose content.

Table 2 Colour parameters of plywood samples before and after heat treatment (T – temperature of treatment; τ - time of treatment)
Tablica 2. Parametri boje uzoraka ploča od uslojenog drva prije i nakon toplinske obrade (T – temperatura tretiranja; τ – vrijeme izlaganja)

***T*, °C**	***τ*, h**	**PF**					**UF**				
		L*	***a****	***b****	***h***	***C****	***L****	***a****	***b****	***h***	***C****
Untreated / *Netretirani uzorci*		83.72	6.44	18.25	1.23	19.35	87.40	6.64	17.02	1.20	18.27
150	1	82.42	7.39	21.69	1.24	22.91	83.64	7.38	20.45	1.22	21.74
	2	82.71	7.12	20.17	1.23	21.39	82.78	7.64	23.83	1.26	25.02
	3	83.13	7.31	20.90	1.23	22.14	82.20	8.21	21.91	1.21	23.40
200	1	62.91	11.4	24.13	1.13	26.67	59.96	12.10	24.74	1.12	27.54
	2	58.72	11.7	23.72	1.11	26.43	50.58	11.80	21.47	1.07	24.50
	3	55.11	11.3	23.40	1.12	25.98	42.41	11.71	18.47	1.01	21.87
250	1	30.00	3.56	5.73	1.01	6.75	28.29	2.36	2.70	0.85	3.59
	2	29.14	2.85	4.38	0.99	5.23	28.64	3.11	3.73	0.88	4.86
	3	29.87	3.59	5.37	0.98	6.46	28.78	2.68	2.81	0.81	3.88

Table 3 Colour differences of plywood samples before and after heat treatment (T – temperature of treatment; τ - time of treatment)
Tablica 3. Razlike u boji uzoraka ploča od uslojenog drva prije i nakon toplinske obrade (T – temperatura tretiranja; τ – vrijeme izlaganja)

***T*, °C**	***τ*, h**	**PF**					**UF**				
		Δ*L**	**Δ*a****	**Δ*b****	**Δ*C****	**Δ*E***	**Δ*L****	**Δ*a****	**Δ*b****	**Δ*C****	**Δ*E***
150	1	-1.30	0.95	3.44	3.56	3.80	-3.76	0.74	3.43	3.47	5.14
	2	-1.01	0.68	1.92	2.04	2.27	-4.62	1.00	6.81	6.76	8.29
	3	-0.59	0.87	2.65	2.79	2.85	-5.20	1.57	4.89	5.13	7.31
200	1	-20.81	4.92	5.88	7.32	22.18	-27.44	5.46	7.72	9.27	29.02
	2	-25.00	5.21	5.47	7.07	26.12	-36.82	5.16	4.45	6.23	37.45
	3	-28.61	4.85	5.15	6.63	29.47	-44.99	5.07	1.45	3.60	45.30
250	1	-53.72	-2.88	-12.52	-12.61	55.23	-59.11	-4.28	-14.32	-14.68	60.97
	2	-54.58	-3.59	-13.87	-14.13	56.43	-58.76	-3.53	-13.29	-13.41	60.35
	3	-53.85	-2.85	-12.88	-12.89	55.44	-58.62	-3.96	-14.21	-14.39	60.45

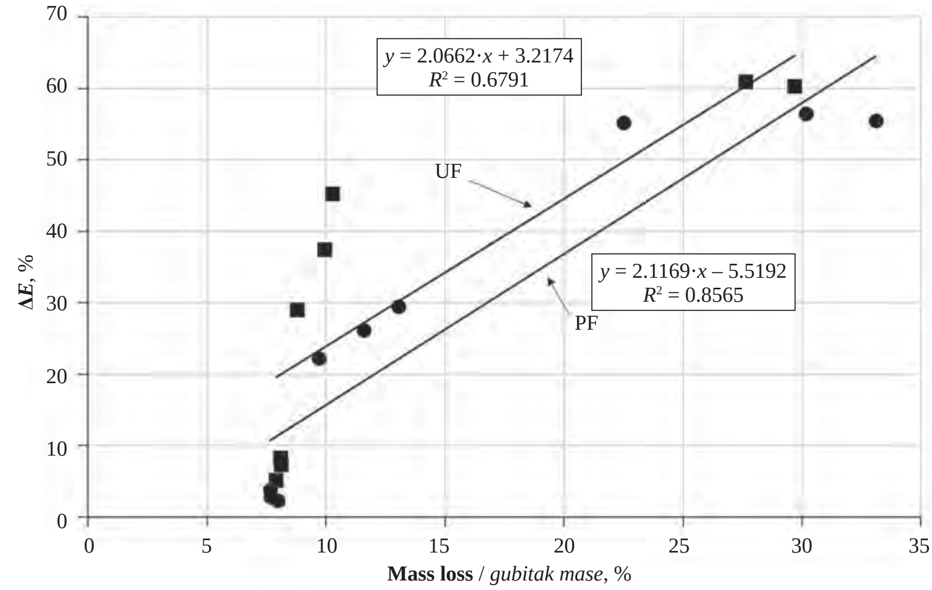

Figure 1 Correlation between total colour difference and mass loss of samples
Slika 1. Korelacija između ukupne razlike u boji i gubitka mase uzoraka

3.3 Shear strength of the plywood samples
3.3. Smična čvrstoća uzoraka ploča od uslojenog drva

Figures 2 and 3 show the dependence of the bonding strength on the temperature and duration of heat treatment. The highest decrease in bonding strength was observed for UF and PF plywood samples treated at 250 °C/3h, and a smaller one for the samples treated at 150 °C/1h.

For the PF plywood samples heat treated at the temperatures of 150 °C, 200 °C and 250 °C for 1-3 hours, the bonding strength is lower than that for the control untreated samples (Figures. 2, 3), but the average values are higher than 1 MPa (except the treatment at 250 °C /3h, 0.98 MPa with cohesive wood failure of 12 %). Therefore, the heat treated PF-bonded samples meet the requirements for plywood for use in interior conditions according to EN 314-2:1993, although shear strength is lower than that for untreated plywood samples. For the UF plywood samples treated at high temperatures of 150 °C and 200 °C for 1-3 h, the average values of bonding strength are also higher than 1 MPa. Further increasing temperature of heat treatment up to 250 °C at these durations leads to the reduction of bonding strength, and the average values are lower than 1 MPa, namely 0.71 MPa (cohesive wood failure of 25 %) and 0.78 MPa (cohesive wood failure of 30 %) for treatments at 250 °C /1h and 250 °C /2h, respectively. For UF-bonded samples heated at 250 °C for 3 h, it was not possible to determine the bonding strength due to the delamination of the samples.

Plywood, is a layered composite that contains wood and resin as adhesive. As plywood has a layered structure, its strength is highly dependent on adhesive between the layers. The degradation of the PF adhesive used in the manufacturing of plywood panels occurs at a temperature above 175 °C, while the degradation of

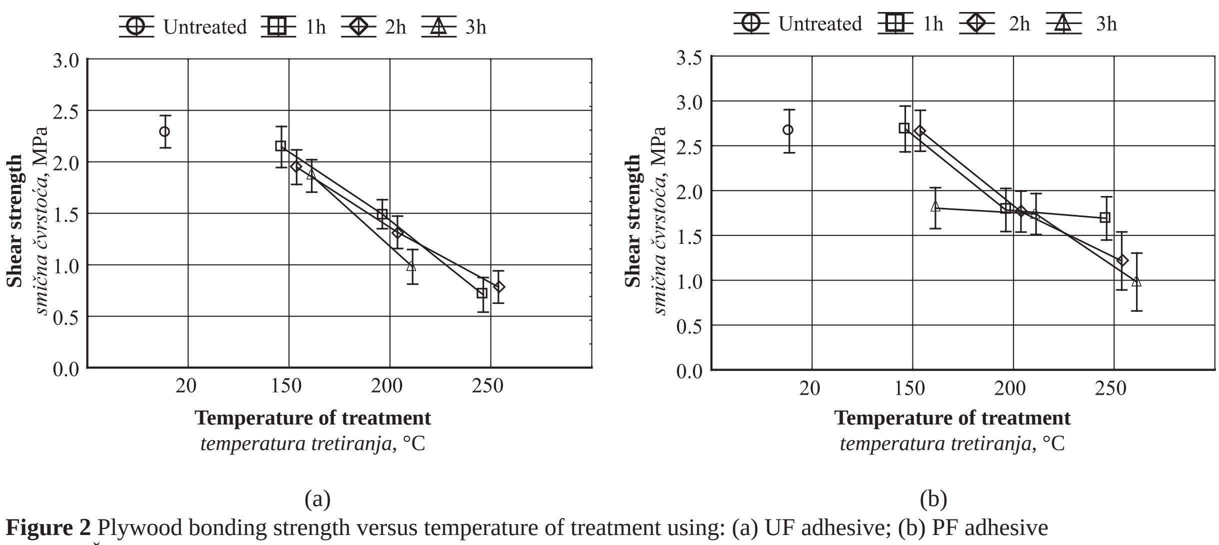

Figure 2 Plywood bonding strength versus temperature of treatment using: (a) UF adhesive; (b) PF adhesive
Slika 2. Čvrstoća lijepljenja ploča od uslojenog drva u ovisnosti o temperaturi tretiranja: (a) ploče s UF ljepilom, (b) ploče s PF ljepilom

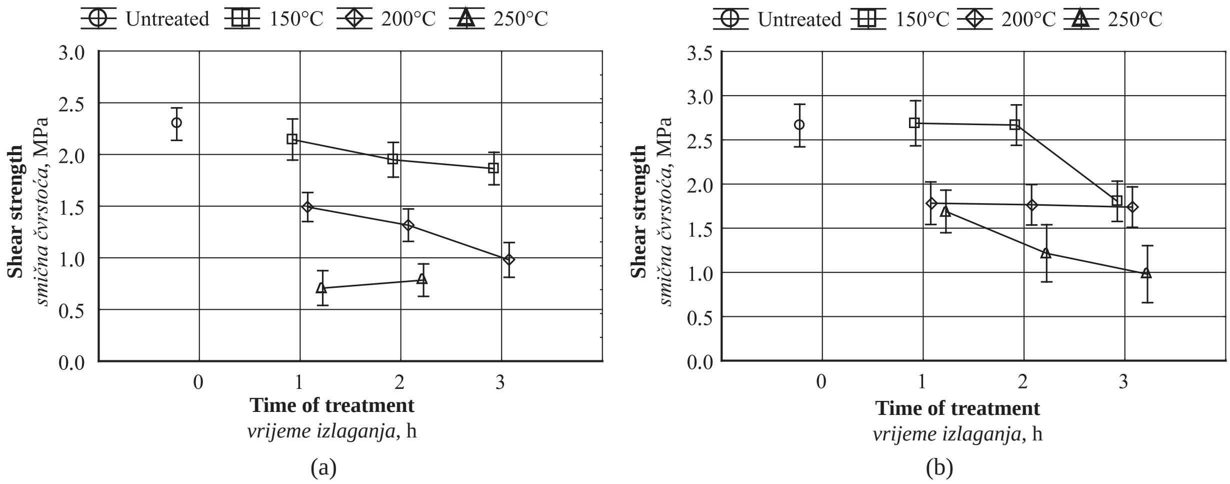

Figure 3 Plywood bonding strength versus time of treatment using: (a) UF adhesive; (b) PF adhesive
Slika 3. Čvrstoća lijepljenja ploča od uslojenog drva u ovisnosti o vremenu izlaganja toplini: (a) ploče s UF ljepilom, (b) ploče s PF ljepilom

UF adhesive occurs at a lower temperature. Therefore, when plywood samples are exposed to an elevated temperature, the degradation of the adhesive lines causes more rapid degradation in strength, especially for UF-bonded samples. The temperatures of 200 °C and 250 °C are high enough to cause both wood and resin to degrade. Therefore, during the heat treatment process, the panels degrade generally not only by degradation of wood veneers, but also by degradation of the adhesive and consequently also the veneer adhesion (Lunguleasa *et al.*, 2018).

As stated above, heat treatment of the plywood samples leads to loss of moisture, evaporation of extractives, degradation of hemicellulose and degradation of the resin. Together, all these lead to mass and density losses as well as to colour changes of the samples. As a result, there is a loss in bonding strength of the samples. Therefore, it was important to find out whether there are correlations between bonding strength and mass/density losses and total colour difference of the samples.

It was established that a good correlation exists between bonding strength loss and mass loss, between bonding strength loss and density loss, and between bonding strength loss and total colour difference of the samples (Figure 4). Linear regression models were

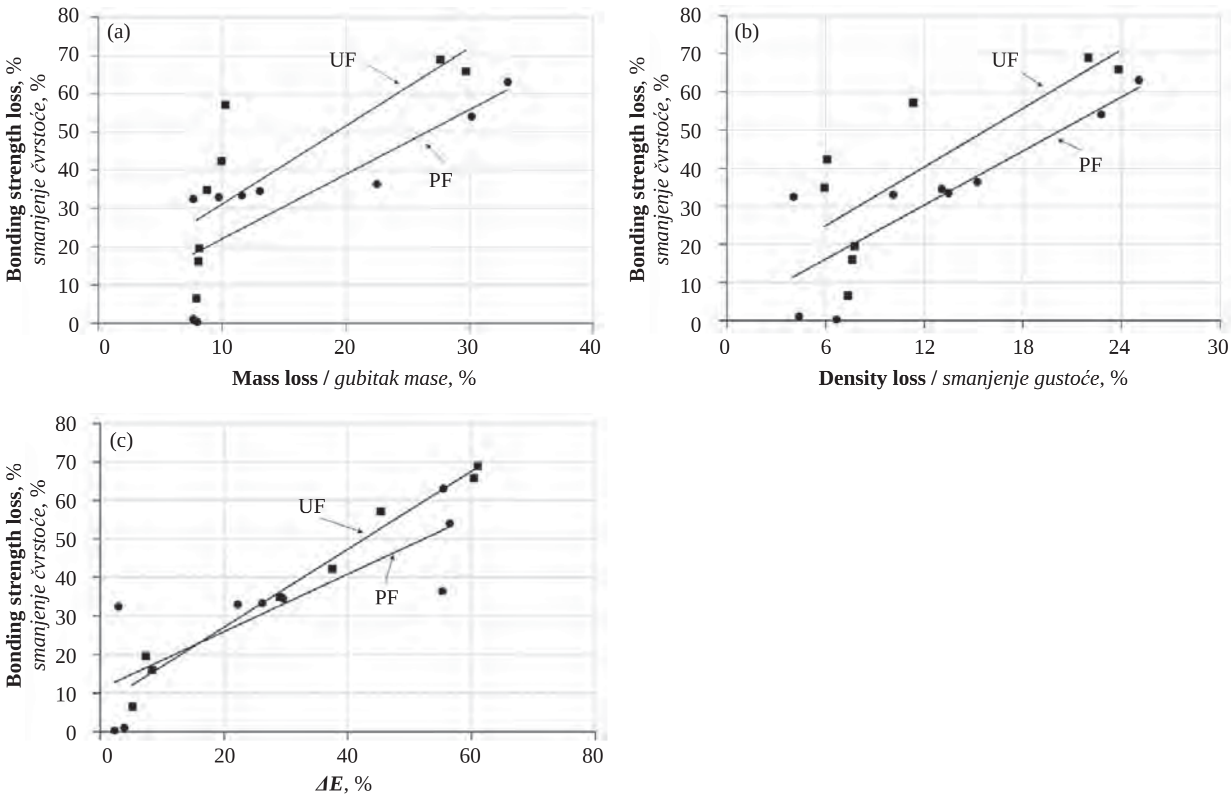

Figure 4 Correlation between bonding strength loss and: (a) mass loss; (b) density loss; (c) total colour difference
Slika 4. Korelacija između smanjenja čvrstoće lijepljenja ploča od uslojenog drva i (a) gubitka mase, (b) smanjenja gustoće, (c) ukupne razlike u boji

proposed to predict bonding strength loss (in %) depending on the mass loss (*ML*), density loss (*DL*) and total colour difference (ΔE) of the samples:

for UF-bonded samples:

Bonding strength loss = 2.0421 × *ML* + 10.795 (R^2 = 0.63)

Bonding strength loss = 2.5634 × *DL* + 9.5515 (R^2 = 0.62)

Bonding strength loss = 1.012 × ΔE + 6.8641 (R^2 = 0.98)

for PF-bonded samples:

Bonding strength loss = 1.6877 × *ML* + 5.2274 (R^2 = 0.67)

Bonding strength loss = 2.3664 × *DL* + 1.9497 (R^2 = 0.73)

Bonding strength loss = 0.7453 × ΔE + 11.093 (R^2 = 0.68).

In our previous study, we also found that the colour parameters can be estimated quantitatively and used as a prediction of wood strength (Bekhta and Niemz, 2003), although some authors (Unsal *et al.*, 2009) consider that darkening is a weak indicator in estimating the static flexural strength of the post heat-treated MDF panels.

4 CONCLUSIONS
4. ZAKLJUČAK

The findings of this study indicated that the exposure of aspen plywood panels to elevated temperature, especially above 200 °C, caused significant degradation of their bonding strength. The effect of temperature on the loss of bonding strength is more significant than the duration of heat treatment. The higher the heat treatment temperature and the longer the time, the more significant are the changes in plywood surface colour and in bonding strength. PF plywood samples lost 63.2 % of their initial strength after 3 h of exposure at 250 °C, while UF samples lost 65.9 % of their initial strength already after 3 h of exposure at the temperature of 200 °C; at 250 °C for 3 h the UF-bonded samples collapsed (delaminated). Statistical regression-based models were also developed for predicting the bonding strength loss of aspen plywood panels as functions of mass and density losses and total colour difference. As the mass/density losses or total colour difference of panels increased, the losses in bonding strength increased too.

5 REFERENCES
5. LITERATURA

1. Bekhta, P.; Łecka, J.; Morze, Z., 2003: Short-term effect of the temperature on the bending strength of wood-based panels. Holz als Roh- und Werkstoff, 61 (6): 423-424. https://dx.doi.org/10.1007/s00107-003-0423-4.
2. Bekhta, P.; Marutzky, R., 2007: Bending strength and modulus of elasticity of particleboards at various temperatures. Holz ald Roh- und Werkstoff, 65 (2): 163-165. https://dx.doi.org/10.1007/s00107-006-0134-8.
3. Bekhta, P.; Niemz, P., 2003: Effect of High Temperature on the Change in Colour, Dimensional Stability and Mechanical Properties of Spruce Wood. Holzforschung, 57: 539-546.
4. Candan, Z.; Buyuksarı, U.; Korkut, S.; Unsal, O.; Cakıcıer, N., 2012: Wettability and surface roughness of thermally modified plywood panels. Industrial Crops and Products, 36: 434-436. https://dx.doi.org/10.1016/j.indcrop.2011.10.010.
5. Del Menezzi, C. H. S.; Tomaselli, I., 2006: Contact thermal posttreatment of oriented strandboard to improve dimensional stability: a preliminary study. Holz als Roh- und Werkstoff, 64 (3): 212-217. http://dx.doi.org/10.1007/s00107-005-0052-1.
6. Hsu, W. E.; Schwald, W.; Shields, J. A., 1989: Chemical and physical changes required for producing dimensionally stable wood-based composites. Part 2: Heat post treatment. Wood Science and Technology, 23 (3): 281-288.
7. Lunguleasa, A.; Ayrilmis, N.; Spirchez, C.; Özdemir, F., 2018: Investigation of the Effects of Heat Treatment Applied to Beech Plywood. Drvna industrija, 69 (4): 349-355. https://dx.doi.org/10.5552/drind.2018.1768.
8. Mendes, R. F.; Bortoletto Júnior, G.; Almeida, N. F.; Surdi, P. G.; Barbeiro, I. N., 2014: Effect of thermal treatment on properties of OSB panels. Wood Science and Technology, 47 (2): 243-256. http://dx.doi.org/10.1007/s00226-012-0494-7.
9. Nazerian, M.; Ghalehno, M. D.; Kashkooli, X., 2011: Effect of Wood Species, Amount of Juvenile Wood and Heat Treatment on Mechanical and Physical Properties of Laminated Veneer Lumber. Journal of Applied Sciences, 11 (6): 980-987. https://doi.org/10.3923/jas.2011.980.987.
10. Ohlmeyer, M.; Lukowsky, D., 2004: Wood-based panels produced from thermal treated materials: Properties and perspectives. In: Conference on Wood Frame Housing Durability and Disaster Issue, 4-6th Oct, Las Vegas, pp. 127-131.
11. Okino, E. Y. A.; Teixeira, D. E.; Del Menezzi, C. H. S., 2007: Post-thermal treatment of oriented strandboard (OSB) made from cypress (*Cupressus glauca* lam.). Maderas Cienca Tecnology, 9 (3): 199-210.
12. Paul, W.; Ohlmeyer, M.; Leithoff, H., 2007: Thermal modification of OSB-strands by a one-step heat pre-treatment – Influence of temperature on weight loss, hygroscopicity and improved fungal resistance. Holz als Roh- und Werkstoff, 65 (1): 57-63. http://dx.doi.org/10.1007/s00107-006-0146-4.
13. Poncsak, S.; Kocaefe, D.; Bouazara, M.; Pichette, A., 2006: Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*). Wood Science and Technology, 40: 647-663. https://dx.doi.org/10.1007/s00226-006-0082-9.
14. Sinha, A.; Gupta, R.; Nairn, J. A., 2011a: Thermal degradation of bending properties of structural wood and wood-based composites. Holzforschung, 65 (2): 221-229. https://dx.doi.org/10.1515/HF.2011.001.
15. Sinha, A.; Nairn, J. A.; Gupta, R., 2011b: Thermal degradation of bending strength of plywood and oriented strand board: a kinetics approach. Wood Science and Technology, 45: 315-330. https://dx.doi.org/10.1007/s00226-010-0329-3.
16. Suchsland, O.; Enlow, R. C., 1968: Heat treatment of exterior particleboard. Forest Products Journal, 18 (8): 24-28.
17. Unsal, O.; Buyuksari, U.; Ayrilmis, N.; Korkut, S., 2009: Properties of wood and wood based materials subjected to thermal treatments under various conditions. In: Proceedings of the International Conference “Wood Science and Engineering in the Third Millennium” – ICWSE 2009, Brasov, Romania, 2009, pp. 81-94.

18. Yildiz, S.; Gezer, E. D.; Yildiz, U. C., 2006: Mechanical and chemical behavior of spruce wood modified by heat. Building and Environment, 41: 1762-1766.
19. Zhang, X. Q.; Lu, R. S.; Wang, W. H.; Pu, A. B., 1997: Heat post-treatment to reduce thickness swelling of particleboard from fast-growing poplars. Journal of Forestry Research, 8 (3): 188-190. https://dx.doi.org/10.1007/BF02855417.
20. Zhang, Y. M.; Yu, W. J.; Zhang, Y. H., 2013: Effect of Steam Heating on the Color and Chemical Properties of Neosinocalamus Affinis Bamboo. Journal of Wood Chemistry and Technology, 33: 235-246. https://dx.doi.org/10.1080/02773813.2013.779714.
21. Zhou, J.; Hu, C.; Hu, S.; Yun, H.; Jiang, G.; Zhang, S., 2012: Effects of Temperature on the Bending Performance of Wood-Based Panels. BioResources, 7 (3): 3597-3606.
22. ***EN 314-1: 1993. Plywood. Bonding quality. Part 1: Test methods. European Committee for Standardization, Brussels, Belgium.
23. ***EN 314-2: 1993. Plywood. Bonding quality. Part 2: Requirements. European Committee for Standardization, Brussels, Belgium.
24. ***EN 323: 1993. Wood-based panels. Determination of density. European Committee for Standardization, Brussels, Belgium.
25. ***FAO, 2018: Global production and trade of forest products in 2017. http://www.fao.org/forestry/statistics/80938/en/.

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On-Line Measurement of Wood Surface Smoothness

Online mjerenje glatkoće površine drva

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ABSTRACT • *The latest progress in the field of optics and microelectronics resulted in the development of new generation vision systems capable of scanning surface topography with very high sampling frequencies. The blue color of illuminating light as well as novel systems for controlling ultra-thin laser line thickness allows the measurement of the porous surface of wood with a triangulation method. Three alternative sensors were tested here in order to verify their suitability for the determination of surface topography in the industrial environment. The scanning head was installed at the exit zone of the four-side profiling moulder and was set to scrutinize the wood surface shape line-by-line, immediately after profiling. The sensor was also tested for automatic detection of surface defects appearing on the elements after sanding, wetting and painting with various finishing products. The set of pilot test results is presented, together with an original algorithm for real-time surface defects detection.*

Keywords: *wood surface smoothness; triangulation scanner; surface defects; in-line*

SAŽETAK • *Najnoviji napredak u području optike i mikroelektronike rezultirao je novom generacijom skenera koji mogu skenirati topografiju površine vrlo visokom frekvencijom uzorkovanja. Svjetlost plave boje, kao i novi sustav za kontrolu vrlo tanke laserske zrake omogućuju mjerenje porozne površine drva metodom triangulacije. Testirana su tri alternativna senzora kako bi se potvrdila njihova prikladnost za određivanje topografije površine u industrijskim uvjetima. Glava za skeniranje postavljena je na izlazu četverostranoga profilnoga glodala kako bi se odmah nakon profiliranja pomno linijski skenirala površina drva. Senzor je također testiran za automatsko otkrivanje površinskih grešaka na elementima nakon brušenja, vlaženja i premazivanja različitim premaznim materijalima. Predstavljen je set rezultata pilot-ispitivanja, zajedno s originalnim algoritmom za otkrivanje površinskih grešaka u realnom vremenu.*

Ključne riječi: *glatkoća površine drva; triangularni skener; površinske greške; linijsko skeniranje*

1 INTRODUCTION
1. UVOD

Surface smoothness of products manufactured from wood is a critical property highly affecting product quality, its value and in-service life performance (Sandak, 2005). In a majority of cases, the surface of wood is an effect of the material allowance removed with a sharp cutting edge. The magnitude of roughness depends on several factors, where material properties, machining process kinematics, cutting tool conditions and machining imperfections are dominant (Škaljić *et al.*, 2009; Sofuoğlu, 2015). The ability for monitoring surface quality at the early stage of the production process was always a desire of process engineers (Nasir and Cool, 2018). Several methods were proposed for that purpose, but none of these were widely accepted by the wood industries. The superior methodology for

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monitoring surface smoothness should be non-contact, very fast, allowing on-line (preferably in-process) assessment and accurate enough to detect undesired defects (Zhao, 1992; Zhao, 1995; Župerl and Čuš, 2019; Dobrzynski *et al*., 2019; Lu *et al*., 2019). The best surface roughness scanner should allow measurement not only of a surface profile but rather the whole surface area (Kiliç *et al*., 2018; Lu *et al*., 2017).

Wood surface measurements can be performed in industrial conditions assuming in-line, on-line or off-line strategies (Figure 1). In-line installation of the smoothness sensor allows early detection of machining imperfections as the sensor monitors roughness directly after the cutting tool. In that case, the scanning frequency must be high enough to assure sufficient representation of the surface, considering very high feed speeds of modern processing systems. The sensor itself has to be very rigid and resistant to harsh environments (dust, vibrations, shocks, etc.). As an alternative to the in-line approach, surface smoothness can be measured on the selected representative samples following an off-line strategy. In that case, the sample is removed from the production line and presented to the measurement system in a specially conditioned place (e.g., laboratory). Off-line measurement allows superior reproduction of surface topography, including whole area evaluation as well as high topography magnification and optimal resolution. An apparent limitation of this solution is manual operation and inability for continuous analysis of a very limited number of samples. In between in-line and off-line is, therefore, on-line strategy, where the roughness sensor is installed separately from the woodworking machines on the main conveyer or for-the-purpose separated by-stream measurement line. On-line installation of the sensor allows measurement of all (or at least a high fraction) of produced surfaces, substantially increasing reliability of the quality assurance system (Lu and Tian, 2006).

The latest advancement in the field of optics and microelectronics resulted in the development of new generation vision systems capable of scanning surface topography. Interferometry, confocal microscopy or image stacking decomposition, are today widely used methods for surface topography mapping in laboratories or off-line applications (de Grot, 2019). On the other hand, triangulation systems allow for scanning surfaces with very high sampling frequencies, while still assuring accurate surface roughness reconstruction (Sandak and Negri, 2007). Problematic red-light scatter on the fibrous surface of wood has been recently minimized by implementing blue lasers as a source of light (Šustek and Siklienka, 2018). In that case, short light wavelengths minimize laser line thickness, diminishing the unwanted "tracheid effect". Such triangulation systems have been recently introduced on the market but never tested for their suitability in wood industries.

Aesthetical function of the wood surface dominates the highly customer-oriented market, where several alternatives to wood are available in a variety of applications (Manuel *et al*., 2015). One of the most demanding sectors is window production, where technical requirements for the surface quality of the final product are extremely high. Wood machining is an integral part of the production process for wooden window frames, where the surface generated by planing directly affects the sequence of operations that follow, especially surface finishing by coating or painting. In practice, it is very difficult to determine the state of cutting tools, where these are required to be re-sharpened or replaced. The excessive presence of surface defects increases production costs and absorbs qualified human resources for reparations. The challenge for this project was, therefore, to investigate the possibility of integrating state-of-the-art optical sensors with running production lines. Such sensors should scan the generated surface topography in-line or on-line, assuring autonomous operation and continuous data acquisition. Use of the sensor-derived data was to both:

- alert operators about the presence of surface defects resulting from the wood cutting process, and
- determine optimal time for replacement of the cutting tools, assuring compromise between long service life of the tool itself and superior surface quality of products.

This paper presents some of the preliminary results obtained during a pilot industrial test, together with a prototype software solution developed for the analysis of data provided by the surface smoothness sensor.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Triangulation sensors
2.1. Senzori za trianguliranje

Three alternative sensors were identified for testing in order to verify their suitability for the determination of wood surface topography in the industrial environment:

- Keyence LJ-7200 (scanned profile length: 62 mm, spatial resolution: 0.10 mm)
- Keyence LJ-7080 (scanned profile length: 32 mm, spatial resolution: 0.05 mm)
- Keyence LJ-7020 (scanned profile length: 7 mm, spatial resolution: 0.01 mm)

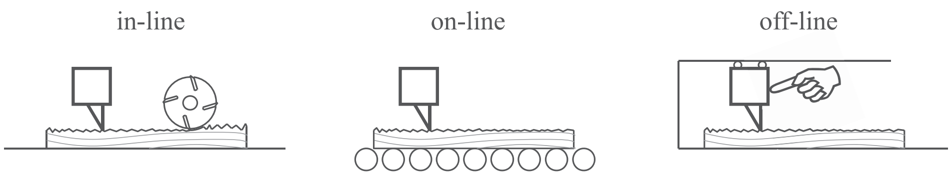

Figure 1 Assessment strategies for wood surface smoothness in the production factory
Slika 1. Strategije procjene glatkoće površine drva u proizvodnji

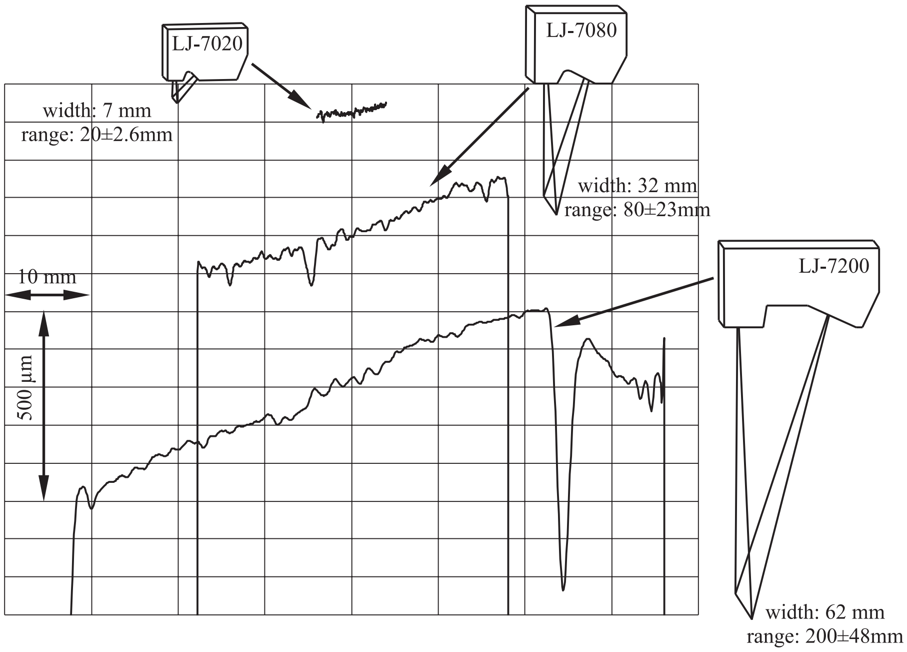

Figure 2 Examples of planed wood (Scots pine) surface profiles acquired with tested sensors: Keyence LJ-7020, LJ-7080 and LJ-7200
Slika 2. Primjer profila površine izblanjanog drva običnog bora dobivenih ispitnim senzorima Keyence LJ-7020, LJ-7080 i LJ-7200

All sensors were equipped with similar CCD detectors but different arrangement of optical components (Keyence, 2019). As a result, with increasing scanning length, the spatial resolution (along the scanned profile) was reduced, as well as accuracy for the determination of the minute surface irregularities, such as wood anatomical components. Figure 2 presents an example of surface profiles acquired by three sensors from the same wood sample (planed friezes made of Scots pine, measured in slightly different positions along the piece). It is evident that LJ-7200 covered a very wide part of the object, but the surface definition was relatively poor, especially when compared with LJ-7020. This disqualified the wide-range sensor for further investigations of surface smoothness assessment; however, this sensor has been identified as an optimal quality control tool for the accuracy of profiling complex frame shapes used in window production. Both LJ-7080 and LJ-7020 sensors were selected for further tests and integrated with production lines.

The scanning frequency of triangulation scanners varied between 200 Hz and 2000 Hz, depending on the expected scanning density and available data for post-processing. It was possible to increase the scanning frequency even more (top scanning speed of 16 μs/62.5 kHz), but, in that case, spatial resolution of the surface maps along the scanned profile decreased due to necessary pixel binning.

Two optional placements for the smoothness sensor were recognized in the production line of the window producing factory:

– in-line: installed directly after the final planing head of the profiling moulder and before the water wetting station, and
– on-line: on the conveyer transporting elements between operations.

Both options were tested during the pilot, providing important decision-making observations and a series of topography maps acquired during scanning of the produced elements. The in-line option was superior from the reliability point of view, assuring very fast and direct detection of surface defects − linking the surface quality with a specific cutting tool. An important disadvantage was limited access to the sensor due to restricted space available in the machine and its vibrations. It is expected that the optical sensor has to be frequently inspected and cleaned from dust present in the vicinity of the cutting tools. The second obstacle for in-line implementation was the fact that, according to the technological process, the wood surface of window frame elements was wetted in order to lift any loose fibers before implementing other operations. The wetting process resulted in dramatic changes of the wood surface smoothness itself (Molnár *et al.*, 2019).

The on-line option was identified as superior for the pilot testing as it allowed the measurement of real production samples as well as pre-selected specimens containing specific surface characteristics. In this case, the belt conveyor was adapted as a sample feeder, while the smoothness sensor was fixed to the conveyor mechanical frame. The feed speed was set at 5 m/min, which corresponded to the real production speeds used in the window frame factory.

In both cases (in-line and on-line), the data from sensors were properly acquired and stored on the computer hard disk for further post-processing.

2.2 Model samples
2.2. Model uzoraka

The engineers supervising the production process in the window factory pre-selected a number of samples representing diverse surface quality grades corresponding to different production stages and examples of surface defects commonly occurring on the produced wooden elements. The samples included: raw resources arriving from the suppliers – before profiling, wooden elements resulting from planing with different configurations of the grain angles, elements after surface sanding, elements with repaired defects by means of filling and finished wooden frames, assuming different coatings, colors and number of layers. The identification, as well as description of surface defects, was conducted in collaboration with process engineers and operators. The most problematic surface defect highlighted was torn grain.

2.3 Software for data post-processing
2.3. Softver za obradu podataka

The quantity of data generated during wood surface scanning with investigated sensors was very high, requiring development of dedicated software tools enabling real-time data acquisition and data mining. Custom software was developed in LabView 2017 (National Instruments) implementing the algorithm presented in Figure 3. The data were acquired as a stream directly from the triangulation sensor controller. These were post-processed twofold:

– grey scale image was generated to simplify visualization of the surface topography, and
– data were processed independently for each scanned profile, determining standardized surface roughness parameters and variation along the sample length.

The surface images (maps) were used for further detailed analysis by means of open-source software Gwyddion (2019), which allowed optional filtering, flattening as well as computation of 3D surface roughness parameters, among others. The flattening of surface topography maps was performed by subtracting the main plane from the primary dataset. No band pass filtering was applied here to extract topography components, with exception of spike removal. Spikes were unwanted artefacts in the primary profiles that were not related to the measured surface but to the triangulation system errors, such as reflectance and shape discontinuity, corner or sensor occlusion (Sandak, 2007). These were removed by implementing “mask of outliers” tool of the Gwyddion software.

From the industrial implementation point of view, however, the second approach (single profile at once analysis) was more efficient. The raw set of data collected from the sensor was first filtered to remove border artefacts and spikes (single pixel wide and exceptionally high data points far from the mean line). The form error was also removed by extracting linear fitting of the surface profile points (r_i). Root Mean Square deviation of the primary profile (Pq) parameter was then computed on the filtered and flattened data according to ASME B46.1-2009 and ISO 4287-1997, as presented in Eq. 1:

$$Pq = \sqrt{\frac{1}{n}\sum_{j=1}^{n} r_j^2} \quad (1)$$

The Pq value can then be confronted with the threshold, and the operator can be alerted if the limit is frequently exceeded. The final adjustment of both

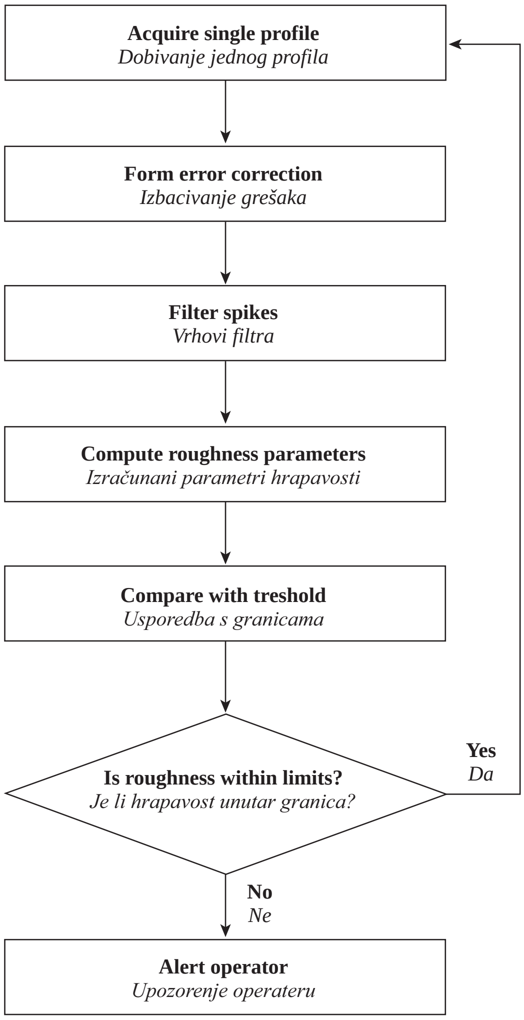

Figure 3 Algorithm for implementing a simple monitoring system alerting machine operation about excessive surface irregularities resulting from the machining process
Slika 3. Algoritam za primjenu jednostavnog sustava praćenja koji upozorava na rad stroja i nastajanje prevelikih neravnina tijekom procesa obrade

threshold and allowed limit exceeding was not performed within the framework of this research. It has to be confronted with real production requirements in the case of future implementation of the system. Nevertheless, the value of the threshold should reflect the specific quality requirements for each component type and be closely related to the statistical process control data provided by the production managers.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Figure 4 presents a direct comparison of profiles extracted for the 3D surface smoothness maps for both sensors tested on-line. It is evident that both provided very similar profile outlines, with LJ-7020 being slightly more precise in representation of the short wavelength components. Both the spatial distribution of irregularities and these heights are matching. It indicates high suitability of both sensors for practical implementation.

The scanning frequency affects the number of details (profiles) used for the detection of surface defects.

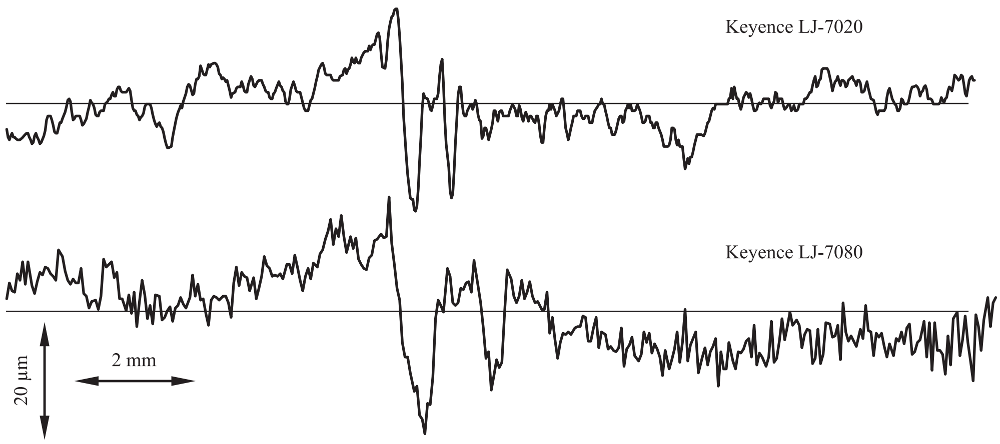

Figure 4 Comparison of profiles extracted from 3D map of sanded and painted window frame surface made of Scots pine measured with Keyence LJ-7080 (top) and LJ-7020 (bottom)
Slika 4. Usporedba profila ekstrahiranih iz 3D karte brušene i premazane površine prozorske okvirnice od borovine i izmjerene uz pomoć senzora Keyence LJ-7080 (gore) i LJ-7020 (dolje)

Figure 5 presents the results of scanning of the same specimen with the frequency of 200, 1000 and 2000 Hz. The arrow corresponds to the same reference length. The spatial resolution is, therefore, 10 times higher in the case of 2000 Hz scanning, providing also 10 times more data to be processed in real time. As the presence of torn grain was hardly detected on the 200 Hz scanning frequency, it was assumed that 1000 Hz was an optimal scanning frequency with conveyor feed speed of 5 m/min.

According to production managers, torn grain was considered the most problematic surface defect (Farrokhpayam *et al*., 2010). The specific characteristics of torn grain (void under the mean surface line of relatively high depth and width) allow automatic detection by simple thresholding of the surface image after removing the form error. Figure 6 presents an example of torn grain as sensed on-line with the triangulation sensor. It is also evident that the appearance of the surface profile corresponding to earlywood and latewood differs. It is not clear, however, if the differences are affected by the anatomical structure topography or by differences in laser light scattered on optically varying wood zones. Additional laboratory tests with benchmark references method are therefore required to ultimately define the triangulation sensor limitations.

Other surfaces were also tested in the pilot installation, with some of the results summarized in Figure 7. The 3D surface map, generated on the basis of sensor readings as well as *P*q smoothness computed for each profile along the scanning length, are presented for samples provided by production managers. As mentioned above, it was rather easy to detect torn grain as these irregularities have high *P*q values. The results follow the expected trends, where the implementation of technological operations (with the exception of wetting) reduced overall smoothness. The surface roughness of finished surfaces was the smallest and most uniformly distributed along the sample length.

Figure 8 presents an example of representative profiles scanned on model samples, including sections covering defects or other distinctive topography features. The presence of torn grain is evident in samples #2, #4 and #6. Moreover, the decrease of smoothness profile amplitude is noticeable during the implementation of subsequent finishing process steps. The smoothest surfaces are perceived for coated samples, with the exception of #6 where wavy structure is related to the presence of miniature torn grains and surface pattern on early- and late- wood caused by water-based coating.

A comparative summary of these measurements is presented in Figure 9 as a histogram of *Pq* smoothness determined for each sample. The roughest were rough planed board (#1) and excessive torn grain (#2), in contrast to the coated white sample (#8) with a single histogram peak in the lowest smoothness bin. The histogram analysis was found as the most promising

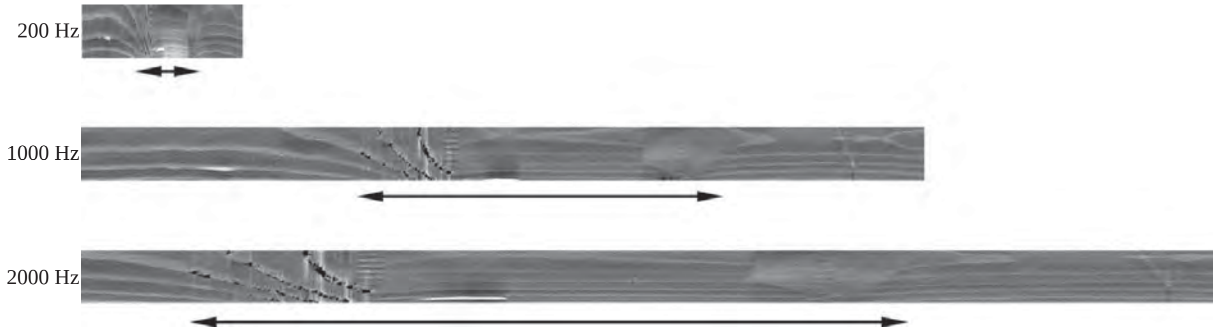

Figure 5 3D surface irregularity map of wooden board including torn grain and filler scanned with different sampling frequencies and constant feed speed (5 m/min)
Slika 5. 3D karta nepravilnosti površine drvene ploče koja obuhvaća iskidanu žicu i kit, skenirana različitom frekvencijom uzorkovanja i uz konstantnu brzinu ulaganja (5 m/min)

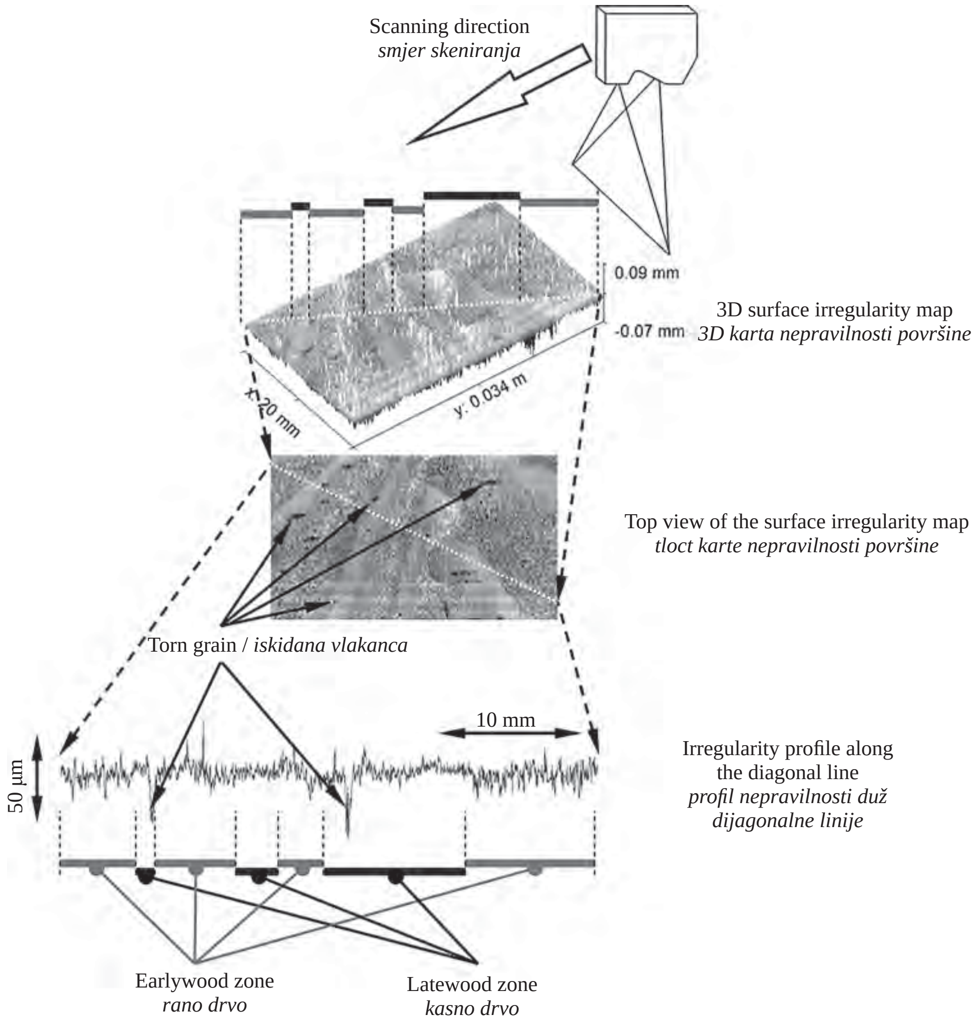

Figure 6 Torn grain, early- and late-wood identified on 3D surface irregularity map of sanded Scots pine surface and on extracted irregularity profile (sensor LJ-7080)
Slika 6. Iskidana žica te rano i kasno drvo otkriveni na 3D karti nepravilnosti brušene površine borovine i na ekstrahiranom profilu nepravilnosti (senzor LJ-7080)

tool for real-time implementation of the on-line surface smoothness measuring system. Again, final adjustments (setting the bin size, threshold level and its value) have to be defined case-by-case during routine operation of the scanner.

4 CONCLUSIONS
4. ZAKLJUČAK

The present research was triggered by discussion with production managers raising an emerging problem of wood surface smoothness assessment in industrial realities. Optimal sensors for refined (Keyence LJ-7020) and accurate enough (Keyence LJ-7080) scanning of the wood surface topography were tested in an industrial environment in-line and on-line. Both sensors proved their usability and were able to access surfaces of diverse qualities and finishing states. A simple algorithm for real-time data processing has been proposed and implemented as a prototype. The follow-up to this project, including the development of a dedicated portable scanner for in-field inspection of produced elements with an optional integration to the processing lines, is currently under way.

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Part of this research has been presented during 24th International Wood Machining Seminar held at Oregon State University, Corvallis (USA) on August 25 - 30, 2019.

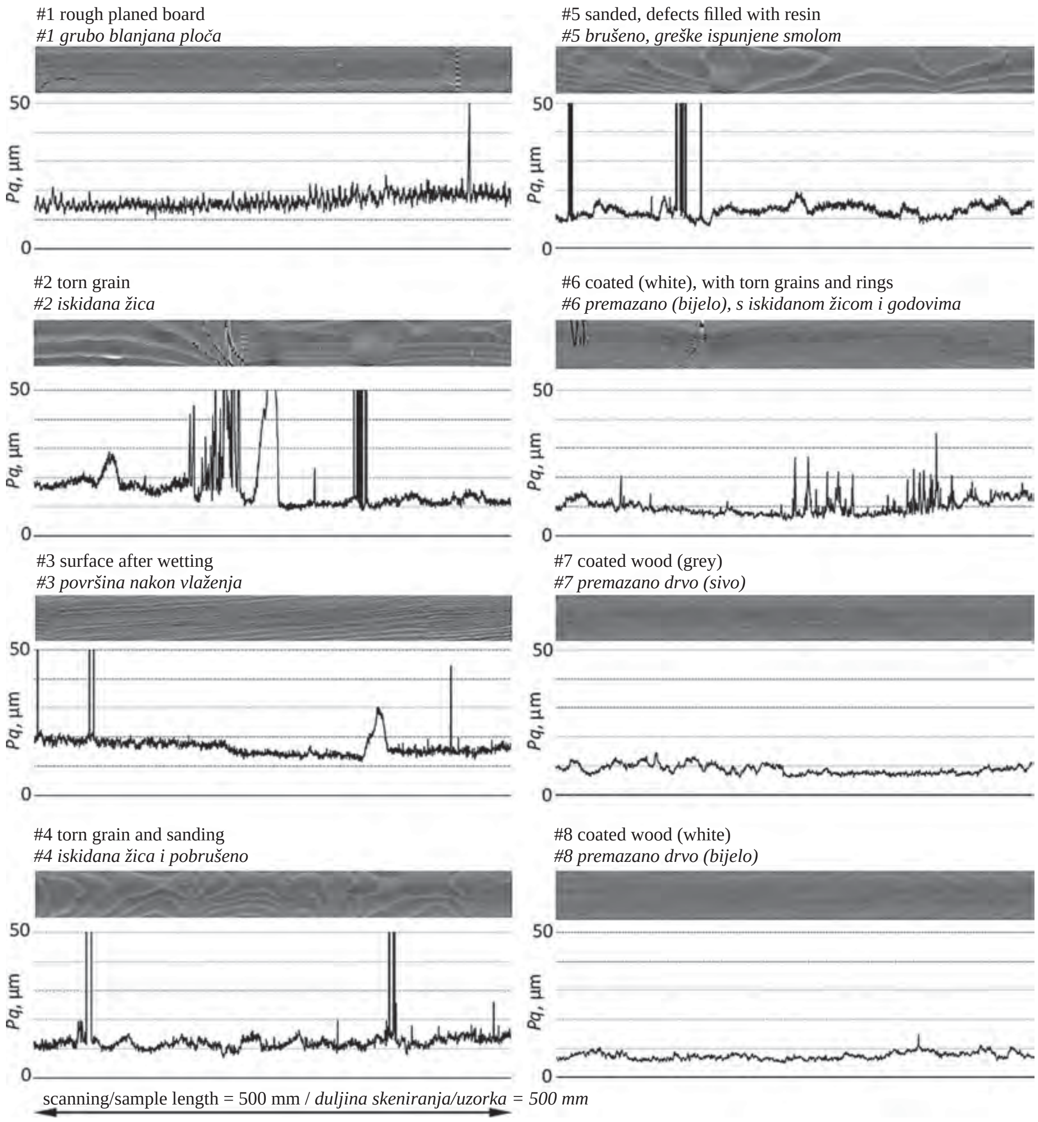

Figure 7 3D surface irregularity maps (grey scale) and *P*q smoothness variation along wooden boards representing diverse stages of window frame finishing as scanned with Keyence LJ-7080 sensor
Slika 7. 3D karta nepravilnosti površine (siva skala) i *P*q varijacija glatkoće uzduž drvenih ploča koje predočuju različite faze površinske obrade prozorske okvirnice kao što je skenirano senzorom LJ-7080

Figure 8 Profiles extracted from 3D surface irregularity maps of Scots pine boards representing diverse stages of window frame finishing as scanned with Keyence LJ-7080 sensor: #1 – rough planed board, #2 – torn grain, #3 – surface after wetting, #4 – torn grain and sanding, #5 – sanded, defects filled with resin, #6 – coated (white), with torn grain and yearly rings, #7 – coated wood (grey), #8 – coated wood (white)
Slika 8. Profili ekstrahirani iz 3D karti nepravilnosti površine ploča od borovine koji predočuju različite faze površinske obrade prozorske okvirnice skenirane senzorom Keyence LJ -7080: #1 – grubo blanjana ploča, #2 – iskidana vlakanca, #3 – površina nakon vlaženja, #4 – iskidana žica i pobrušeno, #5 – brušeno, greške ispunjene smolom, #6 – premazano (bijelo), s iskidanom žicom i godovima, #7 – premazano drvo (sivo), #8 – premazano drvo (bijelo)

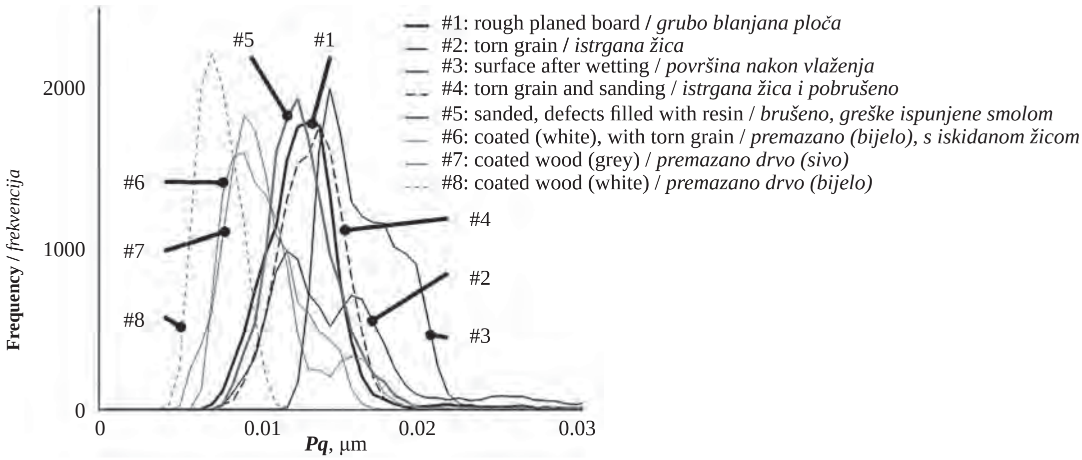

Figure 9 Histogram of *P*q smoothness parameters measured on-line with Keyence sensor LJ-7080 on different wood surfaces (feed speed 2 m/min)
Slika 9. Histogram *P*q parametara glatkoće izmjerenih *online* senzorom Keyence LJ-7080 na različitim površinama drva (brzina ulaganja 2 m/mm)

5 REFERENCES
5. LITERATURA

1. De Groot, P. J., 2019: A review of selected topics in interferometric optical metrology. Reports on Progress in Physics, 82: 056101. https://doi.org/10.1088/1361-6633/ab092d.
2. Dobrzynski, M.; Orlowski, K. A.; Biskup, M., 2019: Comparison of surface quality and tool-life of glulam window elements after planing. Drvna industrija, 70 (1): 7-18. https://doi.org/10.5552/drvind.2019.1741.
3. Farrokhpayam, S. R.; Ratnasingam, J.; Bakar, E. S.; Tang, S. H., 2010: Characterizing surface defects of solid wood of Dark Red Meranti (*Shorea* sp.), Melunak (*Pentace* sp.) and Rubberwood (*Hevea brasiliensis*) in planing process. Journal of Applied Sciences, 10 (11): 915-918. https://doi.org/10.3923/jas.2010.915.918.
4. Kiliç, M.; Pürlusoy, I.; Kurnali, M., 2018: Measuring the surface roughness values of european hop-horn beam. Wood Research, 63 (2): 343-352.
5. Lu, R. S.; Tian, G. Y., 2006: On-line measurement of surface roughness by laser light scattering. Measurement Science and Technology, 17 (6): 1496-1502. https://doi.org/10.1088/0957-0233/17/6/030.
6. Lu, L.; Ding, Y.; Luan, Y.; Yin, Y.; Liu Q.; Xi, J., 2017: Automated approach for the surface profile measurement of moving objects based on PSP. Optics Express, 25 (25): 32120-32131. https://doi.org/10.1364/oe.25.032120.
7. Lu, Z.; Wang, M.; Dai, W., 2019: Machined surface quality monitoring using a wireless sensory tool holder in the machining process. Sensors, 19 (8): 1847. https://doi.org/10.3390/s19081847.
8. Manuel, A.; Leonhart, R.; Broman, O.; Becker, G., 2015: Consumers' perceptions and preference profiles for wood surfaces tested with pairwise comparison in Germany. Annals of Forest Science, 72 (6): 741-751. https://doi.org/10.1007/s13595-014-0452-7.
9. Molnár, Z.; Fuchs, I.; Tatai, S.; Magoss, E., 2019: Stability of planed and precision planed solid wood surface due to wetting. Maderas. Ciencia y tecnología, 21 (1): 123-132.https://doi.org/10.4067/s0718-221x2019005000112.
10. Nasir, V.; Cool, J., 2018: A review on wood machining: characterization, optimization, and monitoring of the sawing process. Wood Materials Science & Engineering, 15 (1): 1-16. https://doi.org/10.1080/17480272.2018.1465465.
11. Sandak, J., 2007: Optical triangulation in wood surface roughness measurement. In: Proceedings of the 18th International Wood Machining Seminar. Vancouver, Canada, vol. 1, pp. 275-284.
12. Sandak, J.; Negri, M., 2005: Wood surface roughness – What is it? In: Proceedings of the 17th International Wood Machining Seminar. Rosenheim, Germany, vol. 1, pp. 242-250.
13. Škaljić, N.; Beljo Lučić, R.; Čavlović, A.; Obućina, M., 2009: Effect of feed speed and wood species on roughness of machined surface. Drvna industrija, 60 (4): 229-234.
14. Sofuoğlu, S. D.; Kurtoğlu, A., 2015: Effects of machining conditions on surface roughness in planing and sanding of solid wood. Drvna industrija, 66 (4): 265-272. https://doi.org/10.5552/drind.2015.1406.
15. Šustek, J.; Siklienka, M., 2018 The effect of laser beam wavelengths on accuracy of surface measurement of unevenness of beechwood by laser beam. Acta Facultatis Xylologiae Zvolen, 60 (1): 137-145.
16. Zhao, X., 1992: Study on measurement of wood surface roughness by computer vision. Journal of Northeast Forestry University, 3 (1): 75-81.
17. Zhao, X., 1995: Inspecting wood surface roughness using computer vision. In: Proceeding of SPIE 2345 Optics in Agriculture, Forestry, and Biological Processing. Boston, United States. https://doi.org/10.1117/12.198860.
18. Župerl, U.; Čuš, F., 2019: A cyber-physical system for surface roughness monitoring in end-milling. Strojniški vestnik - Journal of Mechanical Engineering, 65 (2): 67-77. https://doi.org/10.5545/sv-jme.2018.5792.
19. ***Keyence, 2019: https://www.keyence.com/products/measure/laser-2d/lj-v/index.jsp (Accessed Nov 3, 2019).
20. ***Gwyddion, 2019: http://gwyddion.net/ (Accessed Nov 3, 2019).

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Comparison of Visual and Instrumental Assessment of Colour Differences on Finished Wooden Surfaces

Usporedba vizualne procjene i izmjerene promjene boje površinski obrađenog drva

Preliminary paper • Prethodno priopćenje
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ABSTRACT • *Staining of wood with various substances and processes is an important part of surface finishing of wood. Colour differences as a result of staining and of exposure of coloured wood during its utilisation are usually evaluated by instrumental measurements. However, the measurement results can show something else compared to what our naked eye can see. Due to inhomogeneity of wood, this discrepancy can be even greater in the case of finished surfaces. The aim of our research was to evaluate distinctions between visual perception and numerically determined colour differences on differently finished wooden surfaces, to get information at which starting point the colour difference becomes visible, and to establish whether it is related to the nature of the surface. We established that the visual assessment is influenced by many factors and that there is a correlation between visual and instrumental assessments. The colour difference ΔE^* of 0.5 should be considered as a value when it starts to become visible, and at the value of 2.0, observers already considered the colour difference as a different colour. It was stated that we have some tolerance in perceiving the colour change. This tolerance is more expressed in the case of transparent coating systems.*

Keywords: *coating; colour; gloss; instrumental measurement; visual perception*

SAŽETAK • *Premazivanje drva različitim sredstvima i primjenom različitih postupaka važan su dio površinske obrade drva. Promjene boje kao rezultat premazivanja i izlaganja obojenog drva tijekom njegove uporabe obično se mjere uređajima. Međutim, izmjereni rezultati pokazuju nešto sasvim drugo od onoga što se vidi ljudskim okom. Kad je riječ o površinskoj obradi drva, razlike između izmjerenih rezultata i onoga što se vidi ljudskim okom mogu se povećati zbog nehomogenosti drva. Cilj istraživanja bio je procijeniti razlike između vizualne procjene i izmjerene promjene boje na površinski obrađenom drvu primjenom različitih tehnika kako bi se utvrdila vrijednost pri kojoj je promjena boje vidljiva te kako bi se utvrdilo ovisi li ona o vrsti površine. Ustanovili smo da na vizualnu procjenu promjene boje utječe velik broj čimbenika i da postoji veza između vizualne procjene i izmjerenih vrijednosti promjene boje. Promjena boje ΔE^* od 0,5 vrijednost je pri kojoj promjena boje postaje vidljiva, a promjenu boje od 2 promatrači vide kao različitu boju. Uočeno je da postoji određena tolerancija u percepciji promjene boje, koja je veća pri procjeni promjene boje prozirnih sustava premaza.*

Ključne riječi: *premaz; boja; sjaj; mjerenje promjene boje; vizualna procjena*

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1 INTRODUCTION
1. UVOD

Wood as a natural material has many advantages compared to other materials. Among them, visual properties are most often the reason for selecting wood for a desired product. There are huge differences in the appearance of wood between different tree species and even among wood of the same species. The decorative appearance of timbers is due to the texture, or to the figure, or to the colour of the material and, in many instances, due to combinations of these (Dinwoodie, 2000). Such variability in wood appearance gives endless possibilities for its use. However, at the same time and for the same reason, this could also be a disadvantage that needs to be overcome. Sometimes it is hard to achieve the same appearance between different surfaces or different pieces of a wooden product, especially if it is not produced in a small series. Furthermore, wood surfaces of furniture or some other product are coated for protection or to give them the final look. The appearance of the finished wooden surfaces than depends on the wood used as a substrate, on the materials applied on it and on various other parameters, such as, for instance, an application rate.

In spite of the fact that colour variations are quite frequent and expected in the case of wooden furniture or other wooden products, customers do have certain tolerance limits above which the colour differences are no longer tolerated. Colour vision is an illusion created by the interactions of billions of neurons in our brain. There is no colour in the external world; it is created by neural programs and projected onto the outer world we see. It is intimately linked to the perception of form, where colour facilitates detecting the borders of objects (Gouras, 2013). From this, we can conclude that colour vision and perception of colour differences are unique to every individual. This suggests that colour evaluation can only be objective by the use of equipment that numerically measures the colour according to a certain colour space system. The most commonly used system for measuring the colour, including the one of wood, is CIELAB colour space (Golob and Golob, 2000). There are many studies on using this colour system for the evaluation of colour stability of coated or non-coated wood due to natural or artificial weathering (Vardanyan *et al.*, 2015), and even more, for the determination of wood colour changes after various treatments (modification or drying) (Nemeth *et al.*, 2013; Sikora *et al.*, 2018) or due to fungal attack (Reinprecht and Hulla, 2015).

However, up to our best knowledge, there are only few reports on the relation between visual and instrumental assessment of the colour of wood, as described in the next paragraph (Liu and Furuno, 2002; Buchelt and Wagenführ, 2012; Defoirdt *et al.*, 2012; Hauptman *et al.*, 2012; Bianconi *et al.*, 2013), and there are some more reports about this topic with applications on other materials. For instance, the correlation of perceived colour difference and the measured and mathematically calculated difference with the focus on printing industry was elaborated by Mokrzycki and Tatol (2011). The correlation of the instrumental colour differences with visual assessment is extremely important in automotive coatings (Kirchner and Ravi, 2014; Gómez *et al.*, 2016), in dental medicine (Pecho *et al.*, 2016; Pecho *et al.*, 2016a), in food industry (Pagliarini and Rastelli, 1994; O'Sullivan *et al.*, 2003), in textile industry (Bae *et al.*, 2015), in the production of colour tints (Khimchenko and Eksperiandova, 2014), etc.

There have been only few investigations in the field of wood science and technology dealing with the relation of visual and instrumental assessment of colour. Liu and Furuno (2002) characterised colour variations of the surfaces of fifteen wood species by fractal dimension of the triangular prism surface area method. They came to the conclusion that, for colour matching of wood parts, fractal dimension quantitatively furnishes essential information of colour variation in local and overall features. Buchelt and Wagenführ (2012) measured the natural colour of six precious woods. They established that, within one wood species with equal surfaces, there are colour differences (ΔE^*) with a magnitude of 1 to 2 and concluded that the grading of ΔE^* as a difference that is barely perceptible should be higher than 2. They came to this conclusion by the comparison of established colour differences within one species and colour difference values obtained by visual evaluation performed by Bieske (acc. to Buchelt and Wagenfür (2012)). Defoirdt *et al.* (2012) assessed the colour of oak wood for the production of parquet. They compared visual assessment and spectrophotometer measurements and established that their colour grading methodology is in good correlation with visual assessment and therefore can be adapted to particular automated grading purposes. Bianconi *et al.* (2013) also analysed coloured-based sorting through different colour descriptors of hardwood parquet slabs into lots of similar visual appearance, but they did not do any comparison to visual assessment. Hauptman and coauthors (2012) correlated the visual perception of the oak wood colour of 20 observers with two different colour difference equations, CIELAB from DIN 6174:200712 and CIEDE2000 (CIE, 2001) equation. They established that CIELAB equation showed generally an overestimation of the colour change (ΔE^*).

Taking into account relatively low number of investigations of the relationship between visual perception of colour and colour difference and instrumental assessment of colour in the case of wood, the aim of our research was to additionally elucidate this question. The aim was also to get information at which starting point the colour difference in terms of the CIELAB ΔE^* value becomes visible and to establish whether this is somehow related to the nature of the finished wooden surface. The colour is a psychophysical quantity, acting as an impression during the stimulation of our visual system (Mokrzycki and Tatol, 2011). The dependence on many external factors and individual human characteristics has a significant influence on the perception and comparison of colour experiences (Mokrzycki and Tatol, 2011). We are aware that the perception of colour differences is influenced by many factors and that the effect of each individual factor could be quantified, but such a study would be by far above our intentions to just additionally elucidate this issue in the field of wood surface finishing. Further on, it is also accepted that the effect of texture on colour appearance is important (Kirchner and Ravi, 2014; Bae *et al.*, 2015), but again, it was decided that using the texture model would exceed the purpose of this investigation.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

For the assessment of colour differences, we used 12 pairs of differently finished wooden surfaces. The pairs of surfaces differed by the type of substrate (type of wood or composite), the intention of the use of surface (interior / exterior), the coating system properties (colour, hiding power, build, gloss) and the texture of the surface. The pairs of samples, intended for the interior, were prepared in a way that one sample was cut to two smaller, equally large specimens. The pairs of samples for the exterior were not prepared by cutting one specimen into two pieces, as in the case of the samples for the interior. Instead, in the pairs of samples for the exterior, there were two pieces of the same substrate, each treated with a surface finish of a different manufacturer, but of a very similar colour and gloss.

One sample of each comparative pair was stored in a dark space in which there were constant climatic conditions with the temperature of (23 ± 2) °C and relative air humidity of (50 ± 5) %, while the second sample was irradiated with UV light (Osram ULTRA VITALUX 300 W) to increase the colour differences between samples in a single pair, for 1, 6 and 8 days or until most of the observers detected more than the obvious colour differences between the comparable samples in the pair. This was considered as a different colour. However, the purpose of UV irradiation was not to study its effects on colour or colour change. It was used just as a tool for changing the colour difference between comparative pairs of samples. The colour was measured and colour differences were calculated before each visual assessment. The values were not known to the observers.

2.1 Gloss measurements
2.1. Mjerenje sjaja

To additionally describe the observed surface systems and to see any possible effects of gloss on visual perception of the colour, we measured specular gloss (X-Rite AcuGloss TRI) by the method described in EN ISO 2813 (2015), and did a classification based on specular reflectance values when tested at 60° by the following categories according to EN 927-1 (2013):
a) matt: reflectance up to 10,
b) satin: reflectance greater than 10 and up to 35,
c) semi gloss: reflectance greater than 35 and up to 60,
d) gloss: reflectance greater than 60 and up to 80,
e) high gloss: reflectance greater than 80.

2.2 Colour measurements
2.2. Mjerenje boje

The surface colour difference of samples in a pair was evaluated based on the CIELAB colour coordinates (EN ISO 11664-4:2011). A colour measuring instrument (spectrophotometer X-Rite SP 62) was used to record the colour index with diffuse/8° sphere optical geometry, fixed 14 mm aperture, specular component included, illuminant D65 and a 10° standard observer. The colour parameters of each surface were measured at ten positions and the mean value was recorded. The total colour difference (ΔE^*) was used to assess the colour difference between the samples in the pair and was calculated as follows:

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

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

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

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

where ΔE^* represents the total colour difference, L^* is the lightness and darkness of colour, a^* is the redness and greenness of colour, b^* is the yellowness and blueness of colour, and ΔL^*, Δa^*, and Δb^* are the differences of the compared (1) and reference sample kept in the dark (0) of L^*, a^*, and b^*, respectively.

2.3 Visual assessment of colour differences
2.3. Vizualna procjena promjene boje

Visual assessment of colour differences was done by comparison of 12 pairs under the same light (indoor light, combination of daylight at sunny conditions at 13.00 and laboratory Philips fluorescent light bulbs TL-D 36 W with cool white colour designation and temperature of 4100 K) and background conditions, made by 24 students of Wood Science (University of Ljubljana, Biotechnical Faculty), all male and from 22 to 23 years. The perceived colour differences were not statistically evaluated, like for instance by Bae and coauthors (2015). This was decided because of the relatively low number of observers and especially because the structure of the group of observers did not reflect the structure of general population in terms of age and gender. For each assessment, the observers were asked to mark on the survey sheet if they see the colour difference between the comparative samples or not (None). Furthermore, if their answer was yes, than they were asked to state if in their opinion this colour change could still be inside tolerance limits (Acceptable) or not (Not acceptable), or if they considered the assessed colour difference more than obvious so that the comparative samples could not in any case be considered as the samples of the same colour (Different colour).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

All results of visual and instrumental assessments of colour differences on 12 pairs of different finished wooden surfaces are presented in Table 1. Instrumentally determined differences between paired samples are presented as total colour difference values *ΔE** and differences of each individual colour coordinate (Δ*L**, Δ*a** and Δ*b**). Visual assessment of colour differences is presented with the level of acceptance for each grade separately. The grade with the highest percent of selection from 24 evaluators among all grades is marked with a grey cell.

In the case of the first pair (1), we can see that despite a rather high colour difference measured at the end of the comparison (Δ*E** = 0.83), the majority of the observers (81.8 %) did not see the difference between these two compared samples. However, it is interesting that in case of the similar pair 2 (same finish but different substrate), the observers saw the difference already at quite low measured colour difference (Δ*E** = 0.54). The samples of the first pair (pair 1) were finished with "open pores" due to large vessels of mahogany wood, while the surfaces of the finished samples with spruce wood as a substrate (pair 2) were smooth. From this, we can conclude that surface roughness can blur our ability to detect colour differences. Of course, we must also have in mind that different colour of the substrate underneath the semi-transparent coating film somehow also contributes to different colour of the whole surface system and induces a colour change. It is also interesting that the observers, in the case of another similar pair, pair 3 (same substrate, but different, opaque stain), saw the colour difference (80.9 %), evaluated as not acceptable, already at the measured value of Δ*E** = 0.56. It seems that visibility of the substrate somehow softens our criteria for visual assessment. The tolerance of the observer's vision for the colour difference was even higher in the case of systems without the coating film. The colour difference between black walnut wood samples treated with linseed oil (pair 11) was considered as high (different colour) at a measured Δ*E** value of 7.98 and in the case of untreated spruce samples (pair 12,) at the measured Δ*E** value of 12.60. If the substrate is coated with a transparent coating system, then the situation is reversed (pairs 5, 6 and 7). In the case of pair 5, the observers saw the colour difference that was not acceptable at the measured Δ*E** value of 1.17, while in the systems also with transparent coatings but stained substrate such perception occurred at much higher values (pair 6 – Δ*E** = 2.95; pair 7 – Δ*E** = 3.16). Pair 9 was the only high gloss opaque surface system. The observers mostly did not see the colour difference even in the case of the highest measured Δ*E** value of 0.41. However, these results show a trend which indicates that this perception could easily happen at Δ*E** value around 0.5, which for example is the maximum value of the colour difference according to IKEA specification (Tokarski and Nussbaum, 2014). Regarding the pair of samples with the satin decorative foil (pair 10), even in the case of the highest measured Δ*E** values of 2.28 or 2.80, the observers considered them as the samples with a similar colour with acceptable colour difference (with 63.6 % and 54.5 % of agreement). This pair was the only pair with a decorative foil and, maybe in the case of foils, the observers are subconsciously more tolerant since they consider such surfaces as low cost ones.

The results showed (Table 1) that the observers were very susceptible to detecting the colour differences. The minimum value of the measured colour difference at which most observers detected the colour difference was quite low (Δ*E** = 0.45; pair 8), but it is interesting that the value at which the observers considered the colour difference as no longer acceptable was quite close to this one (Δ*E** = 0.58; pair 3). The minimum value of the measured colour difference at which the observers considered the samples to have a different colour was 2.03 (pair 4). All these values (acceptable and not acceptable colour differences) are quite lower than the ones reported by Buchelt and Wagenfür (2012), who established that the grading Δ*E** = 2 is barely perceptible for visual perception of colour of precious woods (non-treated ones). However, they are closer to the values of evaluation of colour differences (Δ*E**) obtained by Bieske (cited in Buchelt and Wagenfür, 2012):

- up to 0.5: no to nearly no colour difference
- 0.5 – 1.0: difference can be perceptible for the practiced eye
- 1.0 – 2.0: observable colour difference that is barely seen
- 2.0 – 4.0: perceived colour difference that is certainly seen
- 4.0 – 5.0: significant colour difference that is seldom accepted
- above 5.0: the difference is evaluated as another colour

Bieske has worked out a valuation of the perception of light and body colours, where differences of light and body colours were evaluated by a number of subjects of different age groups.

Gómez *et al.* (2016) also examined the correlation between visual and instrumental assessment of colour differences in automotive coatings determined by the colour difference formula AUDI2000 (specific for this sector) (Pecho *et al.*, 2016). They revealed that an acceptable correlation exists. Hauptman and co-authors (2012) and Pecho and co-authors (2016a) used CIELAB and CIEDE2000 colour difference formulas for colour and colour differences. They both concluded that CIELAB is not the best metrics to calculate colour differences and that CIEDE2000 equation is generally better in predicting colour differences. In our investigation, we did not use the CIEDE2000 (EN ISO 11664-6, 2016) or AUDI2000 formula (Gómez *et al.*, 2016), but nevertheless we also found a good correlation between CIELAB colour difference formula and visual perception. Generally, if the measured colour difference (Δ*E**) increased or decreased, the ability of visual perception of colour difference changed in the same way. The only significant exception was in case of pair 1, where the measured colour difference (Δ*E**) increased due to UV irradiation but the observers saw less colour difference between these two paired samples. We cannot explain why this happened. Even if we

Table 1 Instrumentally (ΔE^*, ΔL^*, Δa^* and Δb^*) and visually determined colour differences (the level of acceptance for the grades: none, accepted, not accepted and different colour)
Tablica 1. Izmjerena (ΔE^*, ΔL^*, Δa^* i Δb^*) i vizualno utvrđena razlika u boji (ocjene stupnja prihvaćanja: *nema*, *prihvatljivo*, *nije prihvatljivo* i *različita boja*)

Pair *Par*	**Surface system** *Površinski sustav*		**UV**[2] **(days)** *UV*[2] *(dani)*	ΔE^*	ΔL^*	Δa^*	Δb^*	**Visible colour difference** *Vidljiva promjena boje*			
	Substrate *Podloga*	**Finishing (gloss values in g.u. in parentheses)**[1] *Premaz (u zagradama su vrijednosti sjaja, JS)*[1]						**None** *Nema*	**Acc.** *Prihvatljivo*	**Not acc.** *Nije prihvatljivo*	**Diff. colour** *Različita boja*
1	Mahogany wood *drvo mahagonija*	Satin (12.1) semi-transparent brown exterior stain *poluprozirna smeđa lazura za eksterijer (12,1)*	0	0.33	-0.03	-0.18	0.27	61.9 %	38.1 %	0.0 %	0.0 %
			1	0.42	-0.06	-0.41	-0.06	86.4 %	13.6 %	0.0 %	0.0 %
			6	0.67	-0.29	-0.55	-0.26	63.6 %	36.4 %	0.0 %	0.0 %
			8	0.83	-0.30	-0.66	-0.41	81.8 %	18.2 %	0.0 %	0.0 %
2	Spruce wood *drvo smreke*	Satin (15.8) semi-transparent brown exterior stain *poluprozirna smeđa lazura za eksterijer (15,8)*	0	0.63	0.343	0.34	0.40	4.8 %	23.8 %	66.6 %	4.8 %
			1	0.54	0.15	0.29	0.43	40.9 %	40.9 %	13.7 %	4.5 %
			6	0.43	0.09	0.29	0.30	54.5 %	45.5 %	0.0 %	0.0 %
			8	0.42	0.08	0.35	0.21	50.0 %	36.4 %	13.6 %	0.0 %
3	Mahogany wood *drvo mahagonija*	Satin (15.7) opaque dark green exterior stain / *pokrivna tamnozelena lazura za eksterijer (15,7)*	0	0.56	-0.19	0.14	0.51	4.8 %	9.6 %	80.9 %	4.8 %
			1	0.58	0.03	0.14	0.56	0.0 %	45.5 %	54.5 %	0.0 %
			6	0.62	0.12	0.12	0.59	4.5 %	40.9 %	50.0 %	4.5 %
			8	0.65	0.06	0.06	0.64	9.1 %	27.3 %	50.0 %	13.6 %
4	Spruce wood *drvo smreke*	Satin (27.7) opaque dark green exterior stain / *pokrivna tamnozelena lazura za eksterijer (27,7)*	0	2.03	1.25	1.20	-1.10	0.0 %	0.0 %	23.8 %	76.2 %
5	Fibreboard, fine line veneer *ploča vlaknatica, fine line furnir*	Satin (31.3) transparent coating *prozirni premaz (31,3)*	0	0.72	0.10	-0.45	0.55	57.1 %	38.1 %	4.8 %	0.0 %
			1	1.17	-0.80	-0.36	0.77	0.0 %	9.1 %	63.6 %	27.3 %
			6	2.22	-0.28	-0.34	2.18	0.0 %	4.5 %	40.9 %	54.5 %
6	Fibreboard, fine line veneer *ploča vlaknatica, fine line furnir*	Grey stain and satin (32.9) transparent coating / *sivo močilo i prozirni premaz (32,9)*	0	1.01	-0.58	0.30	0.77	33.3 %	47.6 %	19.1 %	0.0 %
			1	2.95	-0.84	0.23	2.81	0.0 %	9.1 %	18.2 %	72.7 %
7	Fibreboard, exotic wood veneer *ploča vlaknatica, furnir egzota*	Brown-grey stain and satin (26.7) transparent coating / *smeđosivo močilo i prozirni premaz (26,7)*	0	0.91	0.67	0.25	0.55	81.0 %	19.0 %	0.0 %	0.0 %
			1	0.93	0.59	0.15	0.70	40.9 %	59.1 %	0.0 %	0.0 %
			6	3.16	1.98	-0.57	2.40	0.0 %	4.5 %	40.9 %	54.6 %
8	Fibreboard, exotic wood veneer *ploča vlaknatica, furnir egzota*	Dark brown stain and satin (13.9) transparent coating *tamnosmeđe močilo i transparentni premaz (13,9)*	0	0.61	-0.35	-0.25	-0.42	33.3%	28.6 %	28.6 %	9.5 %
			1	0.65	-0.48	-0.25	-0.37	13.6%	68.2 %	18.2 %	0.0 %
			6	0.56	-0.45	-0.31	-0.13	22.7%	63.6 %	9.1 %	4.5 %
			8	0.45	-0.36	-0.23	0.12	18.2%	68.2 %	9.1 %	4.5 %
9	Fibreboard *ploča vlaknatica*	High gloss (84.6) opaque white coating *pokrivni bijeli premaz visokog sjaja (84,6)*	0	0.18	-0.04	0.00	-0.18	95.2 %	4.8 %	0.0 %	0.0 %
			1	0.10	-0.10	0.00	-0.03	90.9 %	9.1 %	0.0 %	0.0 %
			6	0.34	-0.19	-0.06	0.28	100.0 %	0.0 %	0.0 %	0.0 %
			8	0.41	-0.18	-0.07	0.36	59.1 %	40.9 %	0.0 %	0.0 %
10	Chipboard *iverica*	Satin (16.3) decorative foil *dekorativna folija (16,3)*	0	1.38	-1.13	-0.23	-0.77	42.9 %	52.4 %	4.7 %	0.0 %
			1	1.10	-0.51	-0.34	-0.91	63.6 %	36.4 %	0.0 %	0.0 %
			6	2.28	-1.50	-0.59	-1.62	18.2 %	63.6 %	9.1 %	9.1 %
			8	2.80	-1.90	-0.74	-1.91	9.1 %	54.5 %	27.3 %	9.1 %
11	Black walnut wood / *drvo crnog oraha*	Matt (4.9) linseed oil *laneno ulje (4,9)*	0	3.36	1.34	0.37	3.06	4.5 %	40.9 %	36.4 %	9.1 %
			1	7.98	3.42	0.95	7.15	0.0 %	0.0 %	4.5 %	95.5 %
12	Spruce wood *drvo smreke*	(6.3)	0	**3.00**	-2.70	1.27	0.23	14.3%	61.9%	19.0%	4.8%
			1	5.27	-4.75	1.12	1.97	0.0%	40.9%	36.4%	9.1%
			6	12.60	-7.52	2.74	9.73	0.0%	0.0%	9.1%	90.9%

[1]Gloss values in parentheses were only measured prior exposure to UV light. In the case of pairs with exterior coatings of different producers, but very similar colour and gloss, the average values of both specimens in a pair are given. / *Vrijednosti sjaja u zagradama izmjerene su prije izlaganja UV svjetlosti. Ako su premazi za eksterijer slične boje i sjaja bili različitih proizvođača, iskazana je srednja vrijednost sjaja obaju uzoraka u paru.*
[2]The value 0 means that the assessment of colour difference was performed between both samples in the initially prepared pair that was not exposed to UV light. / *Vrijednost 0 znači da je procjena razlike u boji bila provedena na oba uzorka u početno pripremljenom paru koji nije bio izložen UV svjetlosti.*

look at the change of every individual CIELAB colour parameter, we can see the same trend; after every UV irradiation, the exposed sample became darker (–Δ*L**), less reddish (–Δ*a**) and less yellowish (–Δ*b**).

4 CONCLUSIONS
4. ZAKLJUČAK

Visual assessment of colour differences is influenced by many factors. It is not only dependant on the real colour differences, as they can be determined by measurements, but also on the kind of the finished wooden surface system (the type of substrate and coating system, roughness and texture, etc.). Nevertheless, there is still a good correlation between visual and instrumental assessment of colour differences when using the CIELAB formula. For the finished wooden surfaces, the colour difference ΔE* of 0.5 should be considered as a value when the colour difference starts to be visible; in the case of dispute, it can be the matter of discussion till the value of 2.0 is reached, when the colour difference is already considered as a different colour. Our investigation also showed that we have some tolerance in perceiving the colour change. This tolerance is bigger if the coating system is more transparent so that the structure of the wood is more visible.

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5 REFERENCES
5. LITERATURA

1. Bae, J. H.; Hong, K. H.; Lamar, T. M., 2015: Effect of texture on color variation in inkjet-printed woven textiles. Color Research and Application, 40 (3): 297-303. https://doi.org/10.1002/col.21865.
2. Bianconi, F.; Fernández, A.; González, E.; Saetta, S. A., 2013: Performance analysis of color descriptors for parquet sorting. Expert Systems with Applications, 40 (5): 1636-1644. https://doi.org/10.1016/j.eswa.2012.09.007.
3. Buchelt, B.; Wagenführ, A., 2012: Evaluation of color differences on wood surfaces. European Journal of Wood and Wood Products, 70 (1-3): 389-391. https://doi.org/10.1007/s00107-011-0545-z.
4. Defoirdt, N.; Wuijtens, I.; De Boever, L.; Coppens, H.; Van den Bulcke, J.; Van Acker, J., 2012: A color assessment methodology for oak wood. Annals of Forest Science, 69 (8): 939-946. https://doi.org/10.1007/s13595-012-0214-3.
5. Dinwoodie, J. M., 2000: Timber: Its nature and behaviour. Second edition. E & FN Spon, London, pp. 36.
6. Golob, V.; Golob, D., 2001: Teorija barvne metrike. In: Jeler, S., Kumar, M. (eds.), Interdisciplinarnost barve. Del 1. V znanosti. Društvo koloristov Slovenije, Maribor, pp. 201-230.
7. Gómez, O.; Perales, E.; Chorro, E.; Burgos, F. J.; Viqueira, V.; Vilaseca, M.; Martínez-Verdú, M.; Pujol, J., 2016: Visual and instrumental assessments of color differences in automotive coatings. Color Research and Application, 41 (4): 384-390. https://doi.org/10.1002/col.21964.
8. Gouras, P., 2013: "Color vision" (online), http://webvision.med.utah.edu/book/part-vii-color-vision/color-vision (Accessed March 10, 2018).
9. Hauptmann, M.; Pleschberger, H.; Mai, C.; Follrich, J.; Hansmann, C., 2012: The potential of color measurements with the CIEDE2000 equation in wood science. European Journal of Wood and Wood Products, 70 (4): 415-420. https://doi.org/10.1007/s00107-011-0575-6.
10. Khimchenko, S. V..; Eksperiandova, L. P., 2014: Colorimetric and stochastic assessment of the visual limit of color perception for visual colorimetric analysis. Journal of Analytical Chemistry, 69 (4): 322-326. https://doi.org/10.1134/S1061934814040042.
11. Kirchner, E. J. J.; Ravi, J., 2014: Setting tolerances on color and texture in automotive coatings. Color Research and Application, 39 (1): 88-96. https://doi.org/10.1002/col.21767.
12. Liu, J.; Furuno, T., 2002: The fractal estimation of wood color variation by the triangular prism surface area method. Wood Science and Technology, 36 (5): 385-397. https://doi.org/10.1007/S00226-002-0148-2.
13. Mokrzycki, W.; Tatol, M., 2011: Color difference Delta E – A survey. Machine Graphics and Vision, 20 (4): 383-411.
14. Nemeth, R.; Ott, A.; Takats, P.; Bak, M., 2013: The Effect of Moisture Content and Drying Temperature on the Color of Two Poplars and Robinia Wood. BioResources, 8 (2): 2074-2083.
15. O'Sullivan, M. G.; Byrne, D. V.; Martens, H.; Gidskehaug, L. H.; Andersen, H. J.; Martens, M., 2003: Evaluation of pork colour: prediction of visual sensory quality of meat from instrumental and computer vision methods of colour analysis. Meat Science, 65 (2): 903-918. https://doi.org/10.1016/S0309-1740(02)00298-X.
16. Pagliarini, E.; Rastelli, J., 1994: Sensory and instrumental assessment of olive oil appearance. Grasas y Aceites, 45 (1-2): 62-64. https://doi.org/10.3989/gya.1994.v45.i1-2.972.
17. Pecho, O. E.; Ghinea, R.; Alessandretti, R., Pérez, M. M.; Della Bona, A., 2016a: Visual and instrumental shade matching using CIELAB and CIEDE2000 color difference formulas. Dental Materials, 32 (1): 82-92. https://doi.org/10.1016/j.dental.2015.10.015.
18. Pecho, O. E.; Pérez, M. M.; Ghinea, R.; Della Bona, A., 2016b: Lightness, chroma and hue differences on visual shade matching. Dental Materials, 32 (11): 1362-1373. https://doi.org/10.1016/j.dental.2016.08.218.
19. Reinprecht, L.; Hulla, M., 2015: Color changes in beech wood modified with essential oils due to fungal and ageing-fungal attacks with Coniophora Puteana. Drewno, 58 (194): 37-48.
20. Sikora, A.; Kačík, F.; Gaff, M.; Vondrová, V.; Bubeníková, T.; Kubovský, I., 2018: Impact of thermal modification on color and chemical changes of spruce and oak wood. Journal of Wood Science, 64 (4): 406-416. https://doi.org/10.1007/s10086-018-1721-0.
21. Tokarski, P.; Nussbaum, R.; 2014: IKEA specification IOS-MAT-0066: Surface coatings and coverings – general requirements. IKEA of Sweden AB.
22. Vardanyan, V.; Galstian, T.; Riedl, B., 2015: Effect of addition of cellulose nanocrystals to wood coatings on color changes and surface roughness due to accelerated weathering. Journal of Coatings Technology and Research, 12 (2): 247-258. https://doi.org/10.1007/s11998-014-9634-3.
23. Wang, X.; Wang, F.; Yu, Z.; Zhang, Y.; Qi, C.; Du, L., 2017: Surface free energy and dynamic wettability of

wood simultaneously treated with acidic dye and flame retardant. Journal of Wood Science, 63 (3): 271-280. https://doi.org/10.1007/s10086-017-1621-8.
24. ***DIN 6174, 2007: Farbmetrische Bestimmung von Farbmaßzahlen und Farbabständen im angenähert gleichförmigen CIELAB-Farbenraum. Colorimetric evaluation of color coordinates and color differences according to the approximately uniform CIELAB color space (withdrawn).
25. *** CIE, 2001: Technical Report – Improvement to industrial color difference evaluation. CIE Publ. 142. Central Bureau of the CIE, Vienna.
26. ***EN 927-1, 2013: Paints and varnishes – Coating materials and coating systems for exterior wood. Part 1: Classification and selection.
27. ***EN ISO 11664-4, 2011: Colorimetry. Part 4: CIE 1976 L*a*b* Color space (ISO 11664-4:2008).
28. ***EN ISO 11664-6, 2016: Colorimetry. Part 6: CIEDE2000 Color-difference formula (ISO/CIE 11664-6:2014).
29. ***EN ISO 2813, 2015: Paints and varnishes – Determination of gloss value at 20 degrees, 60 degrees and 85 degrees (ISO 2813:2014).

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Numerical Modelling of Stiffness of RTA Furniture with New Externally Invisible and Dismountable Joints

Numeričko modeliranje krutosti RTA namještaja s novim, izvana nevidljivim vezovima

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ABSTRACT • *The distribution of furniture sold in the form of flat packages requires the use of appropriate design solutions. These include joints, which need to facilitate self-assembly with no need to use tools. Such joints should be functional, aesthetically attractive, durable and safe to use. It was decided in this study to manufacture prototypes of innovative furniture joints and evaluate the quality of furniture assembled using these joints.*
For this purpose, the finite element method and the Abaqus program were used. Joints were modelled as objects made of polylactide (PLA). Surface to surface contact and assembly forces resulting from the construction of joints were introduced between the elements of the joint. The furniture case was subjected to torsional loads. The rigidity of furniture and stress distribution in joints were calculated. On the basis of numerical calculations, the joints were positively validated.

Key words: *furniture; FEM; invisible joints; RTA; stiffness*

SAŽETAK • *Prodaja namještaja koji se isporučuje u obliku ravnih paketa zahtijeva primjenu odgovarajućih dizajnerskih rješenja. U takva se rješenje ubrajaju i vezovi koji trebaju olakšati samostalno sastavljanje namještaja bez primjene alata. Ti vezovi trebaju biti funkcionalni, estetski privlačni, izdržljivi i sigurni za upotrebu. Za ovo su istraživanje autori odlučili proizvesti prototipove inovativnih vezova namještaja te procijeniti kvalitetu namještaja sastavljenoga uz pomoć takvih vezova. Za tu je namjenu primijenjena metoda konačnih elemenata i program Abaqus. Vezovi su modelirani kao predmeti izrađeni od polilaktida (PLA). Između elemenata veza djeluju površinske i kontaktne sile koje nastaju konstrukcijom vezova. Korpus namještaja bio je podvrgnut torzijskim opterećenjima. Izračunana je krutost namještaja i raspodjela naprezanja u vezovima. Na temelju brojčanih izračuna vezovi su pozitivno ocijenjeni.*

Ključne riječi: *namještaj; FEM; nevidljivi vezovi; RTA; krutost*

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1 INTRODUCTION
1. UVOD

Furniture design and construction is an applied art and, as such, it must take into consideration not only aesthetic and functional preferences and fashion trends, but also rigidity and strength requirements. This, in turn, is associated with the development of appropriate numerical models of furniture joints in the environment of software calculating with the assistance of the finite elements method (FEM). A different method of joint rigidity was analysed by Tankut and Tankut (2011). A realistic representation of the examined structure in the FEM environment is very labour-consuming, and requires numerous corrections of mesh geometry and meticulous determination of linear elastic properties of applied materials (Dzięgielewski and Smardzewski, 1996; Kasal, 2008, Kasal *et al*., 2008a, b; Smardzewski, 2004a, b; Smardzewski, 2005). However, it is more practical, but equally effective, to replace joints with semi-rigid joints (Kłos, Smardzewski, 2004; Nicholls, Crisan, 2002; Smardzewski, Kłos, 2004; Smardzewski, Ożarska, 2005; Smardzewski, Prekrat, 2002, 2005). Smardzewski *et al.* (2013) determined the effect of creeping on changes in the rigidity of selected joints used in the structures of upholstered furniture, expressed as the substitute modulus of elasticity. For this reason, an attempt was made to elaborate a method for simplified modelling of furniture joint stiffness for the needs of numerical calculations (Smardzewski and Kłos, 2011; Smardzewski *et al.*, 2013). In the proposed method, joint stiffness was expressed by means of a modulus of elasticity in the form of a load and deflection function.

In this paper, an attempt was made to present alternative methods of numerical rigidity modelling for newly designed cabinet furniture joints using nodes of substitute linear elasticity modulus.

The aim of this research project was to determine the values of the substitute linear elasticity modulus for newly designed furniture joints to compare the obtained results and to select the model most favourable for the virtual prototyping of furniture.

2 MATERIALS AND METHOD
2. MATERIJALI I METODE

2.1 Type of new furniture joints
2.1. Novi tip vezova za namještaj

In this study, two new and original joints (Figure 1a, b) were designed so that the connection of furniture elements was externally invisible and easy to assemble with no need to use tools (Krzyżaniak and Smardzewski, 2019). The minifix joint, commonly used in the furniture industry, was used as a reference joint (Figure 1c). In view of the use of one selected type of material: particleboard (PB), three types of joints S, M, E, two mechanical tests consisting of compression and tension of joints, a total of six models were prepared for the analysis.

The experimental tests were performed on L type angle joints. Their shape and dimensions were present-

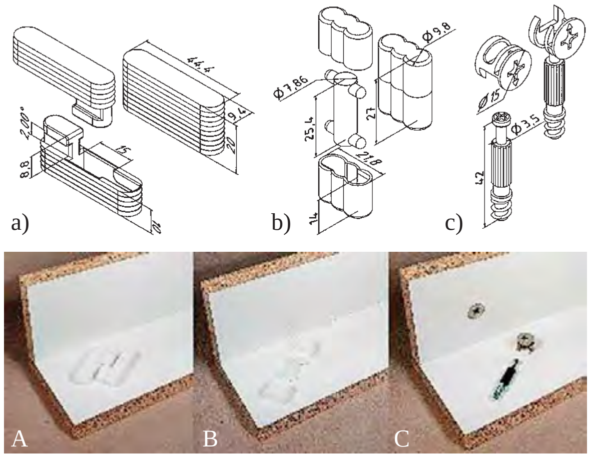


Figure 1 Joints used in tests: a) slide catch (S), b) tension twist (M), c) eccentric (E)
Slika 1. Vezovi obuhvaćeni ispitivanjima: a) klizna kopča (S), b) *tension twist* (M), c) svornjak sa zakretnim klinom

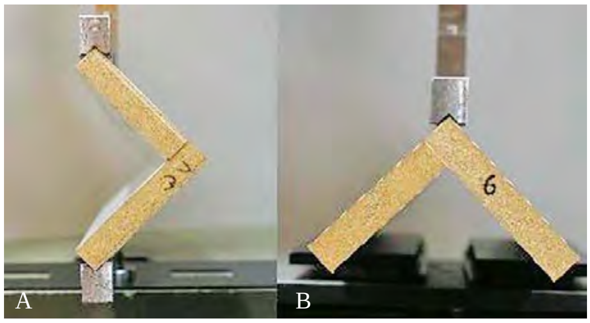


Figure 2 Joints subjected to: a) compression, b) tension
Slika 2. Vezovi izloženi: a) tlačnoj sili, b) vlačnoj sili

ed in a study by Krzyżaniak and Smardzewski (2019) and in Figure 2. The methodology applied to measure force and sample deflection were described in detail by Krzyżaniak and Smardzewski (2019). Based on their results, substitute moduli of elasticity E_s were calculated for the joints.

2.2 Substitute modulus of elasticity
2.2. Zamjenski modul elastičnosti

In order to estimate joint elastic moduli, the authors employed the calculation model presented in Figure 3. In this model, L = 100 mm designates the length of the joint arms, L_2 = 18 mm – height of the arm cross-section, $L = L_1 + L_2$, x_1, x_2 – ranges of integration, E – linear modulus of elasticity of particle board, and E_s – substitute modulus of elasticity.

If the joint is subjected to compression, the constitutive equation describing the deflection DP in the direction of force P assumes the following form (Fig. 3a):

$$DP = 2\left(\int_0^{L_1} \frac{P\cos^2\alpha}{EJ} x_1^2 dx_1 + \int_{L_1}^{L=L_1+L_2} \frac{P\cos^2\alpha}{E_s J} x_2^2 dx_2 \right), \quad (1)$$

$$J = bL_2^3 / 12, \quad (2)$$

where: b – denotes the width of the joint cross-section. It was decided that for the selected joints this width would be equal to 30 mm. The solution of this equation is as follows:

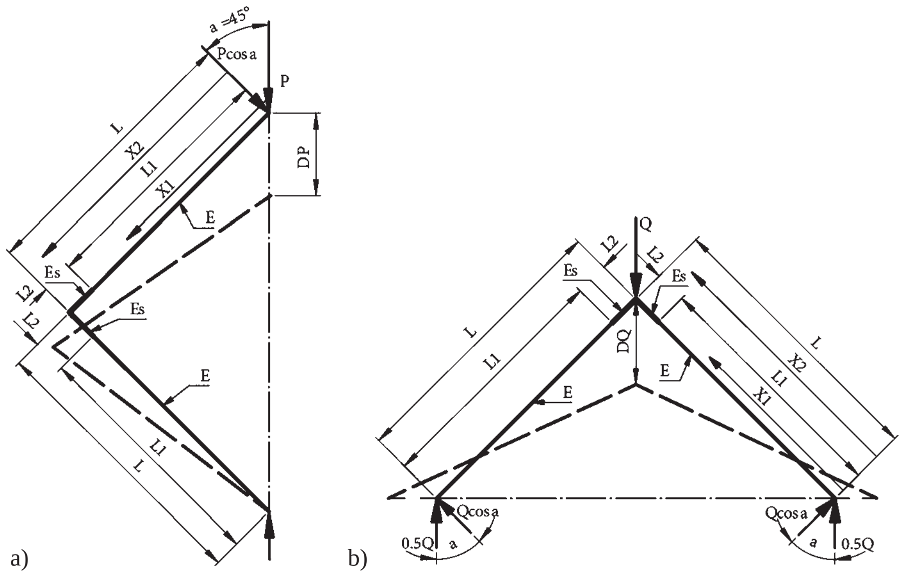


Figure 3 A geometrical model for analytical calculation of substitute moduli of elasticity of joints
Slika 3. Geometrijski model za analitički izračun zamjenskog modula elastičnosti vezova

$$DP = \frac{2P\cos^2\alpha}{3J}\left(\frac{L_1^3}{E} + \frac{L^3 - L_1^3}{E_s}\right). \tag{3}$$

Therefore, the elastic modulus of the joint assumed the following form:

$$E_s = \frac{2PE\cos^2\alpha(L^3 - L_1^3)}{3EJ\,DP - 2P\cos^2\alpha L_1^3}. \tag{4}$$

For the joint subjected to tension, the constitutive equation describing the deflection *DQ* in the direction of action of force *Q* assumes the following form (Fig. 3b):

$$DQ = 2\left(\int_0^{L_1}\frac{Q\cos^2\alpha}{2EJ}x_1^2dx_1 + \int_{L_1}^{L=L_1+L_2}\frac{Q\cos^2\alpha}{2E_sJ}x_2^2dx_2\right), \tag{5}$$

hence,

$$DQ = \frac{Q\cos^2\alpha}{6J}\left(\frac{L_1^3}{E} + \frac{L^3 - L_1^3)}{E_s}\right), \tag{6}$$

and

$$E_s = \frac{QEcos^2\alpha\left(L^3 - L_1^3\right)}{6EJDQ - Qcos^2\alpha\,L_1^3}. \tag{7}$$

It was further decided to determine physical and mechanical properties of the applied particle board species. The linear modulus of elasticity *E*, static bending strength or modulus of rupture (*MOR*) and density were determined in accordance with the EN 310 standard. Using equations 4 and 7, E_s was calculated for each of the examined joints and subsequently the obtained results were used for numerical calculations.

2.3 FEM models
2.3. FEM modeli

Tests were conducted on case furniture items with dimensions as specified in Figure 4. All the furniture body elements were manufactured applying an identical technology and using the same particle boards.

Furniture bodies were supported in three corners (Figure 4) and loaded with a horizontal force *P* (N) in the right upper corner. The value of the loading force was selected so that the deflection was 80 mm. Figure 5 presents an example model for numerical calculations of the furniture. All the furniture elements were modelled using 10–node finite tetrahedral C3D8R elements. Between the narrow surfaces of the furniture structural elements, the points of contact were established for hard surfaces with no friction exerted. The side walls, top and bottom elements were made from particle board (*E* = 2500 MPa, Poisson ratio 0.3). The back wall made from a HDF board (*E* = 3500 MPa, Poisson ratio 0.3) was fixed permanently in the rabbets and connected with bonded type joints. The joints were modelled as cuboids with the base of 18 mm x 18 mm and length of 30 mm, which were connected with the side walls and the tops of the furniture case using an elastic bonded type joint. The joints were ascribed respective substitute moduli of elasticity depending on the character of deformation (compression or tension).

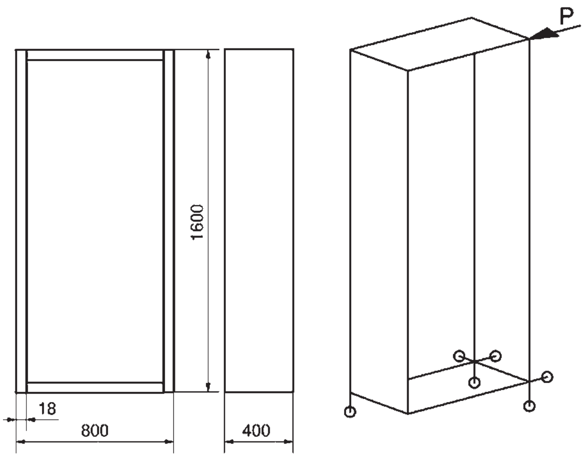


Figure 4 Case furniture used in tests
Slika 4. Ispitivani korpusni namještaj

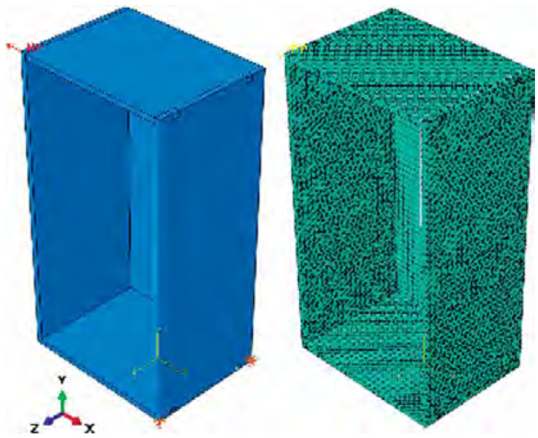


Figure 5 A mesh of finite elements on furniture model
Slika 5. Mreža konačnih elemenata na modelu namještaja

Based on the results of numeric calculations, the dependencies between force and displacement were established for furniture bodies connected using the tested joints.

Moreover, stiffness coefficients were calculated for furniture cases based on formula (8):

$$K = \frac{F}{\delta} \text{ (N/mm)} \tag{8}$$

where: F – force loading the furniture body, δ – displacement in the direction of the force.

The numerical calculations were performed using the Abaqus v.6.16 programme (Dassault Systemes Simulia Corp., Waltham, Ma, USA) at the Poznań Supercomputing and Networking Centre in the Eagle cluster.

3 RESULTS
3. REZULTATI

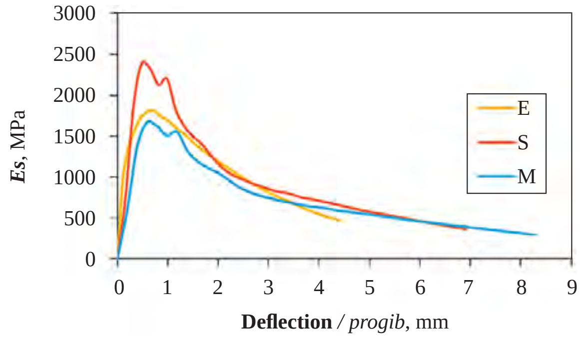
First, the variation in the substitute modulus of elasticity was calculated in the function of joint deflection (Figure 6).

It results from Figure 6 that the greatest values of the modulus of elasticity for the joint are reached for a deflection of approx. 1 mm. Then these values drop rapidly and for a deflection of 3 mm they amount to approx. 40 % of the maximum value. Thus values of E_s presented in Table 1 were selected for numerical calculations.

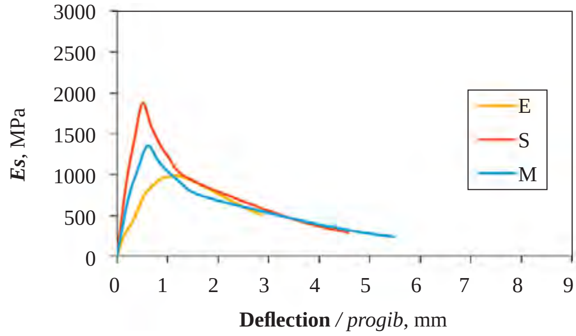
Figure 7 presents a characteristic mode of torsional deformation of the furniture body. We may observe clearances and gaps between elements of the furniture body caused by bending of joints and pressure of panel edges.

Table 1 Substitute moduli of elasticity for the joints
Tablica 1. Zamjenski modul elastičnosti za vezove

Type of joint *Tip veza*	**Deflection, mm** *Progib*, mm	***Es*, MPa**		
		S	M	E
Compression *tlačno naprezanje*	1	2201	1554	1815
	3	847	660	1219
Tension *vlačno naprezanje*	1	1211	918	821
	3	550	439	786



a)



b)

Figure 6 Dependence E_s of deflection in the test of: a) joint compression, and b) joint tension
Slika 6. Ovisnost E_s o progibu u ispitivanjima: a) tlačnog naprezanja vezova, b) vlačnog naprezanja vezova

Stiffness of furniture depending on the type of used joints is presented in Figure 8. It results from this figure that stiffness characteristics are non-linear and progressive. This means that the value of loads increases with an increase in displacements. It is also evident that a change in E_s values within the same joint has no significant effect on changes in stiffness of the furniture body. No significant difference in stiffness coefficients for the furniture bodies is observed between the used joints (Figure 9).

This means that the newly designed joints for case furniture provide this furniture with stiffness com-

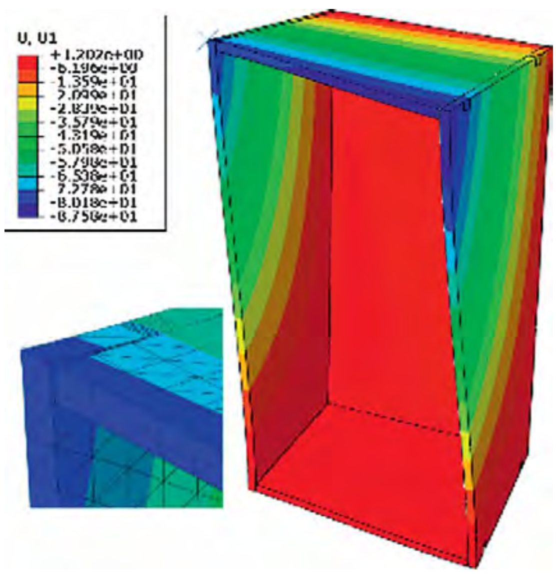


Figure 7 Deformation of furniture (deflection in mm)
Slika 7. Deformacije namještaja (progib u mm)

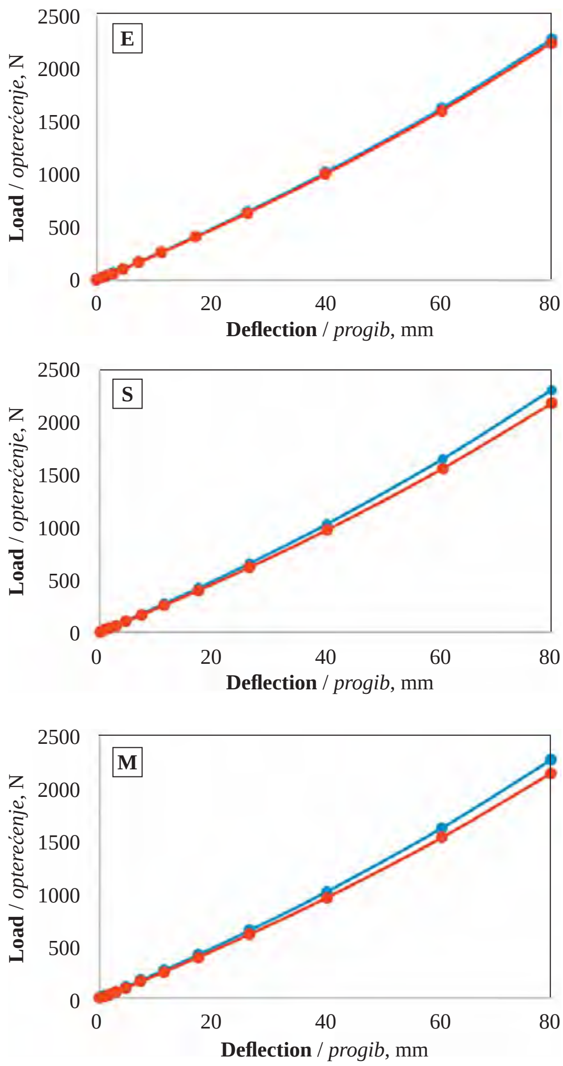


Figure 8 Stiffness of furniture with different joints: eccentric (E), slide catch (S), tension twist (M) (blue: for deflection 1 mm, orange: for deflection 3 mm)
Slika 8. Krutost namještaja pri različitim vezovima: sa svornjakom sa zakretnim klinom (E), s kliznom kopčom (S), s *tension twist* vezom (M) (plavo: za progib 1 mm, narančasto: za progib 3 mm)

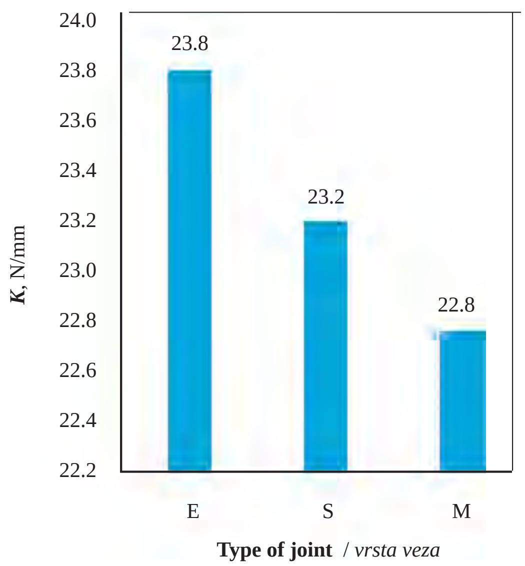


Figure 9 Stiffness coefficient of cabinet furniture
Slika 9. Koeficijent krutosti korpusnog namještaja

parable to that which may be obtained using traditional eccentric joints (E).

4 CONCLUSIONS
4. ZAKLJUČCI

Results obtained based on numerical calculations and their analysis gave grounds for the following conclusions and remarks:

1. The greatest values of the substitute moduli of elasticity are recorded for the slide catch joint. Rigidity of these joints is very close to the rigidity of eccentric joints. For this reason, we can recommend this connection as a good substitute to eccentric connections.
2. The tension twist joints also ensure very good mechanical properties of case furniture. So, it can also be used in furniture industry.
3. Generally, no significant difference was shown between stiffness of case furniture items with traditional eccentric joints and stiffness of furniture items with newly designed joints. This is due to the fact that each of the connections generates internal montage forces. These forces guarantee high rigidity of the case furniture.
4. Relationship between force and displacement of furniture are non-linear. This is due to the interaction of internal montage forces in the connectors and the increase of the contact surface between the elements. It was described in detail in the work by Krzyżaniak and Smardzewski (2019).

5 REFERENCES
5. LITERATURA

1. Dzięgielewski, S.; Smardzewski, J., 1996: Moduł sprężystości połączeń a sztywność mebli skrzyniowych – analiza numeryczna [Modulus of elasticity of joints and stiffness of case furniture - a numerical analysis]. Materials of the 8th scientific session “Research for furniture industry”. Wydawnictwo Akademii Rolniczej im. A. Cieszkowskiego w Poznaniu. Poznań, pp. 23-48.
2. Kasal, A., 2008: Effect of the number of screws and screw size on moment capacity of furniture corner joints in case construction. Forest Prod. J., 58 (6): 36-44.
3. Kasal, A.; Zhang, J.; Yuksel, M.; Erdil, Y. Z., 2008a: Effects of screw sizes on load bearing capacity and stiffness of five-sided furniture cases constructed of particleboard and medium density fiberboard. Forest Prod. J., 58 (10): 25-32.
4. Kasal, A.; Erdil, Y. Z.; Zhang, J.; Efe, H.; Avci, E., 2008b: Estimation equations for moment resistances of L-type screw corner joints in case goods furniture. Forest Prod. J., 58 (9): 21-27.
5. Kłos, R.; Smardzewski, J., 2004: Wielokryterialna optymalizacja mebli skrzyniowych metodą algorytmów genetycznych [Multiple criterion optimisation of case furniture using the genetic algorithm method]. Roczniki Akademii Rolniczej w Poznaniu, 39: 5-14.
6. Krzyżaniak, Ł.; Smardzewski, J., 2019: Strength and stiffness of new designed externally invisible and demountable joints for furniture cases. Engineering Structures, 199, 2019, 109674. https://doi.org/10.1016/j.engstruct.2019.109674.

7. Nicholls, T.; Crisan, R., 2002: Study of the stress-strain state in corner joints and box-type furniture using Finite Elements Analysis (FEA). Holz als Roh- und Werkstoff, 60: 66-71. https://doi.org/10.1007/s00107-001-0262-0.
8. Smardzewski, J., 2004a: Modeling of semi-rigid joints of the confirmate type. Annals of Warsaw Agricultural University, Forest and Wood Technology 55: 486-490.
9. Smardzewski, J., 2004b: Modelowanie półsztywnych węzłów konstrukcyjnych mebli [Modelling of semi-rigid structural nodes of furniture]. Monograph B. Branowski, P. Pohl (eds.). Wydawnictwo AR w Poznaniu 139-170, pp. 218-221.
10. Smardzewski, J., 2005: Nieliniowe modele połączeń zaczepowych [Non-linear models of catch joints]. Polioptymalizacja i komputerowe wspomaganie projektowania. Wydawnictwo Uczelniane Politechniki Koszalińskiej. Mielno, pp. 184-192.
11. Smardzewski, J.; Kłos, R., 2004: Możliwości polioptymalizacji mebli skrzyniowych z wykorzystaniem metody gradientowej [Potential for polyoptimisation of case furniture using the gradient method]. Przemysł Drzewny, 4 (LV): 32-35.
12. Smardzewski, J.; Kłos, R.; Fabisiak, B., 2013: Determination of the impact of creeping of furniture joints on their rigidity. Turkish J. Agric. For. 37: 802-811. https://doi:10.3906/tar-1206-8.
13. Smardzewski, J.; Kłos, R., 2011: Modeling of joint substitutive rigidity of board elements. Annals of Warsaw University of Life Sciences – SGGW Forestry and Wood Technology 2011, 73: 7-15.
14. Smardzewski, J.; Ożarska, B., 2005: Rigidity of cabinet furniture with semi-rigid joints of the confirmat type. Electronic Journal of Polish Agricultural Universities Wood Technology, 8 (2), 32.
15. Smardzewski, J.; Prekrat, S., 2002: Stress distribution in disconnected furniture joints. Electronic Journal of Polish Agricultural Universities, Wood Technology, 5 (2).
16. Smardzewski, J.; Prekrat, S., 2005: Nonlinear strength model of an eccentric joint mandrel. Drvna industrija, 55 (2): 59-67.
17. Tankut, A. N.; Tankut, N., 2005: The effects of joint forms (shape) and dimensions on the strengths of mortise and tenon joints. Turkish J. Agric. For. 29: 493-498.

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Brachystegia cynometroides Harms

NAZIVI I PODRUČJE RASPROSTRANJENOSTI

Brachystegia cynometroides Harms vrsta je drva iz porodice *Fabaceae* (*Leguminosae*), potporodice *Caesalpinioideae*. Na tržištu se pojavljuje zajedno s vrstama *B. eurycoma* Harms i *B. leonensis* Burtt Davy & Hutch. pod nazivima Naga (Njemačka, Francuska), okwen (Velika Britanija, Nigerija), méblo (Obala Bjelokosti), mendou (Gabon), tebako (Liberija), bodgei (Siera Leone). Stabla *Brachystegia cynometroides* Harms nalazimo u zapadnoj Africi. Pretežito rastu u kišnim šumama istočne Nigerije i zapadnog Kameruna. Vrste istoga roda mogu se pronaći u Liberiji, Obali Bjelokosti i Siera Leoneu.

STABLO

Stablo doseže visinu do 25 m. Čisto deblo dugo je 12 do 18 m, a prsni mu je promjer od 0,7 do 1,2 (1,5) m. Debla su valjkastog oblika. Kora mladih stabala je glatka i žućkasta. Na starijim stablima kora je gruba i ljuskasta, crvenonarančaste boje.

DRVO

Makroskopska obilježja

Bjeljika je bjelkasta do svjetlosmeđa, a široka je 6 – 15 cm. Srž drva je boje bakra do crvenkastosmeđa. Tekstura drva je dekorativna, često sa svijetlim ili tamnim prugama, katkad nepravilne žice. Drvo je rastresito porozno. Vidljiva je granica goda s graničnim aksijalnim parenhimom. Pore drva i drvni traci povećalom su dobro vidljivi.

Mikroskopska obilježja

Drvo je rastresito porozno. Traheje su pojedinačne, rjeđe su u malim skupinama i kratkim radijalnim nizovima. Promjer traheja je 85...177...288 mikrometara, a gustoća im je 2...4...7 na 1 mm^2 poprečnog presjeka. Volumni udio traheja iznosi oko 10 %. Traheje ranoga drva u srži ispunjene su tilama.

Aksijalni je parenhim apotrahealno granični i paratrahealno vrpčast. Volumni udio aksijalnog parenhima iznosi oko 20 %. Staničje drvnih trakova je homogeno do slabo heterogeno, katno raspoređeno.

Drvni traci visoki su 100...310...530 mikrometara (do 20 stanica), a široki su 14...24...34 mikrometara. Gustoća drvnih trakova je 5...8 na 1 mm tangentnog presjeka. Njihov volumni udio iznosi oko 13 %. Drvna su vlakanca libriformska. Dugačka su 310...560...1115 mikrometara. Debljina staničnih stijenki vlakanca iznosi 1,9...3,0...3,9 mikrometara, a promjeri njihovih lumena su 10,4...16,0...22,1 mikrometara. Volumni udio vlakanca je oko 57 %.

Fizička svojstva

Gustoća apsolutno suhog drva, ρ_o	oko 600 kg/m^3
Gustoća prosušenog drva, $\rho_{12\text{-}15}$	530...640...730 kg/m^3
Gustoća sirovog drva, ρ_s	900...1000 kg/m^3
Radijalno utezanje, β_r	4,2...5,4 %
Tangentno utezanje, β_t	6,5...7,9 %
Volumno utezanje, β_v	11,9...13,5 %

Mehanička svojstva

Čvrstoća na tlak	43...55...64 MPa
Čvrstoća na savijanje	100...125...150 MPa
Tvrdoća (prema Brinellu), paralelno s vlakancima	30...34...40 MPa
Tvrdoća (prema Brinellu), okomito na vlakanca	16...20 MPa
Modul elastičnosti	9,1...12,0 GPa

TEHNOLOŠKA SVOJSTVA

Obradivost

Drvo se dobro pili, lijepi, blanja i brusi. Katkad je zbog nepravilne žice teško postići glatku površinu. Pri čavlanju i vijčanju može doći do raspucavanja površine drva. Preporučuje se drvo predbušiti.

Sušenje

Drvo se dobro suši. Kako se zbog slabe permeabilnosti drva u procesu sušenja ne bi pojavila skorjelost ili nastao kolaps drva, preporučuje se polagano sušenje. Sklonost promjeni oblika i raspucavanju malena je.

Trajnost i zaštita

Prema normi HRN 350-2, 2005, srž drva *Brachystegia cynometroides* Harms slabo je otporna na gljive uzročnice truleži (razred otpornosti 3) i osjetljiva je na napad termita (razred otpornosti M). Srž je slabo permeabilna (razred 3). Po trajnosti pripada razredu 2 i stoga se može upotrebljavati u interijeru. Za upotrebu na otvorenim prostorima drvo je potrebno prethodno zaštiti.

Uporaba

Drvo se upotrebljava za izradu stolarije, furnira i furnirskih ploča te dijelova namještaja.

Sirovina

Drvo se isporučuje u obliku trupaca i piljenica.

Napomena

Drvo je zbog sličnosti boje moguće zamijeniti s ostalim vrstama istog roda. Furnir drva nage može se rabiti kao zamjena za drvo sapelija (*Entadrophragma cylindricum*) i makorea (*Tieghemella* spp), a masivno drvo kao zamjena za drvo sipa (*Entadrophragma utile*). *Brachystegia cynometroides* Harms za sada nije na popisu ugroženih vrsta međunarodne organizacije CITES, niti na popisu međunarodne organizacije IUCN. Drvo sličnih svojstava imaju i ove vrste: *Brachystegia eurycoma* Harms, *B. leonensis* Burtt Davy & Hutch., *B. nigerica* Hoyle & A. P. D. Jones, *B. laurentii* (De Wild.) Hoyle, *B. spiiciformis* Benth., *Entandropragma cylindricum* Sprague, *Monopetalanthus heitzii* Pelegr., *Tetraberlinia bifoliata* (Harms) Hauman.

LITERATURA

1. Gérard, J.; Guibal, D.; Paradi, S.; Cerre, J. C., 2017: Tropical Timbers Atlas, Technological characteristics and uses. Éditions Quae RD 10,78026 Versailles Cedex.
2. Wagenführ, R.; Scheiber, C., 2006: HOLZATLAS. VEB Fachbuchverlag, Leipzig, pp. 540-542.
3. ***HRN EN 350-2, 2005: Trajnost drva i proizvoda na osnovi drva – Prirodna trajnost masivnog drva, 2. dio.
4. https://tropix.cirad.fr/FichiersComplementaires/EN/Africa/NAGA.pdf (preuzeto 25. travnja 2020.).
5. http://www.wood-database.com/wood-articles/restricted-and-endangered-wood-species/ (preuzeto 25. travnja 2020.).
6. https://www.lesserknowntimberspecies.com/species/naga (preuzeto 25. travnja 2020.).

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

Knjiga koja može svim ljubiteljima drvne struke biti koristan izvor informacija o izgledu, osnovnim strukturnim obilježjima te o fizičkim, mehaničkim i tehnološkim svojstvima 97 vrsta drva…

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13th International Scientific Conference WoodEMA 2020

&

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SUSTAINABILITY OF FOREST-BASED INDUSTRIES IN THE GLOBAL ECONOMY

Vinkovci, Croatia, September 28th- 30th 2020

At the end of September 2020, in the period from 28th to 30th, in Vinkovci, Croatia, two international scientific conferences will be held together in the same venue. Under the joined organization of three partners, International Association for Economics and Management in Wood Processing and Furniture Manufacturing WoodEMA, i.a., University of Zagreb, Faculty of Forestry and Competence Centre Ltd. Vinkovci, 13th International Scientific Conference WoodEMA 2020 and 31st International Scientfic Conference ICWST 2020 will host many internationally recognized scientists and researchers from all over Europe who will present their recent research results under the common main title SUSTAINABILITY OF FOREST-BASED INDUSTRIES IN THE GLOBAL ECONOMY.

Presentations will cover different aspects of sustainability of forestry, wood processing and furniture manufacturing under wide range of topics such as: production management, production and business economics, marketing, human resource management, quality assurance and quality management, innovativeness, information systems, renewable energy from wooden biomass, properties of wood and wood based materials, wood modifications, wood processing technology, wood products, furniture and interior design.

Also, along with the simultaneous conferences, several important scientific projects conducted by Competence Centre Ltd., Faculty of Forestry and wood processing companies in the area, funded by European Union will be presented and discussed.

Rich social program along with the conferences, including some visits and surprise trip in the Eastern Slavonija region of Croatia is planned for all the participants.

We expect your participation on this event.

Internacionalizacija Šumarskog fakulteta „kod kuće“

Na Šumarskom fakultetu Sveučilišta u Zagrebu u tijeku je provedba projekta *Internacionalizacija Šumarskog fakulteta „kod kuće“ (InterSumfak)*. Projekt je sufinanciran u okviru Poziva *Internacionalizacija visokog obrazovanja* iz Europskoga socijalnog fonda (ESF), Operativnoga programa *Učinkoviti ljudski potencijali 2014. – 2020*. Ukupna vrijednost projekta iznosi 1.437.118,85 kuna. Nositelj je projekta Šumarski fakultet, a u svojstvu partnera sudjeluje i Prirodoslovno-matematički fakultet Sveučilišta u Zagrebu, Biološki odsjek. Projekt je započeo u listopadu 2018. godine, a trajat će do listopada 2021. godine.

Kako bi prevladali nedostatak studijskih programa na stranom jeziku, članovi projektnog tima s voditeljicom doc. dr. sc. Martinom Temunović na čelu, rade na povećanju broja predmeta diplomskih studija Šumarskog fakulteta koji se izvode na engleskom jeziku. Projekt će unaprijediti uvjete dolazne mobilnosti studenata, ali će i domaćim studentima omogućiti upis predmeta na engleskom jeziku u međunarodnom okruženju, što predstavlja dobru pripremu za njihovo sudjelovanje u programima međunarodne mobilnosti. Upis predmeta na engleskom jeziku važan je i za studente Šumarskog fakulteta koji nisu u mogućnosti sudjelovati u programima međunarodne razmjene jer im se omogućuje razvoj transverzalnih vještina i jezičnih kompetencija na „domaćem“ terenu, što ih čini konkurentnijima na tržištu rada.

Razvoj i izvedba predmeta na engleskom jeziku „kod kuće“ izravno doprinose jačanju osobnih kompetencija te jezičnih vještina nastavnog osoblja uključenog u projekt. Time se olakšava umrežavanje nastavnika s inozemnim visokim učilištima i njihove međunarodne istraživačke aktivnosti te im se pruža prilika da ojačaju međunarodnu suradnju. Sve to doprinosi boljoj međunarodnoj kompetitivnosti nastavnika te cjelokupnom ugledu i znanstvenoj izvrsnosti Šumarskog fakulteta.

Glavna aktivnost projekta je razvoj i izvedba pet predmeta na engleskom jeziku na diplomskim studijima Šumarskog fakulteta. Za potrebe izvedbe nastave izradit će se i tiskati interne skripte te jedan sveučilišni udžbenik na engleskom jeziku. Kako bi osigurali odgovarajuću razinu jezičnih kompetencija, nastavnici i nenastavno osoblje, koji sudjeluju u projektu, pristupaju međunarodno priznatim ispitima ili pohađaju semestralne tečajeve engleskog jezika. Projektom je predviđen i angažman četiri gostujuća predavača iz zemlje i inozemstva. Upisi predmeta na diplomskim studijima Drvnotehnološkog odsjeka započeli su u akademskoj godini 2019./2020., dok će upisi predmeta na diplomskim studijima Šumarskog odsjeka započeti u akademskoj godini 2020./2021.

Povećan broj predmeta na engleskom jeziku i usavršene jezične kompetencije te iskustva nastavnika u izvođenju nastave na engleskom jeziku, predstavljaju prvi korak prema ponudi cjelokupnih studijskih programa na stranim jezicima, što je jedan od strateških ciljeva Šumarskog fakulteta.

Više o projektu na internetskoj stranici Šumarskog fakulteta:

https://www.sumfak.unizg.hr/hr/znanstveni-rad-i-medjunarodna-suradnja/projekti/internacionalizacija-sumarskog-fakulteta-kod-kuce/

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ESF UČINKOVITI LJUDSKI POTENCIJALI

InterSumfak
Internacionalizacija Šumarskog fakulteta „kod kuće“

RAZVOJ I PROVEDBA STRUČNE PRAKSE NA STUDIJIMA ŠUMARSKOG FAKULTETA

Na Šumarskom fakultetu Sveučilišta u Zagrebu u tijeku je provedba projekta ***Razvoj i provedba stručne prakse na studijima Šumarskog fakulteta***. Projekt je sufinanciran u okviru poziva *Razvoj, unapređenje i provedba stručne prakse u visokom obrazovanju* Europskoga socijalnog fonda (ESF), Operativnoga programa *Učinkoviti ljudski potencijali 2014. – 2020.*

Ukupna vrijednost projekta iznosi 3.902.617,14 kuna. Uz Šumarski fakultet koji je nositelj projekta, u svojstvu partnera sudjeluju i Hrvatska komora inženjera šumarstva i drvne tehnologije, Drvni klaster Slavonski hrast te Centar kompetencija d.o.o. za istraživanje i razvoj. Projekt je započeo u ožujku 2020. godine, a trajat će do ožujka 2023. godine.

Svrha je projekta pružanje podrške studentima Šumarskog fakulteta u povećanju zapošljivosti unapređenjem i provedbom stručne prakse koja će im omogućiti stjecanje potrebnih praktičnih vještina. U projekt je uključeno 404 studenta Šumarskog fakulteta, koji će dobiti priliku da tijekom studija steknu praktične vještine i prvo radno iskustvo sudjelovanjem u aktivnostima koje se temelje na rješavanju stvarnih problema u sektoru. Studenti šumarstva i drvne tehnologije sudjelovat će u aktivnostima mentoriranoga praktičnog rada na Fakultetu, zajedničkoj višednevnoj terenskoj nastavi u drvoprerađivačkim tvrtkama i parkovima prirode te individualnoj praksi u tvrtkama u trajanju od mjesec dana. Na taj će način studenti steći dodatne vještine za uspješniji izlazak na tržište rada. Nadalje, na Fakultetu će se uspostaviti Centar za stručnu praksu i razvoj karijera sa svrhom pomaganja studentima u pronalaženju i organizaciji prakse te usmjeravanju prema tržištu rada u skladu s njihovim afinitetima, mogućnostima i kompetencijama. Projekt će omogućiti i opremanje računalne učionice i radionice za stručnu praksu za studente Drvnotehnološkog odsjeka. Uz postojeći suvremeni 5-osni CNC stroj te 3D skener i printer, studenti će od sada imati priliku koristiti i laserski uređaj za graviranje i rezanje. Stručnom edukacijom nastavnika u suradnji sa sektorskim tvrtkama i mentorima iz realnog sektora ostvarit će se povezivanje visokog obrazovanja i tržišta rada, što je iznimno važno u edukaciji budućih stručnjaka iz područja šumarstva, urbanog šumarstva i drvne tehnologije. Usto, provedbom projekta izravno se doprinosi ciljevima prioriteta iz područja obrazovanja budući da je cilj projekta unaprijediti kvalitetu sustava obrazovanja te poboljšati njegovu učinkovitost i usklađenost s potrebama tržišta rada.

CILJEVI PROJEKTA

1. Pružiti podršku studentima Šumarskog fakulteta u povećanju zapošljivosti unapređenjem i provedbom stručne prakse za 404 studenta, koja će im omogućiti stjecanje potrebnih praktičnih vještina.
2. Uspostaviti Centar za stručnu praksu na Šumarskom fakultetu.
3. Ojačati kompetencije 55 nastavnika u suradnji s partnerima iz sektora: Hrvatskom komorom inženjera šumarstva i drvne tehnologije, Centrom kompetencija d.o.o. za istraživanje i razvoj i Drvnim klasterom Slavonski hrast.

Očekivani rezultati projekta predstavljaju značajne i važne korake u povećanju zapošljivosti studenata Šumarskog fakulteta na tržištu rada, a što je jedan od važnih strateških ciljeva Šumarskog fakulteta.

Voditeljica projekta je doc. dr. sc. Andreja Pirc Barčić.

Više o projektu može se pronaći na web stranici projekta:

https://www.sumfak.unizg.hr/hr/znanstveni-rad-i-medjunarodna-suradnja/projekti/razvoj-i-provedba-strucne-prakse-na-studijima-sumarskog-fakulteta-eu-projekt-up.03.1.1.04.0089/

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Upute

Predani radovi smiju sadržavati najviše 15 jednostrano pisanih A4 listova s dvostrukim proredom (30 redaka na stranici), uključujući i tablice, slike te popis literature, dodatke i ostale priloge. Dulje je članke preporučljivo podijeliti na dva ili više nastavaka. Tekst treba biti u *doc formatu*, u potpunosti napisan fontom *Times New Roman* (tekst, grafikoni i slike), normalnim stilom, bez dodatnog uređenja teksta.
Prva stranica poslanog rada treba sadržavati puni naslov, ime(na) i prezime(na) autora, podatke o zaposlenju autora (ustanova, grad i država) te sažetak s ključnim riječima (duljina sažetka približno 1/2 stranice A4).
Posljednja stranica treba sadržavati titule, zanimanje, zvanje i adresu (svakog) autora, s naznakom osobe s kojom će Uredništvo biti u vezi.
Znanstveni i stručni radovi moraju biti sažeti i precizni. Osnovna poglavlja trebaju biti označena odgovarajućim podnaslovima. Napomene se ispisuju na dnu pripadajuće stranice, a obrojčavaju se susljedno. One koje se odnose na naslov označuju se zvjezdicom, a ostale uzdignutim arapskim brojkama. Napomene koje se odnose na tablice pišu se ispod tablica, a označavaju se uzdignutim malim pisanim slovima, abecednim redom.
Latinska imena trebaju biti pisana kosim slovima (italicom), a ako je cijeli tekst pisan kosim slovima, latinska imena trebaju biti podcrtana.
U uvodu treba definirati problem i, koliko je moguće, predočiti granice postojećih spoznaja, tako da se čitateljima koji se ne bave područjem o kojemu je riječ omogući razumijevanje ciljeva rada.
Materijal i metode trebaju biti što preciznije opisane da omoguće drugim znanstvenicima ponavljanje pokusa. Glavni eksperimentalni podaci trebaju biti dvojezično navedeni.
Rezultati trebaju obuhvatiti samo materijal koji se izravno odnosi na predmet. Obvezatna je primjena metričkog sustava. Preporučuje se upotreba SI jedinica. Rjeđe rabljene fizikalne vrijednosti, simboli i jedinice trebaju biti objašnjeni pri njihovu prvom spominjanju u tekstu. Za pisanje formula valja se koristiti Equation Editorom (programom za pisanje formula u MS Wordu). Jedinice se pišu normalnim (uspravnim) slovima, a fizikalni simboli i faktori kosima (italicom). Formule se susljedno obrojčavaju arapskim brojkama u zagradama, npr. (1) na kraju retka.
Broj slika mora biti ograničen samo na one koje su prijeko potrebne za objašnjenje teksta. Isti podaci ne smiju biti navedeni i u tablici i na slici. Slike i tablice trebaju biti zasebno obrojčane, arapskim brojkama, a u tekstu se na njih upućuje jasnim naznakama ("tablica 1" ili "slika 1"). Naslovi, zaglavlja, legende i sav ostali tekst u slikama i tablicama treba biti napisan hrvatskim i engleskim jezikom.
Slike je potrebno rasporediti na odgovarajuća mjesta u tekstu, trebaju biti izrađene u rezoluciji 600 dpi, crno-bijele (objavljivanje slika u koloru moguće je na zahtjev autora i uz posebno plaćanje), formata jpg ili tiff, potpune i jasno razumljive bez pozivanja na tekst priloga.
Svi grafikoni i tablice izrađuju se kao crno-bijeli prilozi (osim na zahtjev, uz plaćanje). Tablice i grafikoni trebaju biti na svojim mjestima u tekstu te originalnog formata u kojemu su izrađeni radi naknadnog ubacivanja hrvatskog prijevoda. Ako ne postoji mogućnost za to, potrebno je poslati originalne dokumente u formatu u kojemu su napravljeni (*excel* ili *statistica* format).
Naslovi slika i crteža ne pišu se velikim tiskanim slovima. Crteži i grafikoni trebaju odgovarati stilu časopisa (fontovima i izgledu). Slova i brojke moraju biti dovoljno veliki da budu lako čitljivi nakon smanjenja širine slike ili tablice. Fotomikrografije moraju imati naznaku uvećanja, poželjno u mikrometrima. Uvećanje može biti dodatno naznačeno na kraju naslova slike, npr. "uvećanje 7500 : l".
Diskusija i zaključak mogu, ako autori žele, biti spojeni u jedan odjeljak. U tom tekstu treba objasniti rezultate s obzirom na problem postavljen u uvodu i u odnosu prema odgovarajućim zapažanjima autora ili drugih istraživača. Valja izbjegavati ponavljanje podataka već iznesenih u odjeljku *Rezultati*. Mogu se razmotriti naznake za daljnja istraživanja ili primjenu. Ako su rezultati i diskusija spojeni u isti odjeljak, zaključke je nužno napisati izdvojeno. Zahvale se navode na kraju rukopisa. Odgovarajuću literaturu treba citirati u tekstu, i to prema harvardskom sustavu (*ime – godina*), npr. (Bađun, 1965). Nadalje, bibliografija mora biti navedena na kraju teksta, i to abecednim redom prezimena autora, s naslovima i potpunim navodima bibliografskih referenci. Popis literature mora biti selektivan, a svaka referenca na kraju mora imati naveden DOI broj, ako ga posjeduje (http://www.doi.org) (provjeriti na http://www.crossref.org).

Primjeri navođenja literature

Članci u časopisima: Prezime autora, inicijal(i) osobnog imena, godina: Naslov. Naziv časopisa, godište (ev. broj): stranice (od – do). Doi broj.

Primjer

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

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

Primjeri

Krpan, J., 1970: Tehnologija furnira i ploča. Drugo izdanje. Zagreb, Tehnička knjiga.
Wilson, J. W.; Wellwood, R. W., 1965: Intra-increment chemical properties of certain western Canadian coniferous species. U: W. A. Cote, Jr. (Ed.): Cellular Ultrastructure of Woody Plants. Syracuse, N.Y., Syracuse Univ. Press, pp. 551- 559.
Ostale publikacije (brošure, studije itd.)
Müller, D., 1977: Beitrag zür Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanstalt für Forstund Holzvvirt schaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

Web stranice

***1997: "Guide to Punctuation" (online), University of Sussex, www.informatics.sussex.ac.uk/department/docs/punctuation/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.

Other publications (brochures, studies, etc.):
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