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Sadržaj
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Installation of Test Setup and Measurement Procedures in Fir Wood Hydraulic Conductance Measurement

Instaliranje opreme i mjernih postupaka pri određivanju hidrauličke vodljivosti jelovine

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ABSTRACT • *For a hydraulic conductor, through which liquid flows, hydraulic conductance (K, ml·s^{-1}·MPa^{-1}) is defined as the ratio of pressure difference at the inlet and outlet to the fluid amount passing through the hydraulic conductor in a unit time period. This property is one of the key functions of the wood, and is obtained by the flow rate (F – Flow, ml·s^{-1}) along the wood sample divided by the pressure difference driving the flow (ΔP, MPa). This study aimed to establish a test setup to determine the hydraulic conductance values of Uludağ Fir (Abies bornmulleriana Mattf.). A test setup was established to measure the amount of water that flows in samples and pressure difference in characterized capillary tubes. In addition, calibration of the test apparatus is explained in detail. Fir wood samples taken from Yedigoller, which is affiliated to Kale Operation Chieftainship and Bolu Forest Regional Directorate, of 4 mm in diameter and 3 cm in length were prepared and hydraulic conductance measurements were performed, and the results are presented in this article. The installed test setup was used to obtain the following information about trees: operation of the hydraulic conduction system, the amount of needed water, seasonal effects and stress-related changes.*

Keywords: *hydraulic conductance; test setup; fir wood*

SAŽETAK • *Hidraulička vodljivost (K, ml·s^{-1}·MPa^{-1}) definira se kao omjer količine tekućine koja prolazi u određenom vremenu hidrauličkim vodičem i razlike tlaka na ulazu i izlazu vodiča. To je svojstvo jedna od ključnih funkcija drva, a njegova se veličina određuje mjerenjem brzine protoka (F – protok, ml·s^{-1}) uzduž uzorka drva zbog razlika tlakova (ΔP, MPa). Cilj ovog istraživanja bio je instaliranje mjernog sustava za određivanje hidrauličke vodljivosti jelovine (Abies bornmulleriana Mattf.). Postavkama mjerenja utvrđena je količina vode koja teče u uzorcima jelovine i razlika tlaka u karakterističnim kapilarama. Usto je detaljno objašnjeno kalibriranje ispitne opreme. Uzorci jelovine na kojima su provedena mjerenja hidrauličke vodljivosti bili su promjera 4 mm i duljine 3 cm i uzeti su s područja Yedigoller, a rezultati ispitivanja prikazani su u ovom radu. Instaliranim mjernim sustavom dobivene su ove informacije o stablima: djelovanje sustava hidrauličke vodljivosti u drvu, količina potrebne vode, utjecaji godišnjih doba i promjene povezane sa stresom.*

Ključne riječi: *hidraulička vodljivost; mjerni sustav; jelovina*

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1 INTRODUCTION
1. UVOD

The transportation of water in trees is provided by the conduit network that runs along the soil, roots, stem and leaves. This operation is regulated by hydraulic conductance. Hydraulic conductivity of a whole tree is directly related to the length and permeability of the conduit network (Hubbard *et al.*, 1999). Therefore, determining the hydraulic conductance in trees is important for understanding the absorption and transportation of water (Torres-Ruiz *et al.*, 2012). Hydraulic conductance can also be used to comparatively measure the general hydraulic adaptation between species and to assess the impact of environmental change, particularly drought, on transportation of water (Cochard *et al.,* 1996; Davis *et al.,* 1999; Ladjal *et al.*, 2005; Melcher *et al.*, 2012; Sperry and Love, 2015; Fontes *et al.,* 2018).

It is suggested that the water transportation in trees, provided by the pipes from the roots to the leaves, may be similar to the flow provided by the circular and smooth-walled capillary pipes (Tyree and Zimmermann, 2002). Hagen-Poiseuille law was used based on this assumption. Hagen and Poiseuille proposed an equation to describe the flow velocity and rate of fluid flow through a circular tube ($k = \pi \cdot r^4/8 \cdot \eta$). Accordingly, the hydraulic conductance, *k,* is related to the fourth power of the total diameter of the transmission pipes (Tyree and Ewers, 1991). However, since the internal anatomy and interconnections of xylem channels are more complex than a series of parallel flat-walled tubes and small errors in diameter measurement increase by the fourth power, the calculated xylem hydraulic conductance values typically exceed the measured conductance (Tyree and Ewers, 1991; Tyree and Zimmermann, 2002; Sperry *et al.,* 2005). Gibson *et. al.* (1984) state that the hydraulic conductivity values calculated using the tracheid diameters and Hagen Poiseuille equation are generally twice the measured conductance.

Hydraulic conductance measurements are commonly performed on chopped wood samples with measuring devices installed in the laboratory environment. Wood samples are connected to a hydraulic system to measure the pressure difference (ΔP) and mass flow rate (F) of a liquid (usually water) throughout the sample. Hydraulic conductance (K; $\text{kg}\cdot\text{s}^{-1}\cdot\text{MPa}^{-1}$) is calculated with the $F/\Delta P$ ratio in its simplest form. In addition, the hydraulic conductivity (K_h; $\text{kg}\cdot\text{s}^{-1}\cdot\text{MPa}^{-1}\cdot\text{m}$) is the ratio between water flux (F, $\text{kg}\cdot\text{s}^{-1}$) through an excised sample segment and the pressure gradient ($\Delta P/\Delta x$, $\text{MPa}^{-1}\cdot\text{m}^{-1}$) causing the flow (Cruiziat *at al.,* 2002). The specific conductivity (K_s, $\text{kg}\cdot\text{s}^{-1}\cdot\text{m}^{-1}\cdot\text{MPa}^{-1}$) (hydraulic conductivity per sapwood area, K_h/S) is obtained by dividing a unit pressure potential gradient ($\text{MPa}^{-1}\cdot\text{m}^{-1}$) per sapwood cross-sectional area by the flow rate (F, $\text{kg}\cdot\text{s}^{-1}$) generated by a branch or stem (Granier *et. al.,* 1989; Pallardy, 2008).

One of the techniques used to measure the hydraulic conductance in the laboratory was introduced by Sperry *et al.* (1988). In the assembled setup, a pressure difference between 3-10 kPa was created between the inlet and outlet points of the cut root and stem parts to provide the flow of solution. The flow rate was found by measuring the outgoing solution mass per second by a digital balance connected to the end of the wood sample. A similar device (HPFM – High Pressure Flow meter) has likewise been used to make comparative measurements of fluid conduction in roots and shoots, benefiting from the relationship between pressure change and hydraulic conductance (Tyree *et al.,* 1995). A different way of determining the flow rate, which is one of the main parameters in measuring hydraulic conductance, is proposed by Melcher *et al.* (2012). Also, Cochard (2002) disclosed a method for measuring the hydraulic conductivity of cut xylem fragments exposed to high negative pressures. In this method, a centrifugal force is used for creating a negative pressure (P) on the sample and to create a positive hydrostatic pressure difference (ΔP) between the two ends of the sample. The pressure difference (ΔP) allows the water to pass through the sample at a flow rate (F) optically determined during centrifugation. The sample hydraulic conductance (k) is obtained from (ΔP) and F.

In addition to conductance measurements along cut wood samples, measurements can be made along the whole shoot or root. Kolb *et al.* (1996) used a vacuum tube connected to a vacuum pump to create a pressure difference in the apparatus which was set up for this purpose. While the vacuum tube applies vacuum throughout the entire shoot, the stem base of the shoot is in a solution on the balance. Tyree *et al.* (2002) used a similar method (ULFM – Ultra Low Flowmeter) to measure hydraulic conductance along the entire stem. Hydraulic conductance of an individual vessel can also be measured, different from the measurements involving a certain length of cut wood samples and the entire stem-shoot-root system (Christman and Sperry, 2010; Zwieniecki *et al.,* 2001).

This study, which aims to explain the installation of the test setup, operation of the system and measurement steps in order to measure the hydraulic conductance on fir wood samples, is a pioneering work for further studies. The purpose of this study is to contribute to the understanding of issues about how trees transport water and adapt to environmental and seasonal conditions which have aroused curiosity from past to present.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Material
2.1. Materijal

The research sample of Uludağ Fir (*Abies bornmulleriana* Mattf.) was supplied from Yedigoller, which is affiliated to Kale Operation Chieftainship and Bolu Forest Regional Directorate. The fir tree taken from the region at an altitude of 1236 m is 75 years old and has 30 cm in diameter and 25 m in height. Samples were prepared by cutting 15 cm thick pieces like a wheel from the stem, which were taken from a height of 1.3 m. In order to carry out the measurements, longitudinal segments were removed to cover the 7-13th annual rings after cambium. Then, the pieces were turned into thin beads, which were rounded to a diameter of 4 mm. They were cut to 3 cm in length. Prepared samples were immersed in phenol dripped water until the measurement.

To find hydraulic conductance, distilled water at room temperature (25 °C) is used as the liquid in the system. Capillary tubes are characterized with water. All tests are performed with the same liquid and therefore test results can be compared. Another type of liquid can also be used in the system; in this condition all calibration and characterization processes should be performed on this liquid.

2.2 Method
2.2. Metoda

The measurement of the hydraulic conductance is based on the pressure difference between the inlet and outlet points of the samples. In this study, in order to determine the hydraulic conductance of the fir wood in the longitudinal direction, a test setup was established by examining this principle and reviewing the devices established for similar tests in the literature (Pereira and Mazzafera, 2012; Tyree *et al.,* 2002).

2.2.1 Installation of test assembly
2.2.1. Instalacija ispitnog sklopa

The test apparatus for measuring the hydraulic conductance of the wood particles are shown in Figure 1.

In this apparatus:

- 3-way valves were used for routing the pressurized fluid in the system,
- capillary tubes that have 3 different inner diameters and lengths were used to determine different flow rates and to provide comparative data,
- a calibration tube was used to find the pressure difference caused by the internal resistance of the system and to remove the air gaps in the wood samples,
- pressure sensors were used to measure the inlet (Pressure Sensor 1) and outlet pressures (Pressure Sensor 2) as well as the vacuum pressure (Pressure Sensor 3) in the vacuum tube,
- a vacuum pump was used to apply the vacuum in a vacuum tube used to place the sample,
- a peristaltic liquid pump was used to pressurize the liquid that supplied it to the system,
- a measuring cylinder was also used to collect and measure the amount of liquid passing through the pipes.

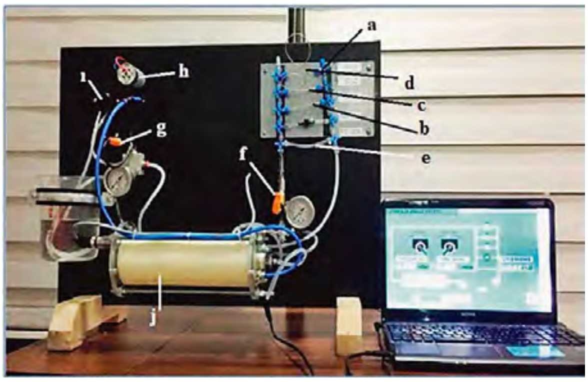


Figure 1 Hydraulic conductance test setup: a) Three-way valve, b) Capillary tube 1, c) Capillary tube 2, d) Capillary tube 3, e) Calibration tube, f) Pressure sensor 1, g) Pressure sensor 2, h) Vacuum pump, i) Peristaltic liquid pump, j) Vacuum tube
Slika 1. Sustav za mjerenje hidrauličke vodljivosti: a) trosmjerni ventil, b) kapilara 1, c) kapilara 2, d) kapilara 3, e) kalibracijska cijev, f) senzor tlaka 1, g) senzor tlaka 2, h) vakuumska pumpa, i) peristaltička pumpa, j) vakuumska cijev

Also, in order to record the data and control test setup via computer, controller (Siemens-Step 7 CPU 315), controller software (Siemens-Step 7 Version 5.5) (Figure 2) and data acquisition system (WinCC Flexible) were installed.

While operating the system, whose schematic view is given in Figure 3a, firstly the properties of the system elements are determined. When the test sample is not connected to the system, the pressurized liquid is passed through capillary tubes to measure the pressure

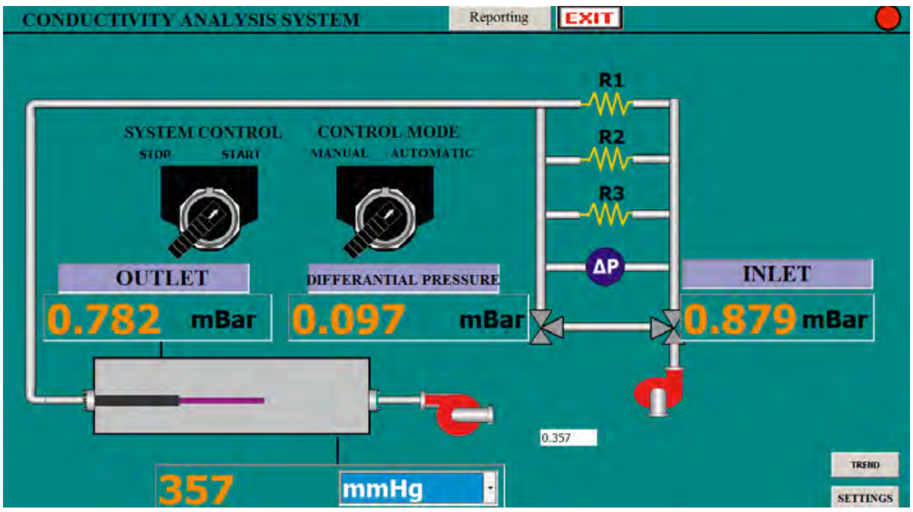


Figure 2 Controller software interface
Slika 2. Sučelje upravljačkog softvera

change and flow rate, thus obtaining the pressure-flow relationship of each capillary tube. The pressurized liquid is applied to the system and liquid flows in scale vessel after passing through the selected capillary tube in a given time period. The pressure difference is measured by the difference between inlet and outlet pressures and the flow rate is determined by water amount at a defined time period. Different pressures are applied to each capillary tube to obtain the pressure-flow characteristics of the tubes. Then, the wood sample in the vacuum tube is connected to the end and pressurized liquid is applied to the system. Then the pressure difference in the capillary tube is measured and after that the amount of liquid passing at a given time is determined by using the previously determined pressure-flow relationship. The measured liquid amount also refers to the amount of liquid passing through the wood sample. Liquid pressure applied to the wood sample that is also the outlet pressure of capillary tubes and the pressure in the vacuum tube is measured, and then the pressure difference on the sample is determined from the difference of these two values. The ratio of the amount of fluid passing at a given time and the pressure difference ($F/\Delta P$) gives the hydraulic conductance of the wood sample.

2.2.2 Test setup measurement calibration
2.2.2. Kalibriranje mjernog sustava

The aim of the system calibration is to adjust the pressure difference when the calibration tube, which has a much greater inner diameter than capillary tubes and ignorable resistance, is used in the system. In other words, the aim of calibration is to find the pressure difference due to the inner resistance of system piping and sensor reading error. Test measuring was calculated with respect to the obtained pressure difference data.

When performing system calibration, the valve position is adjusted so that the fluid passes through the calibration tube. A wood sample is connected to the end of the system in order to create pressure. At this stage, the Vacuum Pump and Pressure Sensor 3 are not used (Figure 3b). The pressure is applied to the system during calibration. After the system pipes are filled with liquid and the system is stabilized, the measurement is made by Pressure Sensor 1 and Pressure Sensor 2. The difference in the measured values is recorded by the data acquisition system.

2.2.3 Capillary tube characterization
2.2.3. Karakterizacija kapilare

In capillary tube characterization, the aim is to determine the pressure-flow relationship characteristics of each capillary tube. Three different capillary tubes were used in the test setup. Capillary Tube 1 has an internal diameter of 0.17 mm and a length of 9.5 cm, Capillary Tube 2 has an internal diameter of 0.17 mm and a length of 28 cm, Capillary Tube 3 has an internal diameter of 0.13 mm and a length of 28 cm. Three capillary tubes, as the combination of same diameter, different length, and same length, different diameter, were used to get reliable and comparable results. The graphs are obtained as a result of the characterization process that is applied separately for all three capillary tubes and, are used to measure the fluid conduction of the wood samples. Different pressures in the range of 50-100 kPa (0.50-1 bar) are applied to the system for each capillary tube to measure the amount of liquid flowing. For each pressure value, there is a flow rate value, and using all measures a trend curve equation can be obtained. With the help of this equation, the measured pressure difference value can be used to find the flow rate.

In capillary tube characterization, the outlet of the system is open to the external environment. A scale vessel is placed to measure the amount of fluid flowing to the outlet. While closing the calibration pipe valve, the valve is set to the position in order to allow fluid to pass only through the pipe to be characterized (Figure 3c). Vacuum Pump and Pressure Sensor 3 were not used for this operation.

During the process, the system is first pressurized and then the system has to be filled with liquid. When the system reaches its balance and liquid is seen at the system outlet, time measurement is started. When a certain amount of fluid is collected in the scale vessel, the system is switched off and the amount of fluid collected in the scale vessel and the elapsed time is recorded. The values of pressure difference are recorded during this time by the data acquisition system. Then, the same process is continued with increasing applied pressure. After different pressures in the range of 95-100 kPa (0.95-1 bar) are applied, the process is terminated and the results are evaluated.

$$\frac{F}{\Delta P}=\frac{\textit{Water amount in scaled vessel in given time}\left(\frac{\mathrm{ml}}{\mathrm{s}}\right)}{\textit{Applied Pressure} - \textit{Outlet Pressure}} \quad (1)$$

2.2.4 Measurement of hydraulic conductance
2.2.4. Mjerenje hidrauličke vodljivosti

Preliminary process

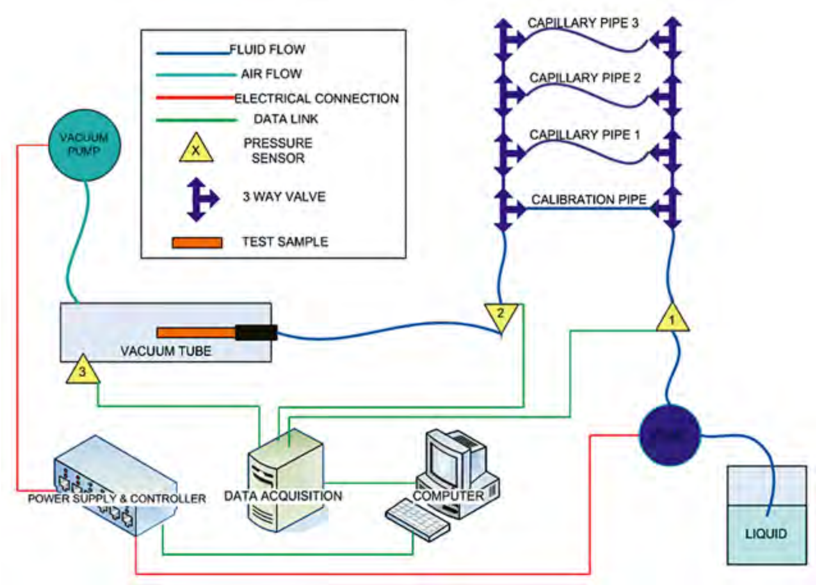
In order to measure the hydraulic conductance of wood samples, pressurized water should be applied to the samples as a preliminary process. The purpose of this process is to remove air and small sediments, which may affect the fluid flow within the sample. While applying pressurized water, the valve positions are adjusted to let the liquid only pass through the selected calibration tube. The sample is connected to the end of the system and the system is pressurized. After waiting for the sample to get completely wet, the system is turned off. This process is applied to each sample to be measured just before the test.

Measurement Procedure

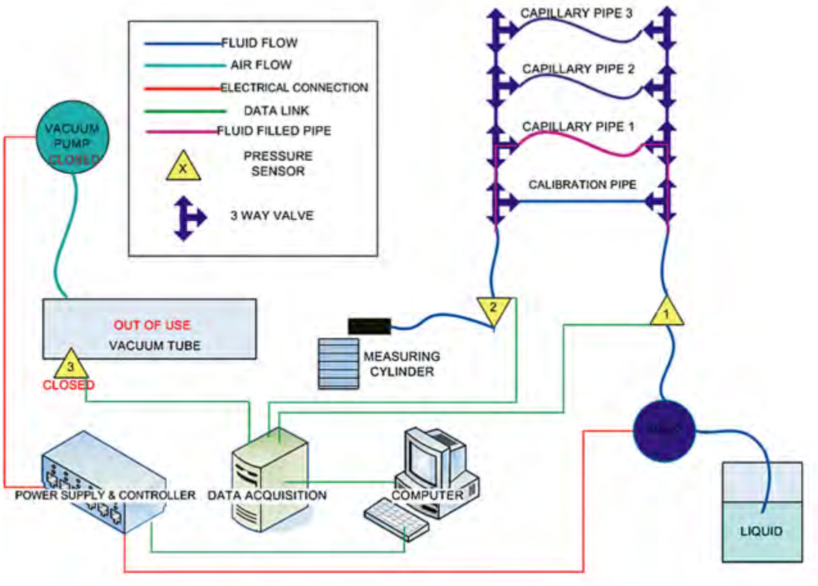
After the preliminary process is applied to wood samples, the hydraulic conductance values for each sample are measured using the calibrated system. Before starting the measurement process, the wood sample that has been subjected to pressurized water is placed in the vacuum tube and the calibration pipe valve is closed.

During the measurement:

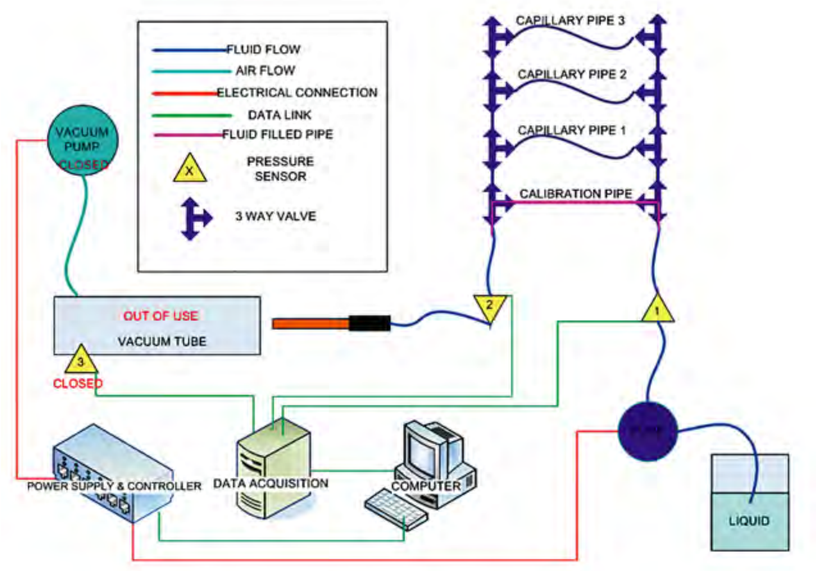
1. The valve is positioned to allow the flow of liquid only through Capillary Tube 1;



(a)



(b)



(c)

Figure 3 a) Schematic view of hydraulic conductance setup, b) System calibration, c) Capillary tube characterization
Slika 3. a) Shematski prikaz sustava za mjerenje hidrauličke vodljivosti, b) kalibriranje sustava, c) karakterizacija kapilare

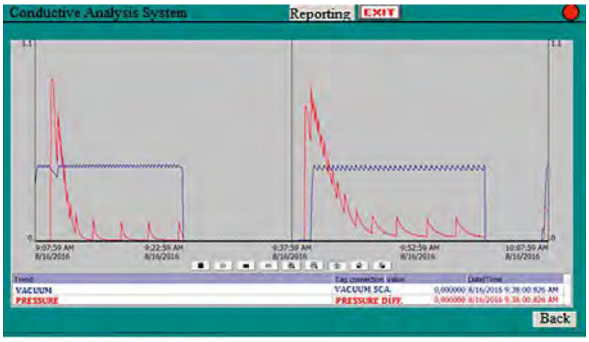


Figure 4 Trend curves showing that the system has reached saturation
Slika 4. Krivulje trenda pokazuju zasićenost sustava

2. The vacuum pump and pump pressure are set;
3. The system is started to operate by the control software;
4. Pressure Sensor 2 values are monitored until giving stable results;
5. The Trend Curve is controlled by the Control Software to determine the time interval for measurement that the system has reached saturation and fluid delivery is smooth and sufficient (Figure 4). Measurement time is about 10 minutes;
6. The system is turned off;
7. The pressure difference value received by the Data Acquisition System, the Pressure Sensor 1 (Output pressure) value and the Pressure Sensor 3 (Vacuum pressure) value are recorded as the average of the values taken over the time interval specified in step 5;
8. Steps 2-7 are repeated after positioning the valve position, which allows the liquid only to pass through the Capillary Tube 2;
9. Steps 2-7 are repeated after positioning the valve position which allows liquid only to pass through the Capillary Tube 3;
10. Fluid conduction quantities are determined by using pressure difference values from curves obtained after capillary tube calibrations;
11. The results are evaluated, and the flow rate of the sample at a given time is determined;
12. Pressure difference part of the sample is determined by using the values of Pressure Sensor 2 and Pressure Sensor 3;
13. Hydraulic conductance is calculated by proportioning the flow rate and pressure difference.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Test setup findings
3.1. Nalazi mjernog sustava

Pressure/flow curves obtained as a result of the characterization of capillary tubes in the hydraulic conductance test setup were used to measure the hydraulic

Table 1 Measurement results of calibration of capillary tubes
Tablica 1. Mjerni rezultati kalibriranja kapilara

Capillary tube *Kapilara*	**Inlet set pressure, kPa** *Tlak na ulazu,* kPa		**Average pressure difference, kPa** *Prosječna razlika tlaka,* kPa	**Liquid quantity, ml** *Količina tekućine,* ml	**Time, s** *Vrijeme,* s	**Flow, ml/s** *Protok,* ml/s
1	50	55	56	20	881	0.0227
	55	60	60	12	491	0.0244
	60	65	64	12	479	0.0250
	65	70	70	10	375	0.0266
	70	75	74	10	350	0.0285
	75	80	79	10	354	0.0282
	80	85	84	12	414	0.0289
	85	90	89	10	350	0.0285
	90	95	94	10	353	0.0283
	95	100	99	20	648	0.0308
2	50	55	56	4	550	0.0072
	55	60	61	4	491	0.0081
	60	65	66	6	846	0.0070
	65	70	71	10	1226	0.0081
	70	75	76	10	1223	0.0081
	75	80	82	8	819	0.0097
	80	85	87	8	894	0.0089
	85	90	91	8	745	0.0107
	90	95	97	4	425	0.0094
	95	100	103	8	730	0.0109
3	50	55	55	6	2454	0.0024
	55	60	60	6	2177	0.0027
	60	65	65	6.5	2265	0.0028
	65	70	71	6.5	2261	0.0028
	70	75	76	6	2007	0.0029
	75	80	81	6	2081	0.0028
	80	85	86	6	1934	0.0031
	85	90	89	6	1722	0.0034
	90	95	96	6.5	1778	0.0036
	95	100	101	5.5	1272	0.0043

conductance of the wood samples. To get reliable and comparable results three different capillary tubes were characterized.

In the characterization process, due to very thin diameters of the capillary tubes, different pressures from 50 to 100 kPa (0.50 to 1 bar) were applied. A relationship was determined over the flow rates corresponding to the different pressures. Accordingly, it has been found that flow rate increases with the increase of inlet pressure. A similar pressure difference-flow relationship was revealed by Cochard (2002). The pressure setpoints, average differential pressures and flow rates used during the characterization process are given in Table 1.

In order to make precise measurements, all processes were applied very carefully, which directly relates to accurate readings of the liquid quantities, accurate determination of the duration and accuracy of the sensor during the characterization process. A long duration test was planned, so the right measurements could be taken in stable conditions.

The three different capillary pipes used in the system have resulted in three different flow values against the different pressures applied. The resulting pressure/flow linear approximation curves and equations are shown in Figure 5.

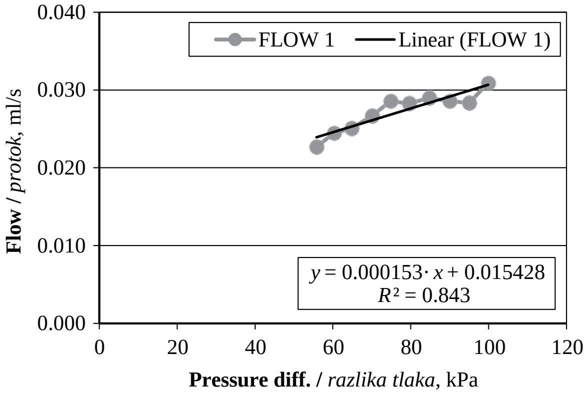
In order to find the pressure difference caused by the internal resistances of the system, the pressure difference was determined as 1 kPa (0.01 bar) during the system calibration. The obtained value was considered in the pressure difference measured during the hydraulic conductance measurement.

The test setup is based on the same principle as established by Tyree *et al.* (2002). Besides the similarity in the test method, the proposed test setup was chosen to be suitable for the determination of hydraulic conductance values along the stem of Uludağ Fir. The main difference is the selection of the liquid pump and vacuum pump to give the desired pressures. In addition, their ability to be controlled via the computer and stabilizing the pump pressures by using feedback from the sensor data, are the outstanding features of the test setup. Another important feature of the system is that there is no need for additional test equipment required for calibration or preparation for the test (e.g. pressurized water). Thanks to the features of the system, such as keeping log records of sensor data, instant control of data and determination of stable measuring ranges, measurement faults or operator-induced measurement errors are prevented. In this way, a more systematic method was introduced.

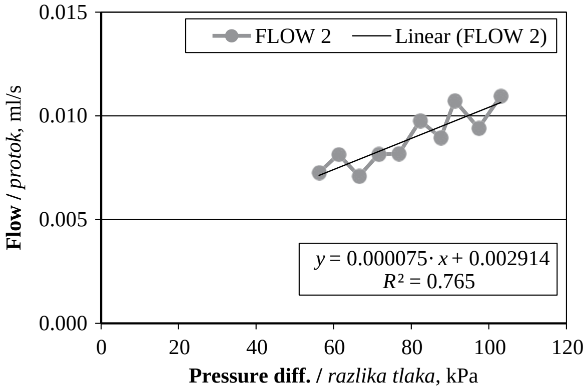
3.2 Hydraulic conductance results
3.2. Rezultati hidrauličke vodljivosti

Nine measurements were made on the samples taken from Uludağ Fir (*Abies bornmulleriana* Mattf.) in the longitudinal direction, with three different capillary tubes and three times of replication of the test. The radial conduction during the measurements was ignored. Table 2 shows the measurement results.

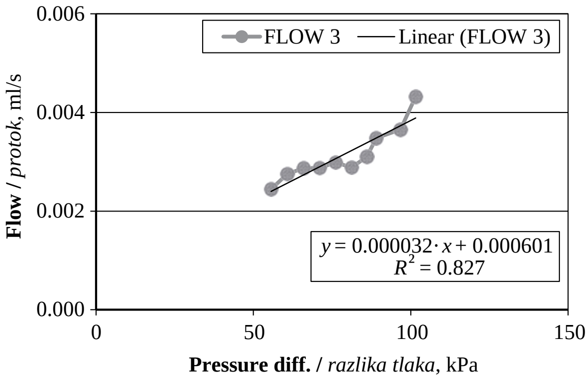
When calculating hydraulic conductance, the "average pressure differences" corresponding to the pressure set values of 85-90 kPa (0.85-0.90 bar) were



(a)



(b)



(c)

Figure 5 a) Capillary Tube 1 pressure/flow linear approximation curve and equation, b) Capillary Tube 2 pressure/flow linear approximation curve and equation, c) Capillary Tube 3 pressure/flow linear approximation curve and equation
Slika 5. a) Graf i jednadžba linearne aproksimacije ovisnosti tlaka i protoka za kapilaru 1, b) graf i jednadžba linearne aproksimacije ovisnosti tlaka i protoka za kapilaru 2, c) graf i jednadžba linearne aproksimacije ovisnosti tlaka i protoka za kapilaru 3

taken from the system and the pressure difference value (1 kPa) determined during the calibration of the system was added to this value. Accordingly, "calibrated average pressure difference" was found. The "pressure difference of the sample" was obtained by subtracting the vacuum tube pressure from the mean outlet pressure, which is read from the system. Then, using the equations obtained during the characterization of capillary tubes, the "flow" amounts corresponding to the

Table 2 Hydraulic conductance value of Uludağ Fir (*Abies bornmulleriana* Mattf.)
Tablica 2. Vrijednosti hidrauličke vodljivosti jelovine (*Abies bornmulleriana* Mattf.)

Capillary tube no *Broj kapilare*	**Pressure set value, kPa** *Postavljena vrijednost tlaka,* kPa		**Measured average pressure diff, kPa** *Izmjerena prosječna razlika tlaka,* kPa	**Calibrated average pressure diff, kPa** *Kalibrirana prosječna razlika tlaka,* kPa	**Average outlet pressure, kPa** *Prosječni izlazni tlak,* kPa	**Average vacuum tube pressure, kPa** *Prosječni tlak u vakuumskoj cijevi,* kPa	**Diff. pressure on sample, kPa** *Razlika tlaka u uzorku,* kPa	**Calculated flow, ml/s** *Izračunani protok,* ml/s	**Hydraulic conductance, ml·s⁻¹·MPa⁻¹·10⁻²** *Hidraulička vodljivost,* ml·s⁻¹·MPa⁻¹·10⁻²
1	85	90	2.9	3.9	86.3	50.5	35.8	0.0021	5.8
	85	90	5.2	6.2	82.7	49.6	33.1	0.0024	7.3
	85	90	12.1	13.1	76.1	50.8	25.3	0.0014	5.5
2	85	90	1.8	2.8	86.1	51.1	35.0	0.0019	5.5
	85	90	3.3	4.3	83.8	51.2	32.7	0.0023	7.1
	85	90	9.9	10.9	76.9	51.6	25.3	0.0013	5.2
3	85	90	1.6	2.6	85.6	51.3	34.3	0.0019	5.5
	85	90	3.5	4.5	83.1	51.5	31.7	0.0023	7.3
	85	90	11	12.0	75.8	51.0	24.9	0.0014	5.5

Table 3 Mean, minimum and maximum value and standard deviation of hydraulic conductance measurement result
Tablica 3. Srednja, najmanja i najveća vrijednost i standardna devijacija izmjerene hidrauličke vodljivosti

n	***x*** ml·*s*⁻¹·MPa⁻¹·10⁻²	**Min. Value** ml·*s*⁻¹·MPa⁻¹·10⁻²	**Max. Value** ml·*s*⁻¹·MPa⁻¹·10⁻²	**Stand. dev.**
9	6.1	5.2	7.4	0.9

average pressure differences were found. Finally, the calculated flow rate is divided into the pressure difference ($F/\Delta P$) to obtain "hydraulic conductance" for each sample. Accordingly, the hydraulic conductance was 6.2 ml·s^{-1}·MPa^{-1}·10^{-2} for Capillary Tube 1, 5.9 ml·s^{-1}·MPa^{-1}·10^{-2} for Capillary Tube 2 and 6.1 ml·s^{-1}·MPa^{-1}·10^{-2} for Capillary Tube 3. The mean, minimum and maximum values and standard deviation of all measurement results are also shown in Table 3.

4 CONCLUSIONS AND RECOMMENDATIONS
4. ZAKLJUČAK I PREPORUKE

In this study, a hydraulic conductance test setup was established to determine the hydraulic conductance, which is one of the important parameters of liquid transport system in trees. The hydraulic conductance of the samples taken from fir wood was measured using the proposed test setup. Measurements were carried out with pressurized water. By applying 0-100 kPa pressure on samples placed in a vacuum tube, successful results were obtained.

To conclude, as seen in Figure 3, meaningful trend lines were obtained indicating that the flow increases with the increase in inlet pressure. Hydraulic conductance results of different samples, prepared with the same procedure from the same tree section, show that measurements are consistent with low standard deviation as shown in Figure 6. With the increasing number of tests, statistical analyses can be improved. Also, in future studies, the conductivity values of fir tree samples taken from different regions, different ages,

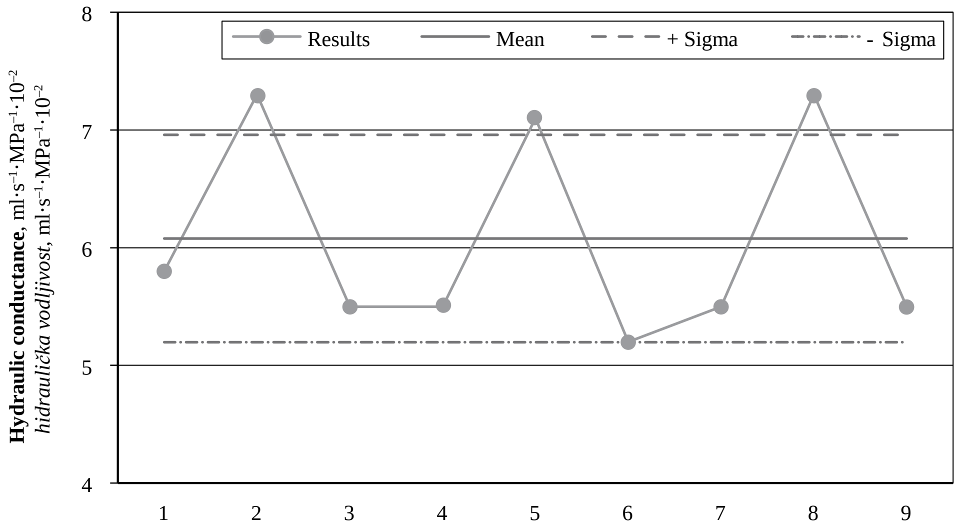


Figure 6 Comparison of results
Slika 6. Usporedba rezultata

and different seasons can be measured and compared with the values found.

The fact that the curves obtained from three different capillary tubes are linear and consistent and that the measured values taken from the samples are similar to each other can be taken as proof that the system works correctly.

In the scope of our study, samples taken from the stem were used in the test setup. On the other hand, the test setup is also adaptable for samples from roots, shoots and leaves. It is foreseen that this system can be used by researchers in their studies that can be carried out in many fields such as plant physiology, ecology and agriculture.

This study may be used other research related to hydraulic conductance such as different tree and plant species, different tree and plant parts, as well as different soil and water properties. With such future studies, it will be possible to get an idea about the liquid transportation system in trees.

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Effect of Soaking/Oven-Drying on Mechanical and Physical Properties of Birch (*Betula* spp.) Plywood

Utjecaj namakanja i sušenja u sušioniku na mehanička i fizička svojstva furnirske ploče od brezovine (*Betula* spp.)

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ABSTRACT • *The objective of this study was to explore some of the physical and mechanical properties of 9-layer birch (Betula spp.) plywood with the addition of phenol-formaldehyde glue, in cases in which the cutting edges of the samples are coated with the damp-proof mastic Fibergum, and in case in which they remain unprocessed (uncoated), following a total of ten cycles of soaking/oven-drying. The properties to be determined were the bending strength (BS), modulus of elasticity in bending (MOE), thickness swelling (TS) and restore dimensions (RD), which were tested according to the European standards (EN). A linear-fractional equation and linear relationship were used for the approximation of any change in the physical and mechanical properties of the samples depending upon the number of soaking/oven-drying cycles. It was shown that the values of the properties investigated were most affected by the first soaking and drying cycle. Thereafter, BS and MOE levels decreased smoothly at a low rate, but the values of TS became stabilised. The BS and MOE values for the wet samples with coated cutting edges were higher than when they were uncoated, as the moisture levels in the former case were lower. After the first soaking of the samples with coated cutting edges, the retention values were as follows: BS at 52.8 % and 66.7 % for the major and minor axes, respectively, with the same applying to MOE at 61.9 % and 64.2 %, while TS was at 105.2 %. To clarify the phenomenon that causes a decrease of the properties, the face plies and edge structures of the initial dry samples and of the samples after the first, second and ninth soaking/oven-drying cycles were studied using the X-Ray technique.*

Keywords: *plywood; bending strength; modulus of elasticity; thickness swelling; restore dimensions; moisture content; X-Ray technique*

SAŽETAK • *Cilj ovog istraživanja bio je odrediti neka fizička i mehanička svojstva furnirske ploče od brezovine (Betula spp.) izrađene od devet slojeva furnira i uz dodatak fenol-formaldehidnog ljepila. Uzorci čiji su rubovi premazani za vlagu nepropusnim premazom Fibregum i uzorci s nepremazanim rubovima namakani su i sušeni u sušioniku tijekom deset ciklusa. Prema europskim standardima, ispitivana su ova svojstva ploče: čvrstoća na savijanje, modul elastičnosti, debljinsko bubrenje i vraćanje dimenzija uzoraka. Za aproksimaciju promjena fizičkih i mehaničkih svojstava uzoraka ovisno o broju ciklusa namakanja i sušenja u sušioniku primijenjeni su linearna frakcijska jednadžba i linearni odnos. Utvrđeno je da je na vrijednost ispitivanih svojstava najviše utjecao prvi*

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ciklus namakanja i sušenja. Nakon tog ciklusa namakanja i sušenja čvrstoća na savijanje i modul elastičnosti polako su se smanjivali, dok su se vrijednosti debljinskog bubrenja stabilizirale. Vrijednosti čvrstoće na savijanje i modula elastičnosti vlažnih uzoraka s premazanim rubovima bile su veće nego za uzorke s nepremazanim rubovima zbog manjeg sadržaja vode u uzorcima premazanih rubova. Nakon prvog namakanja uzoraka s premazanim rubovima zadržane su ove vrijednosti: čvrstoća na savijanje na 52,8 i 66,7 % te modul elastičnosti na 61,9 i 64,2 % za glavnu odnosno sporednu os, dok je debljinsko bubrenje iznosilo 105,2 %. Za objašnjenje fenomena smanjenja ispitivanih svojstava, lica slojeva furnira i rubne strukture uzoraka nakon prvoga, drugoga i devetog ciklusa namakanja i sušenja u sušioniku primijenjena je rendgenska metoda.

Ključne riječi: *furnirska ploča; čvrstoća na svijanje; modul elastičnosti; debljinsko bubrenje; vraćanje dimenzija; sadržaj vode; rendgenska metoda*

1 INTRODUCTION
1. UVOD

Birch (*Betula* spp.) is found in Eurasia and forms a second widespread tree species in Estonia, reaching 29 % of the total land space across the country (Estonian is a country of forests – Statistics). Birch is considered a form of hardwood and has good mechanical properties resulting in an increasing demand when it comes to its use in products such as lumber, sawn timber and plywood. Plywood is made by bonding together several hardwood plies (mostly for indoor products) or softwood plies (mostly for outdoor products) (Dieste *et al.,* 2008; Cosereanu *et al.,* 2010; Lipinskis *et al.,* 2011; Zalemanis *et al.,* 2018). The mechanical properties of hardwood are better when they are compared to those of softwood, which makes hardwood a better research object. In more recent times, Finnish birch plywood has been used outdoors: for concrete shuttering, scaffolding, vessels, vans, and so on (Finnish Forest, 2002, Metsä Wood). There are a good many important factors that affect the physical properties of plywood (such as moisture, thickness swelling and density) and its mechanical properties (strength characteristics), such as: trees species, wood density, slope of grains, shakes, checks, number of plies, type of adhesives, thicknesses of plies and the technological parameters involved in the manufacturing process.

Veneer and plywood (including block board) are the dominating wood-based panel types, which accounted for 42 % (174 million m³) of all wood-based panel production in 2016 (UN 2016). According to different estimates, the global market for plywood is expected to keep growing in the near future (at a compound annual growth rate CAGR of 6.0 %, 7.8 % and 9.7 % in 2018-2028 (Plywood Market Reports, 2018), 2017-2022 (Plywood Manufacturing, 2018) and 2019-2023 (Plywood Market, 2019) respectively.

As a wood-based material, the physical and mechanical properties of plywood are affected by moisture. Plywood is a highly valued construction material, one which is used more widely than other wood-based panels in conditions that involve outdoor exposure. To be able to determine the average moisture of wood and plywood samples, a continuous moisture measurement (CMM) set-up was developed (Van den Bulcke *et al.,* 2009). According to the data gained from a CMM set-up, further analysis was varied out on the relationship between weather data and the number of days with an average *MC* that were higher than 20 % or 25 % (Van den Bulcke *et al.,* 2011). With a similar set-up, an adapted electrical moisture measurement method was introduced by Li *et al.,* (2013) to measure internal moisture levels in plywood.

In practice, weathering conditions with alternating soaking and drying cycles can reduce the mechanical properties of plywood. Li *et al.,* (2016) studied moisture behaviour and structural changes in different layers of plywood specimens that had been exposed to outdoor weather conditions for approximately one year. It became apparent that moisture distribution in plywood was not homogeneous in outdoor conditions. In some plywood types, the second layer can accumulate a significant amount of rain, and long rainy periods and cloudy weather can cause the inner plywood layers to retain high moisture levels. The glue line between the plies was not ruptured after one year of outdoor exposure. River (1994) studied outdoor aging (at a point between 7 to 12 years) in wood-based panels (including one panel of 5-ply, Douglas fir, and marine graded commercial plywood) and its correlation with accelerated aging in the laboratory. The plywood panel that was the subject of the study belonged to a group of panels with the highest levels of resistance to outdoor exposure, managing to retain 99.6 % and 48.6 % of their initial bending strength (*BS*) (modulus of rupture, *MOR*) after one year and ten years, respectively. Significant correlations (Pearson's and Spearman's correlation coefficients >0.90) were found between *MOR* after cyclic boil-dry (*BD*) aging and *MOR* after outdoor aging (River, 1994).

For companies that are involved in producing plywood, quality control is essential for the commercialization of this type of wood. As it has already been established that a wood product will have insufficient levels of strength and dimensional stability during the course of changing moisture levels, it is reasonable to investigate some of the mechanical and physical properties of plywood depending upon the number of soaking/oven-drying cycles.

The objective of this paper was to study changes in *BS, MOE*, and *TS* after ten soaking/oven-drying cycles, with the investigation involving the cutting forehead and the facet edges of the samples being coated with the damp-proof mastic *Fibergum*, see Master's thesis (Kruus, 2016). In the earliest studies, the cutting edges remained unprocessed (uncoated) - see Master's theses (Kasepuu, 2014 and Sooru, 2015).

Approximated experimental data used a linear-fractional expression for the investigated *BS*, and *MOE*, and the linear relationship for *TS* and *RD* depending upon the number of soaking/oven-drying cycles. Also, the statistically significant (p<0.05) coefficient of variation (CV) was estimated and calculated in percentages for average values according to EVS EN 326-1:2002. The effects of soaking/oven-drying have been clarified in terms on the face plies and edge structure of the samples evaluated by means of the X-Ray technique.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Three 9-layer commercial uncoated Wisa birch (*Betula* spp. grown in south-eastern Estonia) plywood moisture-proof panels with nominal dimensions of 3000 mm × 1500mm × 12 mm were produced by UPM-Kymmene, Otepää, Estonia. Engineered hardwood plywood panels were commonly glued together with phenol-formaldehyde resin (PF) as the selected wood adhesive (Manufacturing Process of Veneer and Plywood). The dimensions of each test sample (290 mm × 50 mm × 12 mm) for *BS* and *MOE* were marked out from larger panels and were cut out in the parallel direction (II - major axis) and perpendicular direction (T - minor axis) to the face plie grain. Experiments were carried out with eleven series (with a minimum of twelve samples in a series), the first of them (dry) added also to the calculations for soaked samples. The cutting forehead and the facet edges of the test samples, as extracted from the two panels, were coated with the damp-proof mastic *Fibergum,* and those from the third panel remained unprocessed (uncoated). All samples were divided into two groups. One group of samples was tested in a wet (soaked) state, while the second group was tested in a dried state. The test samples were placed in a tank of room temperature water (22 ± 2) °C for a period of 24 hours. The samples were dried (over 48 hours) in a ventilated drying box at (65 ± 2) °C and after that, they were conditioned in a climatic chamber at a relative humidity level of (65 ± 5) % at (21 ± 2) °C. The dimensions and weight of the bending test samples were measured immediately after they were taken out of the water tank or the climatic chamber, in order to determine their *TS*, *RD* and *MC* (using the weighing method) according to the EVS-EN 317: 2000 and EVS-EN 322: 2002 standards. The dimensions of the samples were measured using a digital calliper with an accuracy of 0.01mm and a screw gauge (Mitutoyo 293-805) with an accuracy of 0.001 mm (EVS-EN 325: 2002); the weight of the samples was measured by means of an electrical balance, a Kern PLB 1000-2 with an accuracy of 0.01 g and samples were tested immediately. The computer-controlled mechanically-actuated universal testing machine, an Instron 3369, was also used. Deflection values for a determination of the modulus of elasticity were measured by means of an optical gauge (Advanced Video Extensometer 2663-821). Samples for determining *BS* and *MOE* were tested following the three-point flatwise bending test in accordance with the EVS-EN 310: 2002 standard. A load was applied at a constant rate so that failure occurred in (60 ± 30) seconds.

In order to be able to evaluate *BS* and *MOE* at static flexion in the directions of the II-major axis and T-minor axis in relation to the grain on the face plies, the process formulated by (Sooru *et al*., 2015) was realised and calculated according to the EVS-EN 310: 2002 standard. Calculation for the coefficient of the variation of the measurements was carried out according to the EVS-EN 326-1: 2002 standard.

Dimensional stability (swelling in thickness) was determined prior to the bending test in the middle zone of the samples (for more details see Figure 1b in Sooru *et al*., 2015).

The following linear-fractional function (equilateral hyperbola) was used to approximate the experimental data obtained for the properties investigated, depending upon the number of soaking/oven-drying cycles (Lille *et al*., 2013 and Sooru *et al*., 2015)

$$Y(x)=(d\,(Y_i-Y_f)/(cx+d))+Y_f, \qquad (1)$$

in this Y_i, Y_f are the calculated initial (x = 0) and final values ($x = \infty$) of the properties investigated, while x is the number of cycles, and c and d are constants.

The initial and final values of the properties and constants should be determined so that the measured experimental data are approximated in the best possible way by minimising the square of error (least squares regression). This problem was solved by using the Mathcad 15.0 programme with the regression function *genfit(vx, vy, vg, F)*. The following assumptions were made for the mathematical expressions (the values of *BS* and *MOE* versus the number of soaking/oven-drying cycles): the approximation curve, first, cuts ordinate; and second, making it possible to determine the limit values, in which *BS* and *MOE* stabilise.

The formula (1) also makes it possible to predict, to a certain extent, the mechanical and physical properties of the samples when their values are known after the application of a small number of soaking/oven-drying cycles (between two and three). The relationship between *TS* and *RD* depending upon the number of cycles is approximated in the best way possible by minimising the square of error, by using the software, *MS Excel*, with the results being reached by means of regression analysis function found by the programme. The YXLON FF35 CT computed tomography system was applied for an X-Ray investigation of the structure of plywood.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Following a degree of room temperature water absorption (22 ± 2) °C by the test samples after a soaking time of 24 hours, the average moisture was about (25.3 ± 1.7) % and (40.0 ± 4.0) % for the coated and unprocessed cutting edges, respectively. Coating the cutting edges of the test samples inhibited water absorption considerably. After drying, the average moisture was (7.7 ± 1.8) %.

The mean values obtained for one cycle of *BS* and *MOE* in the directions of the II-major axis and T-minor axis are presented in Figure 1, for oven-dry (7.7 ± 1.8) % and wet (25.3 ± 1.7) %, where the cutting edges are coated with mastic, and in Figure 2, for wet (40.0 ± 4.0) %, (for oven-dry, see more in Sooru *et al*., 2015), where the cutting edges have remained unprocessed.

All mean values in the experimental data were approximated by means of Eq. 1 and are presented as curves of the calculated values of the properties investigated and their constants. Also, the coefficient of variation (CV) for the mean values was calculated in percentages.

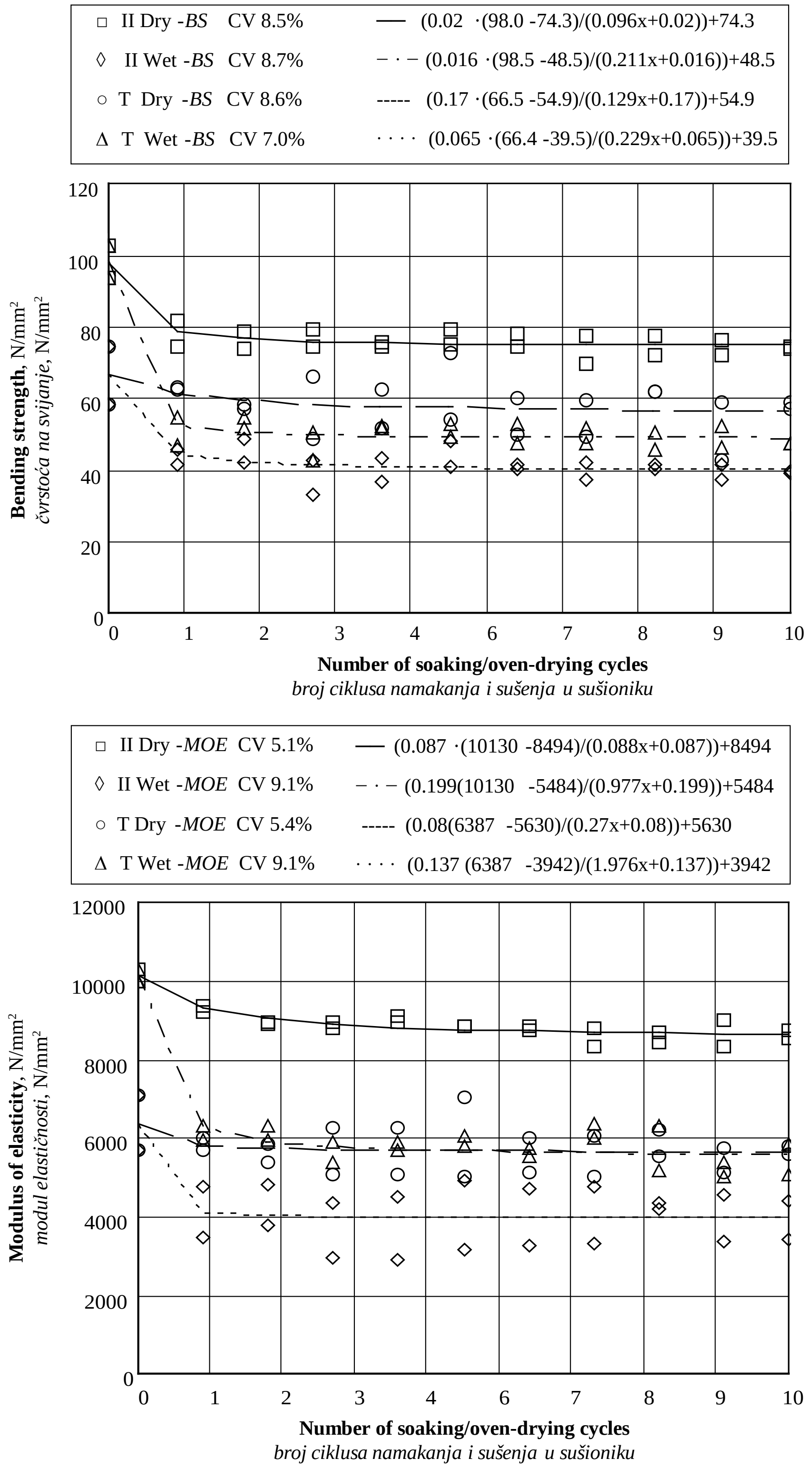
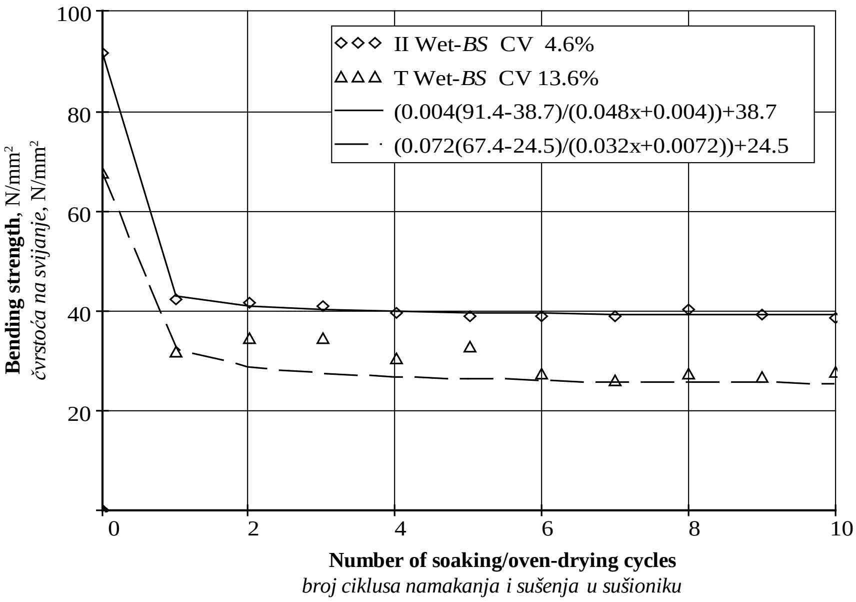


Figure 1 Dependence of *BS* (marked as f_m) and *MOE* (marked as E_m) on the number of soaking/oven-drying cycles, mean values from experimental data with CV and curves of approximation

Slika 1. Ovisnost čvrstoće na savijanje i modula elastičnosti o broju ciklusa namakanja i sušenja u sušioniku, srednje vrijednosti iz eksperimentalnih podataka s koeficijentima varijacije i aproksimacijskim krivuljama



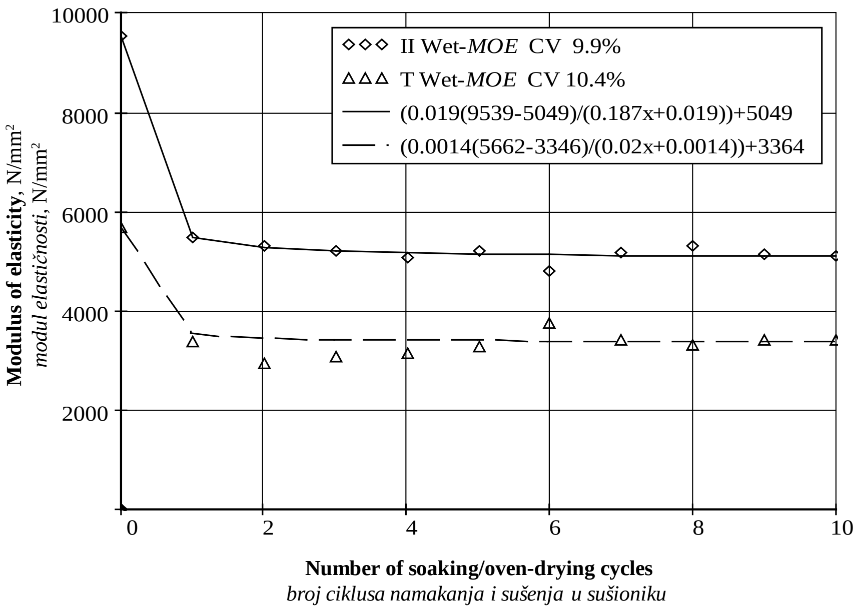


Figure 2 Dependence of *BS* and *MOE* on the number of soaking/oven-drying cycles, mean values from experimental data and curves of approximation
Slika 2. Ovisnost čvrstoće na savijanje i modula elastičnosti o broju ciklusa namakanja i sušenja u sušioniku, srednje vrijednosti iz eksperimentalnih podataka i aproksimacijske krivulje

The experimental data for all the properties studied tended to fluctuate to a moderate extent as the plywood had been produced from heterogeneous wood material and the plies had natural flaws and knots.

Consequently, after 24 hours of soaking, when the cutting edges were coated and water absorption through them was blocked, the moisture (25.3 ± 1.7) % was about 15 % lower than in the samples with unprocessed cutting edges (40.0 ± 4.0) %. On the other hand, considering that the barrier, which had been provided by the glue used for the bonding of the plies, inhibits the absorption of water through the faces, moisture levels in the panels with significantly larger dimensions was lower than in the samples with unprocessed (uncoated) cutting edges. It was shown that the direction of the face grain direction plays an important role in some properties of structural plywood panels. The *BS* and *MOE* values differed significantly depending upon whether they were measured in parallel or perpendicular to the samples. The determined values of the properties investigated for the samples of the T-minor axis fluctuated more than those for the samples of the II-major axis. For the parallel samples, the direction of the experimental load in relation to the face grain was tangential (T), while the direction of the internal load in relation to the face grain was longitudinal (L); for the perpendicular samples, the situation was the opposite. The tensile strength in the T direction of European beech wood was many times lower than in the L direction. It can be seen that the proposed Eq. 1 approximated the experimental data quite satisfactorily. It should be noted that the values for the calculated percentages are taken from the approximation curves and are presented in Table 1.

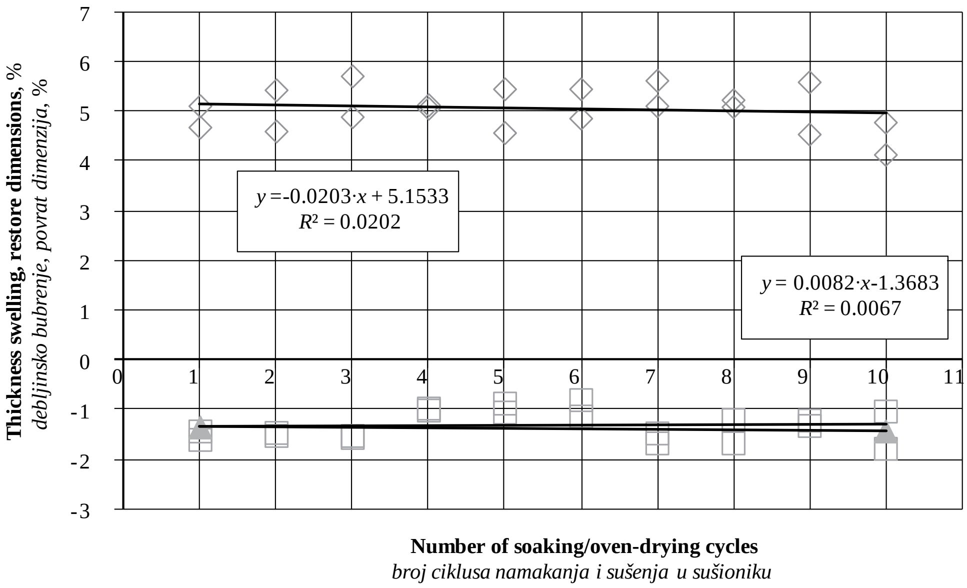


Figure 3 Dependence of Wet-*TS* and Dry-*TS* for plywood on the number of soaking/oven-drying cycles: mean values for trend lines are at 5.15 % and -1.37 %, respectively
Slika 3. Ovisnost mokroga i suhoga debljinskog bubrenja furnirske ploče o broju ciklusa namakanja i sušenja u sušioniku: srednje vrijednosti za linije trenda su 5,15 % odnosno -1,37 %

The linear relations between mean values for one cycle of *TS* and *RD*, depending upon the number of soaking/oven-drying cycles are presented in Figure 3.

The *TS* was 5.2 % and 7.1 % at a moisture of about (25.3 ± 1.7) % and (40.0 ± 4.0) %, respectively, while the thickness *RD* in the dried samples at a moisture of (7.7 ± 1.8) % was 98.6 %. The reduction in *TS* may indicate a volume decrease of the face plies due to plastic deformation during the first soaking period and also to manufacturing residues (including particles and dust) in the plywood, which were washed off during the soaking cycle.

The *TS* for the plywood did not change significantly after the first soaking/oven-drying cycles (7.7 ± 1.8) %. This phenomenon has been noted in the case of wood. Swelling in wood, which is also similar to swelling in plie as a wood product, takes place below the fibre saturation point (FSP) (about 30 %), at which the

Table 1 Mean values for *BS*, *MOE*, *TS* and *RD* for dry and moist test samples and residual values of wet samples versus dry samples
Tablica 1. Srednje vrijednosti čvrstoće na savijanje, modula elastičnosti, debljinskog bubrenja i vraćanja dimenzija za suhe i vlažne uzorke te rezidualne vrijednosti vlažnih uzoraka u odnosu prema suhima

Moisture, axis / *Sadržaj vode, osi*			**Dried** / *Sušeni*, %		**Soaked** / *Namakani*, %			
			7.7 ± 1.8		25.3 ± 1.7		40.0 ± 4.0	
Properties investigated, retention values *Istraživana svojstva, zadržane vrijednosti*			Axis					
			Major II	Minor T	Major II	Minor T	Major II	Minor T
Mean values / *Srednje vrijednosti*, N/mm²								
Bending strength *Čvrstoća na savijanje*	initial, f_{mi}		98.0	66.5	98.5	66,4	91.4	67.4
	final, f_{mj}		74.3	54.9	48.5	39.5	38.7	24.5
Modulus of elasticity *Modul elastičnosti*	initial, E_{mi}		10130	6387	10130	6387	9539	5662
	final, E_{mf}		8494	5630	5484	3942	5049	3364
Mean residual values vs those obtained from initial dry samples, % *Srednje rezidualne vrijednosti u odnosu prema onima dobivenim za početne suhe uzorke, %*								
After first cycle *Nakon prvog ciklusa*	*BS*	f_{m1}/f_{mi}	80.0	92.5	52.8	66.7	46.8	48.0
	MOE	E_{m1}/E_{mi}	91.9	90.9	61.9	64.2	57.3	62.1
Final *Završno*	*BS*	f_{mj}/f_{mi}	75.8	82.6	49.2	59.5	42.3	36.4
	MOE	E_{mj}/E_{mi}	83.8	88.1	54.1	61.7	53.9	35.3
Thickness swelling / *Debljinsko bubrenje*		%			5.2		7.1	
Restore dimension/ *Povrat dimenzija*			98.6					

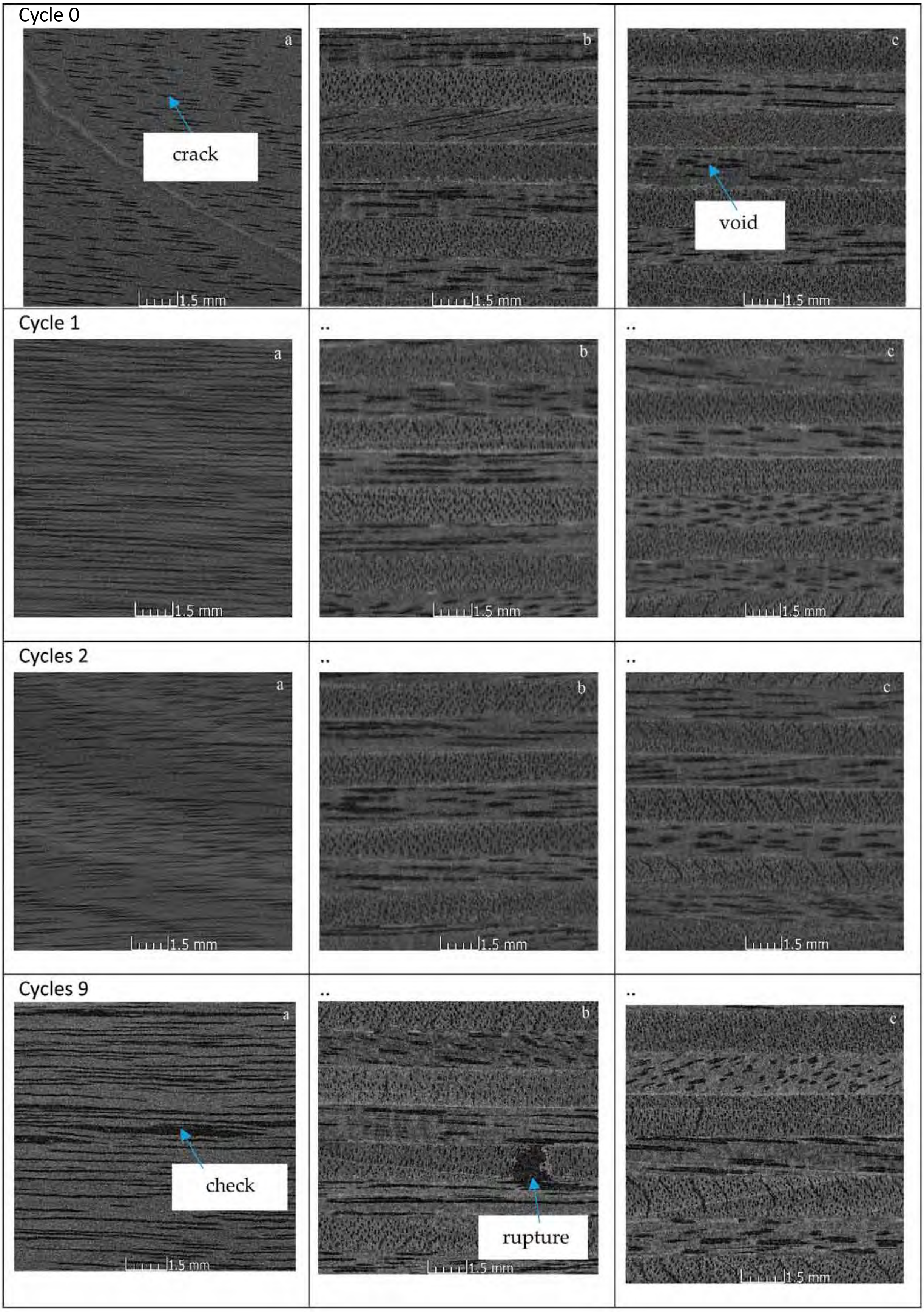


Figure 4 X-Ray images of texture of samples: a) face plies; b) middle edge in parallel with II-axis; c) in parallel with T-axis; purveyance dry (0 cycle), and after the first, second and ninth soaking/oven-drying cycle
Slika 4. Rendgenske slike teksture uzoraka: a) slojevi lica; b) srednji rub paralelno s osi II; c) paralelno s osi T; suho (0 ciklusa), nakon prvoga, drugoga i devetog ciklusa namakanja i sušenja u sušioniku

total amount of water is present within the cell wall (Hiziroglu, 2017). Regardless of the number of soaking/oven-drying cycles, the dimensions of the plywood do not change. The *BS* and *MOE* for samples generally increase when the moisture decreases below the FSP.

The X- Ray images of the structure of the face plies and edge of the dry samples, both at the initial time point and after the first, second and ninth soaking/oven-drying cycles are presented in Figure 4.

Manufactured plywood, especially face plies, contain cracks, which have developed after peeling from wetted logs and consecutive drying (Figure 4a-0). Numerous new cracks appeared in the face plies after the first soaking and oven-drying cycle (Figure 4a-1), which in turn decreased the strength characteristics of the samples. The main factor for the formation of new cracks may be the following: moisture accumulation in the face plies was higher due to the direct contact with water of the outer surface and the surfaces of the existing cracks. This, in combination with the wood species, causes swelling and consecutive plastic deformations, as less swollen core plies (adhesive layers reduce moisture transport across plywood) served to prevent their free elongation and hence the development of compressive stresses during the early soaking period. In the oven-drying period, moisture is first decreased (desorption) in the most swollen face plies, but at the same time, their free shrinkage is resisted by the less swollen core plies. Thanks to this, and due to the development of tensile stresses, new cracks are formed in the face plies when these stresses exceed their corresponding strengths.

The swell and shrinkage of core plies is less small, because adhesive glue lines allow reduced moisture transport across the plywood. As the core plies do not have any resistance to shrinkage during oven/drying, they show no visually discernible changes (Figure 4b-1 and 4c-1).

After the next soaking period, the network of cracks in the face plies eliminates free swelling and in the oven/drying period some of the cracks only expand or extend (Figure 4a-2). At the same time, no noticeable changes were found in the core plies (Figure 4b-2 and 4c-2). This may be the reason for the stabilisation of the properties of the plywood studied. After the ninth soaking/oven-drying cycle, the cracks in the face plies have further expanded (Figure 4a-9) or have extended, and some of the micro fibrils in the core plies and adhesive glue line have ruptured (Figure 4b-9 and 4c-9).

4 CONCLUSIONS
4. ZAKLJUČAK

The mechanical and physical properties of 9-layered birch plywood after soaking/oven-drying cycles were investigated according to European standards. Experiments were carried out with eleven series, with a minimum of twelve samples in a series.

After the first soaking at a moisture level of (25.3 ± 1.7) %, the retention values were as follows: *BS* at 52.8 % and 66.7 % for the major and minor axes, respectively, with the same applying to *MOE* at 61.9 % and 64.2 %, while *TS* was at 105.2 %. At a moisture of (40.0 ± 4.0) %, the retention values were as follows: *BS* at 46.8 % and 48.0 % for the major and minor axes respectively, with the same applying to *MOE* at 57.3 % and 62.1 %, and with *TS* at 107.1 %.

After the first soaking and drying test (with a moisture of (7.7 ± 1.8) %), the retention values were as follows: *BS* at 80.0 % and 92.5 % for the major and minor axes, respectively, with the same applying to *MOE* at 91.9 % and 90.9 %, and with *RD* at a thickness of 98.6 %.

The proposed analytical function satisfactorily approximated the *BS* and *MOE* experimental data, depending upon the number of soaking/oven-drying cycles.

The results of the X-Ray investigations showed that the causes of abrupt change in the properties of the plywood samples were rapid water sorption-desorption and the related swelling-shrinkage of the face plies on the plywood in restrained elongation conditions.

The analysis, as presented here, is limited to data obtained from the aforementioned experiments.

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Development Study of Perceived Institutionalization and Perceived Performance Scales

Studija razvoja ljestvica za percipiranu institucionalizaciju i percipirani učinak

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ABSTRACT • *Institutionalization is necessary for corporations to prevent economic, financial, legal, administrative, and technical chaos and thus improve performance. The concept of performance is the most supporting tool in conducting the control function in business management. While the amount of input and products in the forest industry in Turkey is rising, institutionalization is inadequate. This study attempts to methodologically develop and test scales for perceived institutionalization and perceived performance in furniture and panel businesses, which are two sub-sectors of the forest industry. Data was obtained in 35 cities between March and July 2017, through face-to-face interviews with 797 employees in 462 furniture businesses and 31 panel businesses. In the analysis of the study, content validity of the scales was evaluated through expert opinion and initial application, while construct validity was assessed by EFA and CFA. Cronbach alpha coefficient, CR, and AVE were used to evaluate reliability, while the suitability of perceived institutionalization and performance scale model was assessed through SEM. The scales have high reliability and validity, and an improvement in the institutionalization level of a business will result in improvements in performance (r=0.98). Through this methodological study, scales for perceived institutionalization and perceived performance in furniture and panel businesses operating in Turkey and the relationship between perceived institutionalization and perceived performance were explained by a model.*

Keywords: *perceived institutionalization; perceived performance; furniture and board sector; methodological study; structural equation model; Turkey*

SAŽETAK • *Institucionalizacija je nužan preduvjet za sprečavanje ekonomskoga, financijskog, pravnog, administrativnog i tehničkog kaosa korporacija te za poboljšanje njihova učinka. Koncept učinka najpouzdaniji je alat u provođenju kontrole poslovnog upravljanja. Dok količina sirovine i proizvoda u drvnoj industriji u Turskoj raste, institucionalizacija je neadekvatna. Ovim se istraživanjem pokušavaju metodološki razviti i testirati ljestvice za percipiranu institucionalizaciju i percipirani učinak poduzeća za proizvodnju namještaja i proizvodnju ploča, što su dva podsektora drvne industrije. Podatci su dobiveni u 35 gradova između ožujka i srpnja 2017., i to putem osobnih razgovora sa 797 zaposlenika u 462 tvrtke za proizvodnju namještaja i u 31 tvrtki za proizvodnju ploča. U analizi ovog istraživanja ocijenjena je valjanost sadržaja ljestvica na temelju stručnog mišljenja i inicijalne*

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* This paper is author Ahmet Bora Kırklıkçı's Ph. D thesis. Assoc. Prof. Tarık Gedik is thesis advisor.

primjene, dok je valjanost konstrukcije procijenjena uz pomoć EFA-e i CFA-e. Za procjenu pouzdanosti primijenjeni su Chronbachov alfa-koeficijent, CR i AVE, a prikladnost modela ljestvice za percipiranu institucionalizaciju i učinak procijenjeni su uz pomoć SEM-a. Ljestvice imaju visoku pouzdanost i valjanost, a poboljšanje na razini institucionalizacije poduzeća donijet će i poboljšanje učinka tvrtke (r = 0,98). Ovim su metodološkim istraživanjem objašnjene ljestvice za percipiranu institucionalizaciju i percipirani učinak poduzeća za proizvodnju namještaja i proizvodnju ploča koja posluju u Turskoj te prikazan odnos između percipirane institucionalizacije i percipiranog učinka.

Ključne riječi: *percipirana institucionalizacija; percipirani učinak; sektor proizvodnje namještaja i ploča; metodološko istraživanje; model strukturne jednadžbe; Turska*

1 INTRODUCTION
1. UVOD

1.1 Institutionalization, performance and productivity
1.1. Institucionalizacija, učinak i produktivnost

According to Knight (1992), institutions are defined as "a set of rules that structure social interactions in particular ways in a society and of which knowledge is shared by members of the community". Institutionalists define institutions not in the narrow sense of formal organizations, but in the broader context of socially predetermined behavior as "the widespread and constant way of thinking or acting, which is implanted in habits of a group or in customs of the people" (Dayneko *et al*., 2014). Four general criteria, developed by Huntington (1973), allow us to assess the level of institutionalization of an institution. These are autonomy, adaptability, complexity and coherence. It was noted that these four criteria could be applied to institutional arrangements and are roadmaps for the transformation period that institutions need in order to influence their members and environments and survive.

The concept of "institutional" generally represents the characteristics of institutionalized organizations (Uygun *et al*., 2013). Institutionalization is, however, defined differently in the literature. Institutionalization is defined as the process by which an activity becomes generally accepted or routinized and is then handled in a regularized, structured, and systematic manner (Fuchs and Anderson, 1987). Institutionalization processes involve forming of an official structure, creation of unofficial norms, development of non-personal/objective procedures, focusing on administrative rituals, ideologies, legalization and legitimization. Thus, institutional theory traces the emergence of distinctive forms, processes, strategies, outlooks, and competences as they emerge from patterns of organizational interaction and adaptation (Selznick, 1996).

Through institutionalization, businesses adapt to their business world and this harmony increases performance. Institutional pressures, which compel businesses to institutionalization, have a long-term and extensive impact on administrative performance. As these institutions have the funds provided by entrepreneurs, they spend more effort to accomplish their goals (Han *et al*., 2016; Zhu and Sarkis, 2007). On the other hand, perceived business performance is measured by market share, turnover, profitability and institutional image indicators. These measurements can be performed by taking into consideration components such as market (e.g. market share), accounting (e.g. turnover, sales, profitability) and social performance (e.g. company image).

1.2 Institutionalization in forest industry
1.2. Institucionalizacija u drvnoj industriji

The Forest industry plays an essential role in sustainable development, not only in terms of its specific raw material but also due to the ongoing globalization of the industry (Tuppura *et al.,* 2013). It is noted that the transformations currently occurring in the forest industry are frequently spontaneous and inconsistent and are vastly affected by national, regional, economic and social policy reforms. It is emphasized that even in countries where the forest industry has progressed, the sector cannot respond sufficiently to the policy reforms that affect instructional transformation and that the level of institutionalization is low (Dayneko *et al.,* 2014; Wanat *et al.,* 2018). For instance, the forest industry in Finland has been accused of not being innovative due to insufficient research and development activities (Åkerman *et al.,* 2010).

Data on the forest industry sector in Turkey displays a tendency to expand to new markets. Turkey has established import and export connections with more than 200 countries for forest products. In many subsectors in Turkey, most especially in furniture and panel production, foreign trade balance looks positive. Strong aspects of Turkish furniture and panel sectors in the international market are cheap labor and being close to the middle east market. Iraqi and Syrian markets are possible opportunities for this sector (Serin and Şahin, 2018; İstek *et al.,* 2017). Hence, Turkey has a 0.5 % share of the 128-billion-dollar world wood-based product export, while amounting to 1 % of 132-billion-dollar world wood-based products import. The forest products sector comprises 2.4 % of the added value created in the production sector in Turkey (WMBA, 2017). Turkey's share in world furniture production is around 1 % and it is rapidly increasing. In 2015, 16-billion-dollar worth of production had been achieved in the furniture sector and it was predicted that this figure would reach 22 billion dollars in 2018 (UCCET, 2017). Total furniture export reached 2.4 billion dollars in 2017 and its share in exports was 2.2 %. In 2018, it increased significantly, reaching 3.4 billion dollars. Turkey's share in world furniture export in

2019 was 1.6 %. Furniture imports decreased by 6.6 % in 2019, compared to the previous year. (TMT, 2020). Total panel production in 2016 was 9.2 million square meters, with only 10-15 % of this being exported (JFIB, 2019). The furniture industry capacity usage ratio was 72 % for 2016 (IIBA, 2018). The capacity usage ratio in the panel sector ranged between 75-85 %, and the total installed capacity was 12 million square meters. The installed capacity of the panel sector was 5 million square meter/year in particle board, 7 million square meters/year in medium-density fiberboard (MDF) and 240 thousand square meters in Oriented Strand Board (OSB) (JFIB, 2019). According to figures of General Census of Industry and Business Establishments, the furniture sector employed 133 thousand people, while the panel sector employed 13 thousand people (UCCET, 2015).

Small and medium-sized enterprises in the forest products industry, however, face threats such as a low level of state support (Sarıkahya, 2012), insufficient utilization of national and international financing opportunities, the necessity to import raw materials and have an inadequate number of qualified employees, regional instability, lack of design and adverse effects of Chinese furniture sector (Serin and Şahin, 2018).

While the amount of input and products in forest industry in Turkey are rising, institutionalization, the effectiveness of quality assurance systems, viability of European Union (EU) legislations and research and development expenditure are inadequate (Koç *et al.,* 2017). Due to the rapid growth in the furniture industry in recent years, it is necessary for businesses to innovate their administrative activities and establish quality assessment systems (Altınok and Saçlı, 2009). Thus, it is noted that only basic quality control methods are implemented in the furniture industry, while quality control activities are more systematic and intense in fiber and particle board producers (Cındık *et al.,* 1999). It seems necessary to focus on more advanced competitive elements such as research and development, design and marketing in order to strengthen the competitiveness of the sector and ensure its continuity.

Considering all this data, there is a close connection between business performance and institutionalization in furniture and panel businesses. From this point of view, this study attempts to determine the level of institutionalization of furniture and panel businesses, which are two sub-sectors of the forest industry. Scales for Perceived Institutionalization Scale (PIS) and Perceived Performance Scale (PPS) at the sectoral level were developed and tested methodologically.

Accordingly, the hypotheses below, which are related to independent (institutionalization) and dependent (performance) variables and sub-variables, were made.

H_1 1, There is a relationship between consistency and institutionalization.

H_1 2, There is a relationship between formalization and institutionalization.

H_1 3, There is a relationship between transparency, accountability, and institutionalization.

H_1 4, There is a relationship between productivity and performance.

H_1 5, There is a relationship between operating income and performance.

H_1 6, There is a relationship between product development and performance.

H_1 7, There is a relationship between institutionalization and performance.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Data
2.1. Podatci

The data of the study consists of 2622 furniture and panel businesses registered in UCCET and the Turkish Particle Board Industrialists Association (TPBIA) in 2016. The data of the study is the businesses with ten or more employees within the enterprises mentioned above. The sample size was determined as 346 with a 5 % margin of error and a 95 % level of confidence by means of sampling formula for limited sample groups. The study population was obtained by a stratified sampling method which is set for geographical regions. Data was obtained in 35 cities between March and July 2017, through face to face interviews with 797 employees in 493 businesses, 93.7 % of which (462) are furniture and 6.3 % (31) are panel businesses. While 60.2 % (297) of these businesses employ 10-49 people, 23 % (118) of them have 50-149, 6.7 % (33) of these establishments work with 150-249 employees, and 9.1 % (45) employs more than 250 workers.

2.2 Development steps of PIS and PPS
2.2. Koraci razvoja PIS-a i PPS-a

2.2.1 Generating the item pool
2.2.1. Stvaranje skupa teza

In this step, postgraduate theses in the Council of Higher Education in both Turkish and foreign languages, which include the keywords of institutionalization, corporate governance, performance in their subject of study or name, were scanned. Three hundred fifty-five theses written before 2016 were found. One hundred and seventy of these theses were about institutionalization, 185 of them were about performance. In addition to this, 400 different studies (articles, notices, reports, etc.), which were accessed by scanning through Science Direct and Google Scholar on the internet, were analyzed. One thousand six hundred ninety-nine items included in these separate studies in the literature were listed, compared, and checked for repetitions, which resulted in a pool of 71 items after the omission of repeated items (Table 1). In order to express the level of agreement on the items in the list, 5-point Likert scale (“1” Strongly Disagree, “2” Disagree, “3” Undecided, “4” Agree, “5” Strongly Agree) was used.

2.2.2 Expert opinion (content validity)
2.2.2. Stručno mišljenje (valjanost sadržaja)

Items in the pool were proved by twelve experts (forest industry engineering academic members) to attain content validity. Experts did not call for any changes in the item number but provided suggestions on their content. Necessary editing was completed before pre-application.

Table 1 Item pool related to perceived institutionalization and perceived performance
Tablica 1. Skup teza vezanih za percipiranu institucionalizaciju i percipirani učinak

Categories *Kategorije*	**Item pool** / *Skup teza*
Institutionalization *institucionalizacija*	1. Our company has a mission and vision. 2. Our company has an organizational chart. 3. Each duty, authorization and responsibility is settled and these are acknowledged by employees in our company. 4. Standards for each task and process are specified and documented. 5. There is an effective reporting system in our company. 6. In our company, recruitment, dismissal, and promotions are decided according to a clearly defined procedure. 7. The administrative staff consists of experts. 8. In our company, regular meetings are held, and decisions related to the firm are mostly made during these meetings. 9. Employees are regularly provided with training and reminders related to their tasks. 10. Emotions are at the forefront in decision-making and applications. 11. Our company pays attention to suggestions made by employees and suggestions/ideas that provide added value to the establishment are evaluated. 12. There is a high level of cooperation and communication among units. 13. The administration creates a customer-focused culture in the establishment and all applications are directed towards customer satisfaction. 14. Through market and outside environment analysis, opportunities and threats that the company is facing are regularly followed. 15. In our company, computers and software (such as MRP, ERP, CRP) are being effectively utilized and analysis are regularly made. 16. Activities of competitors are studied in deciding business strategy. 17. Our company has an idiosyncratic organizational culture and identity. 18. Our company is a business admired by other people and establishments, especially by its employees, public, business partners and partner companies. 19. Our company has a name/symbol/logo/sign that represents the firm nationally and internationally. 20. The dominant focus of our company is “not I” but “we”. 21. A transparent understanding of administration is present in our company. 22. The attendance of employees in the decision-making process is essential in our establishment. 23. Our company takes responsibility for the results of its actions. 24. Recruitments are conducted according to objective criteria. 25. The Middle and long-term plans of our company are shared with the shareholders. 26. Financial information users can access financial tables of the establishment with ease. 27. Customer complaints can be observed transparently by customers. 28. Decisions regarding society and the future of the company are shared with employees. 29. Our establishment participates in social responsibility projects (such as the social responsibility projects on environment and education involving people with disabilities and ex-convicts.). 30. Our company is aware of its responsibilities towards the society. 31. Our company expects all employees to abide by ethical (moral) rules accepted by society. 32. Social activities are organized in our company to boost motivation. 33. The activities of our company conform to the norms that are determined by the state, professional and industry associations. 34. The mission, strategies and actions of our company are consistent. 35. Rewards and penalties in our company are imposed according to objective and systematical criteria. 36. The personnel assessment process is fair and transparent. 37. Our company keeps the promises it makes to other firms, customers and its employees.

Table 1 Item pool related to perceived institutionalization and perceived performance (continuation)
Tablica 1. Skup teza vezanih za percipiranu institucionalizaciju i percipirani učinak (nastavak)

Performance *učinak*	1. Our establishment can produce at a lower cost compared to major competitors. 2. An increase in sales income has been achieved. 3. The return of our investments is higher than that of our competitors. 4. The market value of our company is higher than that of our competitors. 5. In our company, there are studies for measuring customer satisfaction. 6. Our company has a high level of customer satisfaction. 7. Our company has a high reputation and image. 8. Defective product rate is low. 9. Compliance with consumer rights has increased in the last three years. 10. There has been a decrease in customer complaints/refunds in our establishment. 11. New product developments or product improvements to meet customer expectations have seen an increase in the last three years. 12. Employees can express their opinions on innovation inside the company. 13. Problem solution committees (e.g. quality circles) in our company hold periodical meetings. 14. The research and Development unit of our company implements innovative activities. 15. Our company keeps up with the technology as much as possible and reduces the costs accordingly. 16. Our company has a higher level of achievement than significant competitors. 17. Our company is able to reach its target market compared to its competitors. 18. Customer orders are fulfilled precisely and on time. 19. Our company carries out planned maintenance activities. 20. Our suppliers are able to deliver raw materials when needed and at the right quality. 21. Our company has a high rate of benefiting from inputs. 22. Our company displays a solution-oriented approach towards the existing and possible productivity setbacks. 23. Production costs of our establishment are lower compared to those of our competitors. 24. Our product prices are lower than those of our competitors'. 25. Our company aims to sustain its function by optimizing resource usage. 26. Job satisfaction is high among employees of our company. 27. Payments in our company are made regularly. 28. Occupational health and safety is valued in our establishment. 29. Physical working conditions of our company (Ventilation, humidity, dust, vibration, noise, etc.) are suitable. 30. Our employees are aware that they play an active role in increasing productivity. 31. Our company maintains a lower level of inventory. 32. In our company, the rate of faulty products is minimized. 33. Our company tries to reduce waste. 34. Results related to the measurement of productivity are shared with all employees.

2.2.3 Initial application
2.2.3. Inicijalna primjena

Items designated according to expert opinion were tested in Konya by face to face interviews with 100 people in the production business active in 22 different sectors. After the analysis, it was concluded that the items had no cases of absence of perception and that none of the items needed to be removed or added.

2.2.4 Factor and reliability analysis
2.2.4. Analiza faktora i pouzdanosti

After the draft scale was applied on 797 people working in 493 furniture and panel businesses, explanatory factor analysis (EFA) was implemented. According to the results of the analysis, items demonstrating construct validity were listed in the final scale. Cronbach Alpha internal consistency coefficient was calculated for the finalized scale. Calculations were made in SPSS 22 (IBM corp., 2013). In order to test the suitability of the structure, which was created through explanatory factor analysis, a confirmatory factor analysis (CFA) was conducted using AMOS 22 (Arbuckle, 2013). It is suggested that EFA should be applied initially in scale development phase, followed by CFA to confirm these new factor structures discovered (Yaşlıoğlu, 2017). In this respect, in order to determine in which sub-dimension or conceptual framework the items were perceived by the participants in the businesses, EFA, which is a process used to discover factors, was used considering the relationships between variables in the first step. The data to be used in factor analysis must display a normal distribution pattern. As a result, it was assumed that skewness-kurtosis coefficients demonstrated normality between -3 and +3 (Bentler, 2006). After the designation of factors constituting the scale, a suitable title for each factor was chosen according to expressions related to items included in every factor. CFA was implemented to test the model determined after EFA application.

2.2.5 Structural equation modeling (SEM)
2.2.5. Modeliranje strukturnih jednadžbi (SEM)

Structural equation modeling (SEM) is a robust analysis as it enables us to study interrelations of implicit along with observed variables, conduct many

Table 2 SEM fit indexes
Tablica 2. SEM indeksi prikladnosti

Fit index* *Indeks prikladnosti**	χ^2 **/df**	**NFI**	**CFI**	**RMSEA**	**GFI**	**AGFI**	**RMR**
Good fit *dobra prikladnost*	$0 \leq \chi^2/df \leq 3$	0.95 - 1.00	0.95 - 1.00	0.00 - 0.05	0.90 - 1.00	0.90 - 1.00	0.00 - 0.05
Acceptable fit *prihvatljiva prikladnost*	$3 \leq \chi^2/df \leq 5$	0.90 - 0.94	0.90 - 0.94	0.06 - 0.08	0.85 - 0.89	0.85 - 0.89	0.06 - 0.08

*AGFI – Adjusted Goodness of Fit Index, CFI – Comparative Fit Index, GFI – Goodness of Fit Index, NFI – Normed Fit Index, χ2/df – Chi Square/Degree of Freedom, RMR – Root Mean Square Residual, RMSEA – Root Mean Square Error of Approximation
*AGFI – *prilagođeni indeks prikladnosti,* CFI – *usporedni indeks prikladnosti,* GFI – *indeks prikladnosti,* NFI – *normirani indeks prikladnosti, χ2/df – Hi-kvadrat/stupanj slobode,* RMR – *korijen srednjeg kvadrata ostatka*, RMSEA – *korijen iz prosječne kvadrirane pogreške aproksimacije*

analyses simultaneously, structure models and speculate on them. Fit indexes used to interpret SEM are given in Table 2 (Byrne, 2010; Schermelleh-Engel *et al.,* 2003).

2.3 Ethics
2.3. Etika

Written consent was obtained from the institutions. The purpose of the study was explained to the workers, and participation was allowed after their consent. It was explained that the information provided by the participants would only be used within the scope of the current study.

2.4 Limitations of the study
2.4. Ograničenja studije

During the study, 50 cities were visited in total; however, due to time limitations, closed businesses, technical and economic difficulties and security issues, the survey study could only be conducted in 15 cities. All registered panel businesses were contacted, in addition to visiting almost 1000 businesses. As some businesses refused to participate, the survey was not conducted in these firms. The study is confined to the responses of 797 employees from 493 companies that participated in the survey.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Demographic and workplace findings
3.1. Demografski nalazi i nalazi na radnome mjestu

A high percentage of participants (75.7 %) (603) were male, 43.3 % (345) were within 26-35 years of age, 70 % of the participants (558) were married, and 47.9 % (382) were university graduates. Almost half of the participants (48 %) (357) were directors, 31.9 % (254) had worked between 1 and 3 years for the same company, and 46.7 % (372) had been working in the same sector for more than 10 years. Similar to the demographics given in this study, a study conducted in the forest products industry in Turkey determined that most of 432 employees involved were university graduates (48 %), male (83 %), between 26-35 (50 %), married (70 %) and at upper and middle levels (49 %). While the rate of employees working for ten or more years was 16 % in the same study, the rate of experienced workers in this study is higher (Aydın and Tiryaki, 2018).

3.2 Suitability assessment of data for factor analysis
3.2. Procjena prikladnosti podataka za faktorsku analizu

Kaier-Meyer-Olkin (KMO) and Barlett test were used to determine whether the data obtained from the study group was suitable for EFA. In this study, Cronbach Alpha Coefficient for PIS is 0.959, KMO value is 0.970, Barlett value is equal to 16896.501. For PPS, Cronbach Alpha Coefficient is 0.942, KMO value is 0.951 and Barlett value is 13832.059. These results show that the scales have high reliability and validity (Yaşar, 2014).

3.3 Determining the factor pattern of PIS
3.3. Određivanje uzorka faktora PIS-a

It was detected that item 19 in the PIS did not demonstrate normal distribution and thus was removed from the analysis. It was calculated that the coefficient of kurtosis ranged between -1.075 and +2.889, while the skewness coefficient had values between -1.997 and -0.344 for the data used in perceived institutionalization. Therefore, it was concluded that these values displayed normal distribution. This three-factor structure accounts for 59.3 % of the total variance.

In the study, the first factor lists items that emphasize the necessity of the firms to focus on consistency and on how important this is for the institutionalization, as well as the importance to keep the focus on these topics. The first factor was thus classified as “Consistency (c)” sub-dimension. Items 7 (c13), 11 (c12), 12 (c15), 13 (c9), 17 (c14),18 (c4), 20 (c5), 21 (c8), 23 (c6), 24 (c7), 30 (c1), 31 (c3), 33 (c11), 34 (c10) and 37 (c2) belong to the first factor. Factor loads for these items range between 0.761 and 0.555. The variance displayed by this factor is 29.4 %. Cronbach Alpha coefficient is 0.944. The second factor was named “Formalization (f)” sub-dimension, due to the fact that the items belonging to this factor express that businesses should focus on formalization. Items 1 (f2), 2 (f1), 3 (f3), 4 (f5) and 5 (f4) were placed in the second factor and their factor loads range between 0.766 and 0.667. Variance declared by this factor is 16.23 %. Cronbach Alpha Coefficient is 0.855. Items expressing that the businesses should focus on transparency and accountability were mostly listed in the third virtual factor. Hence, this factor was named “Transparency and accountability (ta)” sub-dimension. Items number 25 (ta4), 28 (ta3), 32 (ta1) and 35 (ta2) belong to

Table 3 Factor analysis results related to PIS
Tablica 3. Rezultati faktorske analize povezani s PIS-om

Factors / *Faktor*i	**Factor I**		**Factor II**		**Factor III**	
Factor load *Opterećenje faktora*	≠30	0.761	≠2	0.766	≠32	0.772
	≠37	0.742	≠1	0.738	≠35	0.662
	≠31	0.729	≠3	0.708	≠28	0.621
	≠18	0.722	≠5	0.697	≠25	0.528
	≠20	0.664	≠4	0.667		
	≠23	0.656				
	≠24	0.648				
	≠21	0.639				
	≠13	0.635				
	≠34	0.622				
	≠33	0.580				
	≠11	0.579				
	≠7	0.567				
	≠17	0.561				
	≠12	0.555				
Eigen value / *Vlastita vrijednost*	11.533		1.455		1.234	
Explanatory power of the factor, % *Obrazloženje snage faktora,* %	29.4		16.23		13.6	
Reliability / *Pouzdanost*	0.944		0.855		0.727	

the third factor and their factor loads range between 0.772 and 0.528. Variance declared by this factor is 13.6 %. Cronbach Alpha Coefficient is 0.727. The fact that the explained variation exceeds 50 % of the total variation is stated as an important criterion of factor analysis (Yaşlıoğlu, 2017). Accordingly, while the first factor sub-dimension is able to represent, the other two factor sub-dimensions have a lower potential of representation. Items 6, 8, 9, 10, 14, 15, 16, 22, 26, 27, 29 and 36 that do not return a meaningful result in any of the virtual factors, a lower load of a factor (<0.50), return meaningful results for more than one virtual factor or exist alone in a virtual cluster are removed from the scale. Cronbach Alpha Coefficients are perfect fit for (c), a good level of fit for (f) and (ta) (Kalaycı, 2009) (Table 3).

3.4 Determining the factor pattern of PPS
3.4. Određivanje uzorka faktora PPS-a

It was detected that items 27 and 28 in the PPS did not demonstrate normal distribution and thus they were removed from the analysis. It was calculated that the coefficient of kurtosis ranged between -0.685 and +2.38, while the skewness coefficient returned values between -2.035 and -0.242 for the data used in perceived institutionalization. Therefore, it was concluded that these values displayed normal distribution. The factor structure of the PPS is organized in three factors. This three-factor structure accounts for 57.1 % of the total variance.

This factor, which consists of items expressing that the main focus of businesses should be productivity, was named as "Productivity (p)" sub-dimension. Items 7 (p4), 8 (p2), 12 (p13), 18 (p1), 19 (p9), 20 (p12), 21 (p10), 22 (p6), 25 (p11), 26 (p3), 29 (p7), 30 (p 35) and 33 (p8) belong to the first factor and their factor loads range between 0.744 and 0.521. Variance displayed by this factor is 30.6 %. Cronbach Alpha coefficient is 0.925. The second virtual factor, which consists of items related to profitability and efficiency in the study, is named as "Operating income (oi)" sub-

Table 4 Factor analysis results related to PPS
Tablica 4. Rezultati faktorske analize povezani s PPS-om

Factors /*Faktori*	**Factor I**		**Factor II**		**Factor III**	
Factor load *Opterećenje faktora*	≠18	0.744	≠3	0.828	≠14	0.801
	≠8	0.734	≠4	0.769	≠13	0.722
	≠26	0.727	≠16	0.647	≠15	0.576
	≠7	0.716	≠17	0.604		
	≠30	0.711	≠2	0.591		
	≠22	0.707				
	≠29	0.668				
	≠33	0.663				
	≠19	0.648				
	≠21	0.637				
	≠25	0.623				
	≠20	0.605				
	≠12	0.521				
Eigen value / *Vlastita vrijednost*	9.033		1.896		1.065	
Explanatory power of the factor, % *Obrazloženje snage faktora,* %	30.6		14.7		11.8	
Reliability / *Pouzdanost*	0.925		0.798		0.756	

dimension. Items 2 (oi5), 3 (oi1), 4 (oi2), 16 (oi3) and 17(oi4) are placed in the second factor and their factor loads range between 0.828 and 0.591. Variance declared by this factor is 14.7 %. Cronbach Alpha Coefficient is 0.798. Items related to product development are listed in this factor, and thus it is named "Product development (pd)" sub-dimension. Items number 13 (pd2), 14 (pd1) and 15(pd3) belong to the third factor and their factor loads range between 0.801 and 0.576. Variance declared by this factor is 11.8 %. Cronbach Alpha Coefficient is 0.756. Accordingly, while the first-factor sub-dimension is able to represent, the other two factor sub-dimensions have a lower potential of representation. (Yaşlıoğlu, 2017). Items 1, 5, 6, 9, 10, 11, 23, 24, 31, 32 and 34 that do not return a meaningful result in any of the virtual factors, a lower load of a factor (<0.50), return meaningful results for more than one virtual factor or exist alone in a virtual cluster are removed from the scale. Cronbach Alpha Coefficients have a perfect fit for (p), while maintaining a good level of fit for (oi) and (pd) (Kalaycı, 2009) (Table 4).

3.5 Confirmatory factor analysis of PIS
3.5. Potvrdna analiza faktora PIS-a

According to the results of CFA of PIS, GFI was found as 0.90, AGFI as 0.88, RMR as 0.045, NFI as 0.91 and CFI as 0.94. NFI and CFI indexes lower than 0.95 and AGFI index lower than 0.90 prove an acceptable fit, while RMR below 0.05 and GFI showing 0.90 mean a good fit. (Byrne, 2010; Schermelleh-Engel *et al.*, 2003).

In the diagram illustrated according to the analysis conducted, correlation coefficients related to the items range between 0.59 and 0.82. The ratio of Chi-Square value to the degree of freedom is (χ^2 /df) 3.90. Results in the range between 3 and 5 can be interpreted as an acceptable fit. Considering RMSEA results, 0.06 can be seen as an acceptable fit (Schermelleh-Engel *et al.*, 2003). Based on the data obtained as a result of CFA, it is safe to say that 3-factor PIS is confirmed as a model. For the model to have better fit values, modification indices (MI) covariance values among disturbance terms under the same factors were studied (Yaşlıoğlu, 2017). Some changes were made according to disturbance covariances between c5-c6 and c10-c13 as the software suggested. PIS was confirmed as a model (Figure 1).

3.6 Confirmatory factor analysis of PPS
3.6. Potvrdna analiza faktora PPS-a

According to the results of CFA of PPS, GFI was found as 0.93, AGFI as 0.91, RMR as 0.04, NFI as 0.92 and CFI as 0.95. CFI equal to 0.95, AGFI index over 0.90, RMR lower than 0.05 and GFI value over 0.90 display good fit, NFI value being lower than 0.95 corresponds to an acceptable fit (Byrne, 2010; Schermelleh-Engel *et al.,* 2003).

In the diagram generated with the results of the analysis conducted, correlation coefficients related to the items range between 0.50 and 0.84. The ratio of Chi-Square value to the degree of freedom is (χ^2 /df) 3.47. Results in the range between 3 and 5 can be inter-

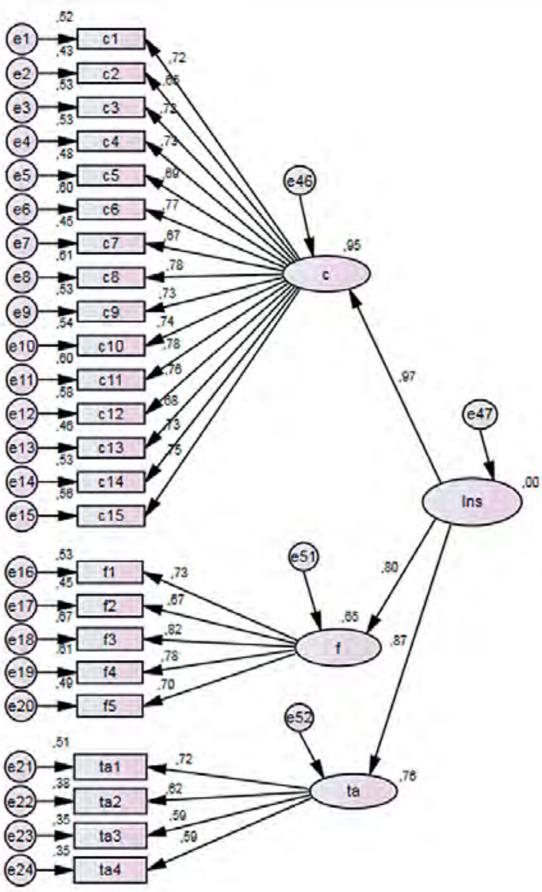

Figure 1 Path diagram related to PIS
Slika 1. Dijagram toka za PIS

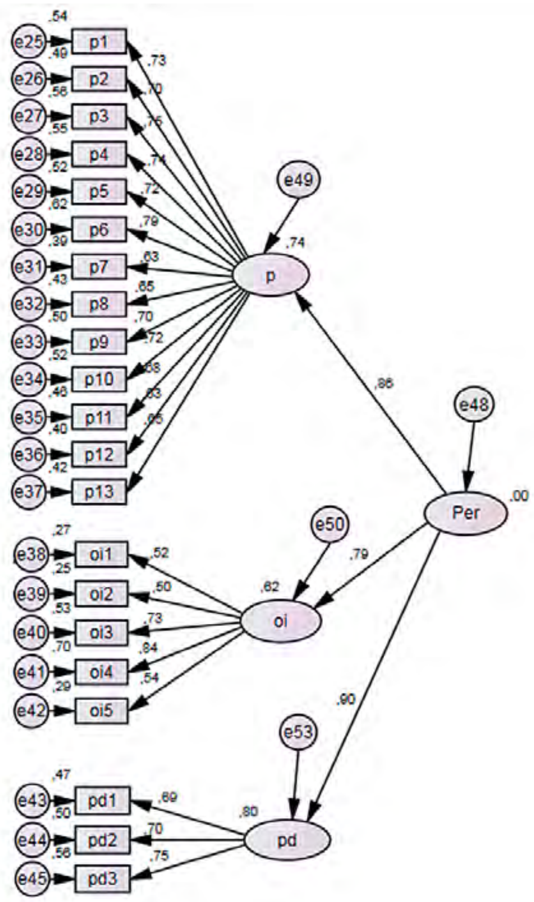

Figure 2 Path diagram related to PPS
Slika 2. Dijagram toka za PPS

preted as an acceptable fit. Considering RMSEA results, it was seen that a fit index on the level of 0.05 was achieved. RMSEA value lower than 0.06 can be interpreted as a good fit (Schermelleh-Engel *et al.,* 2003). In the established model, some changes were made considering disturbance covariances between p5-p7, oi1-oi2 and oi1-oi5. Based on the data obtained as a result of CFA, it can be stated that three-factor PPS is confirmed as a model (Figure 2).

3.7 Reliability values of PIS and PPS
3.7. Vrijednosti pouzdanosti za PIS i PPS

For convergent validity test, composite reliability (CR) and Average Variance Extracted (AVE) were calculated and shown along with standard loading and t values (Table 5). Fornell and Larcker (1981) suggest that composite reliability (CR) should be over 0.70, while AVE value is over 0.50 for a better convergent validity. Accordingly, for PIS, while CR values of all sub-dimensions prove a good fit, AVE value is lower than expected in only (ta) sub-dimension. When we consider PPS, CR values prove a good fit in all sub-dimensions while AVE value proved to be low in only (oi) sub-dimension. On the other hand, it was also stated that construct validity is at a sufficient level when AVE is lower than 0.50 only if CR value is higher than 0.60 (Huang *et al.,* 2013).

3.8 Correlation matrix for scales and sub-scales
3.8. Korelacijska matrica za ljestvice i podljestvice

The correlations among the institutionalization and sub-scales and performance and sub-scales are presented in Table 6 along with a discriminant validity test.

Table 5 Reliability values of PIS and PPS
Tablica 5. Vrijednosti pouzdanosti za PIS i PPS

Institutionalization *Institucionalizacija*	**Items** *Teze*	**Standard loading** *Standardno opterećenje*	*t**	Performance *Učinak*	**Items** *Teze*	**Standard loading** *Standardno opterećenje*	*t**
Consistency *dosljednost* (CR = 0.94, AVE = 0.53)	c1	0.722	21.843	Productivity *produktivnost* (CR = 0.93, AVE = 0.50)	p1	0.735	21.099
	c2	0.652	19.351		p2	0.698	19.955
	c3	0.725	21.919		p3	0748	-
	c4	0.730	22.123		p4	0.739	21.228
	c5	0.694	20.776		p5	0.719	20.583
	c6	0.773	23.728		p6	0.786	22.765
	c7	0.669	19.918		p7	0.628	17.758
	c8	0.781	24.047		p8	0.652	18.513
	c9	0.728	22.038		p9	0.705	20.158
	c10	0.737	22.382		p10	0.723	20.719
	c11	0.777	-		p11	0.680	19.385
	c12	0.760	23.236		p12	0.631	17.855
	c13	0.681	20.343		p13	0.650	18.459
	c14	0.726	21.957	Operating income *operativni dohodak* (CR = 0.77, AVE = 0.41)	oi1	0.517	13.825
	c15	0.750	22.864		oi2	0.496	13.268
Formalization *formalizacija* (CR = 0.86, AVE = 0.55)	f1	0.731	21.032		oi3	0.731	19.882
	f2	0.671	19.070		oi4	0.838	-
	f3	0.816	23.820		oi5	0.540	14.522
	f4	0.781	-	Product development *razvoj proizvoda* (CR = 0.76, AVE = 0.51)	pd1	0.686	16.573
	f5	0.698	19.940		pd2	0.705	-
Transparency and accountability *transparentnost i odgovornost* CR = 0.73, AVE = 0.40)	ta1	0.717	14.865		pd3	0.745	17.656
	ta2	0.617	13.468				
	ta3	0.593	13.088				
	ta4	0.592	-				

*P values belonging to all t values is determined as 0.000. / * *Vrijednosti P koje pripadaju svim vrijednostima t određene su kao 0,000.*

Table 6 Correlation matrix for scales and sub-scales
Tablica 6. Korelacijska matrica za ljestvice i podljestvice

Scales and sub-scales *Ljestvice i podljestvice*	**c**	**f**	**ta**	**ins**	**p**	**oi**	**pd**	**per**
c	1							
f	0.697	1						
ta	0.689	0.556	1					
ins	0.899	0.857	0.868	1				
p	0.857	0.644	0.632	0.805	1			
oi	0.476	0.487	0.450	0.539	0.521	1		
pd	0.626	0.585	0.622	0.699	0.636	0.523	1	
per	0.768	0.678	0.677	0.807	0.840	0.798	0.881	1

3.9 Fit indexes for PIS and PPS
3.9. Indeksi prikladnosti za PIS i PPS

Suitability of PIS and PPS model was tested by RMSEA, GFI, AGFI, RMR, NFI and CFI indexes. In consequence of the analysis, GFI value was found as 0.85, AGFI as 0.85, RMR as 0.047, NFI as 0.90 and finally CFI was found equal to 0.91. NFI and CFI indexes lower than 0.95, GFI value equal to 0.85 and AGFI equal to 0.85 correspond to an acceptable fit, while RMR value below 0.05 indicates a good fit (Byrne, 2010; Schermelleh-Engel *et al.,* 2003). In the diagram of the model generated with the results of the analysis conducted, the ratio of Chi-Square value to the degree of freedom is (χ^2 /df) 3.00. A result equal to 3 can be interpreted as a good fit. RMSEA result that is equal to 0.05 demonstrates that a good fit measure has been obtained (Schermelleh-Engel *et al.,* 2003). In the model established, some changes were made regarding disturbance covariance between c5-c6, c8-c11, c10-c13, p5-p7, oi1-oi2 and oi1-oi5. A total of 45 observed variables were used in the model. 15 of these variables contain items related to (c), 5 of these contain (f), 4 covers (ta), 13 of them include (p), 5 represent (oi), while 3 of these variables demonstrate (pd). The number of implicit variables in the model is 6 in total.

The results of the model analysis show that seven hypotheses (p <0.05) were accepted,

H_1 1. A positive and meaningful relation was detected between (c) and "Institutionalization" (*r*=0.967). Therefore, $H_1$1 hypothesis is accepted. Şanal (2011) and Apaydın (2009) stated that consistency boosts institutionalization and business performance accordingly.

H_1 2. A positive and meaningful relationship was found between (f) and "Institutionalization" (*r*=0.811). Therefore, H_1 2 hypothesis is accepted. These regulations are thought to prevent confusion in duty assignments, conflicts of authorities and task setbacks along with increasing the performance (Gürüz and Gürel, 2009; Tengilimoğlu *et al.,* 2012).

H_1 3. An increase in (ta) has affected "Institutionalization" structure positively (*r*=0.877). Therefore, H_1 3 hypothesis is accepted. Similar to the strong underlying relationships determined in the model, the positive effect of transparency and accountability in increasing the institutionalization in an establishment was also emphasized in previous studies (Gedik, 2010; Yılmaz, 2006; Sözbilen, 2012).

H_1 4. A positive and meaningful relationship was found between (p) and "Performance" (*r*=0.956). Therefore, H_1 4 hypothesis is accepted. In their study on furniture and panel businesses, Kırklıkçı and Gedik (2019) determined that the main factors affecting performance are productivity, operating income, and the ability to develop new products.

H_1 5. A positive and meaningful relationship was found between (oi) and "Performance" (*r*=0.704). Therefore, H_1 5 hypothesis is accepted. It was stated that it is necessary for businesses to search for new markets and thus increase their income, which will increase their competitiveness (Tavşancı, 2009; Yazıcıoğlu and Koç, 2009) and, having a high level of success, will positively affect the performance of the establishment (Yıldız, 2010).

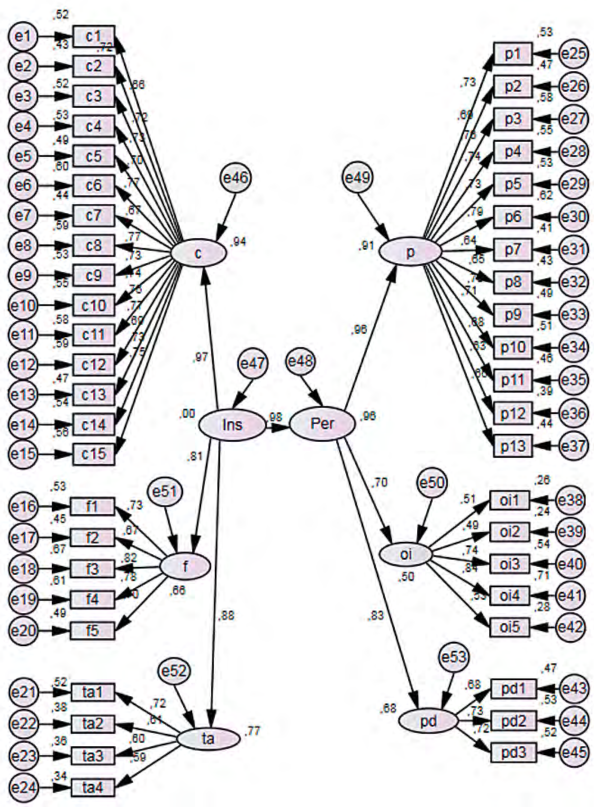

Figure 3 Path diagram related to PIS and PPS
Slika 3. Dijagram toka za PIS i PPS

H_1 6. A positive and meaningful relationship was found between (pd) and "Performance" (*r*=0.826). Therefore, H_1 6 hypothesis is accepted. In literature, product development process is specified as an important factor that influences business performance positively (Keskin *et al*. 2016; Günday *et al.,* 2011; Küçük ve Kocaman, 2014). In addition, there are studies stating that institutionalization increases the performance by compelling businesses to innovate (Tengilimoğlu *et al.,* 2012; Onay and Vezneli, 2011).

H_1 7. As a result of evaluations and statistical analyses, it is concluded that an improvement in the institutionalization level of a business will result in improvements in performance (*r*=0.98). Therefore, H_1 7 hypothesis is accepted. As institutionalization will increase the satisfaction of employees, it will also have positive effects on performance and productivity (Çam, 2002; Erdil *et al*., 2004). In addition, there are studies stating that institutionalization increases the performance by compelling businesses to innovate (Tengilimoğlu *et al.,* 2012; Onay and Vezneli, 2011) (Figure 3).

4 CONCLUSIONS
4. ZAKLJUČAK

Through this methodological study, scales for perceived institutionalization and perceived performance in furniture and panel businesses operating in Turkey and the relationship between perceived institutionalization and perceived performance were explained by a model. As a result of the analyses, it was concluded that 1 unit of institutionalization improvement in a business results in a 0.96-unit betterment (increase) in the performance of the business.

In consequence of analyses, a three-sub-dimensional structure was obtained through factor analyses results in both PPS (21 items) and PIS (24 items). While these sub-dimensions are identified as "Consistency" "Formalization" and "Transparency and accountability" in PIS, they are named as "Productivity", "Operating income" and "Product development" in PPS. Reliability analyses results for both scales and their sub-dimensions are at an acceptable level. It was seen that sub-dimensions of these scales demonstrate a positive meaningful relationship with each other and the total scale. Seven new hypotheses made related to these relationships were accepted.

It is thought that the study will be instructive in (*i*) determining perceived institutionalization and perceived performance in furniture and panel businesses, (*ii*) determining the variables influencing perceived institutionalization and perceived performance, (*iii*) detecting factors influencing perceived institutionalization and perceived performance in food, chemistry, automotive, machine and other manufacturing sectors.

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Industry 4.0 Implementation in US Primary Wood Products Industry

Implementacija industrije 4.0 u primarnoj preradi drva u SAD-u

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ABSTRACT • *Understanding barriers to implementation of Industry 4.0 strategies is a first step to enable companies to begin to use and implement new technologies; using new technologies will allow mills to improve efficiency and stay relevant in the face of increasing international competition. This study uses a mail survey to gather insights regarding awareness of technologies within the US primary wood products industry as well as the barriers to using new technologies. Awareness of technologies is generally low, especially with respect to additive manufacturing, autonomous systems, and big data. Lack of skilled workers is the primary limiting factor to implementation of new technologies with other key factors being out-of-date facilities and unclear financial benefits. Existing expertise was highest in manufacturing process monitoring and data analysis, and lowest in robotics. Only a very small group of respondents have already implemented any form of robotics. Overall, only six respondents (6.7 %) have an Industry 4.0 strategy, while 77 % did not recognize the terms "Industry 4.0" or "Smart Manufacturing." Results suggest considerable room for additional application of I4.0 technologies in the industry.*

Keywords: *industry 4.0; wood products; digitalization; technology*

SAŽETAK • *Razumijevanje prepreka za implementaciju strategija industrije 4.0 prvi je korak koji će omogućiti tvrtkama uvođenje i primjenu novih tehnologija. Uvođenjem tih novih tehnologija pilane će poboljšati svoju učinkovitost uz zadržavanje konkurentnosti. Ovo se istraživanje temelji na poštom upućenoj anketi kako bi se dobio uvid u svjesnost o tehnologijama u industriji primarne prerade drva u SAD-u, kao i o preprekama za primjenu novih tehnologija. Svjesnost o tehnologijama općenito je niska, posebice za aditivnu proizvodnju, autonomne sustave i velike baze podataka. Nedostatak kvalificiranih radnika najveći je ograničavajući faktor za primjenu novih tehnologija, a ostali su otežavajući činitelji zastarjela postrojenja i nejasnoće o financijskim koristima što ih donosi primjena novih tehnologija. Najveća je stručnost zabilježena u području praćenja proizvodnih procesa i analizi podataka, a najmanja u robotici. Samo je vrlo mala skupina ispitanika već primijenila neki od oblika robotike. Ukupno samo šest ispitanika (6,7 %) ima strategiju Industrije 4.0, dok 77 % ispitanika nije prepoznalo pojmove „industrija 4.0" ili „pametna proizvodnja". Rezultati pokazuju da postoji znatan prostor za dodatnu primjenu tehnologija Industrije 4.0 u primarnoj preradi drva.*

Ključne riječi: *Industrija 4.0; proizvodi od drva; digitalizacija; tehnologija*

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1 INTRODUCTION
1. UVOD

Similar to other manufacturing industries, the wood processing industry has undergone rapid changes in recent years. Developments among a host of technologies in manufacturing are making possible advancements to a new era, often referred to as the fourth industrial revolution. Even though it is an omnipresent topic in the media, there are still many obscurities due to the lack of a set definition of the term itself. While referred to as "Industry 4.0" in Europe, the phrase "Smart Manufacturing" is more common in North America (Thoben *et al*., 2017). Throughout the remainder of the text "I4.0" is used.

There is a discrepancy between the promoted image of the technological revolution associated with I4.0 and the real impact on today's companies. I4.0 can be defined as, "technological evolution from embedded systems to cyber-physical systems" (CPSs) (MacDougall, 2014), where CPSs are sensors, machines, workpieces or IT systems, which are connected within a manufacturing facility and/or along the value chain and able to interact with each other by the use of internet-based protocols. According to Jäger and Lerch (2020), CPSs are, "…intended to help plan, design and steer production systems and complete value-added networks by implementing intelligent horizontal and vertical digital networking in the value-added processes."

The transformation to I4.0 is taking place via: Autonomous robots, simulation, horizontal and vertical system integration, the Industrial Internet of Things (IIoT), Cybersecurity, the cloud, additive manufacturing, augmented reality and big data and analytics (Rüßman *et al*., 2015). Many of these technologies are already used in modern businesses, but in the course of I4.0 these individual elements from the physical and virtual world will interconnect to form a fully integrated and automated production system. These core elements of I4.0 enable gathering and analyzing data across machines, which allows for faster, more flexible and more efficient processes; production with decentralized, intelligent systems makes it possible to produce higher-quality goods at reduced costs, which in turn increases overall manufacturing productivity.

The need to implement new digital technologies results from various ongoing challenges. The globalization of markets has resulted in constantly increasing competition, while at the same time consumer demand is increasing for customized, yet, inexpensive products. Customization entails a growing number of variants and increasing complexity in the entire production process, ultimately resulting in a production batch size of one. This requires the use of automation and interconnected systems because the overall aim is to produce as economically as possible, including resource efficiency and short processing times. At the same time, changing demographics translate to a shortage of skilled labor and in turn increases the need for automated and intelligent processes. In order to continuously improve production processes, real-time data for all manufacturing elements is vital. In a smart factory, each part of the production system is monitored and automatically optimized/adjusted. This data collection provides vital information needed for process improvement. For instance, bottlenecks can easily be identified, production flows can be reorganized if necessary, the reliability of single machines and the whole plant can be calculated via downtimes, or short- and long-term production planning can be facilitated.

Naturally, I4.0 developments have also been affecting the wood processing industry. This industry is positioned in a market context of increasing international competition and steadily increasing pricing pressure. In this setting, it becomes vital - especially for smaller companies - to work as effectively, efficiently and economically as possible. In the near future it arguably will be crucial for companies to take advantage of I4.0 to improve innovativeness and maintain competitiveness (Kropivšek and Grošelj, 2020; Jäger and Lerch, 2020). As examples of early implementation of I4.0 tools, robots are becoming more common within wood products manufacturing as are advanced monitoring capabilities enabled via the Internet of Things.

This work focuses on assessing the current situation of the US primary wood products industry to obtain a comprehensive overview of the implementation of I4.0 elements and inhibiting factors within this process. The overall objectives are to:

- Identify the state-of-the-art in the US primary wood products manufacturing industry with respect to implementation of advanced manufacturing techniques and technologies.
- Identify hurdles to the adoption of advanced manufacturing techniques and technologies.

2 BACKGROUND
2. DOSADAŠNJA ISTRAŽIVANJA

I4.0 is the most recent generation of industrial evolution. The first industrial revolution was the mechanization and use of steam power in manufacturing, followed by mass production and the use of electricity (2^{nd}), and flexible automation and the use of computers (3^{rd}). We are currently in the fourth industrial revolution based on cyber physical systems (Basl, 2017), including the use of artificial intelligence, robotics, and other new technologies. Extensive digitalization is necessary for a manufacturing site to fully implement an I4.0 strategy. There is huge potential for integration of systems towards a more fully automated production process. However, there has been limited work thus far investigating I4.0 in forestry and wood products. Advanced technologies have been employed across the sector for some time. For example, cut-to-length harvest systems with advanced sensing and links to digital maps and mill order files have been commonplace for some time. Still, awareness of I4.0 and use of the term is rather limited (Müller *et al*., 2019). Similarly, in the wood products manufacturing sector, vision and sensing systems (e.g., 3D scanning of logs and lumber coupled with software to optimize yields), remote monitoring for preventive maintenance, and automation (e.g., for material handling, detecting and repairing defects in veneer, grading lumber, etc.) are increasingly commonplace in 21st century manufacturing operations. Among a number of manufacturing sectors, wood, paper, and printing was the least I4.0 ready within the Upper-Rhine region of Europe (Jäger and Lerch, 2020). On the other hand, "full" implementation of I4.0 is rare in any sector (Flores *et al*., 2018, Schröder, 2017).

High technology costs and lack of skilled workers are key hurdles to further implementation of I4.0 in the wood products sector (Buehlmann *et al*., 2020; Kropivšek and Grošelj, 2020; Ratnasingam *et al*., 2019). The overall low level of existing technology implementation within a company can also represent a significant hurdle. Many operations lack the IT networking infrastructure and data management abilities required for functional cyber-physical systems (Ratnasingam *et al*., 2019). Based on available resources, larger companies are often better placed to implement I4.0 strategies (Jäger and Lerch, 2020; Schröder, 2017). Due to a higher dependency on low-cost manufacturing in smaller companies, there has been restricted investments in technology in general (Ratnasingam *et al*., 2019).

The limited existing work describing wood products manufacturers suggests that overall awareness of I4.0 is low (Buehlmann *et al*., 2020) and, while companies are implementing various technologies, there are few that have moved significantly towards digitalization and comprehensive adoption of I4.0 (Kropivšek and Grošelj, 2020; Buehlmann *et al*., 2020). Just over half of large US secondary wood products manufacturers have a strategic vision in place for digitalization (Buehlmann *et al*., 2020).

Implementation of I4.0 can be thwarted because of an unwillingness to cooperate due to skills of workers and lack of budget (Müller *et al*., 2019). Along with the studies on the use of I4.0, there are initiatives in which organizations such as FPInnovations have created an FPinnovations Forestry 4.0 Initiative, which includes implementation of the rapidly growing fields of artificial intelligence (AI) and robotics (Gingras *et al*., 2020). Despite a growing literature base and initiatives such as that previously mentioned, there is significant need for insight into the current reality of I4.0 awareness and implementation in wood products manufacturing. This is especially the case for primary wood products manufacturers. While Müller *et al*. (2019) provide an overview of how I4.0 will change the forest value chain (standing trees to the mill gate) and Buehlmann *et al*. (2020) investigate secondary wood products manufacturing, little work addresses the context and situation with respect to primary wood products manufacturers.

3 METHODS
3. METODE

This study was conducted in four distinct phases. Phase 1 and Phase 2 were designed around information gathering, while Phase 3 involved developing and pilot testing a questionnaire. Finally, Phase 4 was a full-scale data collection among US primary wood products manufacturers. In detail, the four stages are: 1) secondary research using industry-focused trade journals, 2) interviews with key experts and representatives of equipment vendors to the industry, 3) an online survey serving as a pilot test of the questionnaire, and 4) a mail survey of primary wood products manufacturers in the U.S.

Phase 1: The purpose of Phase 1 was to identify current techniques and technologies documented in existing literature. Therefore, various international journals, papers and other publications were screened for I4.0 and smart manufacturing topics. Specifically, publications included were:

- Timber and Forestry e-news *(Australia)*
- Logging and Sawmilling Journal *(North Vancouver, B. C., Canada)*
- Timber West *(Edmonds, WA, USA)*
- International Forest Industries *(Berkhamsted, United Kingdom)*
- FDMC – Woodworking Network *(Cedar Rapids, IA, USA)*
- Wood Business - CFI (Canadian Forest Industries) *(Simcoe, ON, Canada)*
- OptiSaw Forum publications *(Canada)*
- Panel World *(Montgomery, AL, USA)*
- Timber Processing *(Montgomery, AL, USA)*
- Millwide Insider – the magazine from USNR *(Woodland, WA, USA)*
- AWISA (Australian Woodworking Industry Suppliers Association Limited) *(Bowral, NSW, Australia)*

The journals listed above were selected because they contain up-to-date information on technological advances in the wood products industry and its suppliers. Journal issues from 2016, 2017, and the first six months of 2018 were methodically examined for relevant information. This rather short period was considered adequate because of rapid technological change. Beyond the journals listed above, independent papers concerning the topic found on the internet were used to extend the compilation of the latest I4.0 developments. The findings of this phase were summarized to provide an overview of the technologies currently employed in wood products manufacturing. These results fed into the subsequent phases of the research.

Phase 2: In Phase 2, in-person visits were made to multiple machinery and equipment manufacturers in the Pacific Northwest region of the United States. Identification of site visits was partially informed by the previous phase and supplemented by knowledge of the research team. Twelve company technical personnel were interviewed from four different companies and five different locations. Questions asked during these visits addressed the techniques and technologies actively applied in the companies' production as well as their plans for development towards I4.0. Furthermore, general questions about technological advances in wood processing gave insight into the personal experience of the managers and their perception of the wood products industry. Facilities tours also helped inform the researchers of the use of technology and working methods. Insights gained from expert interviews were combined with results from Stage 1 to inform questionnaire development.

Phase 3: After gaining a better understanding of the state-of-the-art with respect to manufacturing techniques and technologies currently used by the wood products industry (results of Phases 1 and 2), a questionnaire was designed to assess the overall adoption of key I4.0 techniques and technologies as well as hurdles to implementing those technologies and techniques. All constructs were developed by the authors, specifically for this research. Questionnaire and survey design were conducted according to the principles of the *Tailored Design Method* (Dillman *et al.,* 2014). The questionnaire consisted of 22 questions addressing the context of company operations, awareness of available technologies, use of available technologies, factors inhibiting implementation of technologies, resident expertise within the company, training conducted by the company, and finally, whether the company had a smart manufacturing or I4.0 strategy. These two key terms (i.e., I4.0 or Smart Manufacturing) were not used until the very last question given that it was assumed that many respondents would not be familiar with the terms. Instead, the manufacturing techniques and specific technologies were referenced, such as robotics and AI. The questions are shown in Table 1.

The questionnaire was pretested with employees of Oregon State University, resulting in small changes to question wording. Following this, a pilot test was conducted using all companies listed in the online Oregon Forest Industry Directory (www.orforestdirectory.com). An email was sent to each company (approximately 1800[1]) with a link to an online version of the questionnaire within the Qualtrics platform. The 58 valid responses from this pilot test were sufficient to show that the questionnaire and questions were working as designed. As expected, a very small number (4) claimed to have a smart manufacturing or I4.0 strategy, and each of these was a large company with over 500 employees.

[1] Note that the directory database did not allow for filtering manufacturing firms from service providers, landowners, etc. Therefore, the actual target audience is a small fraction of this number.

Phase 4: The last phase of the research was a national mail survey of primary wood products manufacturers in the US. A list of mills was developed utilizing the 2018 Random Lengths Big Book. The following sectors were included: lumber (hardwood and softwood), plywood (hardwood and softwood), oriented strand board, engineered wood products, particleboard, and medium density fiberboard. This compilation resulted in a total of 444 mill sites. For each mill site, the mill manager was the target respondent. Where the Big Book did not provide mill manager contact information, attempts were made to call the company to identify the appropriate contact. Two attempts were made to contact each site. For those sites that we were unable to make contact, the questionnaire was sent to the "mill manager."

The survey process consisted of two waves of mailed questionnaires, with follow-up calls to non-respondents. A total of 47 questionnaires were returned due to bad addresses. Ninety-two usable responses were received resulting in an adjusted response rate of 22 %. To test for the potential presence of non-response bias, a total of 30 non-responding managers were called and asked four questions from the questionnaire. Their answers were compared to those of the 92 respondents using t-tests through SPSS. We found three significant differences ($p<0.05$) regarding expertise levels with respect to robotics and cloud computing suggesting that our respondents are likely more technologically savvy/oriented than the overall population. Knowledge of the terms Smart Manufacturing and Industry 4.0 was also different with respondents more likely to be familiar with the terms than non-respondents who primarily responded with no knowledge of the terms Smart Manufacturing and Industry 4.0. Additional analyses consisting of means and t-test comparisons ($p<0.05$) were also conducted using SPSS.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Most respondents manufacture lumber (61, which is equivalent to 71 % of respondents), followed by plywood and veneer (8), OSB (8), engineered wood

Table 1 Study constructs and measurement
Tablica 1. Sadržaj upitnika i opis načina ocjenjivanja

Question / *Pitanje*	**Rating scale** *Ocjena*	**Example item** *Primjer*	**Figure in text** *Slika u tekstu*
In which business sector is your location primarily operating? *U kojem poslovnom sektoru primarno djelujete?*	Select all that apply *Odaberite sve što je primjenjivo.*	Lumber; Plywood/Veneer *drvna građa; furnirska ploča/furnir*	
How many employees does your location employ? *Koliko radnika zapošljavate?*	1-5; 6-10; 11-50; 51-100; 500+		
What is the level of awareness within your location regarding these business/manufacturing technologies and techniques? *Kolika je vaša svjesnost o navedenim poslovnim/proizvodnim tehnologijama i tehnikama?*	No awareness 1-5 High awareness *niska svjesnost 1-5 visoka svjesnost*	Robotics; Big Data *robotika; velike baze podataka*	1

Table 1 Study constructs and measurement (continuation)
Tablica 1. Sadržaj upitnika i opis načina ocjenjivanja (nastavak)

Question / *Pitanje*	**Rating scale** *Ocjena*	**Example item** *Primjer*	**Figure in text** *Slika u tekstu*
For each of the issues below to what extent might the techniques and technologies listed in the previous question support your location? *Koliko bi vam za svaki od navedenih problema koristile tehnike i tehnologije navedene u prethodnom pitanju?*	No support 1-5 Strong Support *bez potpore 1-5 snažna potpora*	Providing mass customization; Increasing flexibility *pružanje masovne prilagodbe; povećanje fleksibilnosti*	2
To what extent do each of the following inhibit implementation of the new manufacturing technologies at your location? / *U kojoj mjeri sljedeći navedeni uvjeti sprečavaju implementaciju novih proizvodnih tehnologija u vašem pogonu?*	1 Not at all 5 To a great extend *1 nimalo* *5 u velikoj mjeri*	Lack of skilled workers; No roadmap for implementation / *nedostatak kvalificiranih radnika; nepostojanje plana provedbe*	3
Please indicate the level of expertise at your location in each of the following fields. *Navedite razinu stručnosti u vašem pogonu u svakome od sljedećih polja.*	1 Low level of expertise 5 High level of expertise *1 niska razina stručnosti* *5 visoka razina stručnosti*	Data virtualization; Data analysis *virtualizacija podataka; analiza podataka*	4
Does your location provide employee training in any of the following fields? *Osiguravate li osposobljavanje zaposlenika u bilo kojem od sljedećih područja?*	Yes, No, Intent to in future *da, ne, plan za budućnost*	Robotics; Automation *robotika; automatizacija*	
Does your location process and analyze collected machine data to show the performance of production (key performance indicators)? *Analizirate li prikupljene podatke o stroju kako biste pratili svojstva proizvodnje (ključne pokazatelje proizvodnje)?*	Yes, No *da, ne*	Yes, for management Yes, for real time production, Yes but not real time, no *da, za upravljanje; da, za proizvodnju u stvarnom vremenu; da, ali ne u stvarnom vremenu, ne*	
Does your location use any form of virtual or augmented reality? / *Koristite li se bilo kojim oblikom virtualne ili proširene stvarnosti?*	Yes, No *da, ne*		
For what purpose does your location utilize cloud services. *Za koju se svrhu koristite uslugama u oblaku?*	Select all that apply *Odaberite sve što je primjenjivo.*	To increase mobility *povećati mobilnost*	5
What IT-systems does your location currently utilize? *Kojim se IT sustavima trenutačno koristite?*	Select one or more *Odaberite jedan ili više*	Computer aided manufacturing / *računalno potpomognuta proizvodnja*	6
What types of robotics are integrated in your production? *Koje su vrste robotike integrirane u vašu proizvodnju?*	Select one or more *Odaberite jednu ili više.*	Substituting robots *zamjenski roboti*	7
Does your location use any of the following operations based on analysis of process data? *Koristite li se nekom od sljedećih operacija utemeljenih na analizi procesnih podataka?*	Select one or more *Odaberite jednu ili više.*	Predictive maintenance *prediktivno održavanje*	8
Does your location use remote servicing/maintenance? *Koristite li se servisiranjem/održavanjem na daljinu?*	Yes, No *da, ne*		
How does your location identify/track materials/products? *Kako identificirate/pratite materijale/proizvode?*	Select one or more *Odaberite jedan ili više.*	ID barcode; RFID	9
Does your location apply the pay per use model (Leasing of machines/products)? *Primjenjujete li model plaćanja po korištenju (leasing strojeva/proizvoda)?*	Select one *Odaberite jedno.*	Yes we use it, No *da, primjenjujemo; ne*	
Does your location plan to invest in new manufacturing technologies/techniques in the next three years? *Planirate li u sljedeće tri godine investirati u nove proizvodne tehnologije/tehnike?*	Select One *Odaberite jedno.*	Yes we plan to, No *da, planiramo; ne*	
What technologies would your location like to integrate into operations but are too expensive? / *Koje biste tehnologije željeli integrirati u rad, ali su preskupe?*	Open Ended *otvorenog trajanja*		
Does your location have a smart manufacturing or industry 4.0 strategy? / *Imate li strategiju pametne proizvodnje ili Industrije 4.0?*	Yes, No *da, ne*		

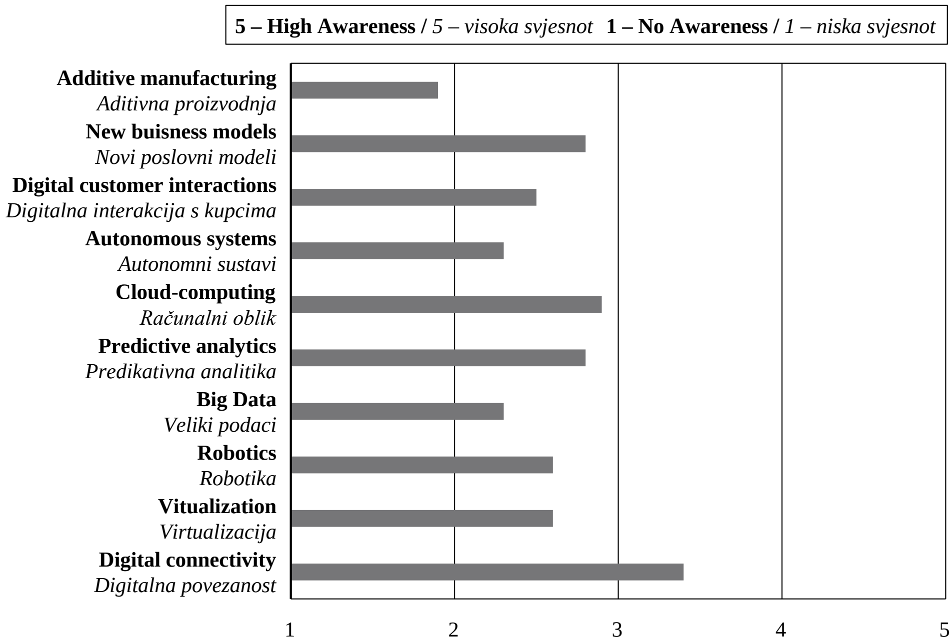

Figure 1 Level of awareness among respondents regarding various technologies (n = 89)
Slika 1. Razina svjesnosti ispitanika o različitim tehnologijama (n = 89)

products (3), non-structural panels (3), Particle board and MDF (6), "other" (2). With respect to size (based on mill site rather than entire company), the responding operations were: 1-5 employees (2), 6-10 employees (1), 11-50 employees (16), 51-100 employees (22), 101-500 employees (47), >500 employees (3). Therefore, 53 % of responding mills had more than 100 employees at their site, while the remaining 47 % had less than 100 employees.

The terms "smart manufacturing" or "Industry 4.0" were deliberately not used until the last question in the questionnaire, given the expectation that respondents would not be familiar with these terms. Further, the concern was that lack of familiarity might discourage participants from completing the questionnaire. As expected, nearly 80 % of respondents were unfamiliar with these terms, 89 % of mills with 1-99 employees were unaware of the terms, while 75 % of mills with over 100 employees were unaware of the terms and only six mills (each with more than 50 employees) stated that they had a smart manufacturing or I4.0 strategy. This level of awareness and implementation should be kept in mind when considering the results that follow.

Overall, awareness of technologies by respondents was quite low (Figure 1). As shown, there is a very low awareness regarding Additive Manufacturing (3D printing), Big Data, and Autonomous Systems. The highest level of awareness of technology is associated with Digital Connectivity, which can involve wireless

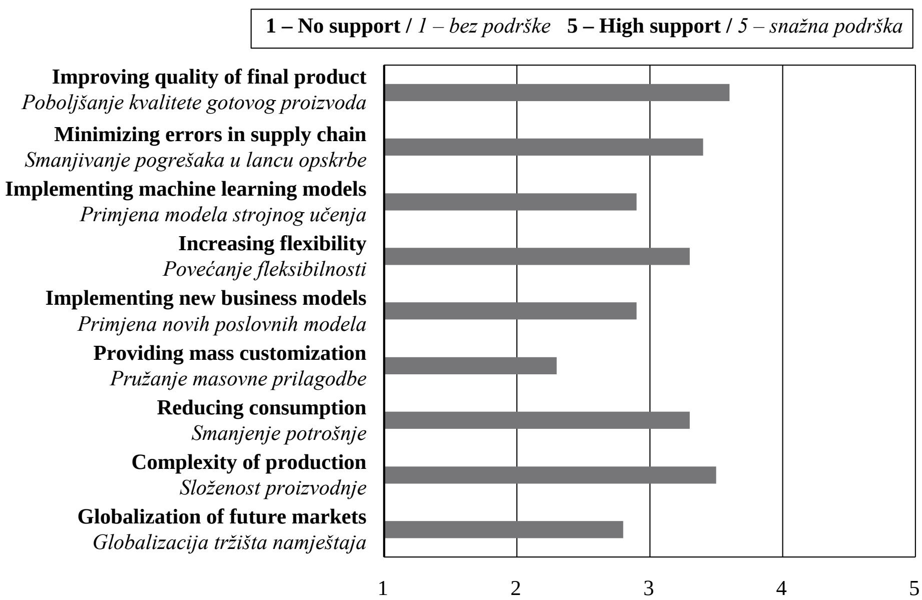

Figure 2 Perceived level of support provided by technologies listed in Figure 1 (n = 87)
Slika 2. Percipirana razina potpore koju omogućuju tehnologije navedene na slici 1. (n = 87)

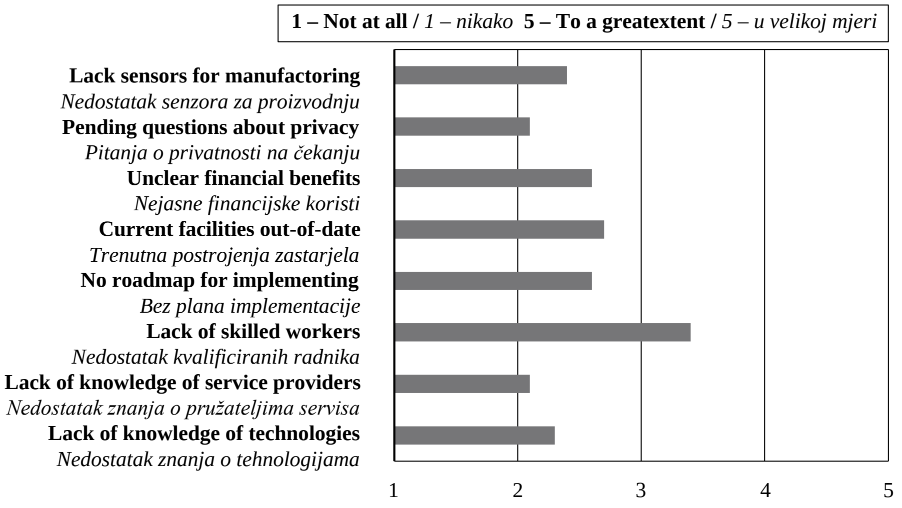

Figure 3 Factors perceived by respondent to inhibit implementation of new technology (n = 90)
Slika 3. Čimbenici za koje ispitanik smatra da sprečavaju primjenu nove tehnologije (n = 90)

networks and machine-to-machine connectivity (Castellina, 2018). Stronger awareness was also seen in cloud computing, new business models, and predictive analysis.

Based on the list of technologies shown in Figure 1, respondents provided their perception of how each might support their operation. Respondents did not perceive the technologies to provide a high level of support for their operations (Figure 2). Respondents were especially skeptical of the technologies helping with mass customization and dealing with globalization of future markets. They did expect some support for dealing with complexity of production and improving quality of final product.

Lack of a skilled workforce was seen as the biggest issue inhibiting implementation of new technologies (Figure 3). Other factors include current facilities being out-of-date, as well as no roadmaps for implementation being available. The lack of knowledge of the services provided by new technologies was something respondents saw as a minor inhibitor to implementation.

More specifically, respondents indicated that the level of expertise within their staff on a variety of technologies was quite low (Figure 4). The highest level of expertise was in Manufacturing Process Monitoring and Data Analysis. The lowest level of expertise was in Robotics and Data Visualization. Although the level of awareness of robotics is high relative to other technologies, the ability of mills to implement robotics is low due to the low level of expertise.

Despite the low level of expertise, there appeared to be little appetite for training; less than half of respondents currently provide training on topics such as automation, data analysis and IT safety. Seven respondents reported intending to provide training in ro-

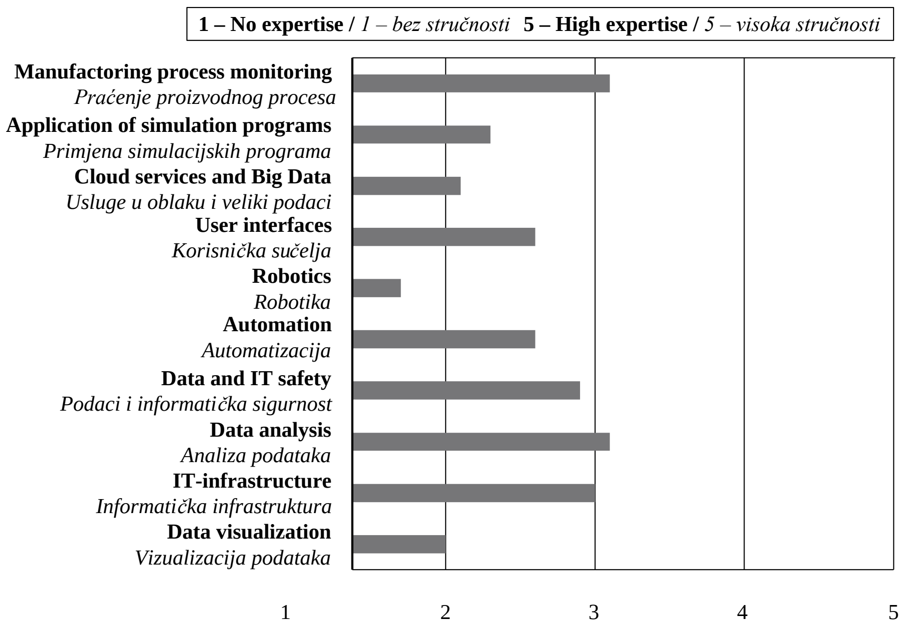

Figure 4 Level of expertise within respondent operations with respect to various technologies (n = 87)
Slika 4. Razina stručnosti operacija u ispitanika s obzirom na različite tehnologije (n = 87)

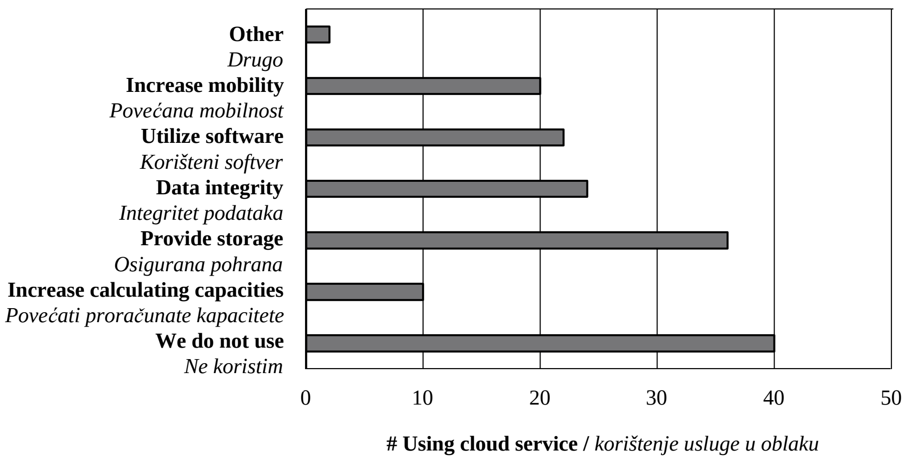

Figure 5 Use and application of cloud services by responding mills (n = 90)
Slika 5. Korištenje i primjena usluga u oblaku kod ispitanika u pilanama (n = 90)

botics in the future. Seven respondents reported the use of virtual reality in their operations. However, most of the examples provided by respondents do not qualify as virtual reality (e.g., display of processing position of logs), providing further evidence of lack of familiarity with many of the techniques and technologies associated with I4.0.

The majority (40) of respondents stated they did not use cloud services for their operations (Figure 5). The greatest use of cloud services was providing storage with systems such as Google Drive and Dropbox. Very few mills (10) use cloud services to increase the computational capacities within mills.

Just over one-quarter of respondents use an enterprise resource planning platform in their operation (Figure 6). The highest use of IT-Systems is Computer Aided Design (CAD) with 48 % of respondents reporting the use of CAD. This result was another red flag to the authors regarding awareness/knowledge since CAD use in the primary wood products industry is typically limited to a few engineers needing to test new design concepts for mill layout or machinery. Twenty seven (30 %) respondents do not use any IT-systems in their operations.

Respondent operations are generally not employing robotics in their operations. Just over half claim that robotics would be useful in their operations (Figure 7). Another quarter of respondents claimed that they had no need of robotics. Of those employing robots, substituting robots was most common, followed by cooperative robots and automated guided vehicles (AGVs). As shown in Figure 4, expertise around robotics is very low, which contributes to the lack of use of robotics within production.

Our respondents actively analyze process data for the purposes of predictive maintenance, performance analysis, and decision-making, but are less commonly doing so for predictive quality manage-

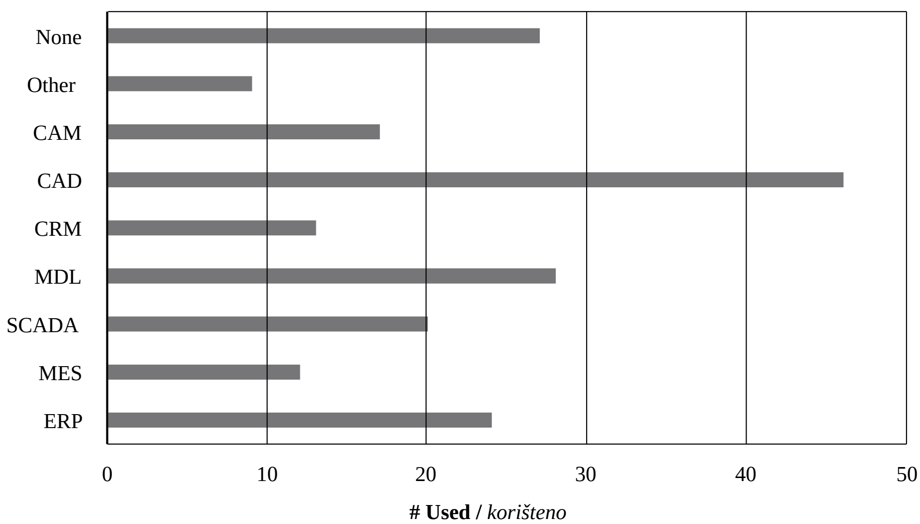

Figure 6 IT-Systems used by responding mills (n = 92) (CAM – Computer Aided Manufacturing; CAD – Computer Aided Design; CRM – Customer Relationship Management; MDL – Machine Data Logging Systems, SCADA – Supervisory Control and Data Acquisition; MES – Manufacturing Execution System; ERP – Enterprise Resource Planning
Slika 6. IT sustavi kojima se koriste ispitanici u pilanama (n = 92) (CAM – računalom podržana proizvodnja; CAD – dizajn podržan računalom; CRM – upravljanje odnosima s kupcima; MDL – strojni sustavi za evidentiranje podataka, SCADA – nadzorna kontrola i prikupljanje podataka; MES – sustav izvršenja proizvodnje; ERP – planiranje resursa za poduzeća)

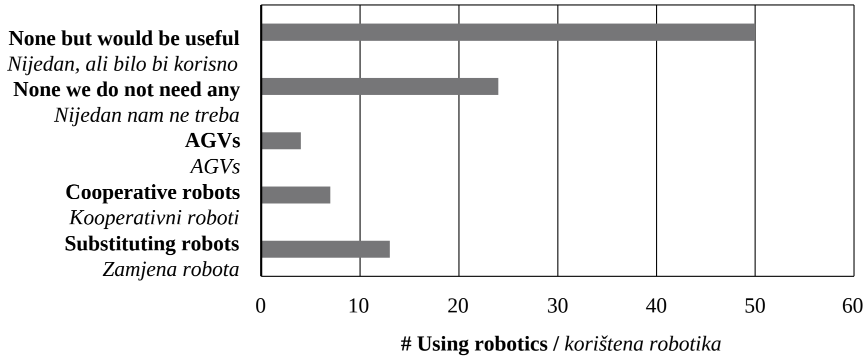

Figure 7 Types of robotics employed in respondent operations (*n* = 92) (AGVs – Automated Guided Vehicles)
Slika 7. Vrsta robotike kojima se ispitanici koriste u operacijama (*n* = 92) (AGVs – automatizirano vođena vozila)

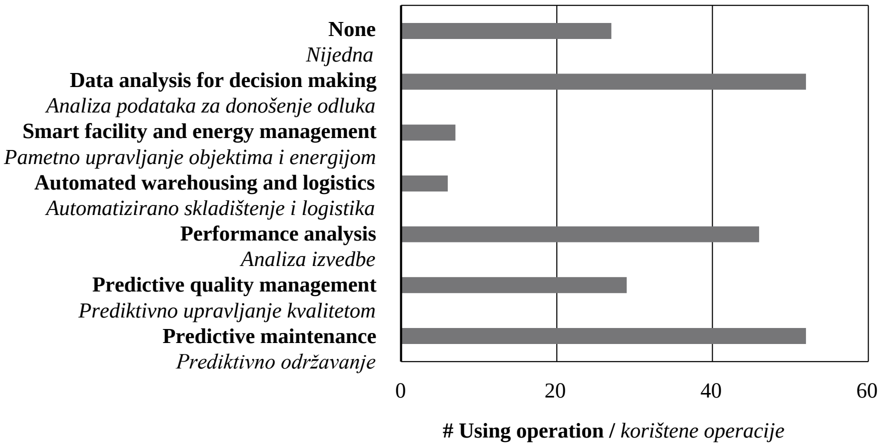

Figure 8 Activities supported by analysis of process data within respondent operations (*n* = 92)
Slika 8. Aktivnosti podržane analizom procesnih podataka u operacijama ispitanika (*n* = 92)

ment, automated warehousing and logistics, and smart facility and energy management (Figure 8).

Nearly half of respondents use remote servicing/maintenance with an additional 15 that would use it if it were possible for them. Bar coding (1D – traditional linear type and 2D –QR Code-type) was by far the most common method of tracking materials/products in respondent operations (57 mills; 61 %). Other technologies such as RFID, photo ID, wood "fingerprint" detection and UV tags were, collectively, used by approximately 20 % of respondents. Over 10 % of respondents still use manual, paper-based methods of tracking (Figure 9).

Just under one-quarter (22; 25 %) of respondents reported using a pay-per-use model for accessing technologies. They are generally open to and looking to

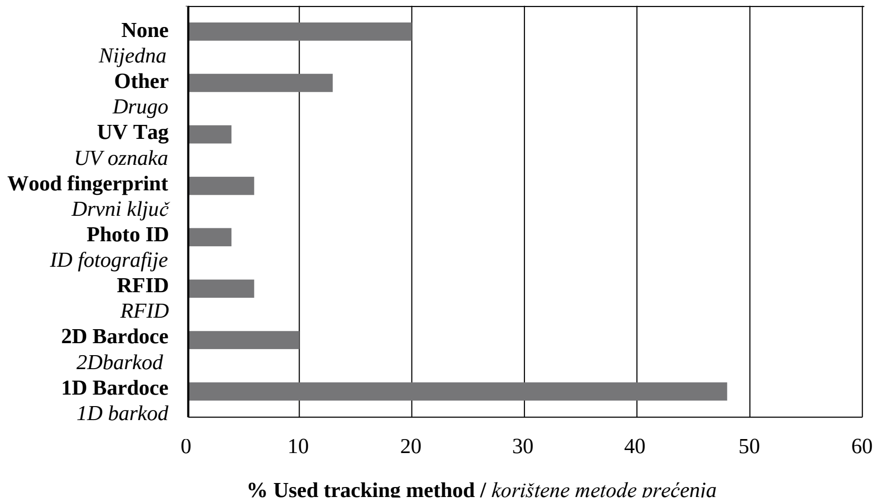

Figure 9 Methods used by respondents to identify and track materials (*n* = 88)
Slika 9. Metode koje ispitanici primjenjuju za identificiranje i praćenje materijala (*n* = 88)

invest in new technologies within the next three years. Seventy-one (80 %) respondents stated that they planned to invest in new technologies within the next three years, while only 19 (21 %) indicated no intention of investing in technologies.

One barrier to technology integration is cost. Respondents were asked to list technologies they would like to integrate into their operations but could not due to high costs. Of the 32 (36%) respondents to this question, 11 (12.5 %) listed robotics and five (5.5 %) listed the use of automation in current technologies, such as lumber grading.

The connection between mill size and level and use of technologies is very prominent in the results. Dividing the mills into two size groups 1-100 (39) and 101-500 (53), t-tests ($p<0.05$) showed that larger mills are more likely to have an overall higher awareness of techniques and technologies. The same pattern is true regarding levels of expertise. We suggest that larger mills have the resources to educate employees, resulting in a higher level of expertise.

4 CONCLUSIONS
4. ZAKLJUČAK

The results of the study show that adoption of I4.0 technologies within the primary wood products sector in the US is far behind what is possible. It is important to keep in mind that our non-response bias testing suggests our respondents are more technically oriented than non-respondents. Therefore, our statement above could likely be even stronger. Key hurdles to adoption of new technologies are a lack of skilled workforce and unclear financial benefits from an investment. As automation and digitization become requirements to stay competitive, the industry needs to accelerate its transition to I4.0. Therefore, awareness must be increased, or the industry in the US is in danger of losing competitiveness.

As suggested by Ratnasingam *et al.* (2019), research and policy work should take a careful look at the potential for moving the industry from current state of operations, which are largely within Industry 3.0, more fully to I4.0. Therefore, based on the results of this survey, an essential first step for the US primary forest products industry is to increase expertise through employee training. Companies stagnate if they do not have the required expertise within their workforce to adopt new technologies and there are few experts who are qualified and responsible to advocate and assist with adoption of advanced technologies. With a shortage of skilled labor in the market, it is not easy to hire new specialists, especially in the wood processing industry. Hiring from the outside may not be the best approach for businesses as it is more sustainable to upgrade the education of existing employees. Offering training to employees who already know the company ensures the best use of already existing technology and its application possibilities. Inclusion of existing employees may also serve to still the fear of what implementation of new techniques and technologies may bring, i.e., that automation, for example, is primarily about workforce reductions. Trainings should be offered through the entire transition and affected employees should be involved in process implementation because this is essential to build up commitment to new technologies. The most important factor for a successful digital change is that the employees understand the technologies they are going to work with. This is the only way companies will be able to maintain the new systems themselves. In the absence of employees that understand the technologies, companies are likely to forego plans to adopt new technology for fear they will not be successful in operation and maintenance.

The inhibiting factor of unclear (financial) benefits from an investment in new technology can also be eliminated by appropriate training for responsible experts and management. Measures to raise awareness should focus on various present and upcoming technologies and the company as a networked system. Results here showed that the majority of participants are convinced that new technologies would improve their production; however, they do not yet know critical details such as the technologies' effects on the production process and financial benefits. Hence, it is important to provide a personalized, systems-level overview about the technology and to illustrate different implementation scenarios within their range of possibilities and for their individual situation. In this way, companies will realize the use and necessity of some of the technologies for their production as well as the potential for increased profit. If adapted effectively for the individual business, implementation may have a short payback time that compensates for the cost of downtime during the switch to the new system. To tap the full potential of already implemented technology and to reveal financial benefits of possible investments, it is essential to identify the current state-of-the-art of the company as the basis for future operations.

Even before investing in employee training, companies might consider an online self-assessment of readiness for Industry 4.0 like that offered by FESTO, PwC or TÜV SÜD. FESTO's quick check for companies, for example, asks for general information about the company and lets the user choose relevant I4.0 targets for their company. The identification of the maturity level is based on questions in five different assessment categories. Additionally, the analysis includes corresponding recommendations for action (FESTO 2020). Based on such a current-state analysis, a next step for every company aspiring to I4.0 should be to develop a roadmap for a future technology strategy. It is important to take action as quickly as possible given the ever-increasing pace of technology adoption and development by competitors.

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Chemical and Structural Characterization of Poplar and Black Pine Wood Exposed to Short Thermal Modification

Kemijska i strukturna obilježja drva topole i crnog bora izloženih kratkotrajnoj toplinskoj modifikaciji

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ABSTRACT • *In this study, poplar and black pine wood was exposed to short thermal treatments, aiming to improve some crucial properties. Using wet chemical analyses and Fourier-transform infrared spectroscopy (FT-IR), the influence of these treatments on the chemical composition of the modified species was investigated, as well as on the wood structure, using scanning electron microscopy. With the increase of heat treatment intensity, a mass loss of both species was recorded, attributed to the moisture loss and degradation of volatile compounds, as well as thermally less stable components. In the first treatment stages, the extractives presented a decrease, whereas with the duration and temperature increase, new extractives were formed. Lignin increased its network through ramification, especially at 200 ºC, while holocellulose was found lower in all modified wood categories of both species than in unmodified wood due to the intense decomposition of hemicelluloses. The findings of FT-IR analyses were in line with the chemical analysis results. The thermal modification process made wood materials more hydrophobic and dimensionally stable, providing protection against decomposing factors. At the same time, they were not intensively thermo-degraded, which increased their utilization perspectives and application range as solid wood of enhanced properties, or as wood particles/fibers participating as raw materials in wood-based composite products, wood-polymers composites etc., enhancing their materials compatibility, properties and performance.*

Keywords: *cellulose; chemical composition; FTIR; lignin; thermal treatment; wood*

SAŽETAK • *U radu se opisuje istraživanje izlaganja drva topole i crnog bora kratkotrajnim toplinskim tretmanima radi poboljšanja nekih njihovih ključnih svojstava. Utjecaj tih postupaka na kemijski sastav modificiranih vrsta drva istražen je primjenom mokre kemijske analize i Fourierove transformirane infracrvene spektroskopije (FT-IR), a utjecaj na strukturu drva određen je uz pomoć pretražnoga elektronskog mikroskopa. Povećanjem intenziteta toplinskog tretmana zabilježen je gubitak mase obiju vrsta drva koji je pripisan gubitku vode te razgradnji hlapljivih i toplinski nestabilnih spojeva. U prvim fazama tretmana smanjio se udio ekstraktiva, dok su se s produljenjem tretmana i povećanjem temperature stvarali novi ekstraktivi. Lignin je povećao svoju umreženost razgranjivanjem, posebno na 200 °C, dok je udio holoceluloze bio manji u modificiranome nego u nemodifici-*

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ranom drvu, i to zbog intenzivnog razlaganja hemiceluloze. Rezultati FT-IR analize u skladu su s rezultatima kemijske analize. Postupkom toplinske modifikacije drvo je postalo hidrofobnije, dimenzijski stabilnije i zaštićeno od čimbenika razgradnje, ali istodobno nije odviše toplinski razgrađeno, čime su se povećale mogućnosti njegove uporabe i proširila područja primjene kao masivnog drva poboljšanih svojstava ili kao sirovine za kompozitne materijale koja pridonosi njihovoj boljoj kompatibilnosti, svojstvima i performansama.

Ključne riječi: *celuloza; kemijski sastav; FT-IR; lignin; toplinski tretman; drvo*

1 INTRODUCTION
1. UVOD

When heating wood, during the heat modification process, in an attempt to improve some of its drawbacks, bound water is lost and some of the extracts evaporate (flammable volatiles), some decompose, some new ones are produced and some may be left intact (Wang *et al*., 2018; Esteves and Pereira, 2008). The first to be lost during treatment are the volatile extracts, such as volatile terpenes, fouraniokarvoxylaldehyde, acetic acid, 2-propane, hydrocarbons, fatty acids, steroids, lactones and other derivatives from the thermal degradation of the wood components (Kocaefe *et al*., 2008), while at the same time, anhydrous and phenolic components appear in the wood mass (Esteves and Pereira, 2008). Resin acids, fats and waxes tend to move to the surface of the wood as the temperature approaches 200 ºC and almost disappear with further increase. When the volatile extracts are removed, the pH of wood decreases (Gündüz and Aydemir, 2009).

The degree and order of degradation of cell wall components is a matter of many parameters, mainly depending on the species, heating temperature, chamber atmosphere, moisture content, etc. Upon thermal modification, a series of chemical reactions takes place simultaneously, combining endothermic and exothermic reactions, making the determination of the starting temperatures for the different reactions almost impossible. Reaction analysis becomes furthermore complicated by the interactions between the different components and between the components and the chamber atmosphere (Hill, 2006; Johansson, 2008).

Thermal modification in the early stages may alter the amount of volatile extracts. In hardwoods, mainly aldehydes (pentanal, hexanal, furfural), carboxylic acids (acetic acid), esters, ketones, aliphatic and aromatic hydrocarbons are recorded, while in softwood species mainly mono-, mix, diterpenes (Peters *et al*., 2008). The change in the extracts, in terms of acidity, reactivity and hydrophobicity, also affects the behavior of wood in welding, dyeing and other processes (Diouf *et al*., 2011). Extracts that are usually of low pH also affect the pH of wood, which usually demonstrates a further decrease during treatment due to the production of various organic acids such as low molecular weight acetic, formic, galacturonic acid derived from hydrolysis and depolymerization carried out on wood (Yao *et al*., 2010). The acids produced during treatment promote further the decomposition of wood components and are responsible for the loss of mass and the decrease in mechanical strength of wood (Wang *et al*., 2018), and especially if they are volatile, it is difficult to evaluate them quantitatively and qualitatively (Gündüz and Aydemir, 2009; Hill, 2006; Peters *et al*., 2008). Recently, Ozcifci *et al*. (2018) focused on the investigation of the effects of catalysts (NaOH, KOH solutions) on the strength loss, mass loss and chemical structure of heat–treated wood, revealing that potassium hydroxide (KOH) can decrease the degree of strength loss and mass loss of heat-treated wood by reducing the release of acid that leads to thermo-degradation during heat treatment.

During thermal modification, the degree of cellulose polymerization is significantly reduced by increasing the temperature, causing an accelerated degradation. Amorphous or less crystalline cellulose is gradually degraded (Wang *et al*., 2018). The first derivative of the cellulose decomposition during thermal treatment is levoglucosan and also anhydroglucose, furan, furan derivatives, etc., and they have low hygroscopicity (Yildiz *et al*., 2006; Rowell *et al*., 2009; Ates *et al*., 2010; Tumen *et al*., 2010; Kamperidou, 2019). Hemicelluloses consist of the most unstable polymeric wood components and produce furfuryl polymers, which are less hygroscopic, as well as methanol, acetic acid and aldehydes and various other volatile heterocyclic components (furans, γ-valerolactone, etc.) and low molecular weight extractable compounds (Diouf *et al*., 2011), which tend to act as catalysts of the polysaccharide depolymerization (Tjeerdsma and Militz, 2005; Kamperidou and Barboutis, 2018). As the treatment intensity increases, carbonyl groups are produced due to the esterification occurring in wood when the acids react with hydroxyls (Tjeerdsma and Militz, 2005; Esteves and Pereira, 2008; Rowell *et al*., 2009). As hemicelluloses degrade, the wood becomes brittle and rigid (Kamperidou and Barboutis, 2017). The hemicelluloses of softwoods (hexoses) are less unstable than those of hardwoods (pentoses), because of the different composition (Esteves *et al*., 2007; Ahajji *et al*., 2009). Also, the hardwoods have a higher proportion of hemicelluloses (xylose) than softwoods (mannose and galactose), and hardwood hemicelluloses carry higher percentages of acetylenes than softwoods (Wikberg and Maunu, 2004; Hill, 2006; Ates *et al*., 2010). The decomposition is more pronounced in the early stages of thermal treatment (Mburu *et al*., 2007).

Lignin proves to be the most stable component of wood and as the intensity of treatment increases, lignin increases in the mass of wood, trapping some by-products of hemicelluloses decomposition and, as it becomes stronger, its phenolic groups increase as well (Tjeerdsma and Militz, 2005; Gonzalez-Pena *et al*., 2009; Diouf *et al*., 2011). Temperatures below 160 ºC do not cause any changes to lignin, whereas at 170 ºC - 190 ºC the glass transition temperature point appears, where the wood becomes plasticized and easier to be processed. Lignin plasticizing, as well as internal friction, makes the wood break into smaller loads than the unmodified one (especially impact bending strength) (Kol, 2010). The breakdown of lignin macromolecule starts at temperatures above 270 ºC, where the gradual cleavage of C-C bonds of lignin begins (Mazela *et al*., 2004). At temperatures below 190 ºC, there may be a slight degradation of lignin, generating different phenolic degradation derivatives. At about 220 ºC, lignin begins to degrade, with the presence of phenolic compounds (vanillin, coniferaldehyde, syringyl aldehyde), where v-aryl ether linkages begin to degrade (Yildiz and Gumuskaya, 2007). Thermal modification results in changes in aromatic structures and cleaves aryl-ether bonds between lignin-phenylpropane units (Wikberg and Maunu, 2004). As the intensity of the modification increases, both the secondary bonds (H and Van der Waals) and natural bonds in the hemicellulose polymer between hemicellulose-cellulose, and covalent bonds between hemicellulose-lignin and new cross-links appear between lignin molecules and other components, and they do not allow water to penetrate easily in wood, as the H bonds (Tumen *et al*., 2010; Diouf *et al*. 2011). Softwoods lignin seems to be more stable to thermal degradation than lignin of hardwoods. Recently, Gonultas and Candan (2018) determined the influences of the press temperature and the press pressure parameters on the chemical components of the eucalyptus wood. They concluded that the holocellulose and extractives were more affected by heat, with hot water, 1% NaOH and EtOH-cyclohexane. According to them, methanol-water solubility of thermally treated wood increased, because of the new substances mainly produced from degradation of the hemicellulose and lignin, while the Klason lignin recorded a significant increase at 180 ºC treatments and a decrease of holocellulose, with a small decrease of α-cellulose.

Although, many studies have been carried out dealing with the resulting changes in wood during heat modification, their findings often seem to be contradictory, since the application of treatments under various different conditions, on different wood species and applying different characterization methods, do not provide a clear picture of the changes that occur in the wood mass during the application of high temperatures, while a lack of information in literature has been identified as regards the short duration thermal treatments.

Therefore, in the current work, low cost and energy consumption thermal treatments are selected to be applied (examining two temperature levels and 3 treatment durations, shorter than that typically applied in industrial heat treatments) to the widely available and commercially significant wood species of poplar and black pine, especially for Greece and the whole Europe, whose properties are in imperative need of enhancement and protection especially prior to their exposure to environments of high humidity. The changes in chemical composition between the modified and unmodified wood materials are investigated using a combination of the conventional method of wet chemical analyses and Fourier-transform infrared spectroscopy (FT-IR analyses) method, while an attempt to record changes in the structure of the modified species is implemented using stereoscope and scanning electron microscopy (SEM), in order to elucidate the response of the specific wood species mass to thermal treatments, aiming to improve the utilization potential of these wood species in a wider range of applications.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Specimens preparation
2.1. Priprema uzoraka

Boards of poplar (*Populus* sp.) and black pine (*Pinus nigra* L.) species of Greek origin (poplar wood was obtained from the Drama region in North Greece and black pine from the Kalampaka region in the central part of Greece) were placed in a conditioned room at a temperature of (20 ± 2) ºC and (60 ±) 5% relative humidity for about 8 months and left there to attain the equilibrium moisture content (EMC) of 10.50 % for poplar and 11.44 % for pine wood (ISO 13061-1). The mean density (mass/volume, measured in the above mentioned moisture contents) of poplar was 0.385 g/cm^3 and of pine 0.662 g/cm^3 (ISO 13061-2). The dimensions of the boards of both species prior to the treatments were 35 mm × 70 mm × 400 mm (with the last to be parallel to grain); they consisted mainly of the part of sapwood, and the sampling method was based on the methodology of ISO 3129.

2.2 Thermal treatments
2.2. Toplinski tretmani

The treatment of the boards was carried out in a laboratory drying chamber (800 mm × 500 mm × 600 mm) at 180 ºC and 200 ºC under atmospheric pressure in the presence of air. The moisture content of the boards was 10.5 % and 11.44 % for poplar and black pine, respectively, when placed in the chamber (10 boards/treatment, chamber preheated to the final temperature). The treatment durations were of 3, 5 and 7 hours, counting 15 minutes more for the chamber reheating after the insertion of the samples. In this study, thermal treatments of such short durations are examined for the first time on the studied wood species, according to the literature. They were chosen to keep cost and energy consumption of the treatments at a low level, in order to be easily applied by small industries, using the simple equipment of the drying chamber. Furthermore, the specific durations were selected as they differentiate from the existing literature of thermal treatment processes, thus providing new data.

After thermal treatment, the boards were placed in large desiccators over silica gel to return gradually to ambient conditions. Only defect-free material was selected for testing.

The mass loss (*ML*) of the specimens induced by the process of thermal treatment (thermo-degradation) was determined by the oven drying method (e.g. Wang *et al.*, 2018) according to the following Eq. 1:

$$ML = \left[\frac{(M_0 - M_1)}{M_1}\right] \cdot 100 \qquad (1)$$

Where:

ML – Mass loss, %

M_0 – Initial oven-dry mass of the specimen before thermal treatment, g

M_1 – Oven-dry mass of the same specimen after thermal treatment, g

Thermal treatment of poplar wood under the above mentioned conditions induced mass losses in the range of 11.24 % – 18.88 %, of which 10.50 % corresponds to moisture, generated by the drying and thermo-degradation process, whereas thermally-treated black pine wood recorded a little lower mass losses of 10.63 % – 15.25 %, of which the 11.44 % refers to moisture content loss. Additionally, the wood of black pine contains a significant amount of resin, and the mass loss could also be partly attributed to the evaporation of the resin during the thermal treatment, as well as other volatile compounds and unstable components (Kamperidou, 2019).

2.3 Infrared spectroscopy (FT-IR)
2.3. Infracrvena spektroskopija (FT-IR)

Wood powder samples were prepared from all categories of modified and unmodified poplar and black pine, using a rotating-blade "Willey" mill (Thomas Scientific, Swedesboro, USA). The samples were obtained through sieving twice to achieve the appropriate dimensions (fraction between grid apertures of 40-60 mesh).

For the preparation of the samples, KBr was mixed with wood powder in the ratio of 1/200 mg and each sample was ball milled for 20 sec to a very fine powder (Mikro Dismembrator, Sartotius). Then, it was placed in a standardized pellet press having a die suitable to form a pellet of 13 mm diameter, applying force of about 10 t through vacuum conditions (75 kN cm^{-2} for 3 min/sample). A non-finite ATI Mattson-type (Mattson ATI Genesis, Illinois, USA) spectrophotometer was used with spectra in the range of 500 cm^{-1} - 4000 cm^{-1} and 64 scans.

2.4 Chemical analyses
2.4. Kemijska analiza

Wood powder used in the chemical analyses was produced using the above mentioned "Willey" mill equipped with a 40 mesh sieve. The wood powder was sieved keeping the fraction (0.18 mm - 0.25 mm). Soxhlet type extractors were used to carry out the extractions. The distilled water used was produced with a GFL 2001/2 distillation apparatus (GFL, Burgwedel, Germany).

Determination of solubility in a mixture of ethanol-toluene was performed on the basis of ASTM D1107-96 using a Soxhlet apparatus. The determination of the total amount of the extracts, soluble in ethanol-toluene mixture, was implemented indirectly through the production of extract-free wood, according to ASTM D1105-96. A least five wood powder samples were used for each type of material and the mean values were calculated.

Holocellulose (cellulose and hemicelluloses) content was quantified by removing lignin from wood powder, which was already free of extracts. Dry wood (atro), free of extracts, with dimensions between 180 and 250 μm was used. 10 ml of the chlorine solution of $NaClO_2$ (25 %) was applied to 1 g atro wood powder in a water bath set at 70 ºC for 5 hours, making lignin oxidized and cleaved into soluble derivatives, which were removed by extraction, whereby the holocellulose remained as a residue. At the end of this process, the sample was rinsed with cold water until Cl_2 was completely removed and placed in a drying chamber. The dry sample was placed in a desiccator and then weighed, and the holocellulose (atro) was quantified as a percentage value of the initial mass of the extracts-free powder sample. For each holocellulose sample obtained after rinsing, the process was repeated till constant mass was achieved. A least two replicates were used for each type of material and the mean values were calculated.

The quantitative determination of lignin was based on the hydrolytic cleavage of polysaccharides with inorganic acids (H_2SO_4 in concentration of 72 %), which resulted in the depolymerization and removal of their soluble derivatives, while lignin remained insoluble. The residue is called Klason lignin and is determined as a percentage of the absolute dry mass of the wood used, according to ASTM D1106-96, in dry and free of extracts wood (extraction with 95 % ethyl alcohol, extraction with alcohol-toluene mixture 1: 2 v/v and extraction with hot water at 100 ºC). At least two replicates were used for each type of material and the mean values were calculated.

2.5 Microscopic observation of cell structure
2.5. Mikroskopsko promatranje stanične strukture

The wood anatomy was examined using a SEM, Scanning Electron Microscope S-3400N (Hitachi, Japan), as well as an electronic stereomicroscope, Nikon SMZ800 (Nikon Instruments Inc., Japan), in which X16 analysis was selected.

2.6 Statistical analysis
2.6. Statistička analiza

SPSS Statistics PASW 18 statistical package was used for the statistical analysis and appliance of one-way analysis of variance (ANOVA) of the recorded values ($p \leq 0.05$) for the evaluation of the importance of differences between the experimental groups.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 FT-IR analysis
3.1. FT-IR analiza

As evidenced by the images of thermally modified and unmodified poplar and black pine wood powder obtained by infrared IR spectroscopy, there are no

Table 1 Match of wood functional groups to IR bands of spectra (Bodirlau and Teaca, 2009; Esteves *et al*., 2013)
Tablica 1. Povezanost funkcionalnih skupina drva s vrpcama na IR spektru (Bodirlau and Teaca, 2009.; Esteves *et al*., 2013.)

Spectrum band position, cm^{-1} *Pozicija vrpce na spektru,* cm^{-1}	**Active wood mass group** *Aktivna grupa u drvu*	**Type of vibration** *Vrsta vibracije*
3450 - 3400	O-H of alcohols, phenols and acids	O-H stretching
2970 - 2850	CH_2, CH- and CH_3	C-H stretching
1750 - 1720	C=O of esters, ketones, aldehydes and acids	C=O stretching, non-conjugated
1700 - 1550	Conjugated C=O and C=C	Conjugated C=O stretching, C=C stretching
1640 - 1618	C=C alkene	C=C stretching
1600 - 1504	Aromatic ring C=C	Benzene ring stretching vibrations
1462 - 1425	CH_2 cellulose, lignin	C-H deformations
1420	Aromatic ring and CH	Benzene skeletal combined with C-H deformations
1384 - 1346	C-H cellulose, hemicellulose	
1330 - 1240	Lignin S and G units and OH	C-O stretching and bending OH antisymmetric stretching vibration of the acetyl ester groups
1140	G-Guaiacyl lignin and C-O	C-H deformations in G lignin and C-O stretching
1128	S-Syringyl lignin and C-O	C-H deformations in S lignin and C-O stretching
1035 - 1025	C-O-C	Deformation
897	Anti-symmetric out-of-phase stretching in pyranose ring	Stretching in pyranose ring

particular differences in anatomy, chemical bonds and the structure between the treated and untreated poplar (Figure 1, 2) and pine (Figure 4), nor between the two species. In the spectra of poplar and pine controls, the spectral line and peaks are quite common, revealing that the types of wood bonds are similar between species and that wood carries the same functional groups, which cause different kinds of vibrations when the light bundle falls onto the sample.

The evaluation of spectra, in order to draw conclusions, was conducted using identification tables of the different bands corresponding to different characteristics of wood groups (Table 1), such as for example hydroxyl groups, carbon chains, carbonyls, double bonds and absorbed water, aromatic rings, etc.

Although the table is quite analytical, the differences between spectra of modified and unmodified wood are difficult to be identified, and even more complicated to be evaluated, since in wood mass a large number of reactions occur at the same time. Frequently, the creation of solution and bonds take place simultaneously, and consequently the reactions cannot be distinguished due to the complexity of the characteristics of the wood during its thermal treatment. A typical example of this is the increase in carbonyls (C=O) of hemicelluloses in the spectrum band of 1700 cm^{-1} - 1730 cm^{-1}

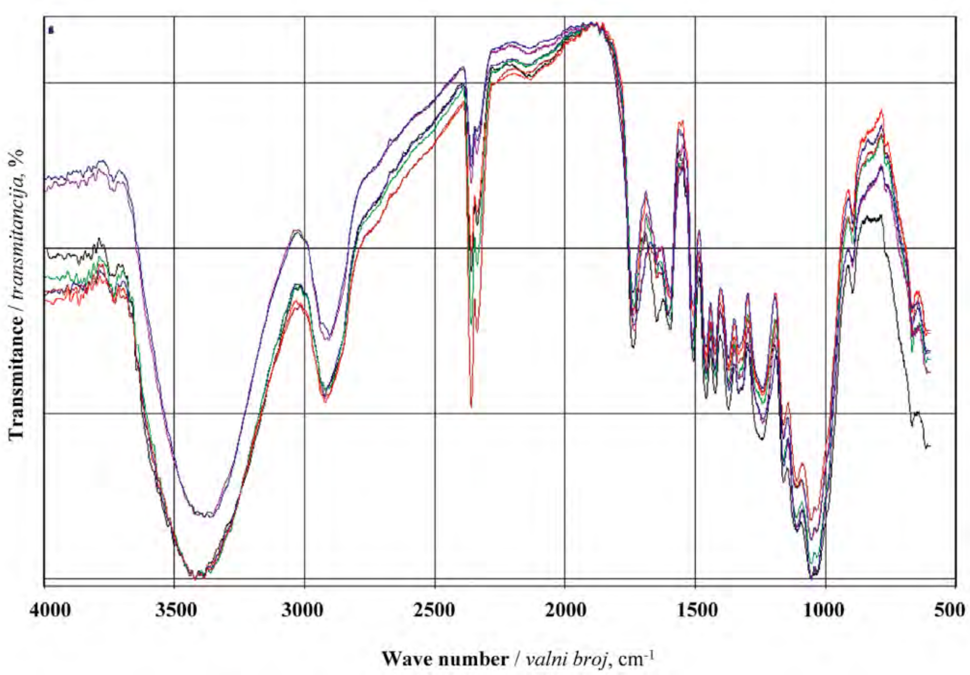

Figure 1 Overlapping IR spectra of a control (black line) and samples thermally modified with six different treatments (colored lines) of poplar over a range of 4000 cm^{-1} – 500 cm^{-1}
Slika 1. Preklapajući IR spektri kontrolnih uzoraka (crna linija) i toplinski modificiranih uzoraka tijekom šest različitih tretmana (obojene linije) drva topole u rasponu od 4000 cm^{-1} do 500 cm^{-1}

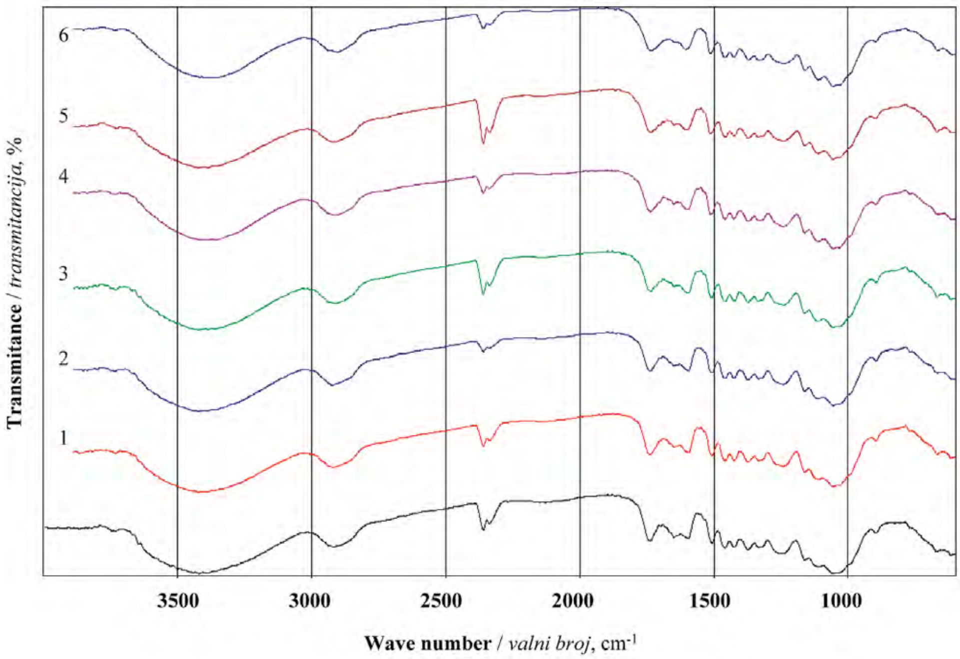

Figure 2 FT-IR spectral analysis of control specimens (black line) and samples heat-modified with six different treatments (1: 180 ºC – 3 h, 2: 180 ºC – 5 h, 3: 180 ºC – 7 h, 4: 200 ºC – 3 h, 5: 200 ºC – 5 h, 6: 200 ºC – 7 h) of poplar over a range of 4000-500 cm^{-1}

Slika 2. Spektralna FT-IR analiza kontrolnih uzoraka (crna linija) i toplinski modificiranih uzoraka tijekom šest različitih tretmana (1: 180 ºC – 3 h, 2: 180 ºC – 5 h, 3: 180 ºC – 7 h, 4: 200 ºC – 3 h, 5: 200 ºC – 5 h, 6: 200 ºC – 7 h) drva topole u rasponu od 4000 cm^{-1} do 500 cm^{-1}

and the simultaneous reduction of C=O of lignin, which applies to both species of wood examined. However, some differences have emerged from the evaluation of the spectra, which are discussed below.

Referring to poplar wood, in the range of 1462 cm^{-1} - 1425 cm^{-1} and 1384 cm^{-1} - 1346 cm^{-1}, where the basic structural components, such as cellulose, hemicelluloses and lignin are depicted, there is a small difference between unmodified and modified samples, which supports the view that thermal treatment affects the levels of wood components even in the mildest treatments. Therefore, all treatments caused small changes and shifts of the spectral lines in the areas of the wood components. More specifically, referring to

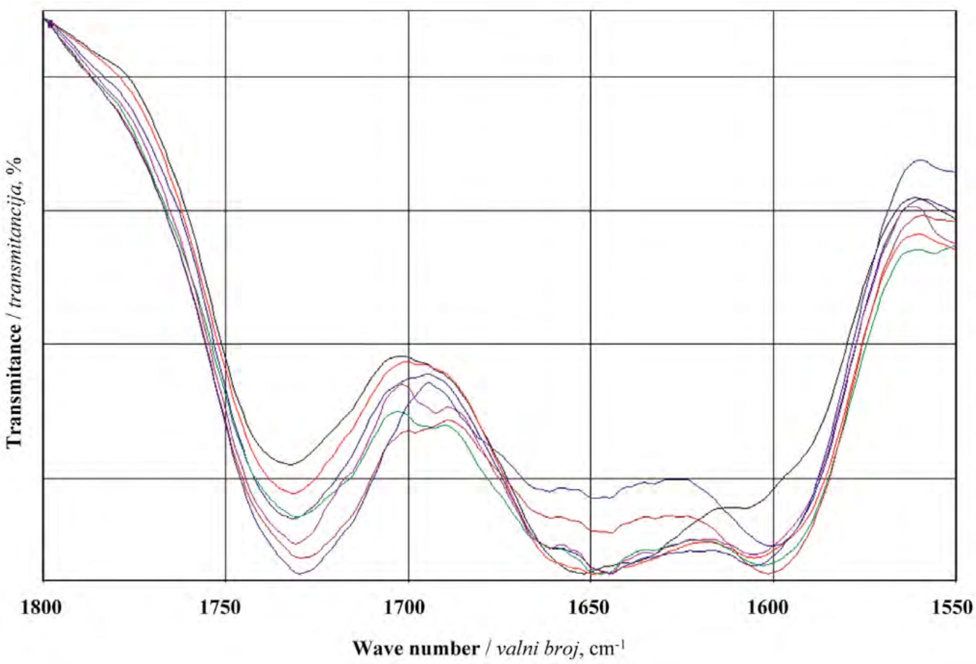

Figure 3 Overlapping IR spectra of control sample (black line) and heat-treated poplar samples with six different treatments (colored lines) over a range of 1800-1550 cm^{-1}

Slika 3. Preklapanje IR spektra kontrolnih uzoraka (crna linija) i toplinski modificiranih uzoraka tijekom šest različitih tretmana (obojene linije) drva topole u rasponu od 1800 cm^{-1} do 1550 cm^{-1}

poplar wood, the data show that there was no major change in the 3430 cm^{-1} band, which corresponds to O-H stretching vibrations of alcohols (3600 cm^{-1} - 3300 cm^{-1}) and carboxylic acids (3300 cm^{-1} - 2500 cm^{-1}) and concerns equally polysaccharides and lignin. This phenomenon was expected, since even though the O-H stretch vibrations due to the polysaccharides decrease, at the same time the O-H vibrations derived from the phenolic groups of the lignin are increased due to the increase in the percentage of lignin in the mass of wood (Esteves *et al*., 2011). The spectra are normalized at about 1900 cm^{-1}.

The two bands at 2900 cm^{-1} and 2800 cm^{-1} consist of the overlapping of the stretch asymmetric vibrations of the $-CH_2-$ (around the 2935 cm^{-1} - 2915 cm^{-1} band) and $-CH_3$ (around the 2970 cm^{-1} - 2950 cm^{-1} band), as well as of the overlapping of stretch symmetric vibrations of the $-CH_2-$ (about 2865 cm^{-1} - 2845 cm^{-1}) and $-CH_3$ (about 2880 cm^{-1}- 2860 cm^{-1}). In these bands, a slight shift is detected.

In poplar wood, the area around 1750 cm^{-1} is not so clear, probably due to the normalization. In respective studies, e.g. Esteves *et al*. (2013), wood of thermally modified eucalyptus and pine initially decreased in this band in mild treatments, while increasing the treatment duration this band increased, recording a shift to lower wavelengths. The same happened here in the case of poplar, which recorded an increase and shifting in the band of 1730 cm^{-1}. The increase and shifting for smaller wavenumbers with increasing treatment severity may be due to an increase of carbonyl or carboxyl groups in lignin or carbohydrates by oxidation. This increase was also observed by Kotilainen *et al*. (2000) with *Pinus sylvestris* and *Picea abies* (160 °C - 260 ºC, 2 - 8 h) and González-Peña *et al*. (2009) (180 ºC - 245 ºC) who attributed this increase to lignin condensation reactions at the expense of C=C double bonds in conjugated carbonyl groups in lignin, vibrating at 1654 cm^{-1}. The spectra of this research seem to corroborate this assumption since there was a clear decrease at 1654 cm^{-1} for both poplar and pine, while there was also some shifting to lower bands.

The band at 1595 cm^{-1} corresponds to vibrations in the aromatic ring of lignin in addition to C=O stretching. The band at 1595 cm^{-1} showed a clear increase. According to Kotilainen *et al*. (2000), this band increases due to the increase in the lignin percentage and network through ramification in treated wood. The aromatic rings usually exhibit a characteristic band at approximately 1500 cm^{-1}, corresponding to benzene ring stretching vibrations. This band is of high importance, since it is located at about 1505 cm^{-1} for hardwood lignin (Guaiacyl - G and Syringyl - S) and about at 1510 cm^{-1} for softwood lignin (guaiacyl - G) (Faix *et al*., 1990). In poplar, the band at 1505 cm-1 was decreased, shifting the spectrum line approximately at 1512 cm^{-1}. This may be attributed to the reduction of the lignin methoxyl groups, which would refer more to a softwood lignin (G-lignin) or to the loss of Syringyl units (S-lignin), since this monomer is generally less condensed with C-C bonds than guaiacyl monomer lignin and is more prone to be released from the thermal degradation (Faix *et al*., 1990). The shift of this band is in agreement with the results of previous studies (Esteves and Pereira, 2008; Windeisen *et al*., 2007)

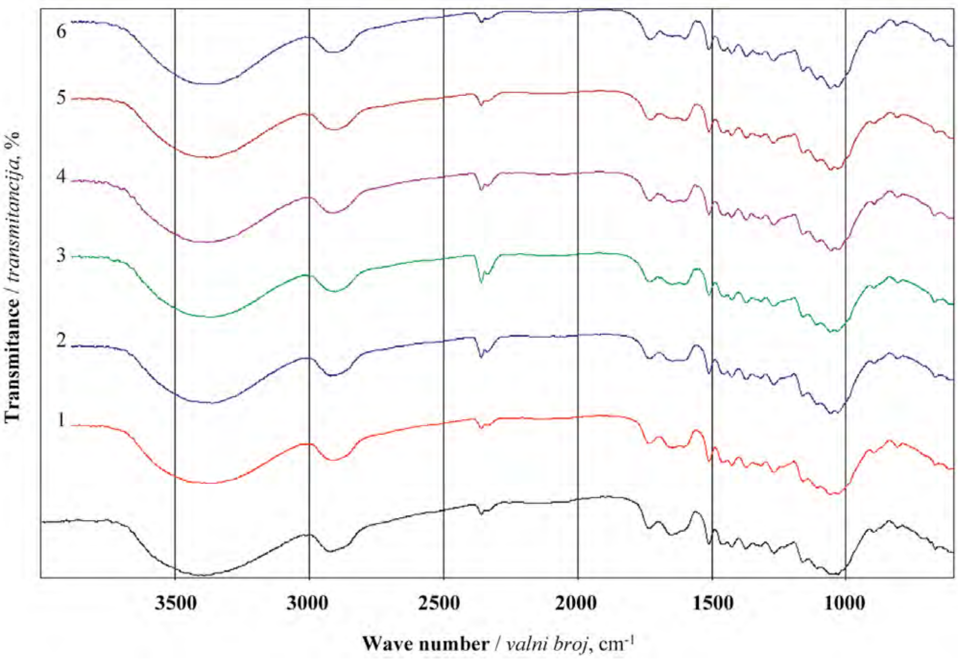

Figure 4 FT-IR spectral analysis of control specimens (black line) and samples heat-modified with six different treatments (1: 180 ºC – 3 h, 2: 180 ºC – 5 h, 3: 180 ºC – 7 h, 4: 200 ºC – 3 h, 5: 200 ºC – 5 h, 6: 200 ºC – 7 h) of black pine over a range of 4000-500 cm^{-1}

Slika 4. Spektralna FT-IR analiza kontrolnih uzoraka (crna linija) i toplinski modificiranih uzoraka tijekom šest različitih tretmana (1: 180 ºC – 3 h, 2: 180 ºC – 5 h, 3: 180 ºC – 7 h, 4: 200 ºC – 3 h, 5: 200 ºC – 5 h, 6: 200 ºC – 7 h) drva crnog bora u rasponu od 4000 cm^{-1} do 500 cm^{-1}

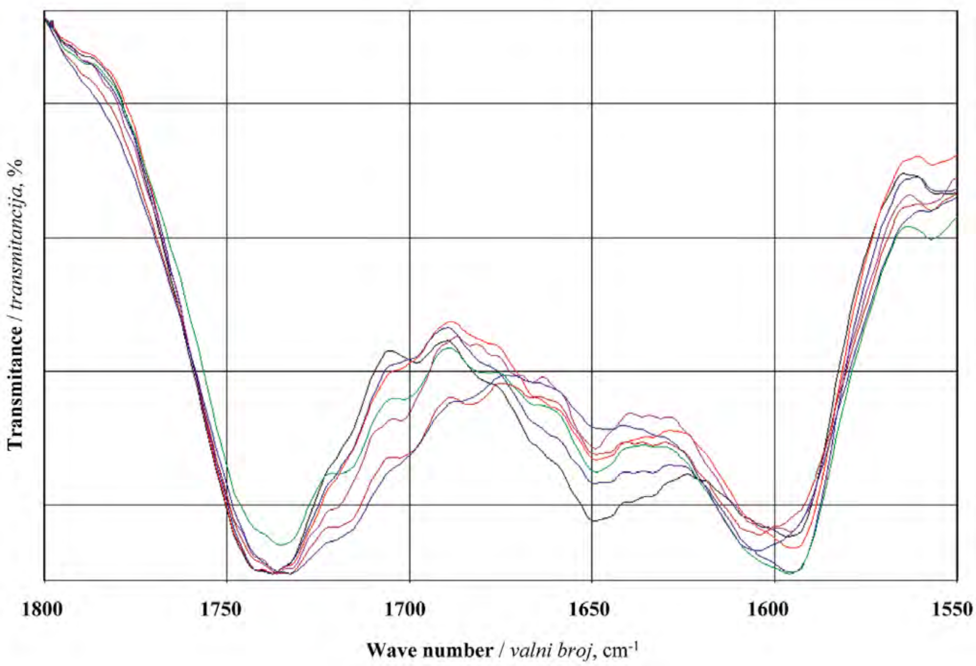

Figure 5 Overlapping IR spectra of control (black line) and thermally modified samples with six different treatments (color lines) of black pine in the range of 1800-1550 cm^{-1}
Slika 5. Preklapanje IR spektra kontrolnog uzorka (crna linija) i toplinski modificiranih uzoraka tijekom šest različitih tretmana (obojene linije) drva crnog bora u rasponu od 1800 cm^{-1} do 1550 cm^{-1}

and is attributable to the cleavage of the aliphatic side chains of lignin and the condensation reactions.

In addition, no significant variation was found in the spectra for peaks at 1460 cm^{-1} and 1420 cm^{-1}. According to Kotilainen *et al*. (2000) and Weiland and Guyonnet (2003), the absorption peaks located at 1460 cm^{-1} and 1420 cm^{-1} increase with heat treatment. The band at 1375 cm^{-1} was broadened to lower wavenumbers, but without marking consistent variance. The band at 1333 cm^{-1} represents the contribution of all the structural components of wood, since it corresponds to the bending of the C-H bending of polysaccharides, which joins the band at 1327 cm^{-1} of S and G lignin condensed units (Faix *et al*., 1990). There was also a clear increase at 1330 cm^{-1}, which corresponds to the increase of lignin condensation. A similar tendency was reported by Windeisen *et al*. (2007).

As regards the black pine wood, the spectra band of 1800 cm^{-1} - 1550 cm^{-1} and more particularly the 1600 cm^{-1} - 1750 cm^{-1} revealed some differences between the C=O bonds of carbonyls and C=C bonds of alkenes of thermally modified and unmodified samples.

In the range of 1462 cm^{-1} - 1425 cm^{-1} and 1384 cm^{-1} -1346 cm^{-1}, where the basic structural components of wood are depicted, a small difference is found between unmodified and modified pine specimens, as in the case of poplar, which reinforces the view that the thermal treatment affects the levels of these components. The hemicelluloses, degraded due to thermal treatment, exhibit the decrease observed at 1730 cm^{-1}. Lignin demonstrated some changes (1505 cm^{-1} - 1512 cm^{-1}) probably attributed to a reduction in the methoxyl groups, the loss of syringyl units or the aliphatic side chain cleavage, with the parallel increase of the mass loss during treatment. Particularly, there was no major change in the 3430 cm^{-1} band, which corresponds to O-H stretching vibrations of alcohols (3600 cm^{-1} - 3300 cm^{-1}) and carboxylic acids (3300 cm^{-1} - 2500 cm^{-1}), concerning equally polysaccharides and lignin. The two bands at 2900 cm^{-1} - 2800 cm^{-1} consist of the overlapping of the asymmetric vibration stretches of the $-CH_2-$ (around the 2935 cm^{-1} - 2915 cm^{-1} band) and the $-CH_3$ (around the 2970 cm^{-1} - 2950 cm^{-1} band), as well as of the overlapping of the asymmetric vibrations of the $-CH_2-$ (about 2865 cm^{-1} - 2845 cm^{-1}) and the $-CH_3$ (around the 2880 cm^{-1} - 2860 cm^{-1} band), whereas in these bands a faint shift is also recorded in the species of pine.

In the area around 1750 cm^{-1}, a clear increase is detected and, as also mentioned by Esteves *et al*. (2007), by increasing the treatment duration, this band tends to increase, recording a shift to lower wavenumbers. The same happened in this case with the observed increase and displacement in the zone of about 1730 cm^{-1}. The spectra also revealed a clear decrease at 1654 cm^{-1}, as in the case of poplar, marking a slight shift to lower bands.

The band point of 1595 cm^{-1}, which corresponds to stretching vibrations in the aromatic ring of C=O, appears to be increased only in the milder treatment, while it was subsequently decreased in more intensive treatments due to the increase in the lignin percentage of heat treated wood. The aromatic rings most often exhibit a characteristic band at a point of about 1500 cm^{-1}, corresponding to stretching vibrations of the benzene rings. Also in the case of pine, a shift of the band at the point of 1505 cm^{-1} was detected, probably attributed to the condensation reactions and the cleavage of the aliphatic side chains in lignin. In addition, a clear increase at 1330 cm^{-1} corresponding to an increase in lignin condensation was also detected in the case of black pine.

3.2 Wet chemical analysis
3.2. Mokra kemijska analiza

The results of the wet chemical analyses revealed changes in the content of wood components due to the influence of the treatments. Modified poplar wood revealed an intense reduction in the extractives percentage compared to unmodified wood, especially in short treatments (3 hours), a tendency recorded at both 180 ºC and 200 ºC temperature levels, while increasing the duration, the percentage of extracts increased again with the most noticeable increase to be detected in the treatment at 180 ºC - 7 hours. Based on the results (Figure 6), a reduction of 73.36 %, 42.13 % and 23.85.43 % was observed in material treated at 180 ºC for 3, 5 and 7 hours, respectively, while treatments at 200 ºC (3, 5 and 7 h) caused an extracts decrease of 65.21 %, 37.27 % and 13.27 %, respectively, compared to control. The extracts rate progress indicates that in the early stages of treatment, the volatile extracts are volatilized and some nonvolatile extracts are decomposed, resulting in an intense drop, while as the treatment time passes, new extracts (derivatives of hemicelluloses and lignin degradation) appear to be composed, which may also contribute to the darkening of wood color (Sahin *et al.*, 2011; Kamperidou and Barboutis, 2018; Výbohová *et al.*, 2018).

The lignin percent did not exhibit pronounced changes due to the treatment. Specifically, it presented a statistically insignificant decrease in the mildest treatment (180 ºC-3 h) of 6.66 %, while it increased as the treatment intensity increased (by 0.81 % at 180 ºC-5 h, 7.65 % at 180 ºC - 7 h and by 9.62 % at 200 ºC – 3 h, 9.87 % at 200 ºC - 5 h and 10.31 % at 200 ºC – 7 h, respectively), with only the treatments at 200 ºC to induce statistically significant differences in lignin content, compared to control values. This tendency could be attributed to the fact that the degradation products of carbohydrates, such as aldehydes, are condensed with lignin and other phenolic compounds (Yildiz *et al.*, 2006; Esteves *et al.*, 2013).

An insignificant decrease in the holocellulose (2.64 %) was noted in the milder treatment (180 ºC - 3 h), as expected, because of the thermal decomposition of hemicelluloses, while as the duration reached the 7 hours, the percentage of holocellulose increased up to 31.16 %, which means that hemicelluloses decomposition produced derivatives that may have been re-polymerized in the cell wall, forming new complexes. Similar behavior was observed in the more intensive treatments at 200 ºC for 3, 5 and 7 h, with the percentage of holocellulose increasing by 4.19 %, 7.27 % and 10.15 %, respectively.

In the case of black pine, a high decrease (78.7 %) in the amount of extracts of the modified wood, especially in the material obtained from the mildest treatment (180 ºC - 3h), as well as the subsequent treatments at 180 ºC for 5 and 7 h (decrease of 64.76 % and 55.13 %) and 200 ºC for 3, 5 and 7 h caused an extract decrease of 51.98 %, 18.41 % and 16.34 % compared to the unmodified wood (Figure 7). Also, in the case of pine, extracts acted similarly as those of poplar, which suggests that in the early stages of treatment the extracts are reduced, while as long as the treatment duration increases, new extracts are formed as a result of the procedures taking place in the wood mass.

The lignin content showed a more pronounced increase after treatment compared to poplar wood. Specifically, the treatments at 180 ºC for 3, 5 and 7 hours caused an increase in the lignin content of pine wood by 2.94 %, 11.66 % and 23.14 %, respectively, while the treatments at 200 ºC (3, 5 and 7 h) caused an increase of 27.85 %, 36.05 % and 45.02 %, respectively. Therefore, as the intensity of treatment increases, the lignin is also increased, which clearly explains the intense change in color of wood and partly its behavior and mechanical performance.

The holocellulose content was found to be lower than that of control in all treatments due to the intense thermal degradation of hemicelluloses. Holocellulose levels were decreased by 29.52 %, 28.64 % and 19.87 % in the treatments at 180 ºC for 3, 5 and 7 hours, respectively. The treatments at 200 ºC (3, 5 and 7 h), re-

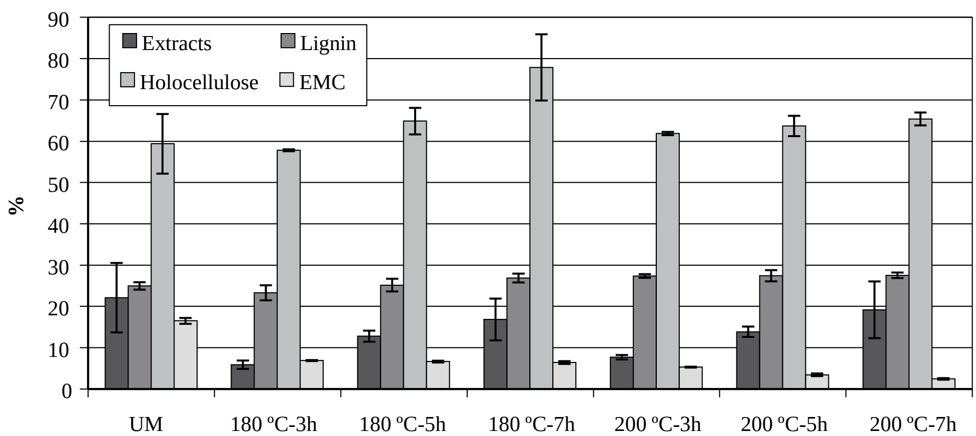

Figure 6 Mean values of chemical components content and equilibrium moisture content (*EMC* - measured after conditioning) of unmodified and modified poplar wood
Slika 6. Srednje vrijednosti udjela kemijskih komponenata i ravnotežni sadržaj vode (*EMC* – izmjeren nakon kondicioniranja) za nemodificirano i modificirano drvo topole

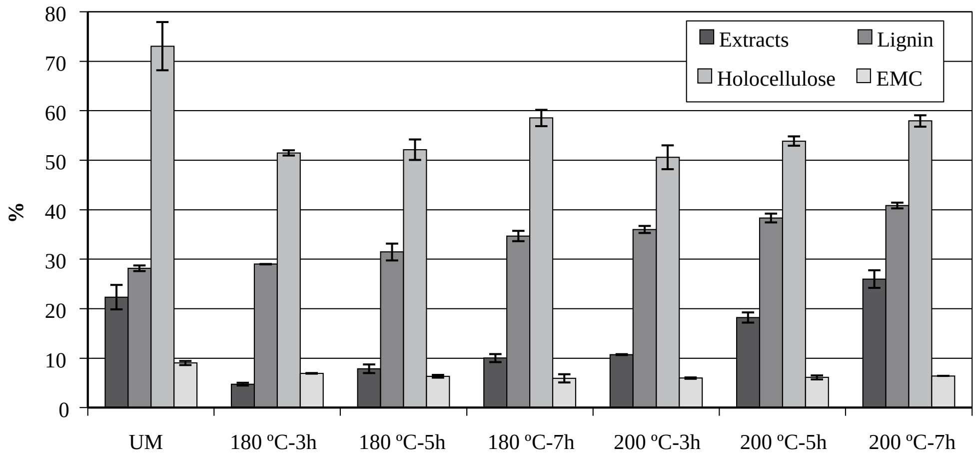

Figure 7 Mean values of chemical components content and equilibrium moisture content (*EMC* – measured after conditioning) of unmodified and modified black pine wood
Slika 7. Srednje vrijednosti udjela kemijskih komponenata i ravnotežni sadržaj vode (*EMC* – izmjeren nakon kondicioniranja) za nemodificirano i modificirano drvo crnoga bora

corded holocellulose reduction of 30.73 %, 26.24 % and 20.69 %, respectively, compared to the unmodified wood. The course of the holocellulose rate indicates that, in shorter and milder treatments, it decreases abruptly due to the decomposition of hemicelluloses and amorphous cellulose parts. Although increasing the treatment duration, an increase is recorded due to the re-polymerization of some thermo-degradation products, without however reaching the corresponding value of the control. Mburu *et al*. (2007) and Ates *et al*. (2010) also recorded a lignin increase after treatment and its ramification was detected above 200 ºC.

Parysek and Zakrzewski (2008) recorded a 32 % reduction in the percentage of substances soluble to 1 % NaOH of thermally modified Scots pine, 62 % decrease in the substances soluble to 2 % HCl and reduction in the ratio of low-molecular-weight hydrocarbons in the wood mass, whereas Bächle *et al*. (2007) noticed an increase in the extracts and a decrease in pH of thermally treated wood. Some of the studies identified in the literature (Bächle *et al*. 2007; Brito *et al*., 2008; Rowell *et al*., 2009; Akgul and Korkut, 2012; Burgos and Rolleri, 2012; Wang *et al*., 2018) present findings that seem to be in agreement with the results of the current research work.

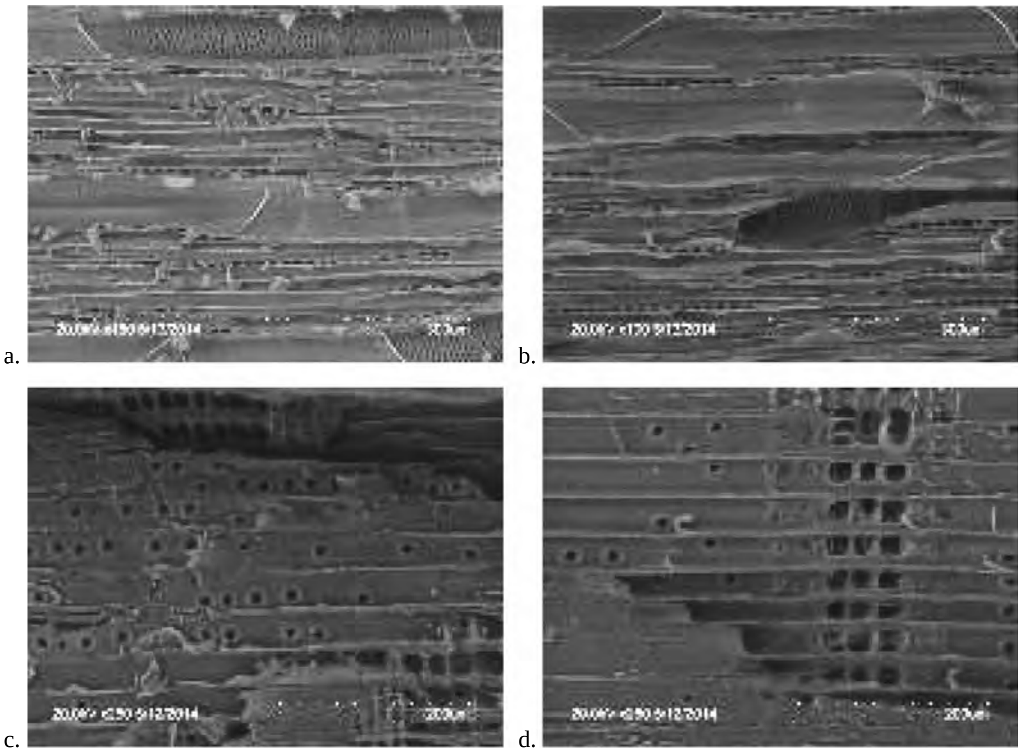

Figure 8 SEM micrographs of tangential view of a poplar control (a), tangential view of modified (200 ºC – 7h) poplar (b), radial view of black pine control (c), radial view of modified (200 ºC – 7h) pine (d) using scanning electron microscopy
Slika 8. SEM mikrografije tangentnog presjeka kontrolnog uzorka drva topole (a), tangentnog presjeka modificiranog (200 °C – 7h) drva topole (b), radijalnog presjeka kontrolnog uzorka drva crnog bora (c), radijalnog presjeka modificiranog (200 °C – 7h) drva crnog bora (d)

3.3 Microscopic observation of cell structure
3.3. Mikroskopska analiza strukture stanica

In the images obtained using a stereomicroscope, as well as a SEM microscope, differences do not appear to be apparent between the appearance of untreated and treated wood cells referring both to poplar and black pine wood (Figure 8). The thermal degradation, usually occurring during treatments, did not cause cracks or could have caused some microcracks in the membranes of pits or at points of the secondary cell wall, which are however very difficult to be detected. Even though high temperatures were used in this experimental work, the thermo-degradation caused by the thermal treatments was not found to be intense, since the temperature alone is not able to cause changes in wood components, but it does in combination with other factors, such as the duration, atmosphere, moisture content, potential pressure, etc. (Garcia *et al.*, 2010).

4 CONCLUSIONS
4. ZAKLJUČAK

FTIR spectroscopy in combination with wet chemical analysis proved to be a practical method that could be used in the characterization of thermally treated wood. Various changes and shifts in the FT-IR spectra lines of all the treated wood categories revealed that the wood components have been considerably affected, even in the shortest treatments. The free hydroxyl groups were decreased, with the parallel degradation of hemicelluloses, and the cross-linking and ramification of lignin seem to increase due to condensation reactions, especially at 200 ºC. These changes in components are in agreement with the results obtained from the wet chemical analyses. In the early stages of thermal treatment, the extracts of pine exhibited a decrease (by 78.7 %), while as the duration and temperature of the treatment increased, new extracts were formed from the processes taking place in wood mass, approaching the extracts percent of unmodified wood. The lignin of pine revealed a pronounced increase after treatment, and it was higher and faster than the lignin increases of poplar. Specifically, the treatments of pine at 180 ºC caused a lignin increase of 2.94 % - 23.14 %, while the treatments at 200 ºC caused a much higher increase (27.85 % - 45.02 %). This increase could be attributed to the degradation products of carbohydrates that are condensed with lignin and other phenolic compounds and clearly explains the intense change in color and partly the mechanical performance of wood. The holocellulose in all treated samples was found lower than in the control, mainly because of the intense decomposition of hemicelluloses (19.87 % - 30.73 %).

Poplar wood components seem to be similarly affected by thermal treatment, with extracts reduced in the short treatments and increased again as the duration and temperature rise. Specifically, a reduction of 23.85 % - 73.36 % was recorded in poplar extracts at 180 ºC treatments and 13.27 % - 65.21 % at 200 ºC, compared to unmodified wood. Lignin was slightly increased in line with the treatment intensity increase. The holocellulose recorded an increase of 4.19 % - 10.15 % as the duration and temperature increased, attributed probably to the repolymerization of the hemicelluloses decomposition derivatives in the cell walls, forming new complexes.

Generally, the short thermal modification process made wood materials of both species of lower EMC more hydrophobic, and therefore more dimensionally stable and protected against decomposing factors. At the same time, they are not intensively thermo-degraded by the treatment, according to FTIR and SEM findings, which is a fact that may increase their utilization perspectives and range of applications - as solid wood acquiring enhanced properties, or as wood particles/fibers participating as raw materials in wood-based composite products, wood-polymers composites, etc. enhancing their properties and performance.

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Ivica Župčić, Ivan Žulj, Ivica Grbac, Kristijan Radmanović[1]

Dependence of Dowel Joint Strength on Welding Temperature in Rotary Welding

Ovisnost čvrstoće spoja s moždanikom o temperaturi pri rotacijskom zavarivanju

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ABSTRACT • *The system for measuring the welding temperature with measuring probes has been developed for the requirements of this but also of future research (at the Faculty of Forestry and Wood Technology, University of Zagreb). The research is based on determining the welding temperature and its impact on the joint strength or the embedded force of the dowel. Based on research results, the impact of the dowel rotation frequency and temperature on the joint strength has been determined. The measured welding temperature increased as the rotation frequency increased (the rotation frequencies of 865 min^{-1} and 1520 min^{-1} were used in the research). The maximum welding temperature in pine samples welded at the rotation frequency of 1520 min^{-1} amounts to 217 °C, while in samples welded at the rotation frequency of 865 min^{-1} it amounts to 179 °C (weld penetration of 20 mm). The maximum welding temperature in beech samples welded at the rotation frequency of 865 min^{-1} amounts to 181 °C, and 213 °C at the rotation frequency of 1520 min^{-1} (weld penetration of 20 mm). The impact of the wood type on the welding temperature has not been proven. In order to avoid difficulties encountered in contact measurement of the welding temperature, a heat transfer model was developed for a more precise determination of the welding temperature.*

Keywords: *welding of wood; embedded force; temperature in rotary welding; dowel joints*

SAŽETAK • *Za potrebe ovoga, ali i budućih istraživanja na Fakultetu šumarstva i drvne tehnologije Sveučilišta u Zagrebu razvijen je sustav za mjerenje temperature zavarivanja uz pomoć mjernih sondi. Istraživanje se temelji na određivanju temperature zavarivanja te na njezin utjecaj na čvrstoću spoja odnosno na izvlačnu silu moždanika. Na temelju rezultata istraživanja utvrđen je utjecaj frekvencije vrtnje moždanika i temperature na čvrstoću spoja. S povećanjem frekvencije vrtnje povećava se i izmjerena temperatura zavarivanja (u istraživanju su primijenjene frekvencije vrtnje od 865 min^{-1} i 1520 min^{-1}). Najveća temperatura zavarivanja uzoraka borovine frekvencijom vrtnje od 1520 min^{-1} iznosila je 217 °C, dok je za uzorke zavarene frekvencijom vrtnje od 865 min^{-1} najviša temperatura zavarivanja iznosila 179 °C (dubina zavarivanja bila je 20 mm). Za uzorke bukovine zavarene frekvencijom vrtnje od 865 min^{-1} najviša temperatura iznosila je 181 °C, dok je za uzorke zavarene frekvencijom vrtnje od 1520 min^{-1} najviša temperatura zavarivanja bila 213 °C (dubina zavarivanja iznosila je 20 mm). Utjecaj vrste drva na temperaturu zavarivanja nije dokazan. Kako bi se izbjegle poteškoće pri kontaktnom mjerenju temperature zavarivanja, radi preciznijeg određivanja temperature zavarivanja razvijen je model prijenosa topline.*

Ključne riječi: *zavarivanje drva; izvlačna sila; temperatura pri rotacijskom zavarivanju; spoj s moždanikom*

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1 INTRODUCTION
1. UVOD

Wood welding is a more recent method of connecting wood or several wood elements or wood-based boards without the use of glue or other binders. Due to friction (rotation or vibration) between wood surfaces in contact, heat is generated, which either softens or melts lignin causing cellulose fibres to interlock in the resulting melt. As the melt hardens, the welded joint is created. There are many factors influencing the strength of the rotary welded joint such as welding duration (dowel displacement in the direction of the vertical axis per rotation), tightness (the difference between the dowel and hole diameters), weld penetration, rotation frequency, wood type, welding direction (parallel to the fibre direction or perpendicular to it), ring width (Pizzi *et al*., 2004; Župčić, 2010). The strength of the welded dowel may be compared to the strength of the glued dowel. Rotary welded joints have statistically slightly greater strength than glued dowels (Gutowski and Dodiuk, 2013; Župčić, 2010).

It is not easy and simple to measure the temperature in the welded joint. There are many attempts to measure the temperature in the joint during dowel rotation and the most common are those by thermovision. This requires the opening of the joint, which influences measured values by all means. Kanazawa *et al*. (2005) studied parameters that affect the dowel during rotational welding. The welding frequency was set at 1200 min^{-1} and the dowel longitudinal displacement rate amounted from 100 mm/min to 400 mm/min. The welding temperature measured by the thermal camera was somewhat over 180 °C. Rodrieguez *et al*. (2010) carried out a study using birch wood (*Betula Alleghaniensis)* and maple wood (*Acer Saccharum* L.) with three rotation frequencies (1000 min^{-1}, 1500 min^{-1} and 2500 min^{-1}). The welding temperature is directly correlated with the rotation frequency, that is, the higher the rotation frequency, the higher the welding temperature in the joint. The average temperature for maple wood at 1000 min^{-1} is between 269 °C and 273 °C, at 1500 min^{-1} between 279 °C and 281 °C, and at 2500 min^{-1} between 311 °C and 323 °C. The average temperature for birch wood at 1000 min^{-1} is between 243 °C and 252 °C, at 1500 min^{-1} between 263 °C and 277 °C, and at 2500 min^{-1} between 306 °C and 308 °C. The authors found that results obtained by the thermal camera are unreliable. Belleville *et al*. (2012) obtained almost identical temperature results with the same parameters, procedures and wood types. Contact measurement of the temperature in the joint welded at the rotation frequency of 1520 min^{-1} (Žulj *et al*., 2017) showed that the measured temperature value depends on the position where it is measured. The highest temperatures were recorded 8 mm from the position where the dowel enters the receiver hole and then the temperature decreases. In vibration welding on the welding line, the average of the maximum temperatures measured was approximately 165 °C, while in the centre it was approximately 200 °C (Ganne-Chedeville *et al*., 2006). It appears that already at 38 mm from the ends of the specimens, the maximum temperature has stabilised around 200 °C.

Zoulalian and Pizzi (2007) made a heath transfer model by establishing a connection between temperatures, welding duration and thermal flows in the rotational welding of the dowel. According to research results, the optimum rotational welding temperature is 183 °C. The temperature of contact surfaces may be determined as the function of time and friction duration according to Eq 1:

$$T_0 = T_i + \frac{2 \cdot \beta \cdot \mu \cdot \tau \cdot \sqrt{\alpha}}{h * \sqrt{\pi}} \cdot \sqrt{t} \qquad (1)$$

Where:

T_0 – welding temperature
T_i – initial wood temperature
t – welding time
τ – friction under pressure
μ – rotation or vibration frequency
β – mechanical energy of friction transformed into heat energy (amounts to 0.080 ± 0.01for rotational and linear welding)
h – thermal conductivity
– wood diffusivity

Vaziri *et al*. (2014) was to develop a computational model to explain the thermal behaviour of welded wood material rather than experimental methods, which are usually expensive and time consuming. This model serves as a prediction tool for welding parameters, leading to optimal thermo-mechanical performance of welded joints. The energy is produced by the friction welding of small wood specimens of Scots pine (*Pinus sylvestris* L.)

Župčić *et al*. (2011) studied the impact of welding time, as an important factor when welding beech wood, on embedded force values. The rotation frequency was 1520 min^{-1}, and dowels were welded at a depth of 20 mm with a 2 mm tightness. Samples welded between 0.56 s and 0.9 s exhibited the best results (the average embedded force amounted to 4994 N). As the welding time increased, the embedded force values decreased. With the welding duration in the interval between 1.81 s and 2.61 s, the average embedded force amounted to 2869bN. Auchet *et al*. (2010) studied a comparison between a constant welding speed and a changing (increasing) welding speed. The welding frequency amounted to 1600 min^{-1}. The highest embedded force (4.7 MPa) was generated at a constant welding speed of 20 mm/s, whereas the changing welding speed generated an embedded force of 3 MPa.

The research results (Župčić *et al*., 2014) reveal that beech wood is the best wood species for welding dowels, regardless of the fibre orientation - parallel or vertical. Also, research results indicate that the dowel welded to the beech base retains the largest strength, whereas the dowel welded to the spruce base reveals the weakest results. The type of wood affects the embedded force or strength of the joint.

Presumably, the temperature in the joint during welding is an important factor of the joint strength. It should also be mentioned that besides rotation frequency, the welding temperature is also influenced by welding duration, so that the optimum welding duration obtained in previous studies was used in this paper. Measuring a joint temperature during welding is very demanding as shown by previous studies. Namely, the opening of the joint that is welded is certainly not the best method as the melt cools down suddenly in the surrounding atmosphere so that measured values are of no relevance. Also, in case of contact temperature measurement, the probe is expected to be very sensitive and not to be in contact with the rotating dowel, and yet close enough to enable the measurement of the relative value. The research results in this paper are different from previous research. It is, therefore, necessary to connect measured temperature values with a mathematic model of theoretical heat transfer. For that purpose, an equation has been developed, which describes the heat source and its transfer to the point where the temperature is measured. The created model is an upgrade of previous heat transfer models as it also includes the influence of the z-axis on the measuring point.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Sample preparation
2.1. Priprema uzoraka

Materials required for the testing were taken from the commercial stack of unknown origin, while dowels were bought from a distributor of an unknown origin as well. Scots pine (*Pinus sylvestris* L.) and beech (*Fagus Sylvatica* L.*)* were used for the research with the water content of 10 % to 12 %. When making and preparing samples, techniques were used, such as sawing, planing, cutting down to final dimensions, drilling receiver holes on samples for dowel welding and drilling receiver holes for probes measuring the welding temperature. The samples of 30 mm × 200 mm × 30 mm for pine and of 30 mm × 300 mm × 30 mm for beech were used for the research. On pine elements, three receiver holes were drilled for dowel welding with four perpendicular receiver holes of 3 mm in diameter and a mutual distance of 4 mm for each receiver hole (Figure 1). Four receiver holes were drilled on beech elements, which is the only difference. Accordingly, four dowels were welded into beech elements and three into pine elements, while all other parameters remained the same. The receiver holes into which the dowel was welded were drilled by a spiral drilling bit of 8.1 mm in diameter and HSS mark. Probes were put in the lateral receiver holes for measuring the welding temperature. All samples had approximately similar radial-tangential texture.

The dowels used for welding were obtained from smooth beech sticks of 1000 mm in length and 10 mm in diameter. As required by the testing, the sticks were cut down to the length of 120 mm and, subsequently, their ends were bevelled by 1mm at the angle of 45˚ to enable an easier welding start. Prepared in this way, the dowels and elements (without cracks or visible damage) were conditioned under laboratory conditions for 45 days at (23 ± 2) °C and (55 ± 5) % relative air humidity.

After conditioning, the samples were welded by a welding machine with the possibility of dowel rotation and automatic displacement along its longitudinal axis. The welding was carried out as the dowel rotated at the set constant rotation frequency with dowel displacement along the longitudinal axis. The rotation frequency during the welding amounted to 865 min^{-1} or 1520 min^{-1} (depending on the sample type) (Table 1). The time required to weld the dowel into the sample amounted to 4 s (regardless of the weld penetration), and the pressure on the dowel after welding (after the rotation stopped) lasted 3 s to 5 s. The tightness in all sample types was 2 mm. The weld penetration amounted to 20 mm or 25 mm (Table 1). The element into which the dowel was welded was static, and the welding direction of the rotating dowel was perpendicular to the direction of wood fibres.

During the welding, the temperature was measured in the rotation zone by measuring probes, and software was developed and created at the Faculty of Forestry and Wood Technology (Figure 2a). The temperature was measured by four probes placed into the receiver hols perpendicular to the dowel welding direction (Figure 1). The distance between probes was 4 mm; the first probe measured the temperature at 4 mm, the fourth at 16 mm from the upper edge of the receiver hole into which the dowel was welded. The software recorded the current temperature and wrote it down in the form of a graph in real time. Due to the

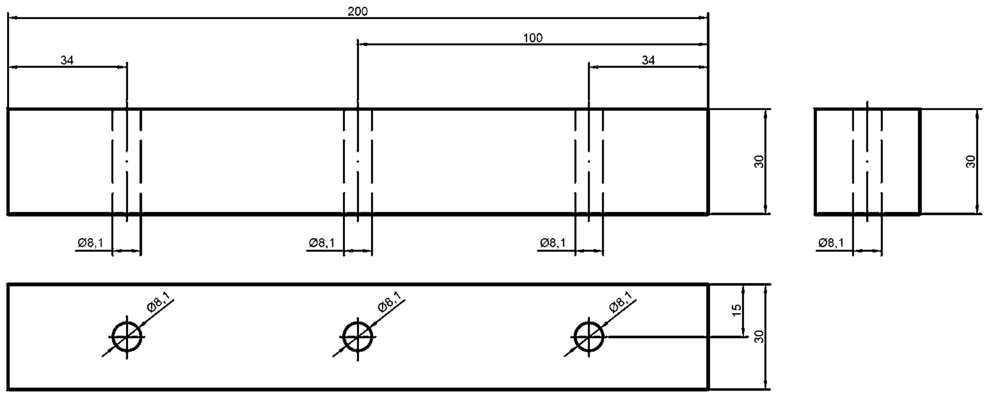


Figure 1 Orthogonal projection of pine elements with measuring probes positions
Slika 1. Ortogonalna projekcija elemenata borovine s pozicijama mjernih sondi

Table 1 Type of samples with designations
Tablica 1. Vrste uzoraka s oznakama

Sample designation *Oznaka uzorka*	**Wood type** *Vrsta drva*	**Rotation frequency, min^{-1}** *Frekvencija vrtnje,* min^{-1}	**Weld penetration, mm** *Dubina zavarivanja,* mm
BO_865_20_x	Pine	865	20
BO_1520_20_x	Pine	1520	20
BO_865_25_x	Pine	865	25
BO_1520_25_x	Pine	1520	25
BU_865_20_x	Beech	865	20
BU_1520_20_x	Beech	1520	20
BU_865_25_x	Beech	865	25
BU_1520_25_x	Beech	1520	25

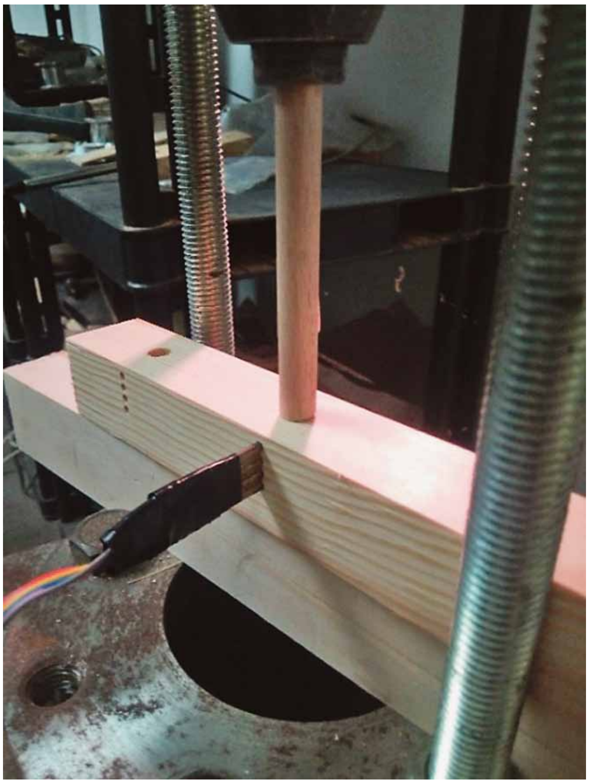
x – indicates the ordinal number of welded dowel (1-30) / *x – označava broj zavarenog moždanika (1-30)*

software deficiency, maximum temperature values were red by Acrobat Reader DC with the possible reading error of ±1.5 °C. PT1000 temperature probes were used for the testing with the temperature range between -70 °C and +550 °C. The probes were of class B with a possible error of 0.3 %. Welded samples were conditioned for seven days under laboratory conditions.

The average water content (HRN ISO 13061-1:2015) of beech samples amounted to 9.33 % (the minimum water content amounted to 8.89 %, and the maximum water content to 11.11 %), the average density (HRN ISO 13061-2:2015) amounted to 0.547 g/cm³ (the minimum density amounted to 0.544 g/cm³, and the maximum 0.556 g/cm³). The average water content (HRN ISO 13061-1:2015) of pine samples amounted to 11.37 % (the minimum water content amounted to 9.67 %, and the maximum water content to 11.48 %), the average density (HRN ISO 13061-2:2015) amounted to 0.503 g/cm³ (the minimum density amounted to 0.496 g/cm³, and the maximum 0.504 g/cm³).

2.2 Testing method
2.2. Metoda ispitivanja

The welded samples were conditioned for seven days and then tested on the universal testing machine. The sample testing was carried out on a computer-controlled Shimadzu AG-X universal testing machine. The testing speed was 5 mm/min. The samples were tested by *articulation* gripping jaws, which enabled their precise positioning (Figure 2b). Embedded force and displacement measurements were done by computer, so that all values were measured exactly and precisely. A total of 239 samples were used for the testing, all of them properly welded, so that there were no visible er-



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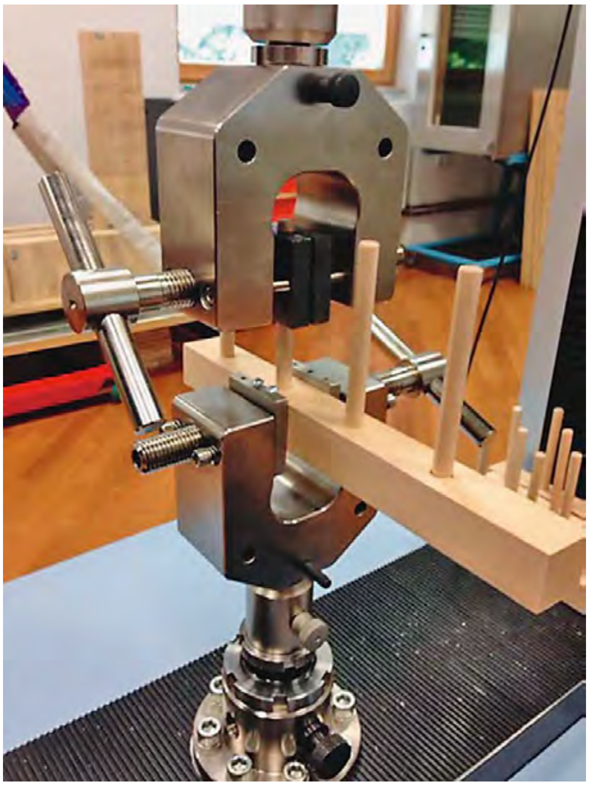

b

Figure 2 Positioning of a) device with probes during welding temperature measurement, b) samples during embedded force testing
Slika 2. Pozicioniranje a) sondi za mjerenje temperature zavarivanja, b) uzorka tijekom ispitivanja izvlačne sile

rors or damages on the samples. The dowel welding temperature and embedded force were measured for all welded samples.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Contact measurement of welding temperature
3.1. Kontaktno mjerenje temperature zavarivanja

The features of the welded joint were determined by measuring the welding temperature and embedded force of the dowel welded into pine or beech. The probe closest to the surface (probe 1) recorded an average temperature of 184 °C in pine samples and 180 ° in beech samples. Slightly higher temperature values were recorded at probe 2 for pine and beech samples. A decrease in the welding temperature was measured at probe 3, although not significant statistically. Probe 4, 16 mm from the surface, exhibited the lowest temperatures because the dowel diameter decreased due to friction so that the tightness was smaller as well, which had a direct impact on the friction between the rotating dowel and the static base. The average temperature of probe 4 was 68 °C for pine and 69.4 °C for beech (Figures 3 and 4). Such welding temperature distribution was expected. The friction is the highest at the beginning of welding because of the maximum tightness, so that the highest welding temperatures are reached. As the weld penetration or welding duration increase (by dowel displacement along the longitudinal axis), the tightness decreases, as well as the welding temperature. Therefore, the dowel top is not welded, but the accumulation of the melt (lignin) appears between fibres in very small quantities. The melt did not form the weld that would achieve certain strength (Figure 5). The optimum weld penetration for a 2 mm tightness is 20 mm. By increasing weld penetration by 5 mm, embedded force increases slightly, but the joint strength decreases (Župčić, 2010).

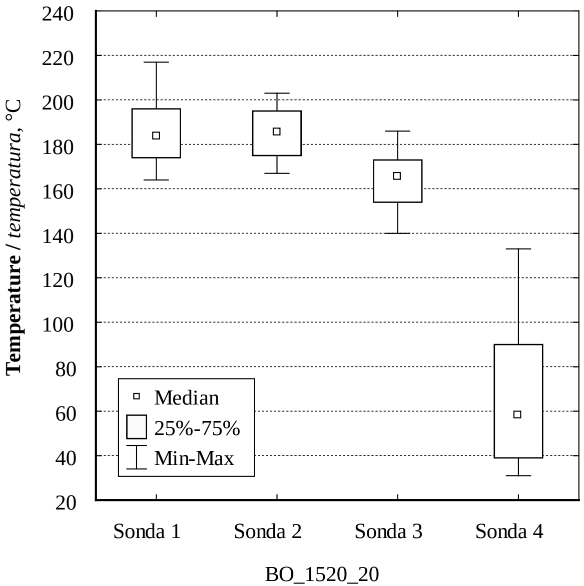

Figure 3 Distribution temperatures by probes in pine wood sample (BO_1520_20)
Slika 3. Raspodjela temperature po sondama u uzorku borovine (BO_1520_20)

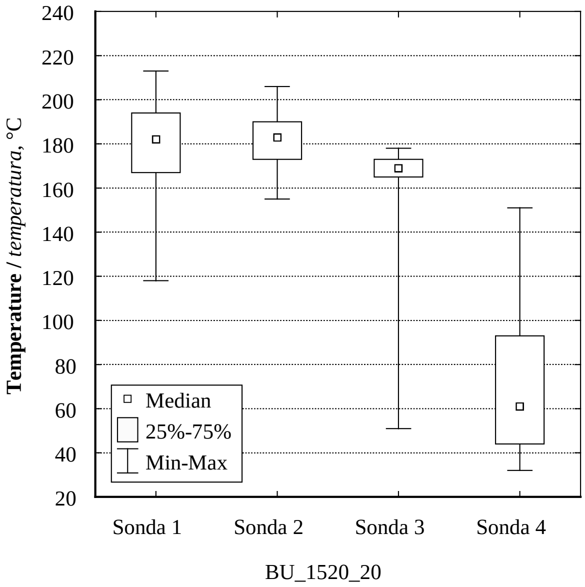

Figure 4 Distribution temperatures by probes in beech wood sample (BU_1520_20)
Slika 4. Raspodjela temperature po sondama u uzorku borovine (BU_1520_20)

The analysis of research results showed that the welding temperature in pine and beech samples depends on rotation frequency (Table 2 and 3, and Figure 6 and 7). Samples welded at a frequency of 1520 min^{-1} exhibited higher temperature values (significant statistically, Scheffe test $p<0.050$) with the rotation frequency of 865 min^{-1} in pine and beech. In percentages, there is a 21 % increase in the welding temperature at the weld penetration of 20 mm for pine, and an 18 % increase for beech. At the weld penetration of 25 mm, there is a 24 % increase in the welding temperature for pine and 22 % for beech. The welding temperature slightly increases (statistically not significantly, Scheffe test $p<0.050$) as weld penetration increases for beech, indicating that the observed weld penetration has no impact on the welding temperature.

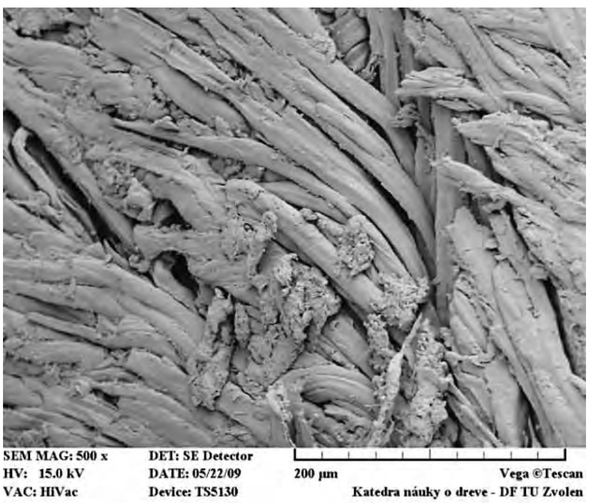

Figure 5 Wear of dowel tip (Župčić, 2010)
Slika 5. Prikaz istrošenosti vrha moždanika (Župčić, 2010.)

Table 2 Descriptive statistics of welding temperature results depending on weld penetration and rotation frequency in pine wood
Tablica 2. Deskriptivna statistika rezultata temperature zavarivanja borovine ovisno o dubini zavarivanja i frekvenciji vrtnje

Code *Oznaka*	**Breakdown table of descriptive statistics** / *Pregledna tablica deskriptivne statistike* *N* = 118							
	Mean, °C *Srednja vrijednost,* °C	**Sample number** *Broj uzoraka*	**Std. Dev, °C**	**Min, °C**	**Max, °C**	**Q25, °C**	**Median, °C**	**Q75, °C**
BO_865_20	144	29	26,59	83	179	128	156	165
BO_865_25	148.93	29	22,65	91	178	136	157	165
BO_1520_20	190.07	30	10,96	167	217	181	191	199
BO_1520_25	187.27	30	17,16	158	222	174	187	201
All groups / *Sve grupe*	167.92	118	29,12	83	222	157	170	190

Table 3 Descriptive statistics of welding temperature results depending on weld penetration and rotation frequency in beech wood
Tablica 3. Deskriptivna statistika rezultata temperature zavarivanja bukovine ovisno o dubini zavarivanja i frekvenciji vrtnje

Code *Oznaka*	**Breakdown table of descriptive statistics** / *Pregledna tablica deskriptivne statistike* *N* = 120							
	Mean, °C *Srednja vrijednost,* °C	**Sample number** *Broj uzoraka*	**Std. Dev, °C**	**Min, °C**	**Max, °C**	**Q25, °C**	**Median, °C**	**Q75, °C**
BU_865_20	174.13	30	3,59	167	181	171	175	177
BU_865_25	176.77	30	4,25	171	192	173	177	179
BU_1520_20	186.97	30	13,42	165	213	175	187	198
BU_1520_25	194.67	30	8,76	171	212	190	195	200
All groups / *Sve grupe*	183.13	120	11,75	165	213	175	179	194

Weld penetration is an important factor influencing the embedded force and strength of the welded joint. The strength of the welded joint increases, as weld penetration increases up to 20 mm and then decreases to the weld penetration of 30 mm (Župčić 2010). Due to dowel wear, friction decreases so that there is no welding. To mitigate the wear problem concerning the dowel tip, the receiver hole should be drilled with different diameter (smaller than the inlet diameter) or the conus hole (Župčić *et al*., 2008; Župčić, 2010).

Figures 8 and 9 show the impact of temperature on embedded force depending on rotation frequency and weld penetration for pine and beech samples. In pine samples, the embedded force of the welded dowel increases as the welding temperature increases. The welding temperature increases as rotation frequency increases. In beech samples, an increase in the welding temperature leads to a slight increase in the embedded force of the welded dowel. An increase in rotation frequency does not result in a significant welding temperature increase. The reason for this is the melt emerging around the measuring probe and influencing the process of temperature measurement. Besides that, the portion of the late growth ring of the wood may also influence the welding temperature so that it should be further looked into. According to results, embedded

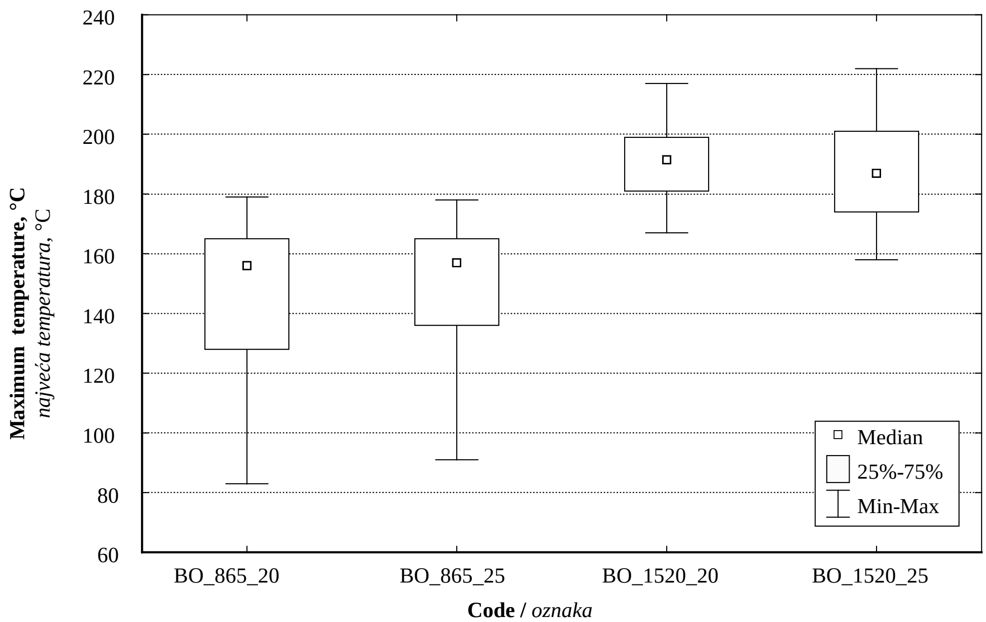

Figure 6 Comparison of welding temperature in pine wood
Slika 6. Usporedba temperatura zavarivanja borovine

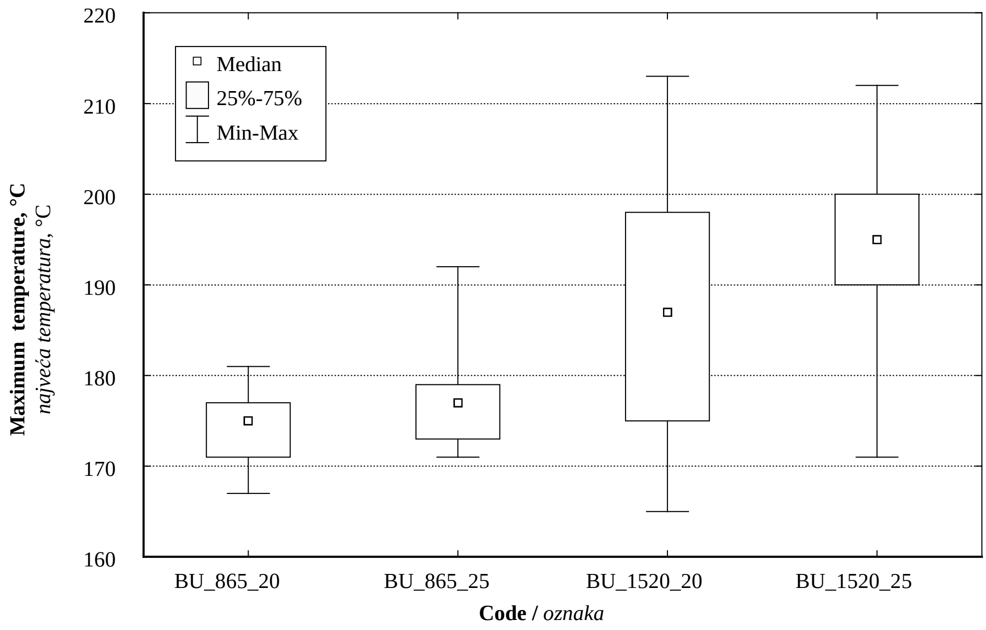

Figure 7 Comparison of welding temperature in beech wood
Slika 7. Usporedba temperatura zavarivanja bukovine

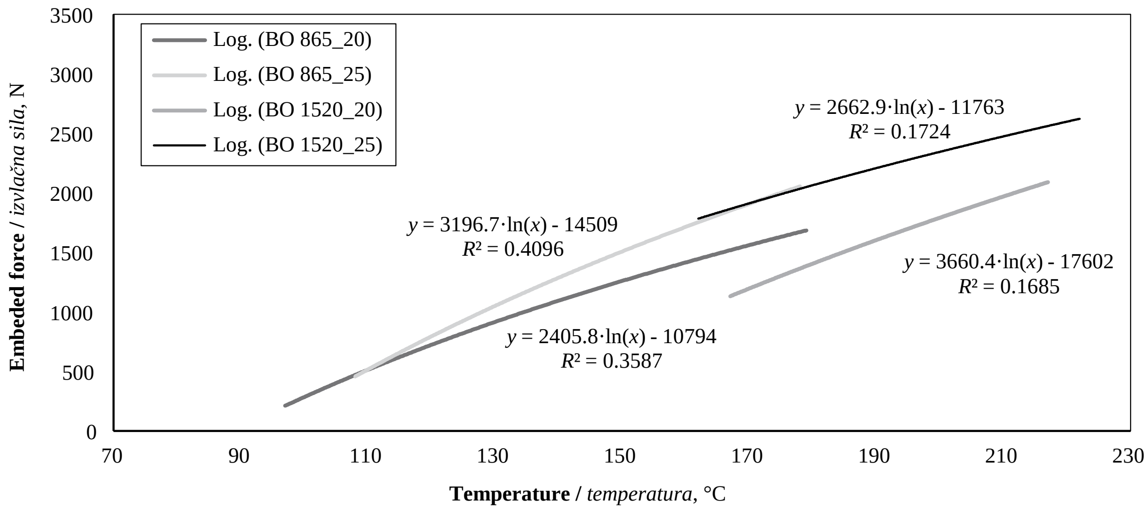

Figure 8 Impact of temperature on embedded force in pine wood samples depending on rotation frequency and weld penetration
Slika 8. Utjecaj temperature na izvlačnu silu na borovim uzorcima ovisno o frekvenciji vrtnje i dubini zavarivanja

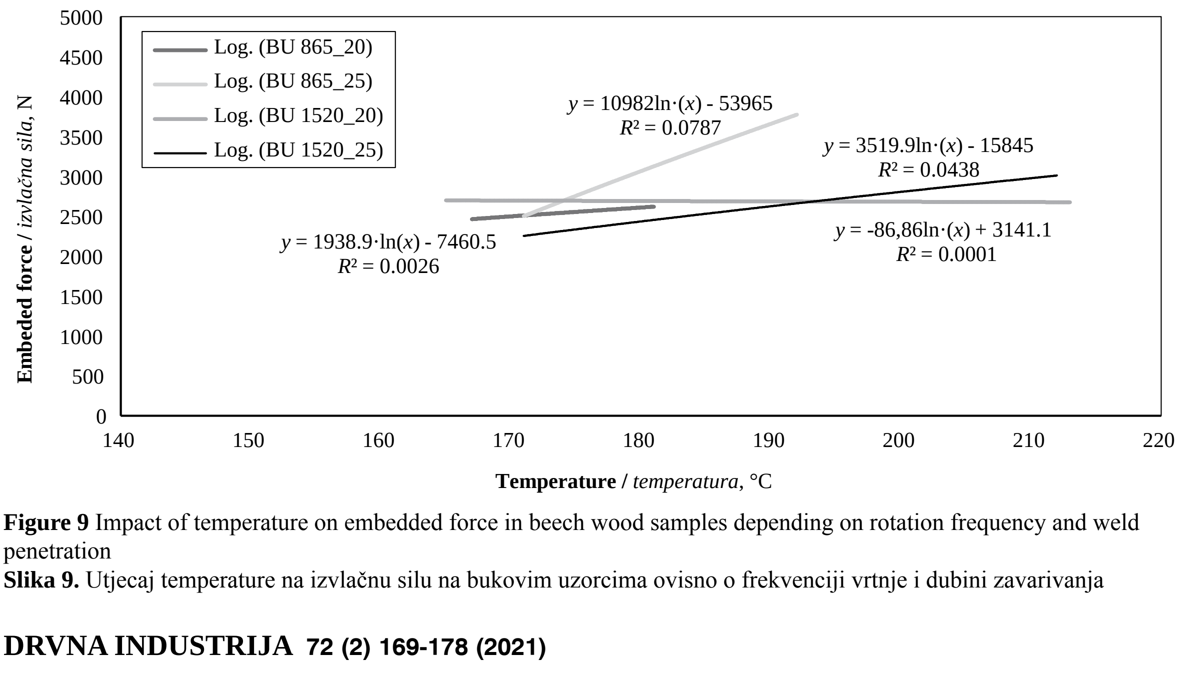

Figure 9 Impact of temperature on embedded force in beech wood samples depending on rotation frequency and weld penetration
Slika 9. Utjecaj temperature na izvlačnu silu na bukovim uzorcima ovisno o frekvenciji vrtnje i dubini zavarivanja

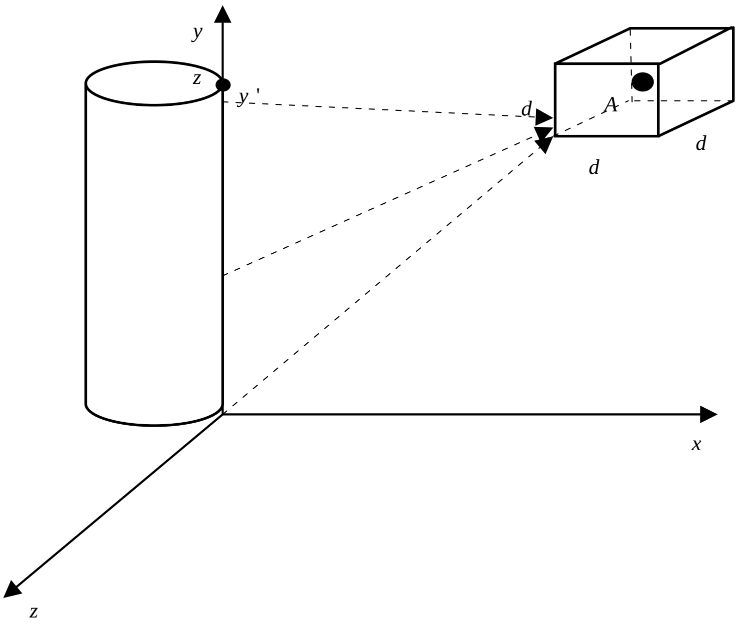

Figure 10 Wood welding in a three-dimensional rectangular coordination system (A – point at which temperature is measured)
Slika 10. Zavarivanje drva u trodimenzionalnom pravokutnom koordinatnom sustavu (A – točka u kojoj se mjeri temperatura)

force of the joints of pine wood is depending more on welding temperature than beech wood (need to be investigated in more detail). Between pine wood and beech wood, there is a difference in wood density, properties of wood and wood structure.

3.2 Theoretical research into heat transfer
3.2. Teorijsko istraživanje prijenosa topline

The wood welding process is shown in a three-dimensional rectangular coordinate system, where welding is done along the y-axis (Figure 10). During the process, the dowel is in dynamic contact with each point along the y-axis, represented by $0 \leq y \leq y'$. For that reason, these points become heat sources. As the time intervals over which the dowel is in contact with every single point along the y-axis differ, so does the intensity of the heat sources.

Around point A, the infinitesimal volume $dV = dx \cdot dy \cdot dz$ is isolated, where dx, dy and dz are the dimensions of the sides of the infinitesimal volume. According to the first law of thermodynamics, the change in the internal energy (dU) of the marked volume is:

$$dU = \delta Q_u - \delta W, \quad (2)$$

Where:

δQ_u – total heat,

δW – work done.

Work may be done if the observed medium changes its volume, and since wood does not significantly change its volume in the given temperature range, the work done may be neglected. After neglecting the work done, there follows:

$$dU = \delta Q_u. \quad (3)$$

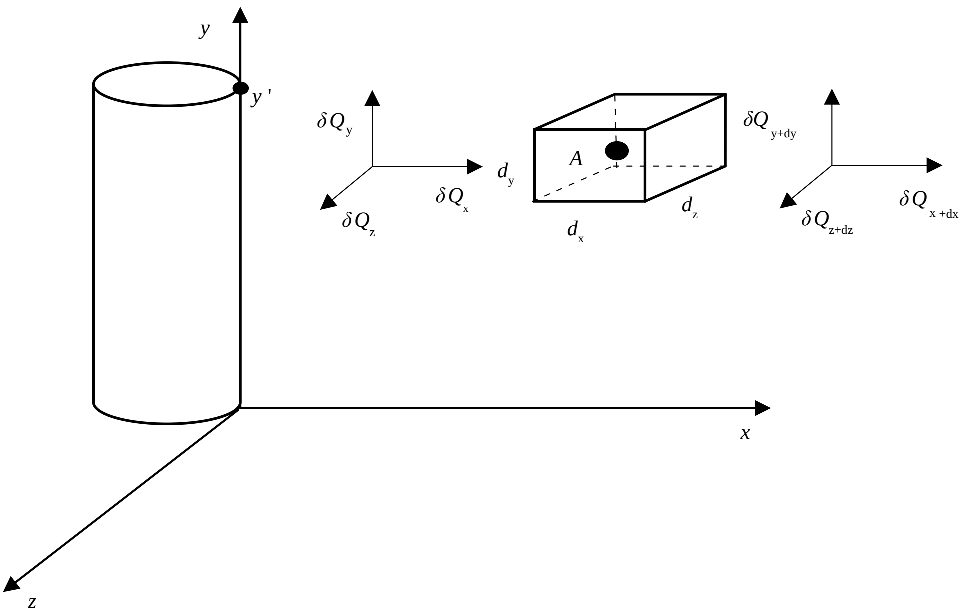

Figure 11 Change in internal energy during wood welding (A – point at which temperature is measured)
Slika 11. Promjena unutarnje energije tijekom procesa zavarivanja drva (A – točka u kojoj se mjeri temperatura)

According to Eq. 3, the change in the internal energy of the observed volume is equal to the total change in the heat of that volume, which may be recorded as a difference between supplied ($\delta Q_{dov.}$) and transferred ($\delta Q_{odv.}$) heat and source heat ($\delta Q_{izv.}$):

$$dQ_u = \delta Q_{dov.} - \delta Q_{odv.} + \delta Q_{izv} \tag{4}$$

$$\delta Q_{dov.} = \delta Q_x + \delta Q_y + \delta Q_z \tag{5}$$

$$\delta Q_{odv.} = \delta Q_{x+dx} + \delta Q_{y+dy} + \delta Q_{z+dz}. \tag{6}$$

In general, heat may be defined by way of heat flux density (Galović, 2002):

$$\delta Q = q \cdot dS \cdot dt. \tag{7}$$

Where:

q – heat flux density,

dS – surface through which heat flux is observed,

dt – time interval.

Supplied and transferred heat may be recorded with regard to the dependence on the axes of the three-dimensional coordinate system:

$$\delta Q_x = q_x \cdot dy \cdot dz \cdot dt \tag{8}$$

$$\delta Q_y = q_y \cdot dx \cdot dz \cdot dt \tag{9}$$

$$\delta Q_z = q_z \cdot dx \cdot dy \cdot dt \tag{10}$$

$$\delta Q_{x+dx} = q_{x+dx} \cdot dy \cdot dz \cdot dt \tag{11}$$

$$\delta Q_{y+dy} = q_{y+dy} \cdot dx \cdot dz \cdot dt \tag{12}$$

$$\delta Q_{z+dz} = q_{z+dz} \cdot dx \cdot dy \cdot dt \tag{13}$$

Heat flux densities of transferred heat (q_{x+dx}, q_{y+dy} i q_{z+dz}) may be developed in the Taylor series so that, while neglecting higher derivation orders, there follows:

$$q_{x+dx} = q_x + \frac{\delta q_x}{\delta x} dx \tag{14}$$

$$q_{y+dy} = q_y + \frac{\delta q_y}{\delta y} dy \tag{15}$$

$$q_{z+dz} = q_z + \frac{\delta q_z}{\delta y} dz \tag{16}$$

The combination of Eq. 8 – 16 determines the equation for the total heat depending on the coordinate axes:

$$dQ_u = \delta Q_{dov.} - \delta Q_{odv.} = -\frac{\delta q_x}{\delta x} dx \cdot dy \cdot dz \cdot dt - \frac{\delta q_y}{\delta y} dx \cdot dy \cdot dz \cdot dt - \frac{\delta q_z}{\delta z} dx \cdot dy \cdot dz \cdot dt = dx \cdot dy \cdot dz \cdot dt \cdot \left(-\frac{\delta q_x}{\delta x} - \frac{\delta q_y}{\delta y} - \frac{\delta q_z}{\delta z} \right) \tag{17}$$

Heat ($dQ_{izv.}$) generated by the source along y-axis may be defined by the heat flux of the source ($\varphi_{izv.}$)

$$dQ_{izv.} = \varphi_{izv.} \cdot dx \cdot dy \cdot dz \cdot dt \tag{18}$$

The change in the internal energy in Eq. 3 may be defined as follows:

$$dU = dm \cdot c \cdot d\theta = \rho \cdot c \cdot dx \cdot dy \cdot dz \cdot d\theta \tag{19}$$

Where:

dm – change in mass

c – specific heat capacity

ρ – density

$d\theta$ – temperature change

By inserting Eq. 17 and 18 in Eq. 4, and after abbreviations, there follows:

$$\rho \cdot c \cdot \frac{d\theta}{dt} = -\frac{\delta q_x}{\delta x} - \frac{\delta q_y}{\delta y} - \frac{\delta q_z}{\delta z} + \varphi_{izv.} \tag{20}$$

Heat flux density may be defined by the thermal conductivity coefficient (λ) in the following way (Galović, 2002):

$$q_x = \lambda_x \cdot \frac{\delta Q_x}{dx} \tag{21}$$

$$q_y = \lambda_y \cdot \frac{\delta Q_y}{dy} \tag{22}$$

$$q_z = \lambda_z \cdot \frac{\delta Q_z}{dz} \tag{23}$$

By inserting Eq. 21, 22 and 23 in Eq. 20, and while neglecting the change in the thermal conductivity coefficient along the coordinate axes ($\frac{\delta \lambda_x}{\delta x}, \frac{\delta \lambda_y}{\delta y} i \frac{\delta \lambda_z}{\delta z} = 0$), there follows:

$$\frac{d\theta}{dt} = -\frac{\lambda_x}{\rho \cdot c} \cdot \frac{\delta^2 Q_x}{dx^2} - \frac{\lambda_y}{\rho \cdot c} \cdot \frac{\delta^2 Q_y}{dy^2} - \frac{\lambda_z}{\rho \cdot c} \cdot \frac{\delta^2 Q_z}{dz^2} + \frac{\varphi_{izv.}}{\rho \cdot c} \tag{24}$$

According to Eq. 24, the temperature measured at point A depends on time ($\frac{d\theta}{dt}$), heat source intensity ($\frac{\varphi_{izv.}}{\rho \cdot c}$) and the ability of material to transfer heat energy from the source to the measuring point ($-\frac{\lambda_x}{\rho \cdot c} \cdot \frac{\delta^2 Q_x}{dx^2} - \frac{\lambda_y}{\rho \cdot c} \cdot \frac{\delta^2 Q_y}{dy^2} - \frac{\lambda_z}{\rho \cdot c} \cdot \frac{\delta^2 Q_z}{dz^2}$).

4 CONCLUSIONS
4. ZAKLJUČAK

Research results show that embedded force values (joint strength) depend on the welding temperature, which is confirmed by the research of Kanazawa *et al.* (2005) and Rodriguez *et al.* (2010).

It was found that pine samples are welded at a higher rotation frequency (1520 min^{-1}) and achieve higher embedded force values on average.

It was also found that the welding temperature depends on rotation frequency, or that samples welded at the frequency of 1520 min^{-1} reach higher temperature values as compared to samples welded at the rotation frequency of 865 min^{-1}. According to the results, there is no statistically significant temperature difference between samples of the same frequency regardless of weld penetration. However, there is a statistically significant difference between samples with different rotation frequencies.

The maximum temperature in pine samples welded at the rotation frequency of 1520 min^{-1} (BO_1520_20 and BO_1520_25) amounts to 220 °C, and in samples welded at the rotation frequency of 865 min^{-1} (BO_865_20 and BO_865_25) to 180 °C. The average welding temperature at 865 min^{-1} regardless of weld penetration amounts to around 143 °C, and at 1520 min^{-1} to 189 °C.

The maximum temperature in beech samples welded at the rotation frequency of 865 min^{-1} (BU_865_20 and BU_865_25) amounts to 210 °C, and in samples welded at the rotation frequency of 1520 min^{-1} (BU_1520_20 i BU_1520_25) to 187 °C. The average welding temperature at 865 min^{-1} is 175 °C, and at 1520 min^{-1} 190 °C.

With regard to difficulties arising from contact measurement of temperature, the heat transfer model was made to obtain more exact welding temperature results related to annul time, heat source intensity and the ability of material when transferring heat energy from the source to the measuring point.

$$\frac{d\theta}{dt} = -\frac{\lambda_x}{\rho \cdot c} \cdot \frac{\delta^2 Q_x}{dx^2} - \frac{\lambda_y}{\rho \cdot c} \cdot \frac{\delta^2 Q_y}{dy^2} - \frac{\lambda_z}{\rho \cdot c} \cdot \frac{\delta^2 Q_z}{dz^2} + \frac{\varphi_{izv.}}{\rho \cdot c} \quad (25)$$

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Evaluation of Creep Characteristics of Single-Staple Furniture Joints Made of Different Wood Species

Procjena obilježja puzanja spojeva namještaja s klamericom izrađenih od različitih vrsta drva

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ABSTRACT • *In this study, creep characteristics of single stapled furniture joints made of Scotch pine, alder and beech wood under three different load levels were considered. Load levels were determined as 30 %, 40 % and 50 % of the maximum load obtained as a result of static shear test before creep load and applied to wood joints. Laboratory test results showed that the highest creep deformation was observed in the joints made of Scotch pine with the lowest density, while the lowest creep deformation was observed in the joints made of beech with the highest density. In addition, the joints were exposed to lowest creep deformation at the 30 % load level, then the creep deformation of the joints increased at 40 % load level and it reached the highest value at 50 % load level. As a result of creep test, deformation in single stapled joints made of Scotch pine, alder and beech were determined as 2.74 %, 3.71 % and 4.37 % of the deformation that occurred as a result of static shear test performed before creep test, respectively. Ultimately, the overall average creep deformation value of a single staple wood joint under creep loading was determined as 3.61 %.*

Keywords: *creep; load level; single staple; wood joint*

SAŽETAK • *U radu su istraživana obilježja puzanja spojeva namještaja s klamericom izrađenih od borovine, johovine i bukovine pri različitim stupnjevima opterećenja. Stupnjevi opterećenja definirani su kao 30, 40 i 50 % najvećeg opterećenja dobivenoga kao rezultat statičkoga smičnog ispitivanja prije opterećenja pri puzanju te su primijenjeni na drvne spojeve napravljene klamericom. Rezultati laboratorijskih ispitivanja pokazali su da je najveća deformacija puzanja zabilježena na spojevima izrađenima od borovine, koja ima najmanju gustoću, a najmanja je deformacija puzanja uočena na spojevima od bukovine, koja ima najveću gustoću. Usto, najmanja deformacija puzanja spojeva zabilježena je pri stupnju opterećenja od 30 %, zatim se deformacija puzanja povećala pri stupnju opterećenja od 40 % i dosegnula najveću vrijednost pri stupnju opterećenja od 50 %. Rezultati ispitivanja puzanja pokazali su da je deformacija spojeva s klamericom izrađenih od borovine, johovine i bukovine iznosila 2,74, 3,71 i 4,37 % deformacije koja je rezultat statičkoga smičnog naprezanja provedenoga prije ispitivanja puzanja. U konačnici, ukupna prosječna vrijednost deformacije puzanja drvenog spoja s klamericom iznosila je 3,61 %.*

Ključne riječi: *puzanje; stupanj opterećenja; klamerica; drveni spoj*

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1 INTRODUCTION
1. UVOD

Staple connected gusset-plate joints can be defined as joints in which at least two elements in a furniture frame structure are connected by the driving of staples through the gusset-plate into the elements. The gusset-plate can be metal, wood or wood-based composites such as wood or plywood. Plywood is generally used as gusset-plate because of its excellent tensile strength (APA, 1997). Since staple connected gusset-plate joints have a higher shear resistance, they connect the places such as the stump and the front rail joints, which were exposed to excessive shear loads in the upholstered furniture frame structure as shown in Figure 1.

Staples as metal fasteners resist horizontal shear forces rather than direct withdrawal forces, particularly during use in furniture frames (Zhang and Maupin, 2005). Therefore, the lateral shear resistance of the staple connected joint depends on the staple holding performance of the wood material used.

Wood material, as a popular product today; is used to achieve many purposes at functional, environmental and aesthetic levels. Wood shows a time-dependent behavior like most materials (Peng *et al.*, 2020). With time, this time-dependent behavior leads to a deformation of the material under load (Kojima and Yamamoto, 2004). This mechanical deformation is called creep (Holzer *et al.*, 1989; Navi and Stanzl-Tschegg, 2009; Du *et al.*, 2013). In creep tests, the material is subjected to a constant loading and the stresses at loading point are followed for a certain period of time.

Creep deformation is quite important in the design of most products. Even though MOR is at an acceptable level, creep deformation is treated as a more disturbing perception for customers. Therefore, creep deformation is an issue to be considered. Moreover, customer satisfaction is considered as an important element in the design of furniture products.

In the modern furniture industry, a joint should meet the load over the whole lifetime of furniture. Therefore, it is not enough to evaluate only the short term behavior after assembling (Dias *et al.,* 2018). When a joint is subjected to load, it deforms. If it is subjected to loading over a certain time, creep deformation increases with time. Therefore, creep deformation should be considered in joints.

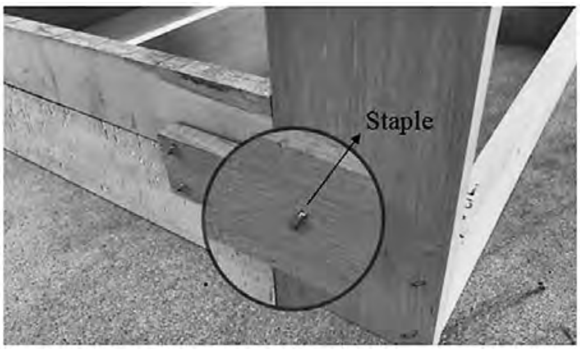

Figure 1 A sofa joint connected with staple exposed to lateral loads
Slika 1. Spoj dvosjeda povezan klamericom izložen bočnim opterećenjima

The performance of a wooden structure is closely related to the joints in the structure or the behavior of joints between the materials (members). Most creep patterns related to the joint are based on studies on lateral shear stiffness. For example, the reduction of lateral shear stiffness of dowel-nailed and nut-screwed joints has been examined (Morlier, 1994; Polensek, 1982).

Smardzewski *et al.* (2013) studied the effect of creeping on changes in the rigidity of selected joints used in constructions of upholstered furniture by changing modulus of elasticity. As a result of the study, it was observed that creeping made a significant change in the mechanical quality of the tested joints by decreasing the modulus of elasticity by 11 % - 16 %.

Xu *et al.* (2015) investigated the effects of pressure load magnitude of the seat cushions commonly used in upholstered furniture and the force-deformation-time behavior of the material used in cushion fabrics. The results showed that the creep behavior of furniture seat cushions consisting of foam, spring and fabric materials can be defined, respectively. The statistical analysis of the experimental data in this study showed that the magnitude of the loads examining the creep behavior had significant effects on the viscoelastic constants in the mathematical expressions to define the force-deformation-time behavior of the cushions evaluated.

Li *et al.* (2019) investigated the creep behavior of balsa wood covered with glass fiber-reinforced polymer from both surfaces. First, static bending test was conducted and ultimate bearing capacities were determined for the specimens. Based on the bearing capacity, four load levels were determined as 20 %, 40 %, 60 % and 80 % for creep loading. Results showed that at small load levels, such as 20 % and 40 %, specimens showed linear viscoelastic behavior; however, they showed creep failure at higher load levels, 60 % and 80 %.

There have been few studies so far that fully explained the creep properties of wood material, both theoretically and practically. Mostly, tests were carried out statically for a short time. However, practical applications and necessary rules for examining the effects of creep of wood material on the service life have not been developed yet. In the furniture area, there is almost no creep study on the joints used for building furniture frames such as sofas. In particular, almost no study has been conducted on creep behavior of the staple connected gusset-plate joints made of beech, alder and Scotch pine, which are mostly used in Turkey and worldwide furniture manufacturing.

The main purpose of this study was to investigate and interpret the creep properties of the joints made of different wood species under different load levels. The specific objectives of this study were to: 1) determine the load levels to be applied for creep testing by applying different percentages of the maximum static load value of the joint as creep load, 2) examine the creep behavior of furniture joints as a result of using different wood species, 3) quantitatively compare the creep behavior of the joints according to the static behavior of the joints.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Material
2.1. Materijal

In this study, creep behavior of the joints made of Beech (*Fagus orientalis*), Scotch pine (*Pinus sylvestris*) and Alder (*Alnus glutinosa*), which have recently gained a new place in Turkish furniture production, have been investigated. For the static shear test, 30 joint specimens for each wood species, i.e. 90 joints in total, were tested. On the other hand, a total of 27 joint specimens were loaded for creep test for three replications for each wood species. The densities of these wood species are shown in Table 1.

As shown in Table 1, beech wood had the highest density value, followed by alder and Scotch pine. The densities of the materials were determined according to TS 2472 standard (TS 2472, 1976). In this study, wood species were used as the main material and the plywood with 9 layers of Scotch pine veneers was used as side material. Each layer of the plywood was prepared perpendicular to one another, and the surface layers were parallel to each other. Senco staples, coated with a nitro-cellulosic based corrosion inhibiting layer, were used as metal fasteners in the attaching of the joint members. Staples have a leg length of 38 mm and a crown width of 11 mm. When attaching the joint members, the staple is driven into the assembled members at an angle of 45 º to ensure the best connection between the members. Figure 2 shows a typical wood joint made of Scotch pine.

Table 1 Densities of wood species used in joint structure
Tablica 1. Gustoća vrsta drva upotrijebljenih za izradu spojeva

	Wood species / *Vrsta drva*			
	Scotch Pine *Borovina*	Alder *Johovina*	Beech *Bukovina*	Plywood *Furnirska ploča*
Density, g/cm^3 *Gustoća,* g/cm^3	0.45 (2)	0.51 (1)	0.54 (4)	0.64 (4)

The values in parenthesis indicate the coefficient of variation. / *U zagradama je naveden koeficijent varijacije.*

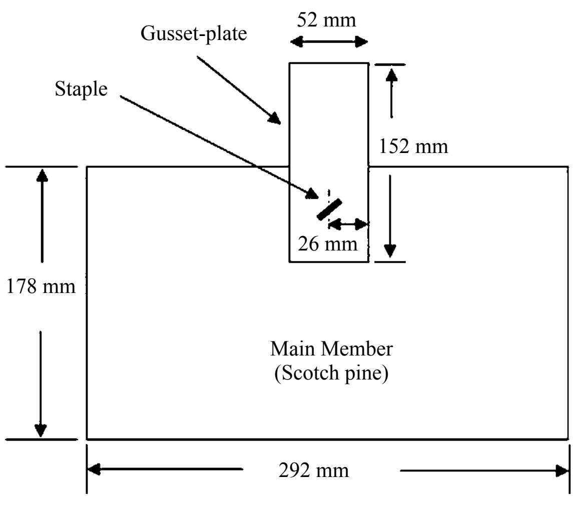

Figure 2 A joint made of Scotch pine
Slika 2. Spoj izrađen od borovine

Figure 3 Static shear test for single staple Scotch pine joint
Slika 3. Statički test na smicanje spoja s klamericom izrađenoga od borovine

2.2 Method
2.2. Metoda

2.2.1 Static shear test
2.2.1. Statičko ispitivanje smicanja

In order to determine the load levels to be applied for creep test, 30 single-staple joint specimens were prepared from each wood species and subjected to static shear test at a loading rate of 2.5 mm / min on MTS Criterion Model 45 Universal testing machine, and static shear loads of the joints were determined. This test was conducted based on ASTM D 1761 standard (ASTM 1761, 2010). Figure 3 shows the static shear test for single-staple wood joints.

2.2.2 Creep test
2.2.2. Ispitivanje puzanja

In order to determine the load levels required for the creep test, firstly, static shear loading was applied to the joints, and then the maximum shear load values were obtained and converted from Newton (N) to kg. Creep test was carried out by taking certain percentage values of the maximum shear values in kg and hanging them to the joint specimens in weight. Figure 4 shows a representative of the five test stations prepared for this creep test.

The deflection measurement was carried out with dial gauges with 0.001 mm accuracy and 0-30 mm measuring rod. The measurements were continuously monitored daily and this monitoring ranged from 1 day to 103 days depending on the behavior of the joint specimens under load. Creep deformation at the joints was recorded based on each movement in the dial

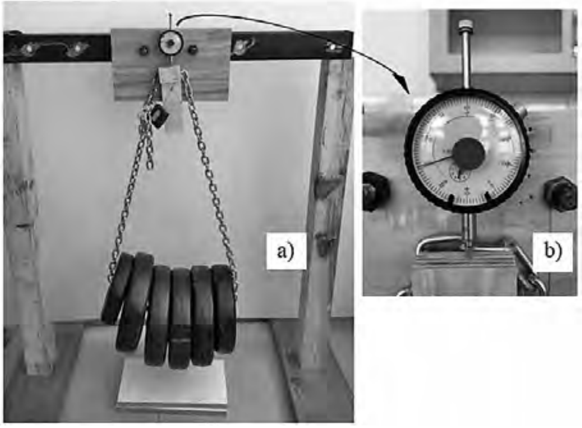

Figure 4 a) Creep test station b) Dial gauge
Slika 4. a) Oprema za ispitivanje puzanja, b) komparator

gauge. Figure 4b shows the dial gauge in which creep deformation is read.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Static shear test and creep test
3.1. Statičko ispitivanje smicanja i ispitivanje puzanja

The average displacement values of each wood joint group evaluated as static shear test results given in this study are presented in Table 2. As shown in the table, beech joints with the highest density show the least displacement, followed by alder joint with less density and the Scotch pine joint with the least density.

The average maximum lateral shear loads of each joint specimen are shown in Table 3. In order to see the statistical difference among the average maximum lateral shear loads, a SAS statistical analysis model based on one- factor (wood species) at 5 % significance level was run and compared with least significance difference (LSD) of 53.57 N.

As shown in Table 3, as a result of the statistical analysis, the highest shear resistance value was obtained from the single-staple joint made of beech wood. This is followed by alder joint and Scotch pine joint.

Within the scope of this study, first of all, 30 single-staple beech joints with Scotch pine gusset-plate were prepared and their maximum static resistance loads were determined in MTS Universal testing machine in N. These values were averaged and converted to kg in order to obtain creep loading information, because the creep loading values were taken as a percentage of the maximum static load of the same joints. Accordingly, the average maximum static load obtained for the beech joints is 125 kg as shown in Table 4, which shows all percentages determined of these average maximum shear loads. The average maximum static shear resistance loads obtained in Table 3 are presented in Table 4 for beech joint. These loads were converted from N to kg and transformed into loadable values for creep test.

According to Table 4, the load of 112.5 kg, which is 90 % of the average maximum static shear loads, was applied to single-staple beech joint and an immediate separation between the members of joints appeared. Then, 80 %, 70 % and 60 % of the average maximum static shear loads of the joint, 100 kg, 87.5 kg, and 75.5 kg, respectively, were applied to the beech joints and again single-staple beech joints were separated between joint members in a short time. However, the joints were able to withstand a period of time under 62.5 kg, which is 50 % of the average maximum static load. Also, the joints were able to withstand 50 kg and 37.5 kg, which is 40 % and 30 % of the average maximum static load, respectively. Therefore, in this study, creep test load levels were determined as 50 %, 40 % and 30 % of the average maximum static loads of the single-staple joints for beech and other wood species. Similarly, certain percentages of the average maximum resistance values of the material were used as different load levels in previous studies for the creep test. Likewise, Hayman (1981) studied the creep properties of three connected arch structures. These joints were subjected to 85 %, 65 %, and 35 % of the main buckling loads. Nilsson and Johansson (2019) studied the creep

Table 2 Maximum static displacements
Tablica 2. Najveći statički pomaci

	Wood species / *Vrsta drva*		
	Scotch Pine *Borovina*	Alder *Johovina*	Beech *Bukovina*
Average displacement, mm *Prosječni pomak,* mm	4.96 (19)	4.89 (18)	4.63(18)

The values in parenthesis indicate the coefficient of variation. / *U zagradama je naveden koeficijent varijacije.*

Table 3 Statistical comparison of static shear resistance values (in N and kg) obtained from each wood species
Tablica 3. Statistička usporedba vrijednosti statičkog otpora na smicanje (u N i kg) dobivenih za ispitivane vrste drva

Unit *Jedinica*	**Wood species** / *Vrsta drva*		
	Scotch Pine *Borovina*	Alder *Johovina*	Beech *Bukovina*
	Maximum shear values *Najveće smične vrijednosti,* N		
Average, N *prosjek,* N	809 (C)	1042 (B)	1233(A)
Average, kg *prosjek,* kg	83	106	125

LSD: 53.57 N
The same letters in parentheses indicate homogeneity groups. / *Ista slova u zagradama označuju homogene grupe.*

Table 4 Percentages of average maximum static load values for beech joints to be used in creep testing
Tablica 4. Postotci prosječnih maksimalnih vrijednosti statičkog opterećenja za spojeve od bukovine koji su korišteni u ispitivanju puzanja

Mean static load, kg *Srednje statičko opterećenje,* kg	**Percentage values, %** / *Postotne vrijednosti, %*						
	90	80	70	60	50	40	30
125	112.5	100	87.5	75.5	62.5	50	37.5

Table 5 Creep test loading values determined for each joint made of different wood species
Tablica 5. Vrijednosti opterećenja pri ispitivanju puzanja utvrđene za spojeve izrađene od različitih vrsta drva

Wood species *Vrsta drva*	**Maximum static load level, %** *Najveći statički stupanj opterećenja,* %		
	30	40	50
Scotch Pine *borovina*	25	33	41
Alder/ *johovina*	32	42.5	53
Beech / *bukovina*	37.5	50	62.5

properties of wood-based boards and applied bending test as static test on the specimens. For creep testing, 30 % of the maximum static bending resistance value was determined and applied as creep load level. The creep test loads (kg) for the joints made of each wood species are presented in Table 5 for this study.

As shown in Table 6, the specimens loaded at 30 % and 40 % load levels completed the creep tests in different number of days. The number of days of creep test is determined as a result of the stopping of the deformation under the creep load.

3.2 Creep-deformation curve
3.2. Krivulja puzanja/deformacije

The joints made of different wood species under creep load showed creep deformation-time curves at different number of stages. Creep deformation-time curves with different number of stages are as follows: (1) two stages of creep deformation, first accelerating, then decelerating; (2) three stages of creep deformation curve with accelerating, then decelerating and breaking movement; (3) also three stages of creep deformation curve with accelerating, then decelerating and stabilizing creep movement; (4) four stages creep deformation-time curve with first accelerating then

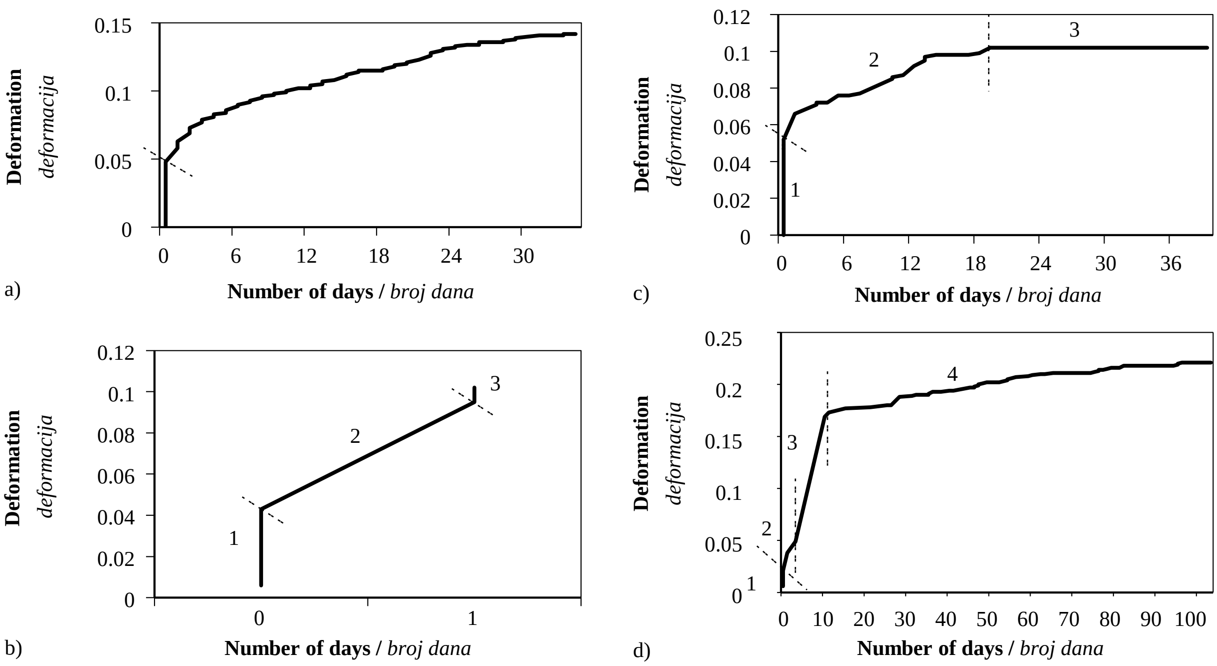

Figure 5 Creep deformation-time curves with a) two stages, mostly for alder joints, b) three stages with separation, mostly for beech joints under 50 % creep load, c) three stages with stabilization, mostly for beech and Scotch pine joint under 30 % and 40 % creep loads d) four stages
Slika 5. Krivulje puzanja/deformacije tijekom vremena: a) dvije faze, uglavnom za spojeve od johovine, b) tri faze s odvajanjem, uglavnom za spojeve od bukovine, uz opterećenje manje od 50 % pri puzanju, c) tri faze sa stabilizacijom, uglavnom za spojeve od bukovine i borovine, uz opterećenje manje od 30 % pri puzanju, d) četiri faze

Table 6 Number of days of testing joints made of different wood species under creep loading
Tablica 6. Broj dana trajanja ispitivanja puzanja pri tri različita opterećenja za spojeve izrađene od različitih vrsta drva

Load level, % *Stupanj opterećenja,* %	**Specimen** *Uzorak*	**Wood species** / *Vrsta drva*		
		Scotch Pine / *Borovina*	Alder / *Johovina*	Beech / *Bukovina*
		The number of days / *Broj dana*		
30	I	62	52	16
	II	66	34	80
	III	34	33	39
40	I	65	32	77
	II	47	32	103
	III	56	50	30
50	I	34	75	2
	II	3	33	2
	III	22	42	1

decelerating, accelerating again and gradually stabilizing creep deformation. Figure 5 shows the curves with different stages under creep loads.

In Figure 5, each stage was separated with a dashed-line and numbered. Accordingly, a beech joint only showed a 4-stage creep deformation curve, while two beech joints showed a 2-stage curve. Most beech joints showed a three-stage creep deformation-time curve. On the other hand, at 30 %, 40 %, 50 % loading levels, all of the alder joints showed a two-stage creep deformation-time curve. In the Scotch pine joint, 4 specimens showed two-stage and 5 specimens showed three-stage creep deformation-time curve. Results showed that the deformation-time curves obtained as a result of creep tests on wood joint had at least two stages and generally three stages. The stress-strain curve obtained by Costa and Barros (2015) had two stages as a result of creep study on epoxy adhesive protective materials. The general trend in the deformation-time curves obtained as a result of the current creep study on wood joints is similar to that established in the study by Costa and Barros (2015).

3.3 Failure modes
3.3. Priroda loma

At the end of the creep test, only two types of failure modes were observed as shown in Figure 6. While most of the joints showed staple release mode, only 6 joints, 5 beech wood joints and 1 Scotch pine joint under 50 % load level, showed complete separation of the staple from the main member.

Figure 7 shows different failure characteristics and their corresponding deformation-time curves according to each stage of a single-staple beech joint. In stage a), an increasing deformation was observed, while in stage b), decreasing creep deformation was observed. Finally in stage c), a stabilizing creep deformation was monitored. This three-stage creep deformation failure characteristic is the most observed one in this study. Figure 8 illustrates the average maximum

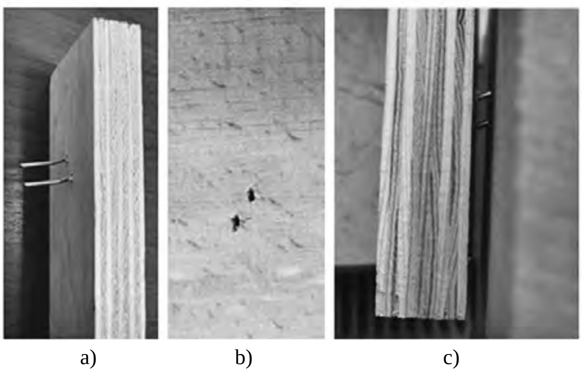

Figure 6 Complete separation mode of the joint: a) staple separated from main wood member, b) damage caused by staple when withdrawing from wood material, c) other joint failure mode with staple release
Slika 6. Potpuno odvajanje spoja: a) klamerica odvojena od glavnoga drvnog dijela, b) oštećenje uzrokovano klamericom pri njezinu izvlačenju iz drvnog materijala, c) druge vrste loma s otpuštanjem klamerice

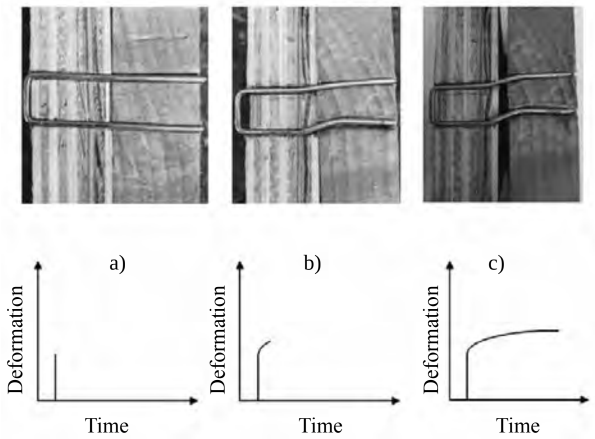

Figure 7 Cross cut view of single-stapled joints under creep load in different stages
Slika 7. Poprečni presjek spoja s klamericom pod opterećenjem pri puzanju u različitim fazama

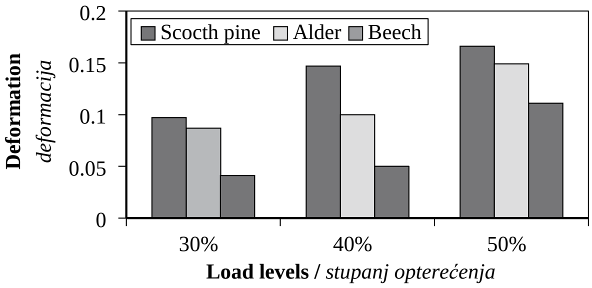

Figure 8 Creep deformation relationship between load levels and wood species as a result of one-day creep data
Slika 8. Deformacija pri puzanju u ovisnosti o stupnju opterećenja i vrsti drva kao rezultat jednodnevnih podataka o puzanju

creep deformation relationship between wood species at 30 %, 40 % and 50 % load levels according to first day data.

As indicated in Figure 8, the Scotch pine joints with the lowest density showed the highest amount of creep deformation under 30 % load levels at the end of the first day and this was followed by the alder joints with higher density and beech joints with the highest density. The relation among different wood species on creep deformation is similar to the deformation under static lateral shear loading. Similar creep relations were observed at the load levels of 40 % and 50 %. Accordingly, the Scotch pine joints showed the highest average creep deformation and the beech joints showed the lowest average creep deformation. It is inferred from the results that the deformation under the creep load decreases as the density of the material increases. Likewise, in his study, Niemz (1993) observed that increasing the density of the wood material decreased creep deformation values. Nilsson and Johnson (2019) examined the creep properties of wood-based panels under a long time load and stated that these panels exhibit the same creep properties as solid wood materials. These scientists stated that there is an inverse relationship between the density of wood material and creep deformation. In this respect, it is obvious that the re-

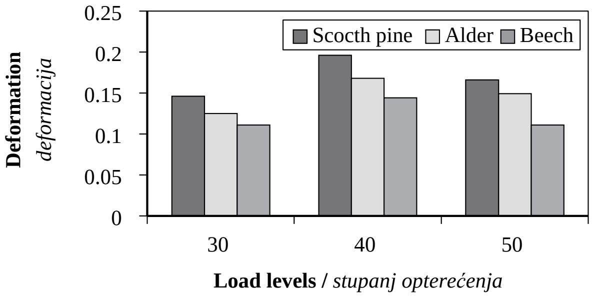

Figure 9 Creep deformation relationships between load levels and wood species as a result of common day creep data
Slika 9. Deformacije pri puzanju u ovisnosti o stupnju opterećenja i vrsti drva kao rezultat uobičajenih podataka o puzanju

sults of the current study are consistent with the previous studies. Additionally, the creep deformation on wood material joints increased as load level increased from 30 % to 40 % and 50 %. Xu *et al.* (2015) tested the specimens under load levels of 250, 600 and 1000 N and reported that creep deformation increased with increasing load levels. Figure 9 shows the average creep values obtained based on the number of common (30) days determined for each load level.

As shown in Figure 9, the lowest average maximum creep deformation at each load level (30 %, 40 %, and 50 %) was observed in the beech joints with the highest density. This was followed by the alder joints with lower density and the Scotch pine joints with the lowest density.

Table 7 Comparison of joints made of different wood species according to their creep deformation
Tablica 7. Usporedba spojeva izrađenih od različitih vrsta drva prema njihovoj deformaciji puzanja

Number of days *Broj dana*	**Wood species** / *Vrsta drva* **Creep deformation** / *Deformacija puzanja*, mm		
	Scotch Pine *Borovina*	Alder *Johovina*	Beech *Bukovina*
1st day	0.136(A)	0.112(AB)	0.072(B)
30th day	0.171(A)	0.145(AB)	0.123(B)

The same letters in parentheses indicate homogeneity groups. / *Ista slova u zagradama označuju homogene grupe.*

A statistical analysis was conducted to see the effect of wood species and load level on creep deformation of all joints by using the 1st day and 30th day creep deformation data at % 5 significance level in SAS statistics program. As a result of the statistical analysis, the relationship between wood species and loading level was found insignificant.

Accordingly, in Table 7, the significance of creep deformation among joints was compared with LSD values of 0.040 and 0.044, respectively, using the creep deformation data on the 1st day and 30th day.

As indicated in Table 7, based on creep deformation data on the first day, single-staple joints made of the lowest density Scotch pine showed significantly the greatest creep deformation. This was insignificantly but marginally followed by alder joints because the alder joint showed insignificantly less creep deformation. The beech joints, on the other hand, showed significantly lower creep deformation than the Scotch pine joints and insignificantly lower creep deformation than the alder joints. In other words, the beech joint showed the lowest creep behavior with its highest density. In general, the joints made of lower density wood were more deformed under creep load, while the lowest creep deformation was observed in joints made of wood with the highest density. An exactly similar relationship is also valid for creep deformations of the joints obtained at the end of the 30th day.

Table 8 shows the values of creep deformation of each sample in the percentage of deformation resulting from the initial static maximum load value, the average values according to the load levels and the overall average value. As shown in Table 8, deformation increases as load level increases from 30 % to 50 %. The overall creep deformation value of the wood joints is 3.61 % of their static deformation obtained initially. Therefore, under long time loading, a furniture joint made of these wood species is subjected to an average creep deformation of 3.61 %. Costa and Barros (2015) found that creep deformation observed on test specimens was 3 % compared to the initial static shear test deforma-

Table 8 List of deformation values of joints made of different wood species in three different load levels under creep load, as a percentage of deformation of the same joints under static shear load
Tablica 8. Vrijednosti deformacija puzanja spojeva izrađenih od različitih vrsta drva pri tri različita stupnja opterećenja kao postotak deformacije istih spojeva pri statičkome smičnom opterećenju

Load level, % *Stupanj opterećenja, %*	**Creep deformation amount** / *Iznos deformacije pri puzanju, %*				
	Specimen *Uzorak*	Scotch Pine *Borovina*	Alder *Johovina*	Beech *Bukovina*	Average *Prosjek*
30	I.	2.25	2.43	2.5	
	II.	5.1	2.82	2.1	
	III.	3	2.68	1.81	2.74
40	I.	4.17	3.48	2.16	
	II.	4.92	3.37	4.13	
	III.	4.47	4.27	2.4	3.71
50	I.	3.13	4.01	2.34	
	II.	4.34	4.76	4.44	
	III.	6.29	7.03	3	4.37
Overall average / *Ukupan prosjek*					3.61

tion of the specimens. In this respect, the results of the current study are very close to the results in the study by Costa and Barros (2015).

4 CONCLUSIONS
4. ZAKLJUČAK

Creep properties of single stapled furniture joints, made of wood species widely used in furniture industry such as Scotch pine, alder and beech, were investigated. For creep test, 30 %, 40 %, and 50 % were determined as load levels based on the maximum static lateral shear loads of the same joints.

Results indicated that most of the joints under creep load showed deformation curve with three stages - first accelerating then decelerating and finally stabilizing creep movement.

Based on the first day creep data, the joints made of Scotch pine with the lowest density showed significantly higher creep deformation than the joints made of beech with the highest density. This was insignificantly followed by alder joints with a medium density as compared to other wood species. This also means that the alder joints showed insignificant but mathematically observable higher creep deformation than the beech joints. As a result, increasing wood density decreased creep deformation. Additionally, results showed that increasing load levels from 30 % to 50 % increased the creep deformation of the wood joints.

After creep loading, the deformation of the Scotch pine, alder and beech joints was determined as 2.74 %, 3.71 % and 4.37 %, respectively, of their deformation after static shear loading performed before the creep test. Ultimately, this value was obtained as 3.61 % for single-staple wood joints as the average of three wood species. In other words, the average creep deformation value of a single-staple wood joint under load levels of 30 %, 40 % and 50 % was determined as 3.61 %.

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Fiberglass Plaster Mesh as Reinforcement for Cement Bonded Particleboard

Učinci ojačanja cementom vezane iverice primjenom fasadne mrežice od stakloplastike

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ABSTRACT • *The effects of fiberglass plaster mesh (FPM) as reinforcement on some physical and mechanical properties of cement bonded particleboard (CBP) were examined. Experimental CBP with and without FPM were manufactured in laboratory conditions using wood particles, cement, tap water and chemical accelerators. Two plies of FPM, manufactured using fiberglass and polyester resin, were laid within the experimental CBP. The target density of CBP was 1300 kg/m*^{3} *in the study. Three different types of chemical accelerators (*$CaCl_2$*, KCl, DARASET® 580) were used in the experiments. Properties of CBP evaluated include 2- and 24-hour - thickness swelling (TS), 2- and 24-hour - water absorption (WA) and bending stiffness (MOE) and strength (MOR). The results indicate that all the board properties tested were significantly improved by FPM application. The average MOE values of the CBP boards with FPM was two times higher than those of the boards without FPM. Dimensional stability and MOR of the CBP boards were also significantly improved with the use of FPM. FPM can be used to improve inferior properties of the CBP, so as to make it more compatible with other wood based construction materials.*

Keywords: *cement bonded particleboard; fiberglass plaster mesh; physical and mechanical properties*

SAŽETAK • *U radu su ispitani učinci fasadne mrežice od stakloplastike kao ojačanja cementom vezanih iverica na neka njihova fizička i mehanička svojstva. Eksperimentalne cementom vezane iverice proizvedene su s fasadnom mrežicom od stakloplastike i bez nje u laboratorijskim uvjetima, i to upotrebom drvnog iverja, cementa, vode iz slavine i kemijskih ubrzivača. Dva sloja fasadne mrežice od stakloplastike, izrađene od staklenih vlakana i poliesterske smole, položena su u eksperimentalnu cementom vezanu ivericu. U istraživanju je ciljana gustoća cementom vezane iverice bila 1300 kg/m*^{3}*. U pokusima su upotrijebljene tri različite vrste kemijskih ubrzivača (*$CaCl_2$*, KCl, DARASET® 580). Proučavana su ova svojstva cementom vezane iverice: debljinsko bubrenje nakon 2 i 24 sata, upijanje vode nakon 2 i 24 sata, modul elastičnosti i modul loma. Rezultati pokazuju da su upotrebom fasadne mrežice od stakloplastike sva proučavana svojstva znatno poboljšana. Prosječne vrijednosti modula elastičnosti cementom vezane iverice s dodatkom fasadne mrežice od stakloplastike bile su dva puta veće od vrijednosti iverice bez dodatka takve mrežice. Dimenzijska stabilnost i modul loma cementom vezane iverice također su znatno poboljšani primjenom fasadne mrežice od stakloplastike. Fasadna mrežica od stakloplastike može se rabiti za poboljšanje lošijih svojstava cementom vezane iverice kako bi ona bila kompatibilnija s drugim građevnim materijalima na bazi drva.*

Ključne riječi: *cementom vezana iverica; fasadna mrežica od stakloplastike; fizička i mehanička svojstva*

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1 INTRODUCTION
1. UVOD

Cement bonded boards, which are a mixture of wood particles with cement, water and some additives (Marteinsson and Gudmundsson, 2018), have been in use for almost a century. Compared to organic bonded wood products, some advantages such as durability, dimensional stability, acoustic and thermal insulation properties and low production cost make them desirable in the construction industry (Lee, 1984; Ramirez-Coretti *et al*., 1998; Savastano *et al*., 2003; Okino *et al*., 2005; Del Menezzi *et al*., 2007). Despite the advantageous properties of CBP, its flexural properties are mostly inferior compared to other wood-based composites. The properties of CBP are significantly influenced by the amount of the cement, woody material and density (Youngquist, 2010). Thus, flexural properties are mostly controlled by the amount of cement. Utilization of alternative woody materials also lower its flexural properties and worsen its dimensional stability.

In order to improve flexural properties of CBP, some pretreatments such as cold or hot water soaking of the particles were found promising (Frybort *et al*. 2008). During the last few decades, fiberglass has been used with a variety of materials in order to improve strength and stiffness properties (İlhan and Feyzullahoğlu, 2019). Solid wood and wood-based materials are also reinforced with fiberglass and remarkable improvements in bending and other properties were observed (Smulski and Ifju, 1987). Christoforo *et al*. (2016) obtained doubled bending properties for particleboard by applying fiberglass. Cassidy (2002) observed a 39 % increase in bending strength of oriented strand board (OSB) when reinforced with fiberglass. Fonseca *et al*. (2011) evaluated the influence of fiberglass reinforcement in plywood panels. Their results showed a 58 % and 43 % increase in bending strength for both longitudinal and transverse directions, respectively. Medium density fiberboard (Cai, 2006) and hardwood panels (Smulski and Ifju, 1987) were also reinforced and significant enhancement was achieved in bending properties.

Reinforcement of CBP with some natural fibers such as bagasse (Aggarwal, 1995) and jute (Deng and Furuno, 2002) were investigated and some improvements in physical and mechanical properties were observed. The literature concerning fiberglass reinforcement of CBP is scarce. A study by Wei and Tomita (2001) investigated the effects of discontinuous glass fiber on cement bonded boards and reported an increasing *MOR* and internal bond strength but also a decreasing *TS* and *WA*.

The use of fiberglass reinforcement may help reducing the use of wood material for large and heavy structural wood members as well as minimize mechanical property variability (Rowlands et al. 1986). In this study, FPM was used as reinforcement, and its effects on some physical and mechanical properties of the CBP manufactured were investigated.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Experimental CBPs with the size of 500 mm × 500 mm, a thickness of 12 mm and an average target density of 1300 kg/m^3 were prepared in laboratory conditions. Wood particles were mixed with commercial cement (CEM I 42.5), water and accelerator. Wood/cement ratio was 1:2 and 1:3; water/cement ratio was 1/2.5. Coarse particles of Red pine wood (*Pinus brutia*), which are used in the core layer of commercial three layer particleboard, were provided from a local particleboard factory. *MC* of wood particles was 12 %. The size distribution of wood particles used in the production of experimental CBP is given in Table 1.

Table 1 Size distribution of wood particles used in the study
Tablica 1. Raspodjela drvnog iverja upotrijebljenog u istraživanju

Particle size, mm / *Veličina iverja,* mm	%
6.3	0.6
4	4.5
2	29
1	49
0.85	6.6
0.5	8.5
0.25	1.3
0.125	0.5

The amount of 5 % of chemical additives ($CaCl_2$, KCl, DARASET® 580) based on cement mass was added to the water before mixing. $CaCl_2$ is one of the most known accelerators used in wood cement composites. KCl is usually added to cement mixtures in order to improve the cement/formation bond. DARASET® 580 is an admixture for concrete, used to accelerate cement hydration, which causes shortened setting times and increased early compressive strength. FPM (FileTex160 brand) used in the study was woven glass fiber fabric at 4 mm intervals. Bidirectional FPM weighed 160 g/m^2 and consisted of 80 % fiberglass (E-glass) and 20 % polyester resin binder. In general, FPM is used in exterior plastering, where it helps to prevent stress caused by humidity and extreme temperature changes. It also has the features of anti-corrosion and resistance to alkalis.

Experimental CBP were prepared with and without FPM (Table 2) as follows: first, wood particles were sprayed with water that contains previously dissolved accelerator. Then, cement was added to the mixture until a homogeneous distribution was obtained. The experiment was carried out by spreading the mixture on the steel plate. In the production of experimental CBP with FPM, two plies of FPM were embedded approximately 3 mm below the board surface. The mixture was placed between steel plates and left for curing under the pressure of 1.8 N/mm^2 - 2.0 N/mm^2. Wax paper was used between cement mixture and steel plates. The cured boards were conditioned in the laboratory climate at approximately +20 °C and relative humidity (RH) of 65 %. After curing, samples were

Table 2 Experimental design used in the study
Tablica 2. Dizajn eksperimenta

Wood - cement ratio *Omjer drvo – cement*	**Accelerator used** *Dodani ubrzivač*	**FPM**
33 % wood	$CaCl_2$	yes
		no
	KCl	yes
		no
	Daraset	yes
		no
50 % wood	$CaCl_2$	yes
		no
	KCl	yes
		no
	Daraset	yes
		no

prepared in order to determine *WA, TS* and bending properties.

WA and *TS* values after 2 and 24 hours of immersion in water were determined according to TS EN 317. *MOR* and *MOE* of the boards were determined according to TS EN 310. Five replicates were used for each test and the obtained data were subjected to an analysis of variance. Experimental results were analyzed using ANOVA tests to identify their statistical significance. Duncan's multiple range tests were performed in order to find the least significant difference between all the variables. The obtained results were also compared to standard values of TS EN 634-2.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 3 and 4 show *TS* and *WA* values of the laboratory manufactured CBP samples. Density of the experimental CBP ranges from 1221 to 1345 kg/m^3 and was not significantly different among the tested group. The use of FPM did not significantly alter the density of the CBP manufactured. 2- and 24-hour *TS* values of the CBP vary between 2.39 % - 12.39 % and 2.6 % - 16.57 %, respectively.

Overall, *TS* values of CBP were significantly affected by all the variables involved in the study ($p < 0.001$, $R^2 = 0.83; 0.96$). The average 2-hour - *TS* values (3.66 %) of 33% wood boards were increased to 5.425 % when the amount of wood particles was increased to 50 %. $CaCl_2$ and KCl seemed to yield lower 2-hour - *TS* values (3.5 % and 4.09 %, respectively) compared to the DARASET (6.028 %). The use of FPM remarkably dropped the average 2- hour *TS* values from 5.5 % to 3.5 %.

The increase in the amount of wood volume resulted in higher 24-hour *TS* values as expected (4.69 % to 7.5 5%). Results are compatible with the literature. 24–hour *TS* values of boards manufactured using KCl (4.2 %) were lower than those manufactured using $CaCl_2$ and DARASET (5.8 % and 8.35 %). The use of FPM remarkably dropped the average 24-hour *TS* values from 7.8 % to 4.3 % (80 %).

In general, *WA* values of CBP were significantly affected by all the variables involved in the study ($p < 0.001$, $R^2 = 0.96; 0.97$). *F*-values indicate that FPM had the greatest influence on *WA* values than other variables involved. The average 2-hour *WA* values (9.33 %) of 33 % wood boards were increased to 12 % when the amount of wood particles was increased to 50 %. $CaCl_2$ seemed to yield lower 2-hour *WA* values (5.3 %) compared to KCl and DARASET (13.1 % and 13.4 %, respectively). The use of FPM drastically decreased the average 2-hour *WA* values from 15.54 % to 5.78 %. The average 24-hour *WA* values (11.83 %) of 33 % wood boards were increased to 16.5 % when the amount of wood particles was increased to 50 %. $CaCl_2$ seemed to yield lower 24-hour *WA* values (9.5 %) compared to KCl and DARASET (14.6 % and 18.3 %, respectively). The use of FPM drastically decreased the average 24-hour *WA* values from 20 % to 8.3 %.

In general, dimensional stability of the CBP is measured with *TS* and *WA,* which are dependent on wood particle content (Moslemi and Pfister, 1987; Savastano *et al*., 2003; Olorunnisola, 2009). Higher wood particle content means lower dimensional stability. In addition to higher particle content, dimensional stability can also be affected by the type of chemical

Table 3 Thickness swelling values after 2 and 24 hours
Tablica 3. Vrijednosti debljinskog bubrenja nakon 2 i 24 sata

Wood – cement ratio *Omjer drvo – cement*	**Accelerator used** *Dodani ubrzivač*	**Plaster net** *Fasadna mrežica*	***TS* (2 hours), %**	***TS* (24 hours), %**
33 % wood	$CaCl_2$	yes	4.50 (0.35)*	5.55 (0.43)
		no	2.97 (0.46)	4.93 (0.46)
	KCl	yes	4.14 (2.36)	2.60 (0.96)
		no	3.35 (0.55)	4.10 (1.09)
	Daraset	yes	2.39 (0.33)	4.50 (0.35)
		no	4.61 (0.29)	6.46 (0.35)
50 % wood	$CaCl_2$	yes	2.74 (0.36)	5.04 (0.73)
		no	3.81 (0.63)	7.71 (0.76)
	KCl	yes	3.73 (1.26)	5.47 (1.02)
		no	5.94 (3.33)	7.39 (1.2)
	Daraset	yes	4.71 (1.02)	5.89 (1.16)
		no	12.39 (0.6)	16.57 (0.11)

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

Table 4 Water absorption values after 2 and 24 hours
Tablica 4. Vrijednosti upijanja vode nakon 2 i 24 sata

Wood – cement ratio *Omjer drvo – cement*	**Accelerator used** *Dodani ubrzivač*	**Plaster net** *Fasadna mrežica*	***WA*** **(2 hours), %**	***WA*** **(24 hours), %**
33 % wood	$CaCl_2$	yes	6.28 (2.17)*	7.85 (0.18)
		no	2.81 (1.02)	6.47 (0.78)
	KCl	yes	5.46 (1.27)	7.14 (1.34)
		no	17.79 (0.91)	17.80 (1.03)
	Daraset	yes	5.48 (1.24)	8.41 (0.2)
		no	18.15 (0.54)	23.33 (0.69)
50 % wood	$CaCl_2$	yes	7.23 (1.1)	12.38 (4.02)
		no	4.89 (1.18)	11.39 (1.19)
	KCl	yes	5.92 (1.56)	9.65 (3.94)
		no	23.88 (4.15)	26.43 (1.22)
	Daraset	yes	4.61 (0.12)	6.92 (0.18)
		no	25.73 (0.79)	34.68 (0.97)

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

accelerators, which are highly hygroscopic, and type of wood particles (Olorunnisola, 2009) and (Moslemi and Pfister, 1987). It seems that *TS* values of all experimental boards were higher than 1.5 % as required by the standard, while most of the *WA* values were less than 32 % (TS EN 634-2). Application of pre-treatment or using smaller particles in the board production may help lowering *TS* and *WA* values (Moslemi *et al*., 1983; Lee, 1984; Zhengtian and Moslemi, 1985; Badejo, 1988; Lee and Short, 1989). Compared to 10.4 % - 19.2 % decrease in TS values obtained by the use of discontinuous glass fiber (Wei and Tomita, 2001), FPM causes a significant decrease of 80 % in TS. Compared to 14.1 % - 19.9 % decrease in *WA* values obtained by the use of discontinuous glass fiber (Wei and Tomita, 2001), FPM resulted in a remarkable decrease of 140 % in *WA*. It seems that embedded FPM, 3 mm below the surface, plays an important role in control of dimensional stability. Improved dimensional stability may be attributed to higher surface area of bonding between FPM and cement thus blocking the penetration of water molecules through to wood particles of the CBP (Wei and Tomita, 2001).

The bending properties of CBP manufactured in the study are presented in Table 5. *MOR* and *MOE* of the experimental CBP were significantly affected by the variables involved in the study ($p < 0.001$, $R^2 = 0.94, 0.98$). FPM seemed to have a serious effect on bending properties of CBP manufactured. Lowering the amount of wood in the mixture increases the *MOE* and *MOR* of the boards from 2485 N/mm² to 3241 N/mm² and 10.2 N/mm² to 11.9 N/mm², respectively. Since stiffness of the CBP is dependent on the amount of cement, which is more rigid than wood, it is expected to achieve higher *MOE* values with lower wood particle content (Moslemi and Pfister, 1987). The use of FPM resulted in an overall increase of 105 % in bending MOE (1876 N/mm² to 3850) of the manufactured boards. The use of different chemical accelerators also showed significantly different results in *MOE* values of CBP manufactured. The use of $CaCl_2$ yielded higher average *MOE* values than other chemicals used.

In general, lowering cement–wood ratio results higher *MOR* (Moslemi and Pfister, 1987; Papadopoulos *et al*., 2006), which is contrary to the findings of the present study. This may be a result of interactions of

Table 5 Bending properties of boards
Tablica 5. Savojna svojstva ploča

Wood – cement ratio *Omjer drvo – cement*	**Accelerator used** *Dodani ubrzivač*	**Plaster net** *Fasadna mrežica*	***MOR*****, N/mm²**	***MOE*****, N/mm²**
33 % wood	$CaCl_2$	yes	15.45 (0.35)*	3903 (276)
		no	10.95 (0.12)	3353 (276)
	KCl	yes	17.11 (0.33)	4235 (234)
		no	5.95 (0.66)	1354 (26)
	Daraset	yes	11.52 (0.17)	4457 (637)
		no	10.71 (0.72)	2145 (119)
50 % wood	$CaCl_2$	yes	15.54 (0.74)	3322 (112)
		no	9.86 (0.33)	3073 (907)
	KCl	yes	11.88 (0.121)	3660 (881)
		no	7.05 (0.65)	633 (30)
	Daraset	yes	13.15 (0.15)	4247 (253)
		no	3.72 (0.33)	702 (24)

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

the variables used in the study. The use of FPM created an overall increase of 75 % in bending *MOR* (8.04 N/mm^2 to 14.1 N/mm^2). The use of different chemical accelerators also resulted in significantly deviating results in *MOR* values of CBP manufactured. The use of $CaCl_2$ yielded higher average *MOR* (12.95 N/mm^2) values than other chemicals used.

Compared to 15.6 % - 23.2 % *MOR* increase obtained by the use of discontinuous glass fiber (Wei and Tomita, 2001) and 52 % increase of bagasse (Aggarwal, 1995), FPM provides superior bending resistance.

The average *MOR* values of the experimental CBP with FPM satisfy the minimum standard value of 9 N/mm^2 required by the standard (TS EN 634-2). *MOR* values of CBP without FPM are mostly inferior. *MOR* values are satisfied when $CaCl_2$ is used as accelerator. No experimental CBP resulted in an acceptable *MOE* value required by the standards (TS EN 634-2), although *MOE* values were increased with the use of FPM. Higher *MOE* may be achieved with lower particle content for cement bonded boards (Al Rim *et al*., 1999) or with higher density (Moslemi and Pfister, 1987; Oyagade, 1990). According to Bejo *et al*. (2005), mechanical properties of CBP may be increased when densification is increased. Since fiberglass in general has superior tensile strength and stiffness, two plies of FPM make great contribution to the bending properties of CBP.

The main reason behind the inadequate physical and mechanical properties of the boards manufactured in the study could be the use of only coarse wood particles. Coarse particles could not be easily compressed as fine particles, which resulted in some gaps or voids during manufacturing, thus yielding undesirable board properties. Bending properties of the CBP may also be improved by the application of pretreatments, which were found acceptable for many lingo-cellulosic materials (Moslemi *et al*., 1983; Lee, 1984; Zhengtian and Moslemi, 1985; Lee and Short, 1989).

4 CONCLUSIONS
4. ZAKLJUČAK

The effects of FPM as reinforcement on selected mechanical and physical properties of CBP were studied. The results indicated that embedment of two plies of FPM near the surface of CBP improves *MOE* and *MOR* as well as resistance to *TS* and *WA*. An application of two plies of FPM increased *MOE* and *MOR* of CBP by 75 % and 105 %, respectively, reduced *WA* up to 140 % percent, and reduced TS up to 80 %. FPM could be used for improvement of CBP properties, as an alternative to other pretreatments, chemical additives or reinforcing materials. Besides improving inadequate board properties, the application of FPM may help lowering the weight of the CBP, which is a disadvantage compared to similar wood base composites. Furthermore, utilization of agricultural residues, which usually result in inferior board properties in the manufacture of CBP, may be facilitated.

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MOR and *MOE* of Serbian Spruce (*Picea omorika* Pančić/Purkyně) Wood from Natural Stands

Modul loma i modul elastičnosti drva omorike (*Picea omorika* Pančić/Purkyně) iz prirodnih sastojina

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ABSTRACT • *The paper presents the results of testing the bending stress of Serbian spruce wood from natural stands. In testing the samples, in addition to the modulus of rupture, the bending stress at the proportionality limit, the ratio between the stress at the proportionality limit and the modulus of rupture as well as the modulus of elasticity of wood were determined. The study included nine trees from natural stands, and a total of 261 samples were tested. Regression analysis determined the dependences of these mechanical properties on the annual ring width, the proportion of late wood and wood density, as well as the dependence of the modulus of elasticity on the modulus of rupture.*

Keywords: *Picea omorika; modulus of rupture; modulus of elasticity; natural stands*

SAŽETAK • *U radu su prikazani rezultati ispitivanja naprezanja pri savijanju drva Pančićeve omorike podrijetlom iz prirodnih sastojina. Osim modula loma, pri ispitivanju uzoraka utvrđeni su i savojno naprezanje u točki proporcionalnosti, odnos čvrstoće na savijanje u točki proporcionalnosti i modula loma, kao i modul elastičnosti drva. Istraživanje je obuhvatilo devet stabala iz prirodnih sastojina, a ispitan je ukupno 261 uzorak. Regresijskom su analizom utvrđeni odnosi navedenih mehaničkih svojstava i širine goda, udjela kasnog drva i gustoće drva, kao i odnos modula elastičnosti i modula loma.*

Ključne riječi: *Picea omorika; modul loma; modul elastičnosti; prirodne sastojine*

1 INTRODUCTION
1. UVOD

Serbian spruce (*Picea omorika* Pančić/Purkyně) is naturally distributed in Bosnia and Herzegovina and Serbia in the area around the middle and lower reaches of the Drina River. It is found on steep, rocky cliffs, mostly on limestone, rarely serpentine, at altitudes of 300 to 1700 m (Vidaković and Franjić, 2004).

Serbian spruce is interesting from many aspects, both to the science and profession, and to the general public. A large number of scientific and professional papers deal with various issues related to Serbian

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spruce, ranging from its distribution, the configuration of the terrain as well as the habitat where it occurs (Fukarek, 1935, 1950; Čolić, 1953, 1957) to the latest genetic research (Aleksić and Geburek, 2010, 2014; Mataruga *et al*., 2020). However, it is very difficult to find information in the literature concerning the mechanical properties of Serbian spruce wood, especially the wood originating from natural stands. Lukić-Simonović (1970) investigated in more detail the mechanical properties of Serbian spruce from its natural stands in western Serbia, while no such research has been done in Bosnia and Herzegovina.

Modulus of rupture (*MOR*) and modulus of elasticity (*MOE*) are among the most important parameters for determining the wood quality, especially for the usage of wood in construction (Bodig and Jayne, 1982). The modulus of elasticity, as a measure of stiffness, can be used to estimate strength because there is a positive correlation between stiffness and strength (Panshin and de Zeeuw, 1980). Popović (1990) states that the ratio between the bending stress at the proportionality limit and the modulus of rupture is a very important fact in the practical application of wood, where, if this ratio is known, the use of loads exceeding these values and leading to permanent deformation or fracture can be prevented.

Knowledge of the stress at the proportionality limit, maximum stress and their ratio, as well as the knowledge of the effect of certain factors on the specified bending characteristics has both scientific and practical significance. These factors are very important for designing the bending tools and for determination the stress that products can be exposed to during use (Svoboda *et al*., 2017).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The material for the research comes from three localities of the natural stands of Serbian spruce managed by the FE Panos - Višegrad. These are Gostilja (GO), Stolac 1 (S1) and Stolac 2 (S2). Location GO is at 1130 m above sea level, and the total area of this stand is 25.8 ha. S1 is located at 1200 m above sea level, and S2 at 960 m above sea level, while the total area of the stands is 29.5 ha.

According to Mataruga *et al*. (2011), Serbian spruce has been listed as an endangered plant species from 2010. Considering that, the selection of trees was taken into account when planning the research so that the relevant information was obtained with a minimum number of trees. From each locality, three trees were selected and harvested, and the average values of their characteristics by locations are given in Table 1.

Figure 1 Bending testing
Slika 1. Ispitivanje svojstava pri savijanju

Three logs, 1.2 m long, were cut from each tree. One log was taken from a height of 1.3 m, one from the part of the bole just below the first green branch, and one log was taken from the height in the middle between the two mentioned heights. From them, 30 mm thick radial planks were cut, out of which, after natural drying for three months and processing on the thickener, they were reduced to a thickness of 20 mm. From them, samples (20 mm × 20 mm × 320 mm) for bending testing were made. The test was performed at the Material Testing Laboratory at the Faculty of Mechanical Engineering, University of Banja Luka, using a Messphysik "Beta 200", a universal testing machine used to test mechanical properties of different types of materials specialized in the testing of materials (Figure 1). The ISO 3133:1975 standard was used for bending testing.

For this test, 261 samples were selected. During selection, samples that are closest to the pith and that have natural defects were avoided. Before testing, the mass and dimensions in radial, tangential and axial directions of samples were measured. These data were used to calculate the wood density at the time of testing using Eq. 1:

$$\rho = \frac{m}{T \cdot R \cdot A} \cdot 1000 \left(\frac{g}{cm^3}\right) \quad (1)$$

Where:

m – sample mass at the time of testing (g)

T, R, A – sample dimensions in tangential, radial and axial direction at the time of testing (mm)

The samples were scanned in cross-section in order to determine the average annual ring width and the average proportion of late wood, using CDendro 7.6 and CooRecorder 7.6. Three-point bending tests were carried out to investigate the static behavior of sam-

Table 1 Average values of characteristics of Serbian spruce trees
Tablica 1. Prosječne vrijednosti svojstava stabala Pančićeve omorike

Location *Lokalitet*	**Characteristics of trees** / *Svojstva stabala*			
	Number of rings at 0.3 m *Broj godova na 0,3* m	**Diameter at brest height, cm** *Prsni promjer,* cm	**Tree height, m** *Visina stabla*, m	**Trunk length, m** *Duljina debla*, m
GO	112	29.13	22.2	18.5
S1	131	30.00	28.4	24.4
S2	128	30.97	25.8	20.7
Average value *Prosječna vrijednost*	124	30.03	25.4	21.2

ples. Samples were placed so that they were on one radial side and the distance between the supports was 280 mm. The loading speed was set to 10 mm/min. Load-deflection graphs were obtained by testing and they were used to obtain the values of bending stress at the proportionality limit, *MOR* and *MOE*. The calculation formulas for *MOR* (Eq. 2) and bending stress at the proportionality limit (Eq. 3) are:

$$\sigma_s = \frac{3 \cdot F_{max} \cdot l}{2 \cdot b \cdot h^2} \ (\text{MPa}) \qquad (2)$$

$$\sigma_{sp} = \frac{3 \cdot F_p \cdot l}{2 \cdot b \cdot h^2} \ (\text{MPa}) \qquad (3)$$

Where:

F_{max} – maximum load (N)

F_p – load at proportionality limit (N)

l – distance between supports (mm)

b – width of the sample (mm)

h – height of the sample (mm)

The calculation formula for *MOE* is:

$$E_s = \frac{F \cdot l^3}{4 \cdot b \cdot h^3 \cdot f} \ (\text{MPa}) \qquad (4)$$

Where:

F – load from elastic zone (N)

l – distance between supports (mm)

b – width of the sample (mm)

h – height of the sample (mm)

f – deflection (mm).

The calculation formula for the ratio between the bending stress at the proportionality limit and *MOR* is:

$$P_\sigma = \frac{\sigma_{sp}}{\sigma_s} \cdot 100 \ (\%) \qquad (5)$$

After the test, all samples were weighed and then dried to an oven dry state to determine moisture content at the time of testing using Eq. 6:

$$v_a = \frac{m - m_0}{m_0} \cdot 100 \ (\%) \qquad (6)$$

Where:

m – sample mass at the time of testing (g)

m_o – sample mass in oven dry state (g)

In order to compare the obtained values of *MOR* and *MOE* with literature data, results of bending test were reduced to values at standard moisture content (12 %) using Eq. 7:

$$\sigma_{s12}(E_{sv}) = \sigma_{sv}(E_{sv}) \cdot [1 + 0.02 \cdot (v_a - 12)] \ (\text{MPa}) \qquad (7)$$

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The average values of wood density and moisture content at the time of testing the samples from all three locations are given in Table 2. The average density of investigated Serbian spruce wood is 0.517 g/cm³ at a moisture content of 15 %, while the average value of Serbian spruce wood density investigated by Lukić-Simonović (1955), from the territory of Serbia, at the same moisture content, was 0.482 g/cm³. The average annual ring width of investigated Serbian spruce wood is 1.76 mm and the average proportion of late wood is 15.24 %.

Table 3 shows the average values and other statistical indicators of *MOR* at standard moisture content by locations. Trees from GO have the lowest average values of *MOR* (84.23 MPa), and trees from S1 the largest (94.86 MPa). The smallest variation in *MOR* was found at S2 (12.19%) and the largest at GO (16.17 %).

The average value of *MOR* at all locations (89.72 MPa) is slightly lower than the *MOR* at standard moisture content obtained in research by Lukić-Simonović (1970), namely 96.7 MPa. Studying the *MOR* of Serbian spruce wood from plantations in Germany, Kommert (1993) found that its average values at moisture content of 12 % are in the range of 57.6 MPa (average density of samples is 0.424 g/cm³) to 86 MPa (average density of samples is 0.510 g/cm³).

As the number of studies on the mechanical properties of Serbian spruce wood is limited, comparison with the mechanical properties of spruce wood was made. According to Karahasanović (1992), the *MOR* of spruce at a moisture content of (12 ± 3) % is 64 MPa. Gorišek *et al.* (2004) stated that the average *MOR* of spruce from Slovenia is 77.4 MPa, while Pushinskis *et al*. (2002) tested spruce from western Latvia and found that the average *MOR* is 106.42 MPa.

In addition to the *MOR*, the bending stress at the proportionality limit was determined, as well as the ratio between the bending stress at the proportionality limit and *MOR*. The obtained values are shown in Table 4 and 5.

The average bending stress at the proportionality limit for all three locations is 44.72 MPa, while the coefficient of variation is 15.92 %. The average ratio of

Table 2 Average values of annual rings width, proportion of late wood, density and moisture content of wood at the moment of testing
Tablica 2. Prosječne vrijednosti širine goda, udio kasnog drva, gustoće i sadržaja vode u drvu u trenutku ispitivanja

Location *Lokalitet*	***arw***	***plw***	***n***	v_a	***ρ***		
	AV, mm	*AV*, %		*AV*, %	*AV*, g/cm³	*SD*, %	*CV*, %
S1	1.66	15.64	88	14.77	0.534	0.035	6.61
S2	1.68	15.44	83	15.15	0.509	0.024	4.62
GO	1.90	14.80	90	15.30	0.508	0.028	5.54
	1.76	15.24	261	15.07	0.517	0.032	6.12

n – number of tested samples / *broj testiranih uzoraka*; v_a – moisture content at the moment of testing / *sadržaj vode u trenutku ispitivanja*; *arw* – annual ring width / *širina goda*; *plw* – proportion of late wood / *udio kasnog drva*; *ρ* – density of wood at the moment of testing / *gustoća drva u trenutku ispitivanja*; *AV* – average value / *prosječna vrijednost*; *SD* – standard deviation / *standardna devijacija*; *CV* – coefficient of variation / *koeficijent varijacije*

Table 3 Statistical analysis of *MOR* of Serbian spruce from three different stem heights
Tablica 3. Statistička analiza modula loma Pančićeve omorike na uzorcima s tri različite visine debla

Location *Lokalitet*	**Height of stem** *Visina debla*	***n***	σ_s,				
			AV, MPa	-95, MPa	+95, MPa	*SD*, MPa	*CV*, %
S1	I	30	94.97	90.55	99.39	11.84	12.47
	II	30	95.82	90.65	100.99	13.84	14.44
	III	28	94.47	90.05	98.89	11.40	12.07
		88	95.10	92.50	97.71	12.30	12.93
S2	I	25	84.61	78.37	90.84	15.11	17.86
	II	31	94.61	92.46	96.76	5.87	6.20
	III	27	89.59	86.09	93.08	8.84	9.87
		83	89.96	87.56	92.37	11.01	12.24
GO	I	30	84.00	78.62	89.37	14.39	17.13
	II	30	84.13	80.40	87.87	9.99	11.88
	III	30	84.55	78.50	90.60	16.20	19.16
		90	84.23	81.37	87.08	13.62	16.17
		261	89.72	88.12	91.32	13.14	14.64

σ_s – modulus of rupture, *MOR* / *modul loma*; *n* – number of tested samples / *broj testiranih uzoraka*; *AV* – average value / *prosječna vrijednost*; -95 – lower boundary of estimation interval with a probability of 95 % / *donja granica intervala procjene s vjerojatnošću od 95 %*; +95 – upper boundary of estimation interval with a probability of 95 % / *gornja granica intervala procjene s vjerojatnošću od 95 %*; *SD* – standard deviation / *standardna devijacija*; *CV* – coefficient of variation / *koeficijent varijacije*

the bending stress at the proportionality limit for all tested samples is 50.18 % of the maximum bending stress, while the variation is 12.73 %. Popović (1990) states that the bending stress at the proportionality limit for beech wood is on average 54.4 % and 56 % in the radial and tangential direction, respectively, from the value of the maximum bending stress.

Table 6 shows the average values of modulus of elasticity (*MOE*) at standard moisture content as well as other statistical parameters. The lowest average value of *MOE* was found in trees from GO (10953.99 MPa), and the highest in trees from S2 (12161.92 MPa). The smallest variation of *MOE* is at S2 (9.83 %) and the largest at S1 (21.46 %).

According to Šoškić and Popović (2002), the average value of *MOE* for spruce is 11000 MPa, which is approximately the value of *MOE* for Serbian spruce obtained in this study (11566.23 MPa). Johansson and Kliger (2000) state that the average value of MOE determined from bending for spruce is 12500 MPa, according to Aanerød (2014) 12800 MPa, with a coefficient of variation of 19.5 %, while according to Pushinskis *et al*. (2002) it is 13660 MPa.

Analysis of the variance of *MOR* showed that there is statistically significant difference between the locations, while there is no difference between the locations in the ratio between bending stress at the proportionality limit and *MOR*. Using the Duncan test in the analysis of the variance of MOE, the locations were classified into two homogeneous groups, i.e. it was noticed that there is no statistically significant difference between the locations S1 and S2. In the analysis of the variance of the bending stress at the proportionality limit, locations were classified into two homogeneous

Table 4 Statistical analysis of bending stress at proportionality limit of Serbian spruce from three different stem heights
Tablica 4. Statistička analiza savojnog naprezanja u točki proporcionalnosti Pančićeve omorike na uzorcima s tri različite visine debla

Location *Lokalitet*	**Height of stem** *Visina debla*	***n***	σ_{sp}				
			AV, MPa	-95, MPa	+95, MPa	*SD*, MPa	*CV*, %
S1	I	30	49.67	47.04	52.31	7.06	14.20
	II	30	47.10	44.00	50.20	8.30	17.63
	III	28	47.85	46.14	49.55	4.40	9.20
		88	48.21	46.76	49.66	6.84	14.19
S2	I	25	42.73	40.27	45.20	5.98	13.99
	II	31	45.45	43.57	47.33	5.13	11.29
	III	27	42.78	40.45	45.11	5.89	13.78
		83	43.76	42.51	45.01	5.73	13.09
GO	I	30	41.17	38.64	43.70	6.77	16.45
	II	30	41.47	38.77	44.16	7.22	17.41
	III	30	43.89	41.03	46.76	7.67	17.46
		90	42.18	40.66	43.70	7.25	17.19
		261	44.72	43.85	45.58	7.12	15.92

σ_{sp} – bending stress at proportionality limit / *savojno naprezanje u točki proporcionalnosti, n* – number of tested samples / *broj testiranih uzoraka*; *AV* – average value / *prosječna vrijednost*; -95 – lower boundary of estimation interval with a probability of 95 % / *donja granica intervala procjene s vjerojatnošću od 95 %*; +95 – upper boundary of estimation interval with a probability of 95 % / *gornja granica intervala procjene s vjerojatnošću od 95 %*; *SD* – standard deviation / *standardna devijacija*; *CV* – coefficient of variation / *koeficijent varijacije*

Table 5 Statistical analysis of ratio between bending stress at proportionality limit and *MOR* of Serbian spruce from three different stem heights
Tablica 5. Statistička analiza odnosa savojnog naprezanja u točki proporcionalnosti i modula loma Pančićeve omorike na uzorcima s tri različite visine debla

Location *Lokalitet*	**Height of stem** *Visina debla*	***n***	P_σ, %				
			AV	-95	+95	*SD*	*CV*
S1	I	30	52.35	50.82	53.87	4.08	7.80
	II	30	49.16	47.41	50.92	4.70	9.57
	III	28	51.14	48.92	53.36	5.73	11.20
		88	50.88	49.82	51.94	4.99	9.81
S2	I	25	51.61	48.00	55.22	8.75	16.95
	II	31	48.01	46.49	49.53	4.15	8.64
	III	27	47.82	45.77	49.87	5.18	10.84
		83	49.03	47.65	50.42	6.33	12.92
GO	I	30	49.53	46.85	52.20	7.16	14.45
	II	30	49.50	46.51	52.49	8.00	16.17
	III	30	52.67	50.04	55.31	7.07	13.42
		90	50.57	49.00	52.14	7.49	14.81
		261	50.18	49.41	50.96	6.39	12.73

P_σ – ratio between bending stress at proportionality limit and *MOR* / *odnos savojnog naprezanja u točki proporcionalnosti i modula loma*; *n* – number of tested samples / *broj testiranih uzoraka*; *AV* – average value / *prosječna vrijednost*; -95 – lower boundary of estimation interval with a probability of 95 % / *donja granica intervala procjene s vjerojatnošću od 95 %*; +95 – upper boundary of estimation interval with a probability of 95 % / *gornja granica intervala procjene s vjerojatnošću od 95 %*; *SD* – standard deviation / *standardna devijacija*; *CV* – coefficient of variation / *koeficijent varijacije*

Table 6 Statistical analysis of *MOE* of Serbian spruce from three different stem heights
Tablica 6. Statistička analiza modula elastičnosti Pančićeve omorike na uzorcima s tri različite visine debla

Location *Lokalitet*	**Height of stem** *Visina debla*	***n***	E_s				
			AV, MPa	-95, MPa	+95, MPa	*SD*, MPa	*CV*, %
S1	I	24	11267.32	10400.02	12134.63	2053.95	18.23
	II	27	12182.87	11216.82	13148.92	2442.07	20.05
	III	26	11442.37	10597.84	12286.91	2090.90	18.27
		77	11647.47	11144.18	12150.76	2529.33	21.46
S2	I	25	11699.33	11118.42	12280.24	1407.31	12.03
	II	30	12625.86	12240.59	13011.12	1031.75	8.17
	III	27	12074.75	11684.79	12464.71	985.78	8.16
		82	12161.92	11899.33	12424.50	1195.06	9.83
GO	I	30	10674.33	10053.79	11294.88	1661.86	15.57
	II	30	10879.25	10313.77	11444.72	1514.37	13.92
	III	30	11308.40	10649.02	11967.78	1765.85	15.62
		90	10953.99	10607.69	11300.29	1653.42	15.09
		249	11566.23	11342.61	11789.85	1791.57	15.49

E_s – modulus of elasticity (*MOE*) / *modul elastičnosti*, *n* – number of tested samples / *broj testiranih uzoraka*; *AV* – average value / *prosječna vrijednost*; -95 – lower boundary of estimation interval with a probability of 95 % / *donja granica intervala procjene s vjerojatnošću od 95 %*; +95 – upper boundary of the estimation interval with a probability of 95 % / *gornja granica intervala procjene s vjerojatnošću od 95 %*; *SD* – standard deviation / *standardna devijacija*; *CV* – coefficient of variation / *koeficijent varijacije*

Table 7 Analysis of variation of *MOR*, *MOE*, bending stress at proportionality limit, ratio between bending stress at proportionality limit and *MOR*
Tablica 7. Analiza varijance modula loma, modula elastičnosti i savojnog naprezanja na granici proporcionalnosti te odnosa savojnog naprezanja na granici proporcionalnosti i modula loma

	Location / *Lokalitet*			**ANOVA**		
	S1	S2	GO	*F*	*p*	Post-hoc*
σ_s, MPa	95.10[c]	89.96[b]	84.23[a]	17.16	0.0000	3
E_s, MPa	11647,47[a]	12161.92[a]	10566.23[b]	8.18	0.0004	2
σ_{sp}, MPa	48.21[b]	43.76[a]	42.18[a]	19.53	0.0000	2
P_σ, %	50.88[a]	49.03[a]	50.57[a]	2.04	0.1320	1

*Number of homogeneous groups by Duncan's test / *broj homogenih grupa prema Duncanovu testu*
[a, b, c] Homogeneous groups / *homogene grupe*

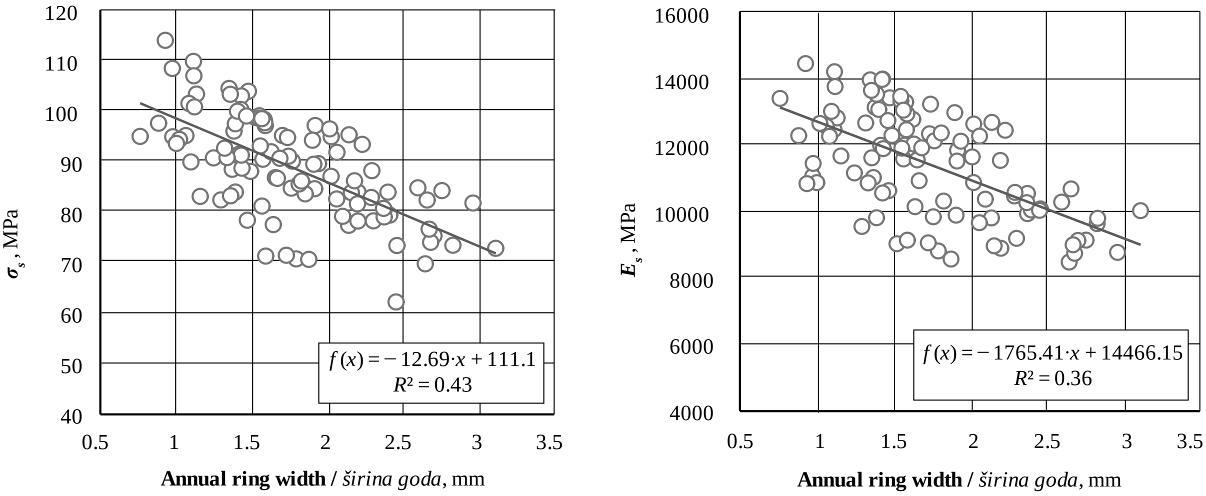

Figure 2 Dependence of *MOR* and *MOE* on annual ring width
Slika 2. Ovisnost modula loma i modula elastičnosti o širini goda

groups, i.e. the analysis showed that there is no statistically significant difference between sites S2 and GO (Table 7).

In addition to wood density, which is considered to be the most significant factor affecting wood properties, the influence of compression and juvenile wood, the angle of the microfibrils and the width of the growth ring, which have the same, if not greater, influence on the wood properties, should not be neglected (Alteryac *et al.*, 2006). The influence of the annual ring width on the MOR and MOE can be seen in Figure 2. According to Roemer-Orphal table for determining the strength of correlation dependence (according to Vasilj, 2000), there is a strong negative correlation between these parameters.

Proportion of late wood has a positive effect on *MOR* and *MOE* (Figure 3). Based on the correlation coefficients, it can be concluded that the correlation is moderate.

The dependence of *MOR* on wood density has been tested by a number of researchers. Thus, Schlyter (1927) states that this dependence is linear, while according to Baumann (1922) it is curvilinear. In any case, as the density of wood increases, the bending strength also increases, which is confirmed by this research (Figure 4). As wood density of Serbian spruce grows, so does the modulus of elasticity, although these correlations are slightly smaller than the correlations between density and *MOR*. In their study, Raiskila *et al*. (2006) state that the same is the case with spruce wood.

In order to obtain a model for strength estimation, the regression analysis included the dependence of *MOR* on annual ring width and wood density. Multiple regression equation (Function 8) was obtained by stepwise multiple regression method. The parameters of the obtained equation and the regression characteristics (Table 8) show that there is a pronounced dependence of *MOR* on the included elements. All regression coefficients are statistically significant at the $p<0.001$ level, as is the regression as a whole. On the basis of the coefficient of determination, 33 % of the variation of the *MOR* value is explained by the variation of the observed elements.

$$\sigma_s = a + b \cdot arw^{\,2} + c \cdot \rho^2 \quad (8)$$

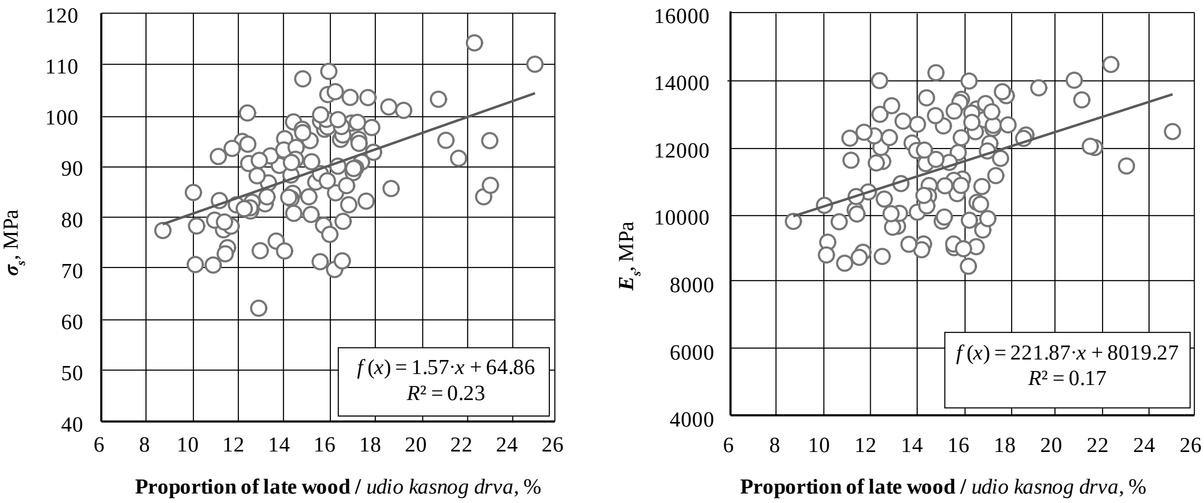

Figure 3 Dependence of *MOR* and *MOE* on proportion of late wood
Slika 3. Ovisnost modula loma i modula elastičnosti o udjelu kasnog drva

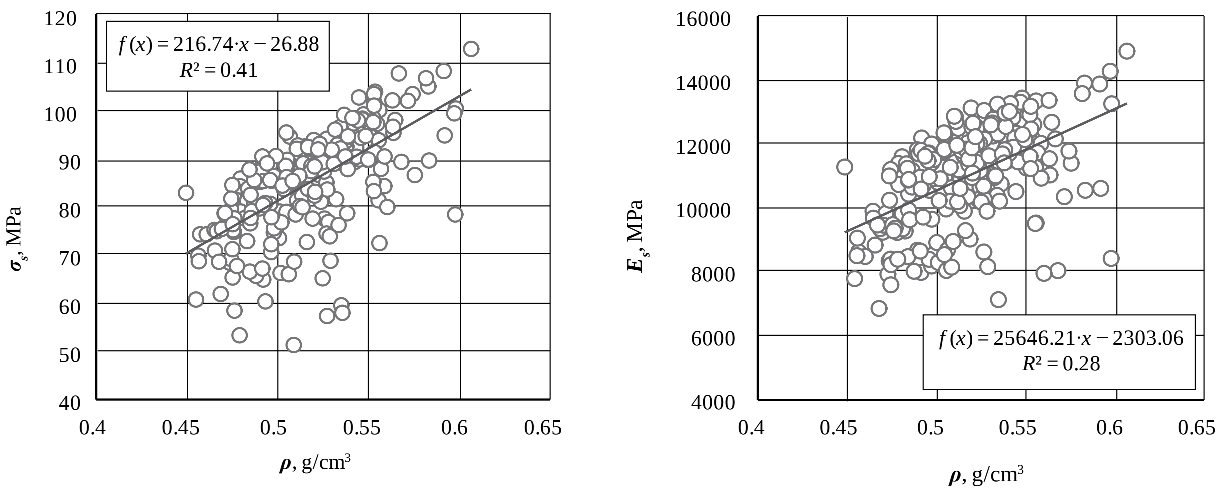

Figure 4 Dependence of *MOR* and *MOE* on wood density at the moment of testing
Slika 4. Ovisnost modula loma i modula elastičnosti o gustoći drva u trenutku ispitivanja

Generally, the *MOE* is considered the most important strength predictor parameter (Baar *et al*., 2015). Investigating the correlation between *MOR* and *MOE* in spruce, Johansson and Kliger (2000) found that the coefficient of determination was 0.51. The equation of relation between bending strength and modulus of elasticity reported by Johansson *et al*. (1992) is:

$$\sigma_s = 0.00383 \cdot E_s - 2.4 \quad (9)$$

The dependence of *MOR* on *MOE* examined in this paper can be seen in Figure 5. The correlation is linear and positive, and based on the correlation coefficient of 0.77, it can be concluded that the correlation is very strong.

4 CONCLUSIONS
4. ZAKLJUČAK

The results obtained in this paper have substantially improved the knowledge of certain mechanical properties of Serbian spruce from the territory of Bosnia and Herzegovina. It can be observed that Serbian spruce

Table 8 Regression characteristics (dependence of *MOR* on annual ring width and wood density at the moment of testing)
Tablica 8. Obilježja regresije (ovisnost modula loma o širini goda i gustoći drva u trenutku ispitivanja)

Regression coefficient *Koeficijent regresije*		**Std. Err. of coeff.** *Standardna pogreška koeficijenta*	***t***	***p***	S_e, **mm**	***R***	R^2	***F***	***p***	***n***
a	60.1964	10.77431	5.58703	0.000000	9.25774	0.58	0.33	25.42762	0.0000	101
b	-2.0408	0.56226	-3.62969	0.000453						
c	111.4477	36.67212	3.03903	0.003043						

S_e – standard error of regression / *standardna pogreška regresije, R* – correlation coefficient / *koeficijent korelacije,* R^2 – determination coefficient / *koeficijent determinacije*

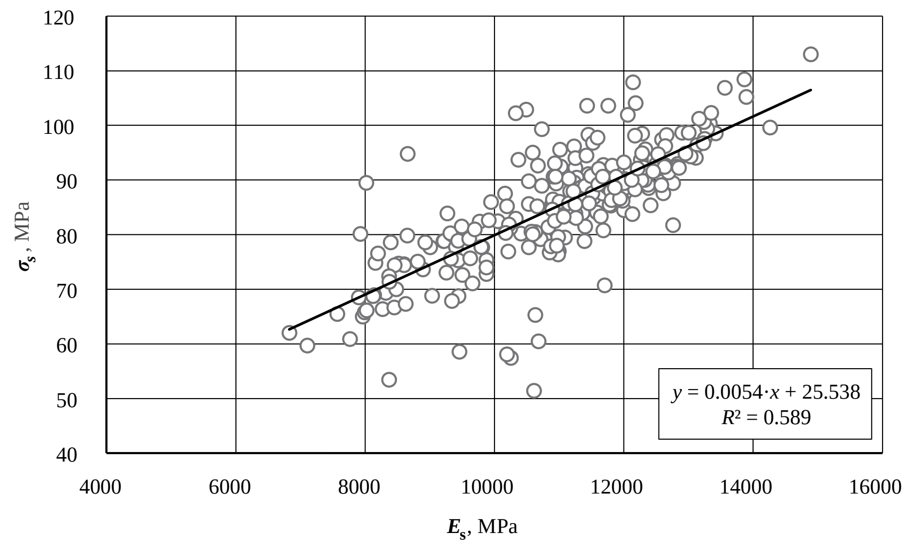

Figure 5 Dependence of *MOR* on *MOE*
Slika 5. Ovisnost modula loma o modulu elastičnosti

has quite high values of *MOR* and *MOE*. Serbian spruce is known to be a protected species and not industrially significant. However, given its good mechanical properties, consideration should be given to establishing larger surfaces of planted forests with the aim of using Serbian spruce wood as a technical wood. Since there is a correlation between the width of the annual rings and *MOR*, care should be taken to achieve optimum growth in establishing and managing the new forest.

The modulus of elasticity may be a good predictor for determining the bending strength, given the very strong correlation between these two parameters.

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An Investigation of Flexural Behavior of Pure and Hybrid Wood Composite Panels Using Weibull Analyses

Istraživanje savijanja čistih i hibridnih kompozitnih drvnih ploča uz pomoć Weibullove analize

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ABSTRACT • *The production of inexpensive wood products compared to their strength is important both in terms of economy and meeting the expectations of users. For this purpose, the use of hybrid wood products is increasing in the furniture industry. With the hybridization process, relatively cheap and flimsy material is combined with a material that has a stronger structure. Thus, stronger bonded material is manufactured cheaper. In this study, the flexural behavior of pure and hybrid wood composite panels, which were prepared by applying longitudinal jointing techniques from different wood materials, was investigated. In this context, pure chipboard, pure medium density fiberboard (MDF), chipboard-east beech and MDF-east beech hybrid wood composite panels were produced. During the hybridization process, oriental beech was combined by using the self-grooving technique in three different numbers as one row, two rows, and three rows. Flexural test results were analyzed according to the Weibull distribution method. The results of the analyses showed that the hybridization process increased the flexural strength and flexural modulus of pure wood panels by up to 214 %, and 95 %, respectively.*

Keywords: *flexural behavior; chipboard; MDF; oriental beech, Weibull analysis*

SAŽETAK • *Proizvodnja jeftinijih proizvoda od drva uz očuvanje njihove čvrstoće ima veliku važnost u ekonomskom smislu i u smislu ispunjavanja korisničkih očekivanja. Rezultat tog nastojanja jest sve veća uporaba hibridnih proizvoda od drva u industriji namještaja. Postupkom hibridizacije relativno jeftin i krhak materijal kombinira se s materijalom jače strukture te se na taj način postiže čvršći a jeftiniji materijal. U ovom je radu istraženo ponašanje čistih i hibridnih kompozitnih drvnih ploča pri savijanju, proizvedenih uzdužnim lijepljenjem različitoga drvnog materijala. Za potrebe istraživanja izrađene su čista ploča vlaknatica srednje gustoće (MDF) i hibridne kompozitne ploče od iverice i bukovine te od MDF ploče i bukovine. Tijekom postupka hibridizacije bukovi su elementi povezivani uz pomoć utora, a izrađeni su uzorci imali jedan, dva ili tri bukova elementa. Rezultati ispitivanja svojstava ploča pri savijanju analizirani su uz pomoć Weibullove distribucije. Pokazalo se da je postupak hibridizacije pridonio povećanju čvrstoće ploča na savijanje za 214 %, a modula elastičnosti za 95 %.*

Ključne riječi: *savijanje; iverica; MDF; bukovina; Weibullova analiza*

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1 INTRODUCTION
1. UVOD

Furniture used in houses or offices is faced with various loads, either directly or indirectly, depending on the place of use. These loads cause tensile, compression and bending deformations in the elements forming the furniture and their connection points. As a result of these deformations, damages occur such as breakage of wood joints or wooden structural elements. To fully understand the structural characteristics of furniture, it is necessary to analyze the mechanical behavior of joints used in wooden structures. The length, stiffness, and strength of the joints applied in wooden constructions affect the strength of the furniture system.

In the furniture industry, joints are used to connect furniture elements, reuse solid and composite wood materials that would be wasted, or to obtain larger surfaces. Straight jointing, lamp jointing, foreign slat jointing, self-slating jointing, dowel joining and edge joining are commonly used. The joining points of the wooden structural elements formed by joining are the potential error starting regions for the structure. The joining performance should be examined for the strength of the structure. Joints are usually regions where stresses are concentrated (Eshaghi *et al.*, 2013). Furniture joints are also subjected to axial, tensile or compression, shear, and bending or rotational forces. This necessitates the use of more resistant and stronger joints.

Dourado *et al.* (2019) studied the bending performance of two different wood panels, which they joined by using wood dowel connection, experimentally and numerically. Cagatay *et al.* (2012) compared the bending moment capacity and elasticity of T-type furniture joints by applying different wood materials and joining methods. Likos *et al.* (2012) investigated the effects of tenon geometry, grain orientation, and shoulder-length on the bending moment capacity and moment rotation of wood structures. Baszeń (2017) discussed the joint flexibility problem in wood light-frame structures and presented the results on rotational and axial stiffness of joint in wood light-frame structures. Also, adhesive bonding is more frequently used than mechanical joints in some wooden structures. Edgards *et al.* (2017) examined the flexural performance of wood-based sandwich panels adhesively bonded under four-point bending loading. Augeard *et al.* (2018) investigated the mechanical behavior of bonded hybrid wood-concrete beams and panels, experimentally and analytically.

Oriental beech (*Fagus orientalis* L.), Scotch pine (*Pinus slyvestris* L.), Oak (*Quercus borealis* L.), chestnut (*Castanea sativa* mill), Oriental black sea fir (*Abies nordmanniana*) and walnut (*Juglans regia L.*) massifs were used in the studies related to wood end to end-grain joint (Efe *et al.*, 2015). Using these massifs, many kinds of joining operations such as polyvinyl acetate (PVAc) glue mortise bonding (Altun *et al.,* 2010), dovetail length bonding (Efe *et al.*, 2014), L type lamp tenon bonding (Kasal *et al.*, 2015), dowel and foreign slat hybrid jointing (Tas, 2011), dowel and lamp jointed hybrid jointing (Ozgan and Kap, 2008) were performed and their joint performances were examined.

In the past, the scattering of experimental data was relatively insignificant because manufacturers used large safety factors in design. However, increasing material costs and dimensional constraints in design prevented from using large safety factors. In particular, the designer must consider the weakest member of the population, not only the mean, mode or other central tendency of the distribution. The scatter in the experimental values measured from mechanical tests for wood materials is usually described by Weibull statistical distribution, either two or three-parametric. In this study, the flexural strength and flexural modulus of elasticity of pure and hybrid wood panels under three-point bending load were investigated. For pure wood panels, wood coated chipboard and medium-density fiberboard (MDF) board materials were used. To produce hybrid composite panels, chipboard and MDF plates were individually combined with oriental beech (*Fagus orientalis* L.) using a self-grooving technique. During the production of hybrid wood composite panels, oriental beech was used as one row, two rows, and three rows, and it reinforced the weaker chipboard and MDF panels in strength. To understand the effect of the hybridization process on the flexural strength of wood panels, the test results were compared with the flexural test results of pure chipboard and pure MDF wood material. Also, two-parametric Weibull statistical analysis is used to get the variability of flexural strength and flexural modulus of pure and hybrid wood composite panels. According to the Weibull analysis, the test result, which has an 80 % reliability percentage, is accepted as the main value.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood and wood-based composite materials
2.1. Drvo i drvnokompozitni materijali

In this study, oriental beech (*Fagus orientalis* L.) wood, which is widely used in industry, was used as a reinforcement phase in the hybridization process. Chipboard coated with synthetic resins, manufactured according to TS EN 312-2 standard, and medium density fiberboard (MDF) coated with synthetic resins, produced according to TS 64-3 EN 622-3 standard, were used as wood-based composite material. Beech timber material was provided from a timber company located in Karabük in Turkey. In the selection of beech wood material, care was taken to ensure that the timber was flawless, that the fibers of timber were smooth, knot-free, and had no fungus or insect damage. The physical properties and mechanical strengths of wood and wood-based composite materials, which were used to produce hybrid wood panels, are given in Table 1.

2.2 Adhesive material
2.2. Ljepilo

Kronen Holzleim D4 polyvinyl acetate glue was used for the bonding of self-grooving test specimens. It

Table 1 Physical and mechanical properties of used wood and wood-based materials (Cai and Ross, 2010)
Tablica 1. Fizička i mehanička svojstva upotrijebljenog drva i materijala na bazi drva (Cai and Ross, 2010.)

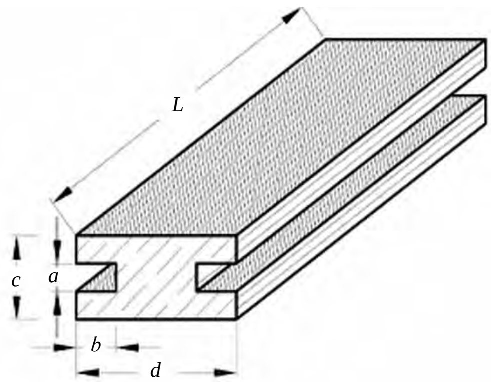
Material type *Vrsta materijala*	**Humidity, %** *Sadržaj vode, %*	**Density, g/cm³** *Gustoća, g/cm³*	**Dry density, g/cm³** *Gustoća apsolutno suhoga drva, g/cm³*	**Flexural strength, MPa** *Čvrstoća na savijanje, MPa*	**Modulus of elasticity, MPa** *Modul elastičnosti, MPa*
Oriental beech / *bukovina*	8.42	0.65	0.69	120	13400
MDF lam / *MDF lamela*	6.51	0.69	0.70	120	4435
Chipboard lam / *lamela od iverice*	5.93	0.78	0.40	27	4347

is an odorless and fireproof, easy to apply, quick hardening glue that can be used in cold temperatures and quickly solidified. However, mechanical resistance of PVAc D4 glue decreases with increasing heat. It loses bonding resistance capacity over 70 °C. On the condition that the adhesive is applied to only one surface, using 150 g/m² - 200 g/m² adhesive seems to be suitable. The physical properties of this glue were determined as press pressure of 0.1 MPa - 0.8 MPa, pH 3.5, viscosity (at 20 °C) 16000 MPa·s - 15000 MPa·s, density 1.08 g/cm³. It is stated by the manufacturer that the wood bonding time is 35-40 minutes at room temperature. TS 3891 standard procedure was used for applying PVAc D4 adhesive (Tankut and Tankut, 2009).

2.3 Preparing of flexural test samples
2.3. Priprema uzoraka za savijanje

The oriental beech wood materials, which were used for reinforcement phase, were first stacked in planks under suitable conditions for six months. Afterward, they were cut to appropriate dimensions and, with fir laths between them, kept for a year in a ventilated central heating system with no sunlight. After this stage, oriental beech planks were machined into final dimensions of 18 mm × 36 mm × 720 mm by using a thickness planer and circular sawing machine, respectively. On the edge surfaces of wooden materials, the width joining parts were prepared by opening a 1/3 width and 1/2 depth of the piece thickness in the wood profile machine. The dimensions of the oriental beech joint element used in the study are given in Figure 1.

In the experimental study, wood-based chipboard and MDF were used as the material to be strengthened.



a	*b*	*c*	*d*	*L*
6 mm	9 mm	18 mm	36 mm	720 mm

Figure 1 Oriental beech width joint element used in the production of hybrid panels
Slika 1. Širinski spojni elementi bukovine upotrijebljeni za proizvodnju hibridnih ploča

Thus, both endurances had to be increased and waste chipboard and MDF materials had to be reused in combination with more resistant materials. To this scope, chipboard and MDF materials were subjected to hybridization, where they were joined with oriental beech wood in one row, two rows, and three rows. A general view of the self-groove wood-based composite parts used in joints is given in Figure 2. The dimensions of the self-groove elements used in the edge and mid part vary depending on the number of rows of joints. The dimensions of the self- groove chipboard and MDF elements are given in Table 2.

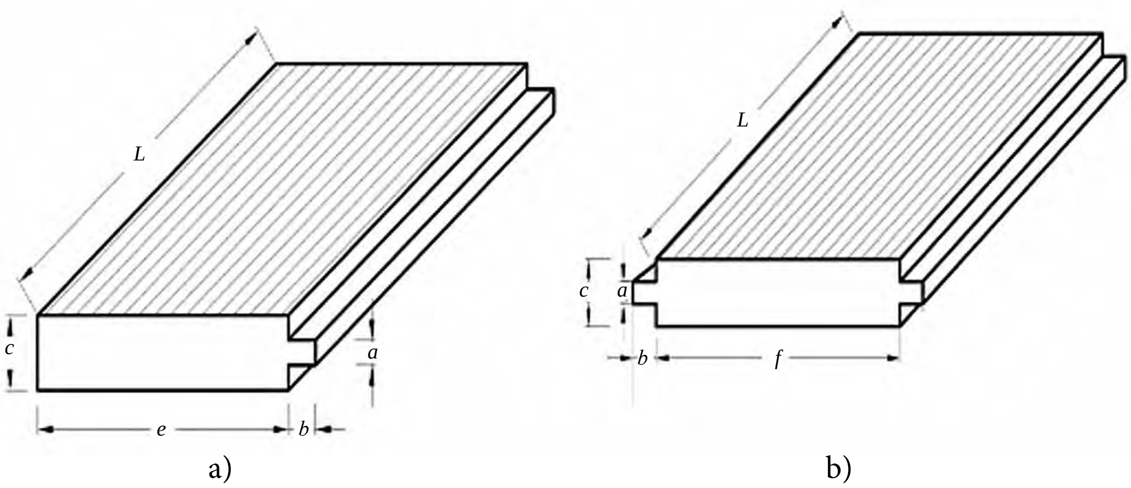


Figure 2 Self-groove wood-based composite parts used in joints for: a) edge part and b) mid part
Slika 2. Dijelovi kompozita s utorom upotrijebljeni za spajanje: a) rubni dio, b) srednji dio

Table 2 Dimensions of self- groove chipboard and MDF elements
Tablica 2. Dimenzije elemenata iverice i MDF ploče

Type of element / *Vrsta elementa*	***a*, mm**	***b*, mm**	***c*, mm**	***e*, mm**	***f*, mm**
Edge part for one row / *rubni dio za ploče s jednim bukovim elementom*	6	9	18	162	-
Edge part for two rows / *rubni dio za ploče s dva bukova elementa*	6	9	18	96	-
Edge part for three rows / *rubni dio za ploče s tri bukova elementa*	6	9	18	63	-
Mid part for two rows / *središnji dio za ploče s dva bukova elementa*	6	9	18	-	144
Mid part for three rows / *središnji dio za ploče s tri bukova elementa*	6	9	18	-	78

During the preparation of test specimens, self-groove jointing was used as one of the conventional glue bonding techniques. PVAc-D4 glue was used for conventional glue bonding. Taking into consideration the recommendations of the manufacturer, PVAc-D4 glue was applied to the joint cross-sections, groove surfaces and groove nests with an average amount of glue of 160 g/m² -180 g/m² and then the elements were bonded to each other. The glued parts were firmly squeezed together and then allowed to dry under room conditions and under pressure. The prepared hybrid wood panels are illustrated in Figure 3. The final dimensions of the dried test specimens were 18 mm × 360 mm × 720 mm.

2.4 Three-point bending test
2.4. Ispitivanje savijanja u tri točke

Static three-point bending tests were carried out on a universal tester according to TS 2478 standards. This standard specifies a method for determining the modulus of elasticity of wood in static bending by measuring deflection in the bending area (TSE 2478, 1976). Test samples with the dimensions of 18 mm × 360 mm × 720 mm were kept in the air-conditioned cabinet with a temperature of 20 ºC and 65 % relative humidity until they reached constant weight before the flexural test. Also, the equilibrium moisture value of the test atmosphere of 12 % was measured. Flexural tests were performed on a U-test 50 kN computer-controlled universal testing machine. The speed of the loading-head was set to be 2 mm/min. Load-displacement data were recorded for each sample during the test depending on time. Figure 4 shows, schematically, the three-point bending test setup. In the flexural tests, ten test replicates were performed for pure and hybrid wood composite panels.

According to the data obtained from the flexural tests, the flexural strengths and flexural modules of the pure panels and hybrid wood composite panels were calculated according to Eq. 1 and Eq. 2, respectively.

$$\sigma_f = \frac{3 \cdot P_{cr} \cdot L_S}{2 \cdot b \cdot h^2} \tag{1}$$

$$E_f = \frac{L_S^3 \cdot m}{4 \cdot b \cdot h^3} \tag{2}$$

Where: P_{cr} denotes the damage load value of the test sample, L_S span width, b is the width of the test sample, h is the height of the test sample and m is the slope of the load-displacement curve.

2.5 Weibull distribution analysis
2.5. Weibullova distribucija

In hand-made production, it is not expected that every material produced will have the same physical and mechanical properties. No matter how precise the hand-made production is, the quality of the production

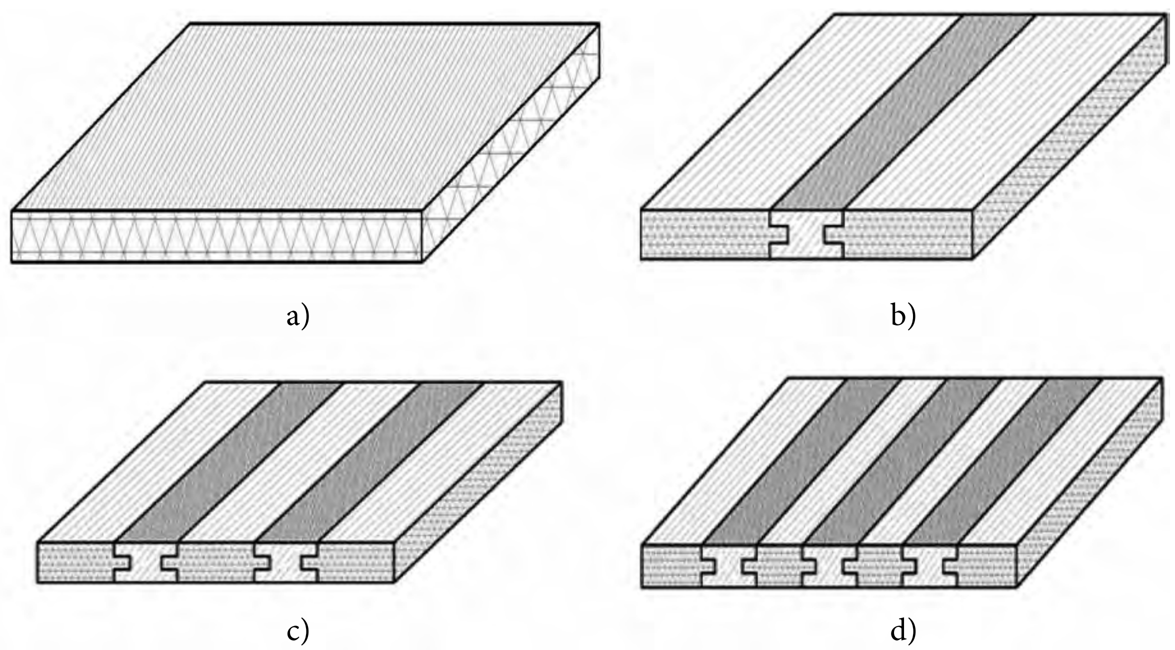


Figure 3 Flexural test specimens: a) pure, b) one-row reinforced, c) two-rows reinforced and d) three-rows reinforced
Slika 3. Uzorci za ispitivanje savijanja: a) čisti, b) ojačani jednim bukovim elementom, c) ojačani dvama bukovim elementima, d) ojačani trima bukovim elementima

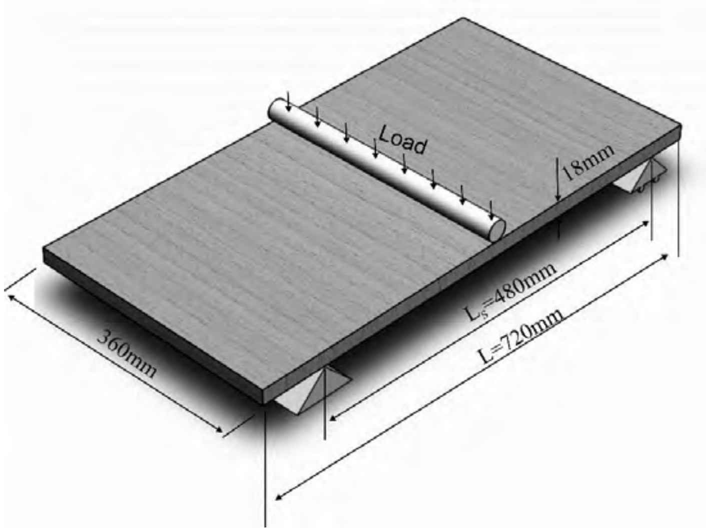


Figure 4 Three-point bending test setup
Slika 4. Ispitivanje savijanja u tri točke

will have lower standards than the production made by sensitive machines. In this framework, the reliability of the test results of hand-made materials is important. In the literature, in most of the experimental studies with repeated tests, the average test results were taken as the main value. The average value does not always represent the actual result. This situation obligates the reliability analysis of the test results. The Weibull distribution, which was put forward by Swedish mathematician Ernst Hjalmar Waloddi Weibull, is one of the most widely used methods in reliability problems (Karabulut *et al.*, 2018)

The most widely used distribution model in the literature is the Weibull statistical analysis with two and three parameters. In the present study, two-parameter Weibull statistical analysis is used to get the variability of flexural strength and flexural modulus of pure and hybrid wood composite panels. The experimental data given in Tables 3 were modeled by a linear curve fit by using Weibull distribution. Weibull distribution, which can be used for damage analysis of wood materials, was considered. The probability density function (PDF) and the associated cumulative density function (CDF) for two-parametric Weibull distribution are given in Eq. 3 and Eq. 4 (Selmy *et al.*, 2014; Karabulut *et al.*, 2018)

$$PDF(x) = \left(\frac{\beta}{\alpha}\right)\left(\frac{x}{\alpha}\right) exp\left[-\left(\frac{\beta}{\alpha}\right)^{\beta}\right] \quad (3)$$

$$CDF(x) = 1 - exp\left[-\left(\frac{\beta}{\alpha}\right)^{\beta}\right], \beta \geq 0, \alpha \geq 0 \quad (4)$$

Where x presents the random variable value (experimental results such as flexural stress or flexural modulus), β is the shape parameter or Weibull slope, and α represents characteristic life or scale parameter. The shape (β) and scale (α) parameters, which were obtained by Weibull analysis, are given for pure and hybrid composite wood panels in Tables 3 and 4.

Table 3 Shape and scale parameters of pure and MDF- oriental beech hybrid composite wood panels for flexural test
Tablica 3. Parametri oblika i skale za ispitivanje savijanja čiste MDF ploče i hibridne kompozitne drvne ploče MDF – bukovina

Material type / *Vrsta materijala*	**Flexural stress** / *Čvrstoća na savijanje*		**Flexural modulus** / *Modul elastičnosti*	
	β	α, MPa	β	α, MPa
Pure MDF / *čisti MDF*	8.241	22.565	11.619	3039.427
One row hybrid *hibrid s jednim elementom*	8.393	31.941	9.408	4566.925
Two rows hybrid / *hibrid s dva elementa*	12.723	37.929	24.150	5060.702
Three rows hybrid / *hibrid s tri elementa*	12.830	51.013	13.612	5680.379

Table 4 Shape and scale parameters of pure and chipboard- oriental beech hybrid composite wood panels for flexural test
Tablica 4. Parametri oblika i skale za ispitivanje savijanja čiste iverice i hibridne kompozitne drvne ploče iverica – bukovina

Material type / *Vrsta materijala*	**Flexural stress** / *Čvrstoća na savijanje*		**Flexural modulus** / *Modul elastičnosti*	
	β	α, MPa	β	α, MPa
Pure Chipboard / *čista iverica*	6.718	15.874	9.555	2985.543
One row hybrid *hibrid s jednim elementom*	4.904	22.233	8.003	4427.424
Two rows hybrid / *hibrid s dva elementa*	8.287	33.006	20.983	5033.132
Three rows hybrid *hibrid s tri elementa*	7.299	49.409	33.886	5511.588

The reliability function (R) is defined as Eq. 4 is converted to

$$R(x) = exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right], \beta \geq 0, \alpha \geq 0 \quad (5)$$

by taking the logarithms twice of both sides of Eq. 5, it becomes

$$\ln\left[\ln\left(\frac{1}{R(x)}\right)\right] = \beta \ln(x) - \beta \ln(\alpha) \quad (6)$$

As can be seen from Eq. 6, there is a linear functional relationship between $\ln\left[\ln\left(\frac{1}{R(x)}\right)\right]$ and $\ln(x)$. The slope of this linear function graph gives the shape parameter β. Scale parameter α is determined from the second term of Eq. 6 (Gorjan and Ambro, 2012).

If the accepted average flexural strength and modulus values are higher than the real strength and modulus values of the material, safety problems can occur in design. Each main strength value, which is equal to real strength value or less, provides an opportunity to create a safer design. In this study, the flexural strength and flexural modulus values, which have 80 % reliability level (R80), were accepted as the main strength and modulus values for the pure and hybrid wood composite panels. The reliability and probability function of Weibull distribution, which belongs to pure and MDF oriental beech hybrid wood composite panels, is illustrated in Figure 5 and 6. Weibull analysis graphics of pure chipboard and chipboard-east beech hybrid wood composite panels are not included due to the similar behavior of the curves.

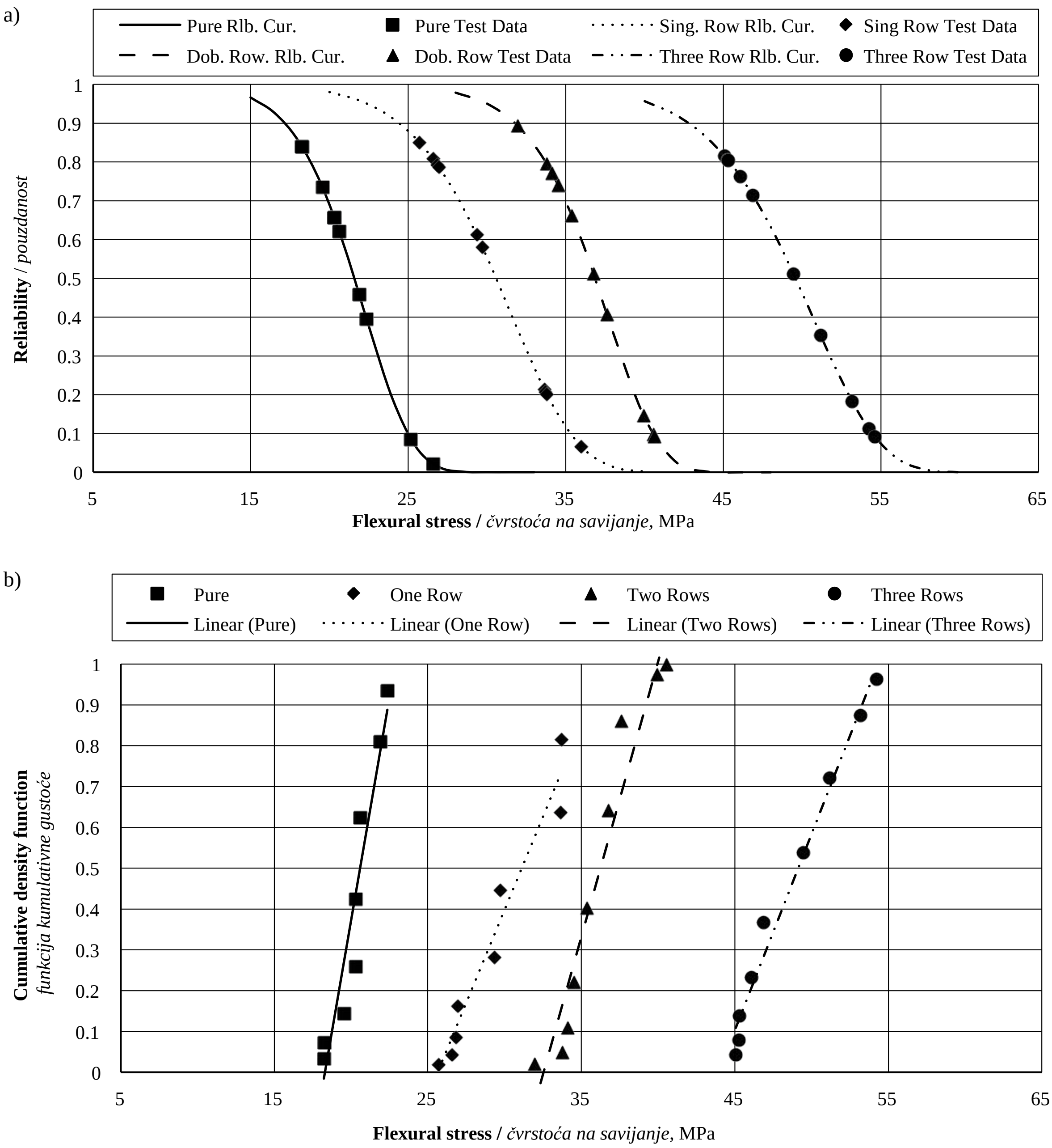


Figure 5 a) Reliability function and b) cumulative density function of pure MDF and MDF – oriental beech hybrid wood composite panels for flexural stress

Slika 5. a) Funkcija pouzdanosti, b) funkcija kumulativne gustoće čiste MDF ploče i hibridne kompozitne drvne ploče MDF – bukovina za čvrstoću na savijanje

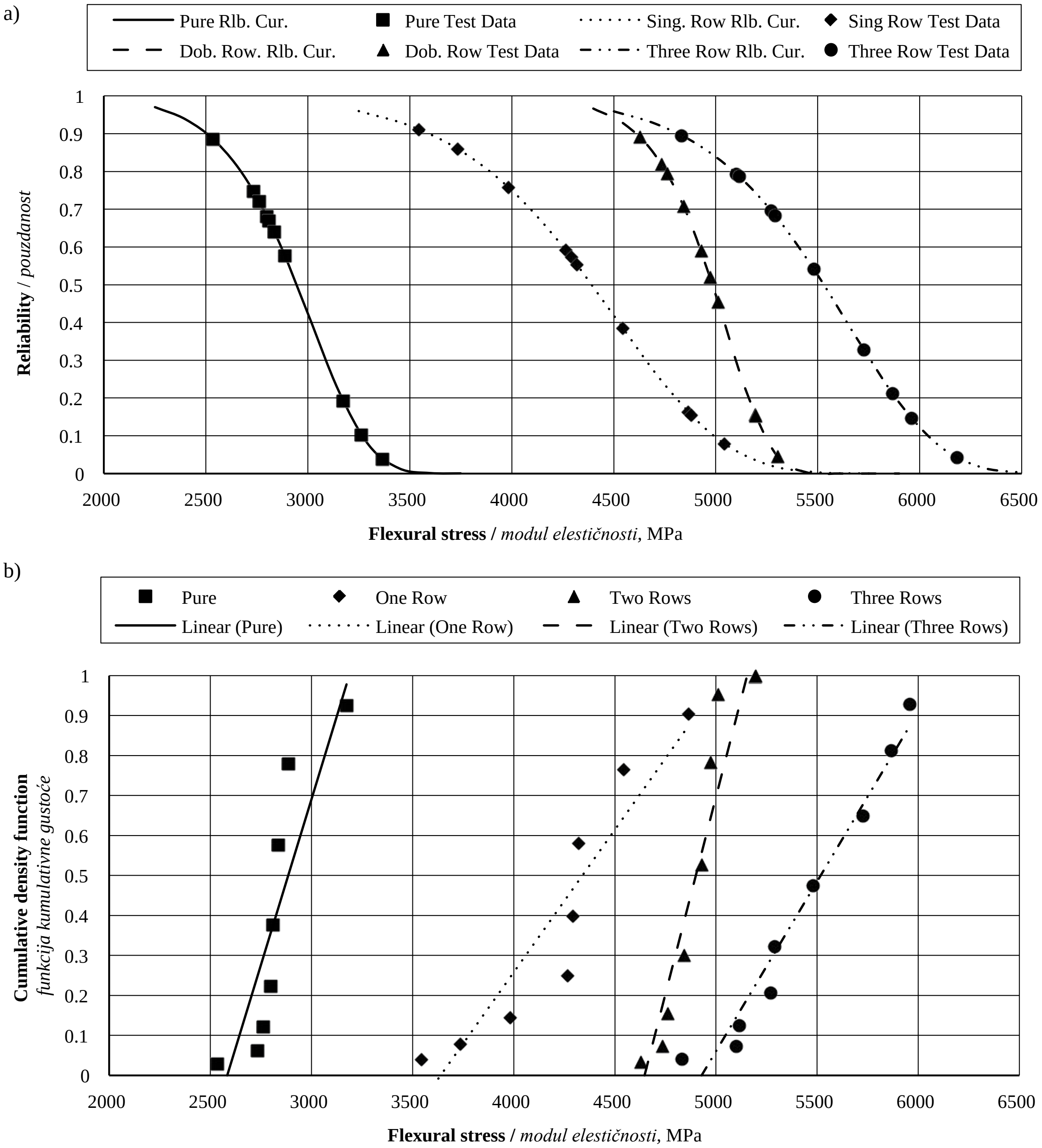


Figure 6 a) Reliability function and b) cumulative density function of pure MDF and MDF – oriental beech hybrid wood composite panels for flexural modulus

Slika 6. a) Funkcija pouzdanosti i b) funkcija kumulativne gustoće čiste MDF ploče i hibridne kompozitne drvne ploče MDF – bukovina za modul elastičnosti

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

In this study, flexural strength and flexural modulus of pure chipboard, pure MDF, chipboard- oriental beech and MDF- oriental beech hybrid wood composite panels under three-point bending loading were investigated. Within the scope of the study, flexural performances of eight different wooden materials, two pure and six hybrid wood composite panels, were examined. The typical load-displacement behavior of wooden materials under a three-point bending load is given in Figure 7.

Among the test samples, pure chipboard and pure MDF wood samples are the materials with the lowest strength. Under the three-point bending loading, these wooden materials were damaged by breaking brittle. When pure chipboard and pure MDF wood materials were hybridized by using oriental beech, both strength and deformation ability of wood material increased. As seen in Figure 7, both chipboard-east beech and MDF-east beech hybrid wood composite panels showed deformation as they lost their load-bearing capacity after the start of damage. The linear form of the fracture line shows that damage occurred as a brittle and suddenly in pure chipboard and pure MDF wood material (Figure 8a). Since the oriental beech has a natural, flexible, and fibrous structure, the fracture occurred in a ductile form. This can be understood from the zigzag form of the fracture line (Figure 8b). When the number of east

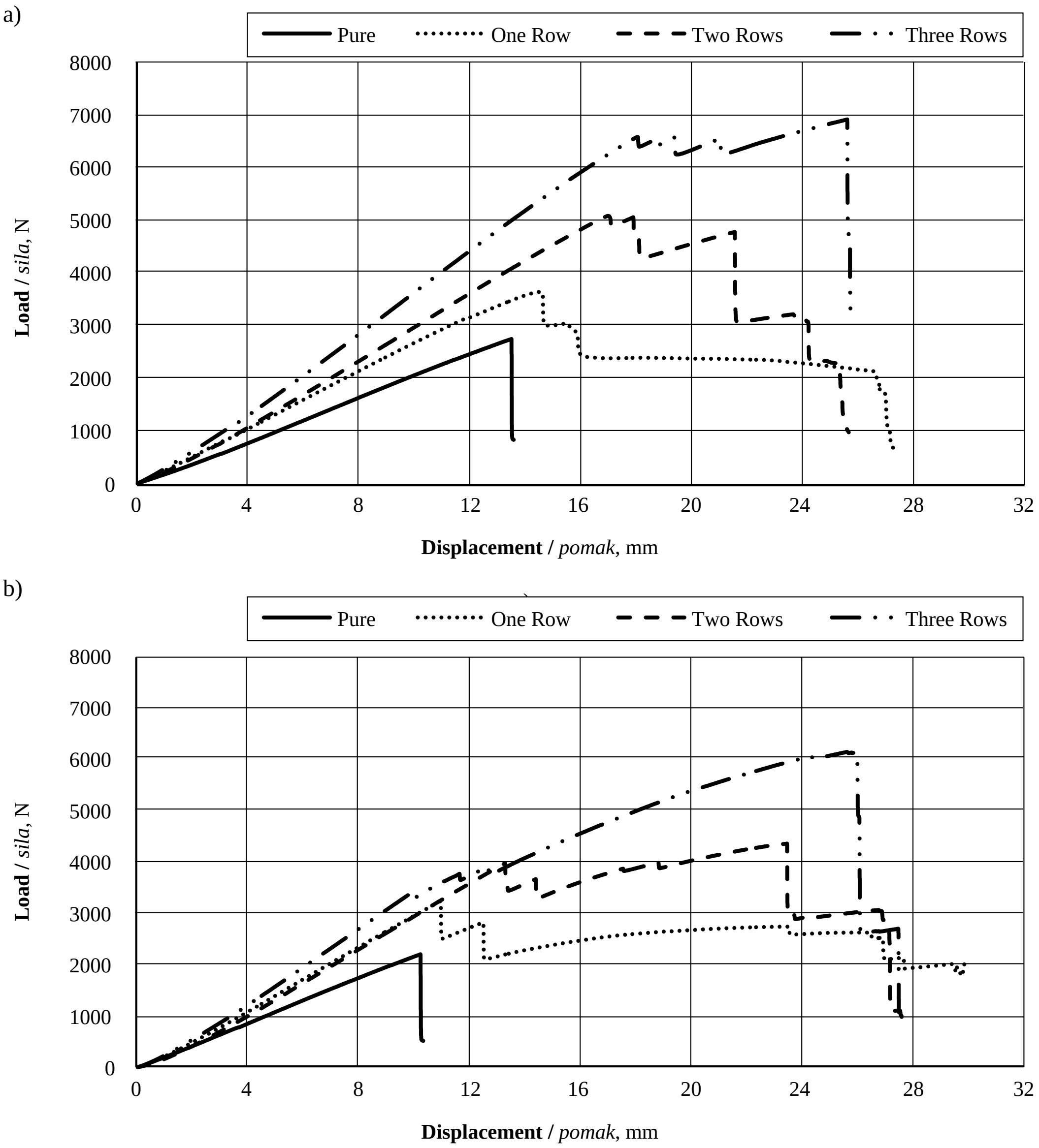
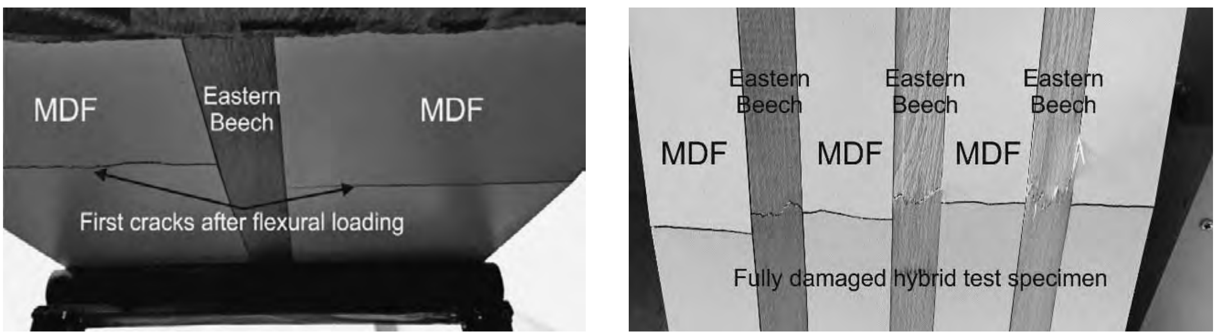


Figure 7 Load-displacement behavior of pure and hybrid wooden materials: a) MDF – oriental beech and b) chipboard – oriental beech
Slika 7. Odnos sile i pomaka čistoga i hibridnoga drvnog materijala: a) MDF – bukovina, b) iverica – bukovina

beech rows used for hybridization increases, the load-carrying capacity, and deformation ability of hybrid wood composite panels increases in direct proportion.

These experimental results were analyzed according to two-parametric Weibull distribution, and the flexural strength and flexural modulus value of 80 % reliability were accepted as the main value. As seen in Figure 6, at least one test sample data for each material type was obtained with a reliability rate of 80 % and greater. For this reason, after performing Weibull anal-



a) b)

Figure 8 Damaged test samples: a) half damaged and b) fully damaged
Slika 8. Lom na ispitnim uzorcima: a) lom na polovici uzorka, b) lom po cijelom uzorku

Table 5 Flexural stress and modulus of pure MDF and MDF- oriental beech hybrid wood composite panels
Tablica 5. Čvrstoća na savijanje i modul elastičnosti čiste MDF ploče i hibridne kompozitne drvne ploče MDF – bukovina

Material types *Vrsta uzorka*	**Flexural stress, MPa** *Čvrstoća na savijanje,* MPa	**Flexural modulus, MPa** *Modul elastičnosti,* MPa
Pure MDF / *čisti MDF*	18.76	2668.36
One row hybrid / *hibrid s jednim elementom*	26.65	3885.42
Two rows hybrid / *hibrid s dva elementa*	33.67	4751.63
Three rows hybrid / *hibrid s tri elementa*	45.31	5086.32

Table 6 Flexural stress and modulus of pure chipboard and chipboard- oriental beech hybrid wood composite panels
Tablica 6. Čvrstoća na savijanje i modul elastičnosti čiste iverice i hibridne kompozitne drvne ploče iverica – bukovina

Material types *Vrsta uzorka*	**Flexural stress, MPa** *Čvrstoća na savijanje,* MPa	**Flexural modulus, MPa** *Modul elastičnosti,* MPa
Pure chipboard / *čista iverica*	12.69	2548.21
One row hybrid / *hibrid s jednim elementom*	16.25	3652.32
Two rows hybrid / *hibrid s dva elementa*	27.54	4685.31
Three rows hybrid / *hibrid s tri elementa*	39.95	4983.52

ysis, the value of 80 % reliability was accepted as the test result. Flexural strength and flexural modulus of pure and hybrid wood composite panels are given in Table 5 and 6.

In Table 5, the maximum flexural strength of 45.31 MPa was obtained from hybrid wood composite panels with three rows of oriental beech. The minimum value of 18.76 MPa was obtained from pure MDF panels. If the flexural strength value of pure MDF panels is taken as a reference, the hybridization process has achieved an improvement of 141.52 % in the flexural strength. Similarly, the maximum flexural module of 5086.32 MPa and the minimum flexural module of 2668.36 MPa were obtained from MDF- oriental beech hybrid with three rows and pure MDF wood material, respectively. According to these results, it can be said that the hybridization of MDF wood material with oriental beech provides an improvement of 90.61 % in the flexural modulus of the material.

The maximum flexural strength and the maximum flexural modulus value obtained from the tests of pure chipboard and chipboard- oriental beech hybrid wood materials is 35.95 MPa and 4983.52 MPa, respectively. Samples subjected to hybridization in three rows with oriental beech, showed the best performance under the three-point bending load. Also, pure chipboard wood material was found to be the material with the lowest strength against the three-point bending load. The minimum flexural strength and flexural modulus values were found to be 12. 69 MPa and 2548.21 MPa, respectively. The hybridization process increased the flexural strength and flexural modulus of chipboard wood material up to 214.81 % and 95.57 %, respectively.

Since chipboard wood material has a coarse and porous internal structure, its bending strength is lower when compared with MDF material. Therefore, the results obtained in flexural tests have shown that the flexural performance of pure MDF and hybrid structures with MDF is higher. The reason for this may be the density differences, structural properties, mechanical properties of wood materials and different degrees of their adhesion ability.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, hybridization with oriental beech was performed to improve the flexural performance of chipboard and MDF wood materials, which are frequently used in the furniture industry. As a result of the experiments, the test samples, which were combined using different hybridization techniques, showed different flexural characteristics in terms of the bending groups. The data obtained from the flexural tests were analyzed according to the Weibull reliability distribution and the results with an 80 % reliability were accepted as the main value. The results of the analyses showed that, with the hybridization process performed in different techniques on chipboard and MDF, wood materials improved in terms of flexural strength and flexural modulus. Also, it was determined that the type of wood material has an effect on flexural strength and flexural modulus.

The production costs of high strength materials used in engineering structures are expensive. However, the use of low-quality materials creates customer dissatisfaction. For this reason, manufacturers have been searching for materials that are suitable in terms of price/performance. In recent years, the use of materials with a hybrid structure has been increasing due to their advantages in terms of cost, strength and lightness. The use of hybrid wood products in the furniture industry will both reduce the number of waste-separated products and produce cheaper wood products compared to their relative strength. Besides, considering the functions of furniture and the loads it will bear, knowing the properties of the hybridization methods to be used will positively affect the value and economic life of the furniture.

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Drvo tika (*Tectona grandis* L.f.)

NAZIVI

Drvo tika, tj. tikovina, trgovački je naziv vrste *Tectona grandis* L. f. iz porodice *Verbenaceae*. Usto, trgovački su nazivi tog drva i teak (Njemačka, Velika Britanija, Nizozemska, Nigerija); Teck (Francuska, Italija), a lokalni su nazivi Kyun (Burma); Gia thi (Vijetnam); tadi, tek, sàgwan, kembal, semarang (Indija); Djati (Indonezija, Malezija); may sak (Laos, Kambodža, Tajland); jat, sak (Tajland); djatti (Gabon). Standardni nazivi u Europi su teak (engleski), Teck (francuski) i Teak (njemački).

PODRUČJE RASPROSTRANJENOSTI

Drvo tika potječe s prirodnih staništa južne i jugoistočne Azije, Indije, Indonezije, Mijanmara, Tajlanda, Laosa, Kambodže, Vijetnama i Jave. U Mijanmaru raste u čistim sastojinama, a u Tajlandu, na Javi i u Indoneziji čini oko 28 % šumskih površina. *Tectona grandis* kultivira se u Togu, Kamerunu, Nigeriji, Gabonu, Tasmaniji, Beninu, Maleziji, Hondurasu, Brazilu i Panami, i to uglavnom na plantažama. Raste u vlažnim tropskim zelenim kišnim šumama, u tropskim poluzelenim kišnim šumama, na 400 do 800 m nadmorske visine, ponegdje i do 1400 metara. Drveće *Tectona grandis* osjetljivo je na prekomjerno natapanje.

STABLO

Stablo doseže visinu do 40 m i prsnog je promjera debla od 40 do 100 cm. Deblo doseže visinu do 20 m, ravno je i valjkastog oblika. Kora mu je debela od 1 do 2 cm.

DRVO

Makroskopska obilježja

Bjeljika je bjelkasta do siva, široka 1 – 3 cm (katkad i šira), a srž drva je zlatnožuta do žutosmeđa, svjetlosmeđa do tamnosmeđa, a zbog izlaganja atmosferilijama posivi. Drvo ima dekorativnu teksturu, grubu, često nepravilnu, umjerenoga do niskog sjaja. Žica drva je ravna, kadšto valovita i isprekidana. Sirovo drvo ima miris svježe obrađene životinjske kože.

Drvo je prstenasto ili poluprstenasto porozno. Pore ranog drva velike su do vrlo velike i golim su okom vidljive. Pore kasnog drva radijalno su raspoređene, po 2 do 3 zajedno. Ispunjene su tilama, kalcijevim fosfatima, silicijevim dioksidima, te bjelkastim do žućkastim supstancijama lapahola. Drvni su traci jedva vidljivi bez povećala.

Mikroskopska obilježja

Promjer traheja ranog drva velik je do vrlo velik. Iznosi 200 do 300 mikrometara. Traheje kasnog drva, pak, imaju promjer od 70 do 100 mikrometara. Gustoća traheja je 4...6...9 na 1 mm^2 poprečnog presjeka. Volumni udio traheja iznosi 8,7...11,6...15,7 %. Staničje drvnih trakova je homogeno, katkad i heterogeno. Visoki su do 280...800 mikrometara, odnosno 5...21...34 stanica. Široki su 25...40...90 mikrometara, odnosno 3 do 5 stanica. Gustoća drvnih trakova je 5...6...7 na 1 mm tangentnog smjera. Volumni udio drvnih trakova iznosi 14,2...15,5...19,2 %. Aksijalni je parenhim u ranom drvu paratrahealno vrpčast, a u kasnome je rijedak i paratrahealan, na granici goda i terminalan. Volumni udio aksijalnog parenhima je 3,6...6,6...10,4 %. Drvna su vlakanca libriformska i vlaknaste traheide. Dugačka su 700...1200...1400 mikrometara. Debljina staničnih stijenki vlakanaca iznosi 2,8...3,7...4,8 mikrometara, a promjeri njihovih lumena su 8,4...15,9...24,4 mikrometara. Volumni udio vlakanaca je 63,5...66,3...71,0 %.

Fizička svojstva

Gustoća apsolutno suhog drva, ρ_0	440...630 kg/m^3
Gustoća prosušenog drva, ρ_{12-15}	520...660...700 kg/m^3
Gustoća sirovog drva, ρ_w	800...900 kg/m^3
Radijalno utezanje, $ß_r$	2,1...3,0 %
Tangentno utezanje, $ß_t$	4,2...5,8 %
Volumno utezanje, $ß_v$	6,9...9,4 %

Mehanička svojstva

Čvrstoća na tlak	42...59 MPa
Čvrstoća na savijanje	58...109 MPa
Čvrstoća na vlak, paralelno s vlakancima	95...120...150 MPa
Čvrstoća na vlak, okomito na vlakanca	2,3...5,4 MPa
Čvrstoća na smicanje	8,3...9,5 MPa
Tvrdoća (prema Brinellu), paralelno s vlakancima	63...71 MPa
Tvrdoća (prema Brinellu), okomito na vlakanca	28...39 MPa
Modul elastičnosti	9,5...13,2 GPa

TEHNOLOŠKA SVOJSTVA

Obradivost

Drvo se dobro pili, blanja, buši, obrađuje glodanjem, brusi, lijepi i polira. Minerali i kristali u porama ubrzano zatupljuju oštrice alata. Stoga se za obradu tog drva primjenjuju alati s oštricama karbidnih vrhova. Preporučuje se brzina rezanja 50 m/s. Tikovina se površinski odlično obrađuje zbog uljastih sadržaja u njemu koji ga čine masnim. Pri dodiru s metalima drvo ne korodira. Prije čavlanja ili vijčanja drvo je potrebno predbušiti.

Sušenje

Drvo tika dobro se suši prirodnim putem i u sušionicama. Pri sušenju se ne iskrivljuje, ne puca i ne vitoperi se. Stabilnih je dimenzija i u literaturi se navodi kao „drvo koje ne uzrokuje brige“ (*no trouble timber*).

Trajnost i zaštita

Za razliku od bjeljike, srž tikovine vrlo je otporna na gljive uzročnice truleži (razred 1), a na termite je srednje otporna (razred otpornosti M). Bjeljika je uska, teško se impregnira (razred 3), a srž se impregnira krajnje teško (razred 4). Prirodna otpornost svrstava tikovinu u razred upotrebe 5: u tlu ili u dodiru s vodom. Tikovina iz plantažnog uzgoja ima slabiju trajnost. Ako je u upotrebi izložena vlaženju, nije ju potrebno tretirati zaštitnim sredstvima.

Uporaba

Drvo tika ima široku primjenu. Upotrebljava se za izradu furnira, namještaja i parketa, za uređenje interijera i eksterijera, za proizvodnju unutarnje i vanjske građevne stolarije, za palube u brodogradnji, a primjenu nalazi i u mostogradnji. Zbog otpornosti i stabilnosti dimenzija u uvjetima izmjeničnog vlaženja i sušenja, ugrađuje se u kupaonice, praonice i kuhinje. Zahvaljujući otpornosti na kiseline, tikovina se primjenjuje i u kemijskim laboratorijima. Od tikova se drva izrađuju i obloge bazena, palube, dokovi i čamci. Nekada su se od tikovine izrađivali željeznički vagoni i pragovi.

Sirovina

Tikovina je na tržištu dostupna u obliku trupaca, ali češće se nudi u obliku piljene građe, rezanog furnira i elemenata za drvene obloge i parket.

Napomena

Drvo tika nije na popisu ugroženih vrsta u međunarodnoj trgovini CITES. Na popisu ugroženih vrsta međunarodne organizacije IUCN tikovina je svrstana u razred vrsta najmanje zabrinjavajućeg opstanka. Drvo sličnih svojstava imaju i ove vrste: *Tectona hamiltoniana* Wall, *T. philippinensis* Benth. & Hook. f., *Pericopsis elata* (Harms) Meeuwen, *Chlorophora excelsa* (Welw.) Benth., *Chlorophora regia* A. Chev. Upotrebljava se kao zamjena za drvo bukve te za sljedeće vrste: Doussié, Kokrodua, Iroko, Coubaril, Merbau, Boiré.

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prof. dr. sc. Jelena Trajković
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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…

… od 1995. do 2019. izašlo je stotinu brojeva časopisa Drvna industrija i sve su naslovnice obuhvaćene u ovoj knjizi. Uz svaku naslovnicu, odnosno uz svaku vrstu drva s naslovnice u knjizi se na desnoj strani nalazi pripadajući tekst o nazivima i području rasprostranjenosti navedene vrste te o svojstvima tog drva kao materijala. Stručno nazivlje usuglašeno je s Pojmovnikom hrvatskoga drvnotehnološkog nazivlja, odnosno s bazom STRUNA (http://struna.ihjj.hr/browse/?pid=45). Na kraju svakog teksta navedeni su autori, a sva korištena literatura objavljena je u poglavlju Literatura. Slika drva na lijevoj stranici knjige istovjetna je pripadajućoj naslovnici, osim u nekoliko slučajeva, kada su radi bolje kvalitete izrađene nove slike. U naslovu teksta o pojedinoj vrsti drva uz komercijalni je hrvatski naziv napisan i važeći znanstveni naziv. Znanstveni nazivi usklađeni su s najnovijim znanstvenim spoznajama, odnosno navedeni su prema Međunarodnom indeksu naziva biljaka (IPNI), u skladu s Međunarodnim kodeksom nomenklature algi, gljiva i biljaka iz 2018.

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70

1950 2019

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Opće odredbe

Časopis Drvna industrija objavljuje znanstvene radove (izvorne znanstvene radove, kratka priopćenja, pregledne radove, prethodna priopćenja), te ostale priloge i stručne obavijesti s područja građe, svojstava i zaštite drva i drvnih materijala, primjene drva i drvnih materijala, mehaničke i hidrotermičke obrade te kemijske prerade drva, svih aspekata proizvodnje drvnih materijala i proizvoda te trgovine drvom i drvnim proizvodima te drugih događaja povezanih s drvnom industrijom.

Predaja rukopisa podrazumijeva uvjet da rad nije već predan negdje drugdje radi objavljivanja ili da nije već objavljen (osim sažetka, dijelova objavljenih predavanja ili magistarskih radova odnosno disertacija, što mora biti navedeno u napomeni) te da su objavljivanje odobrili svi suautori (ako rad ima više autora) i ovlaštene osobe ustanove u kojoj je istraživanje provedeno.

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Upute

Predani radovi smiju sadržavati najviše 15 jednostrano pisanih ISO A4 listova (210 mm × 297 mm) 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 docx 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 dopisnog autora s Uredništvom. Znanstveni 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. Obavezna 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 (dodatkom 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. Količina slika mora biti ograničena 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 boji moguće je na zahtjev), formata jpg ili tiff, potpune i jasno razumljive bez pozivanja na tekst priloga. Svi grafikoni i tablice izrađuju se kao crno-bijeli prilozi (osim na zahtjev). Tablice i grafikoni trebaju biti na svojim mjestima u tekstu te originalnog formata u kojemu su izrađeni radi naknadnog ubacivanja hrvatskog prijevoda. Ako ne postoji mogućnost za to, potrebno je poslati originalne dokumente u formatu u kojemu su napravljeni (MS 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. (Krpan, 1970). Nadalje, bibliografija mora biti navedena na kraju teksta, i to abecednim redom prezimena autora, s naslovima i potpunim navodima bibliografskih referenci. Popis literature mora biti selektivan, a svaka referenca na kraju mora imati naveden DOI broj, ako ga posjeduje (http://www.doi.org) (provjeriti na http://www.crossref.org).

Primjeri navođenja literature

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

Primjer

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

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

Primjeri

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

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

Ostale publikacije (brošure, studije itd.)

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

Web stranice

***1997: “Guide to Punctuation” (online), University of Sussex, www.informatics.sussex.ac.uk/department/docs/punctuation/node00.html. First published 1997 (pristupljeno 27. siječnja 2010).

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Materials and methods should be as precise as possible to enable other scientists to repeat the experiment. The main experimental data should be presented bilingually.

The results should involve only material pertinent to the subject. The metric system shall be used. SI units are recommended. Rarely used physical values, symbols and units should be explained at their first appearance in the text. Formulas should be written by using Equation Editor (MS Word add-in). Units shall be written in normal (upright) letters, physical symbols and factors in italics. Formulas shall be consecutively numbered with Arabic numerals in parenthesis (e.g. (1)) at the end of the line.

Discussion and conclusion may, if desired by authors, be combined into one chapter. This text should interpret the results relating to the problem outlined in the introduction and to related observations by the author(s) or other researchers. Repeating the data already presented in the "Results" chapter should be avoided Implications for further studies or application may be discussed. A conclusion shall be expressed separately if results and discussion are combined in the same chapter. Acknowledgements are presented at the end of the paper.

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Figures should be inserted into the text. They should be of 600 dpi resolution, black and white (color photographs only on request and extra charged), in jpg or tiff format, completely clear and understandable without reference to the text of the contribution.

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Author's second name, initial(s) of the fi rst name, year: Title. Journal name, volume (ev. issue): pages (from - to). DOI number.

Example:

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

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Examples:

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

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

Other publications (brochures, studies, etc.):

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

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