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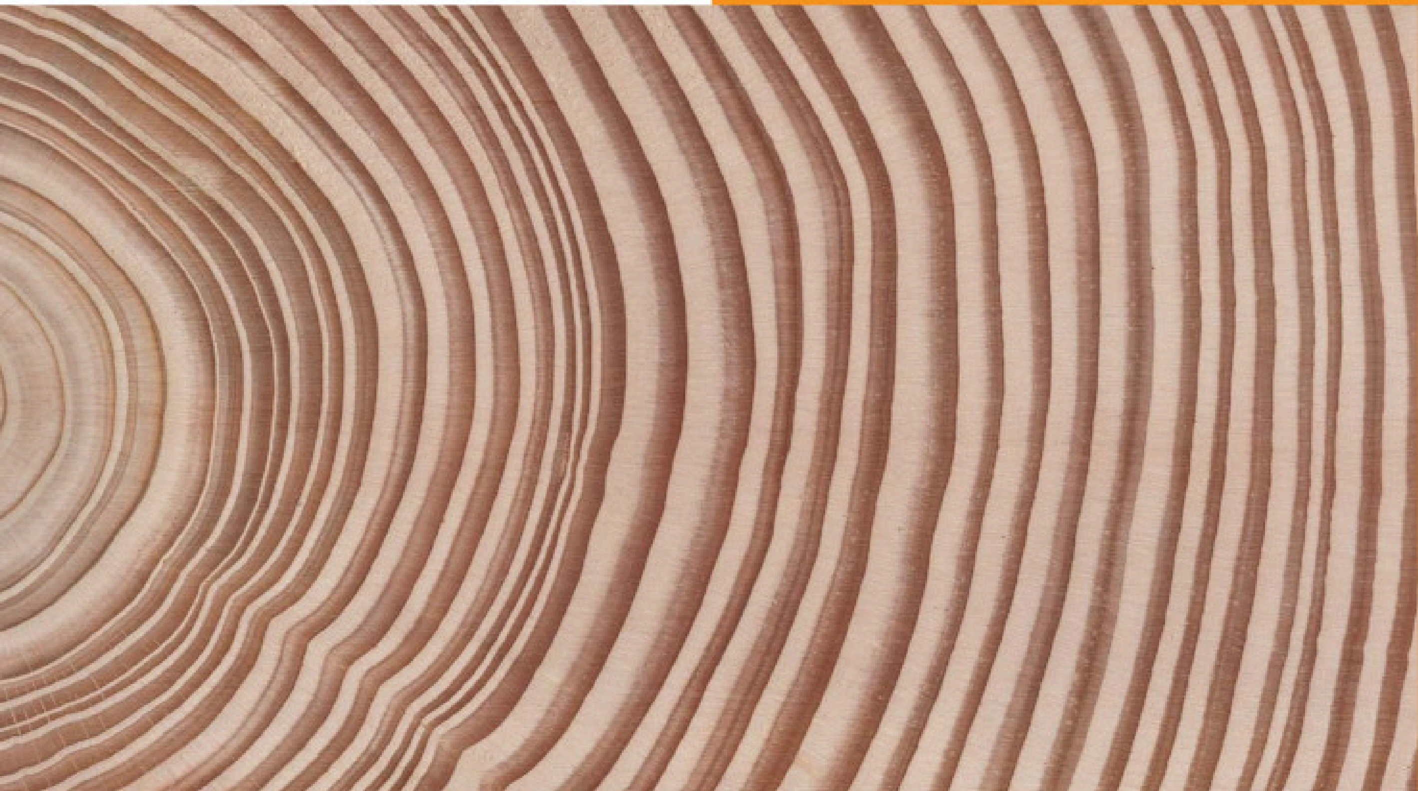

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ORIGINAL SCIENTIFIC PAPERS
Izvorni znanstveni radovi 3

Financial Literacy in Micro-Scale Enterprises Operating in Forest Products Sector: Sample of Gumushane, Turkey
Financijska pismenost u mikropoduzećima sektora prerade drva: provincija Gumushane, Turska
Yener Top, Adem Özbek 3

Diagonal Tension Performance of Impregnated Woodworking Corner Joints
Svojstva dijagonalnog naprezanja impregniranih kutnih spojeva od drva
Şemsettin Doruk 15

The Effect of Sheathing Material on Racking Performance of Plywood Shear Wall
Utjecaj materijala za oblaganje na svojstva posmičnog zida od furnirske ploče
Cenk Demirkir, Aydin Demir, Hasan Ozturk, Ismail Aydin 25

Multivariate Hotelling T^2 Control Chart for Monitoring Some Quality Characteristics in Medium Density Fiberboard Manufacturing Process
Multivarijatni kontrolni dijagram *Hotelling* T^2 za praćenje nekih svojstava kvalitete u proizvodnji ploča vlaknatica srednje gustoće
Sebahattin Tiryaki, Aytaç Aydın 35

Reinforcement of Joints Between LVL Members with GFRP and Finite Element Analysis
Ojačanje spojeva između LVL elemenata polimerima ojačanim staklenim vlaknima i analiza metodom konačnih elemenata
Mosayeb Dalvand, Ghanbar Ebrahimi, Kambiz Pourtahmasi 47

Long-Term Hygroscopic Thickness Swelling Rate of Hydrothermally Treated Beech Wood / Polypropylene Composites
Brzina dugotrajnoga higroskopskog debljinskog bubrenja kompozita od polipropilena i hidrotermički tretirane bukovine
Seyyed Khalil Hosseinihashemi, Farhad Arwinfar, Abdollah Najafi, Ferhat Özdemir, Nadir Ayrilmis, Abbas Tamjidi 59

Tensile Performance of Traditional and Modern Corner Joints in Wooden Structures
Vlačna svojstva tradicionalnih i modernih kutnih spojeva u drvnim konstrukcijama
Musa Atar, Fazlı Göde, Mustafa Kucuktuvek, Asli Er Akan, Hilal Tugba Ormecioglu, Hakan Keskin 69

Analysis of Operational Efficiency of Wooden Chair Manufacturing Companies in Serbia using DEA
Analiza učinkovitosti poslovanja tvrtki za proizvodnju drvenih stolica u Srbiji primjenom DEA metode
Aleksandra Lazarević, Branko Glavonjić, Leon Oblak, Miljan Kalem, Dragan Čomić 81

PRELIMINARY PAPER
Prethodno priopćenje 91

Effect of Acetylation and Accelerated Weathering of Nigerian Grown Rubberwood (*Hevea brasiliensis,* Müll. Arg.) on Equilibrium Moisture Content and Colour Change
Utjecaj acetilacije i ubrzanog izlaganja vremenskim utjecajima na ravnotežni sadržaj vode i promjenu boje drva kaučukovca uzgojenoga u Nigeriji (*Hevea brasiliensis*, Müll. Arg.)
Samuel Oluyinka Olaniran 91

REVIEW PAPER
Pregledni rad 99

Biomass Pelletizing Process: A Review
Proces peletiranja biomase - pregled literature
Marin Dujmović, Branimir Šafran, Matija Jug, Kristijan Radmanović, Alan Antonović 99

SPECIES ON THE COVER
Uz sliku s naslovnice 107

Yener Top[1], Adem Özbek[2]

Financial Literacy in Micro-Scale Enterprises Operating in Forest Products Sector: Sample of Gumushane, Turkey

Financijska pismenost u mikropoduzećima sektora prerade drva: provincija Gumushane, Turska

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ABSTRACT • *Enterprises are one of the main components of the economic system and they are indispensable for maintaining the sustainability of economic activities. The majority of these enterprises are small and medium-sized enterprises (SMEs). Sustainability of SMEs depends on their good financial management. Inadequate financial literacy causes SMEs' owners to make inaccurate financial decisions. The forest products sector is mostly composed of micro-scale enterprises in which financial problems are common. Therefore, this study aims to reveal the financial literacy status of the owners of micro-scale and wood-processing enterprises. For this purpose, 78 enterprises were selected as study population. Data were collected by applying a structured questionnaire to 43 of these companies by the face-to-face interview method. The structured questionnaire consisted of multiple-choice and open-ended questions and statements prepared on the Five Likert scales. Data were analysed by using the Independent-Sample T-Test, Mann-Whitney U-Test and correlation test. The reliability coefficient of the data was found to be 0.791. Of the enterprises, 58 % produced in the furniture sub-sector and 42 % in the wood products sub-sector. This study provides evidence that there was no statistically significant difference between the knowledge means of economics and financial behaviour of the furniture and wood products sectors. However, the enterprise owners' knowledge of financial analysis positively affected their financial literacy and financial behaviour.*

KEYWORDS: *wood products; financial literacy; micro-sized enterprises; furniture*

SAŽETAK • *Jedna od glavnih sastavnica gospodarskog sustava jesu poduzeća kao komponenta neophodna za održivost gospodarskih aktivnosti. Većina njih su mala i srednja poduzeća. Održivost malih i srednjih poduzeća ovisi o njihovu dobrom financijskom upravljanju. Neadekvatna financijska pismenost vlasnika tih poduzeća nerijetko je uzrok donošenja pogrešnih financijskih odluka. Sektor prerade i obrade drva većinom se sastoji od mikropoduzeća u kojima su financijski problemi uobičajeni. Stoga je cilj ovog rada bio otkriti razinu financijske pismenosti vlasnika mikropoduzeća za preradu drva, zbog čega je istraženo 78 poduzeća. Podatci su prikupljeni unutar 43 poduzeća uz pomoć strukturiranog upitnika, metodom osobnog intervjua. Upitnik se sastojao od otvorenih pitanja i pitanja s višestrukim odgovorima te tvrdnji pripremljenih na Likertovoj ljestvici s pet stupnjeva.*

[1] Author is associate professor at University of Gumushane, Vocational School of Gumushane, Gumushane, Turkey.
[2] Author is assistant professor at University of Gumushane, Vocational School of Gumushane, Gumushane, Turkey.

Rezultati su analizirani primjenom T-testa, Mann-Whitneyjeva U-testa i korelacijskog testa. Utvrđeno je da je koeficijent pouzdanosti podataka 0,791. Podsektoru proizvodnje namještaja pripadalo je 58 % poduzeća, a podsektoru proizvoda od drva 42 % njih. Ova je studija pokazala da nema statistički značajne razlike u znanju iz ekonomije i financijskog ponašanja između poduzeća u podsektoru proizvodnje namještaja i onih u podsektoru proizvoda od drva. Međutim, poznavanje financijske analize vlasnika poduzeća pozitivno je utjecalo na njihovu financijsku pismenost i financijsko ponašanje.

KLJUČNE RIJEČI: *proizvodi od drva; financijska pismenost; mikropoduzeća; namještaj*

1 INTRODUCTION
1. UVOD

An economic system consists of three main units: household, enterprise and the state. Enterprises perform the most important duty in the continuation of economic activities in this system. Especially small and medium-sized enterprises (SMEs) need to be well managed financially to ensure the sustainability of their activities. In general, SMEs are managed by owners that take all business decisions and for this reason, the financial literacy level of the enterprise owners has a far-reaching effect especially on the success of SMEs.

Management of limited financial resources is important for SMEs. Successful financial management requires having a certain level of financial knowledge. Persons who access, interpret and use financial knowledge are called financial literate. The most important concept of financial literacy is knowledge. SME owners, who are likely to experience economic difficulties, should have financial knowledge, such as credit, interest, capital, budget management, balance sheet, inflation and risk management. The lack of financial information and financial management will make the owner/manager take inaccurate, incomplete and ineffective financial decisions (Agyapong and Attram, 2019).

Enterprises should observe and analyse the inside and outside environmental conditions of their enterprises while making decisions about their economic future. In this context, financial knowledge enables the interpretation of internal unit activities of enterprises as well as read the external environmental economic indicators. Persons with low financial literacy can make mistakes in their finance-related decisions and thus waste their scarce resources (Şahin and Serin, 2018). Entrepreneurs with knowledge about basic financial concepts such as budgeting, savings, borrowing and investment and the ability to use this information in their decisions (Banks Association of Turkey, 2020) can use their scarce resources more rationally. Karadağ (2015) reported that financial difficulties are common for the majority of the SMEs in Turkey as in many developing countries and that the past experiences and knowledge of owners have an important role in solving financial problems.

SMEs[1] constitute the largest part of the total number of enterprises in the countries where they are located. For example, in countries such as America, Germany, Japan and South Korea, SMEs comprise 97.2 %, 99.8 %, 99.4 % and 97.8 % of the total number of enterprises, respectively (Demir and Sütçü, 2002). Micro-sized enterprises (1-9 employees) constitute the majority of the SMEs and consist of the micro, small and medium-scale enterprises. The micro-sized enterprises in Turkey comprised 96 % of all sized enterprises according to result of the latest census of industry and business carried out in 2002 (Anonym, 2006). SMEs account for 99 % of all businesses in 28 countries of the European Union (EU). Of these 99 %, 93 % are micro, less than 6 % are small and less than 1% are medium-sized businesses (Rotar *et al.*, 2019). Micro-sized enterprises in the EU account for about 30 % of total employment and therefore play an important role in creating economic growth and employment (Rotar *et al.*, 2019).

The mortality rate of small and medium enterprises is very high. In Turkey, 109 722 enterprises were opened and 33 094 enterprises were closed in total in all sectors in 2019. The ratio of closed businesses to opened businesses was 30 %. In other words, 10 enterprises were opened while 3 were closed in 2019. In the manufacturing sector, which is a subsector of all sectors, 16 332 enterprises were opened and 3 227 enterprises were closed in the same year. The ratio of enterprises closed was 19.7 % in the manufacturing sector. The rate of closure in the manufacturing sector, which also includes the forest products sector, was less than the overall rate (The Union of Chambers and Commodity Exchanges of Turkey, 2020). 80 % of enterprises established in Turkey were closed within the first 5 years and 96 % of them within the first 10 years. The failure of getting new technologies and low cost finance were in the first place among factors that shorten the life of SMEs (Capital, 2007). This situation is not unique to Turkey. For ex-

[1] "The category of micro, small and medium-sized enterprises (SMEs) is made up of enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million" as defined by European Commission (2003/361/EC).

ample, in Nigeria, 80 % of SMEs are closed within the first five years and some are closed within 6 to 10 years. Only 5-10 % of these businesses survive, grow and reach maturity. This means that the survival rate of SMEs in Nigeria is less than 5 %. There are various reasons for the high mortality rates of enterprises in Nigeria, but the "lack of financing" is one of these reasons (Sharma, 2019).

Studies on financial literacy was focused on three main cases: (i) measuring the level of financial literacy in a country, (ii) determining how financial literacy affects financial decisions, and (iii) determining the relationship between financial literacy and financial education (Shen *et al.*, 2016). This study has the characteristics of the first case (i) and the third case (iii) according to the above classifications. However, the subject of this study was not a country but two sub-sectors of the manufacturing industry. Micro-sized enterprises, which are considered to be more important in having financial literacy, were selected within these sub-sectors. Hakim *et al.* (2017) reported that there is a large number of studies on factors that contribute to financial literacy, whereas research on the financial literacy levels of small and medium-sized business owners is still limited (Hakim *et al.*, 2017).

According to the Industry Report of the Turkish Furniture Products Assembly, financial difficulties and high credit costs are one of the important issues faced by enterprises in this sector and it is considered among the 10 main issues which should be solved to gain a place in the international markets in the long term (The Union of Chambers and Commodity Exchanges of Turkey, 2012). Akyüz *et al.* (2004) examined the financial structure of 14 sectors making up the manufacturing sector and found that the wood products and furniture industries, which make up the forest products industry, were in the last place in terms of financial structure. In a SWOT analysis carried out for the furniture sector, capital and financing limitations were found to be one of the weaknesses of the sector (Istanbul Chamber of Industry, 2015). Özgülbaş and Koyuncugil (2011) reported that 36 % of the enterprises in the furniture sector perceived funding problems as the biggest issue. The shortness of capital was found to be the most frequent problem faced by enterprises operating in forest products sectors in Gumushane with 28.1 % (Top *et al.*, 2014). In this context, the primary aim of this study was to measure and compare financial analysis, general economy, financial behaviour and financial literacy knowledge of micro-sized business owners manufacturing furniture and wood products. The second aim was to investigate the bilateral correlations between business owners' financial analysis, general economy, financial behaviour and financial literacy knowledge, without discriminating the sector.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

The International Standard Industrial Classification of All Economic Activities Rev.4 (ISIC Rev.4) consists of 21 sectors and 99 sub-sectors. The manufacturing sector, which is one of these 21 sectors and coded with C, consists of the sub-sectors arranged from 10 to 33. Forest products sectors are also classified as 3 different sub-sectors within the manufacturing sector, which are (i) Manufacture of wood and of products of wood and cork (C16), (ii) Manufacture of paper and paper products (C17) and (iii) Manufacture of furniture (C31) (United Nations, 2008).

In this study, micro-sized enterprises producing furniture and wood products in the Gumushane province were selected for analysis. The Gumushane province is located in the north of Turkey, as shown in Figure 1, and is one of Turkey's 81 provinces. Its surface area covers 6575 km^2 of which about 29 % is forested. Its population was 141702 in 2020. Enterprises in sectors C16 and C31 in Gumushane constituted 0.12 % and 0.1 % of the number and employment in sectors C16 and C31 in Turkey, respectively (Top *et al.*, 2014). There is no company that manufactures paper and paper products in Gumushane. In terms of employment, the total of sectors C16 and C31 constituted 26.8 % of the manufacturing sector employment and 4.4 % of the total of all sectors in Gumushane (Anonym, 2006). The enterprises that make up the forest products sector in Gumushane were divided into scale groups as follows: all 46 enterprises in C16 were included in the micro-sized group and 32 of 33 enterprises in C31 were micro-sized (96.9 %) and 1 out of 33 enterprises was in medium-sized (3.1 %) group (Anonym, 2006). However, one enterprise in the medium-sized group was

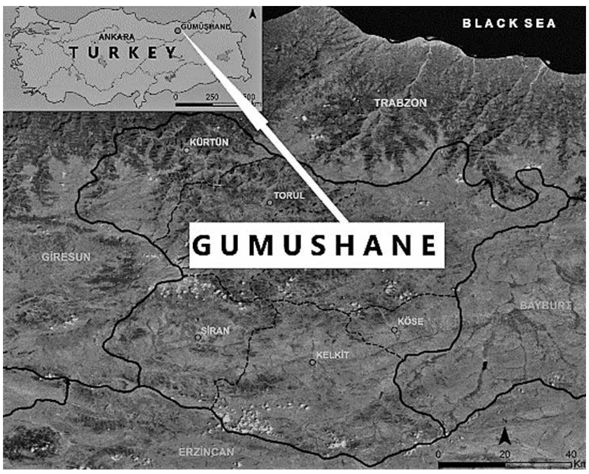

Figure 1 Geographical settlement of Gumushane province
Slika 1. Zemljopisni položaj provincije Gumushane

Table 1 The number of enterprises and employments by economic activity (ISIC Rev.4), country and size
Tablica 1. Broj poduzeća i zaposlenost prema gospodarskim djelatnostima (ISIC Rev.4), zemlji i veličini poduzeća

Number of *Broj*	**Sector** *Sektor*	**Country** *Zemlja*	**Size class** *Razred veličine*	**Year** / *Godina* 2014	2015	2016	2017
Enterprises *Poduzeća*	C16	Turkey	1-249 (SMEs)	23 923	23 182	23 003	23 185
			250+ (Large enterprises)	20	19	23	22
		Croatia	1-249 (SMEs)	1 713	1 674	1 624	1 623
			250+ (Large enterprises)	5	6	7	7
	C31	Turkey	1-249 (SMEs)	35 682	35 972	37 168	38 426
			250+ (Large enterprises)	52	57	54	51
		Croatia	1-249 (SMEs)	943	930	941	959
			250+ (Large enterprises)	6	7	7	8
Total Employments *Ukupna zaposlenost*	C16	Turkey	1-9 (Micro enterprises)	41 570	40 499	40 181	40 381
			1-249 (SMEs)	74 251	74 073	71 691	73 234
			250+ (Large enterprises)	12 338	12 621	14 067	14 106
		Croatia	1-9 (Micro enterprises)	3 665	3 361	3 310	3 386
			1-249 (SMEs)	14 465	14 079	13 982	14 874
			250+ (Large enterprises)	1 935	2 578	2 998	3 124
	C31	Turkey	1-9 (Micro enterprises)	74 081	75 162	76 807	79 252
			1-249 (SMEs)	174 417	177 637	176 955	178 593
			250+ (Large enterprises)	32 366	34 034	32 176	31 475
		Croatia	1-9 (Micro enterprises)	2 006	1 985	1 990	2 036
			1-249 (SMEs)	6 793	6 656	7 165	6 959
			250+ (Large enterprises)	2 928	3 173	3 605	3 876

closed on 7 April 2004 by the Privatization Department (Gumushane Expres, 2019).

Micro-scale enterprises are important for the country's economy. The number of micro-sized enterprises, their contribution to employment and other characteristics may be similar or different between countries. For example, when the number of enterprises and employment in Turkey and Croatia (Organization for Economic Co-operation and Development, 2021) in Table 1 are evaluated, it is seen that the rates of micro-scale enterprises in the total sector are different. According to Table 1, the ratio of employment created by micro-scale enterprises in Croatia accounted for 20.6 % of the total employment created by all size enterprises in the sector C31 in 2014, while the employment ratio created by enterprises in the same sector in Turkey was 35.8 %. Micro-scale enterprises operating in the sector C16 in 2017 constituted 18.8 % and 46.2 % of the employment created by all enterprises in this sector in Croatia and Turkey, respectively.

2.2 Method
2.2. Metoda

2.2.1 Data collection
2.2.1. Prikupljanje podataka

The face to face interview method, which is a type of survey method, was used as a data collection tool. The structured questionnaire was applied to 43 enterprises that made up 55 % of the study population in the time between March and April, 2020. Previous studies have been used in the preparation of survey questions (Serin *et al.*, 2016; Danışman *et al.*, 2016; Özbek, 2019). The questionnaire consisted of multiple-choice and open-ended questions related to the demographic structures of the enterprises as part one, 32 statements in Table 2 prepared on a five-point Likert scale as part two and ability of calculation of inflation and interest and risk reduction as part three. Participants rated whether they agree with the statements presented to them about knowledge of financial analysis, knowledge of general economics, knowledge of financial behaviour, and knowledge of financial literacy. The rating was designed as «I totally agree» (1), «I agree» (2), «I am indecisive» (3), «I disagree» (4) and «I strongly disagree» (5). Simple random sampling method was used in the determination of the enterprises to be surveyed.

2.2.2 Data analyses
2.2.2. Analiza podataka

In order to examine statistical differences between the averages of forest products sub-sectors, the following analyses were performed. First, it was tested whether the distribution of variables approximated the normal distribution. Those satisfying the normal distribution were then tested for homogeneity of variance. The comparison of the averages of the variables that met these two conditions was made according to the Independent-Sample T-Test. In cases where the normal distribution and variance homogeneity condition were not met, the Mann-Whitney U-Test, which is the non-parametric equivalent of Independent-Sample T-Test,

Table 2 Statements used to survey the knowledge of finance
Tablica 2. Izjave korištene u anketi o financijskim znanjima

Questions *Pitanja*	Knowledge of / *Znanje*			
	Financial analysis *O financijskoj analizi*	**Economics** *O ekonomiji*	**Financial behaviour** *O financijskom ponašanju*	**Financial literacy** *O financijskoj pismenosti*
Q1	I compare the cost and benefit of my economic choices	I understand the effect of the stock market on economy	I plan what the money will be paid for	Inflation is the increase in the general level of prices
Q2	I make realistic choices by using my financial resources	I understand the effects of international economic resources on the market	I spend the money according to needs (raw materials, machinery, etc.)	The risk of a highly profitable investment is high
Q3	I understand the difference between profit and cost	I describe the change in inflation rates	I take note of where and how much money has been paid	Inflation reduces the purchasing power of money
Q4	I organise my general consumption expenditures in accordance with my income	I interpret the effects of the economic crisis on unemployment	I save money for a rainy day	The speed of converting an asset with high liquidity into money without losing value is high
Q5	I interpret the effect of increase and decrease in the amount of product on market prices	I evaluate the benefits and costs of economic policies.	I control my income and expense constantly	Having a credit card increases one's purchasing power
Q6	I can understand how the lack of supply and demand reflects on prices	I understand the effect of interest rates on the market	I control whether I act on plan with my income	I consider the risk in my business-related decisions
Q7	I make realistic choices by evaluating my resources	I interpret the reasons for the changes in foreign exchange and gold prices	I fulfill my urgent cash needs with a bank loan	
Q8	I consider my needs while deciding on a product		I regularly save money for investment	
Q9			I fulfill my urgent cash needs with my saving	
Q10			I sell and buy resources without researching prices	
Q11			Before I borrow money, I take into account its cost	

was performed for comparison. The suitability of the data for normal distribution was determined according to the Shapiro-Wilk test. The Levene test was used for the homogeneity test of variances. In these tests, the H_o hypothesis is accepted if the p value is greater than 0.05 and rejected if it is smaller than 0.05. The Cronbach Alpha coefficient was calculated for the reliability of the data. All analyses were carried out for the 0.05 significance level. To investigate the relationships between variables, the Pearson correlation coefficient was used to analyse normally distributed data and the Spearman correlation coefficient was calculated for non-normally distributed data (Bursal, 2017).

2.2.3 Model and hypotheses
2.2.3. Model i hipoteze

The model used to measure the correlations between variables was designed as in Figure 2. In this model, no sector distinction was made. The model has two independent variables such as knowledge of financial analysis and economics of enterprise owners, an intermediary variable such as knowledge of financial literacy and a dependent variable such as financial behaviour.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

To determine whether the data collected were reliable, the Cronbach Alpha Test was performed and the reliability coefficient was found to be α = 0.791. Since this coefficient (α) was greater than 0.70, the data were accepted as reliable (Bursal, 2017). Serin *et al.* (2016) reported a reliability coefficient of 0.76 in their research to determine the economic literacy levels of the forest products industry (Serin *et al.*, 2016).

The demographic values of the enterprise owners regarding age, working year in the sector and monthly income were found as shown in Table 3. According to this table, 58 % of the researched enterprises were ac-

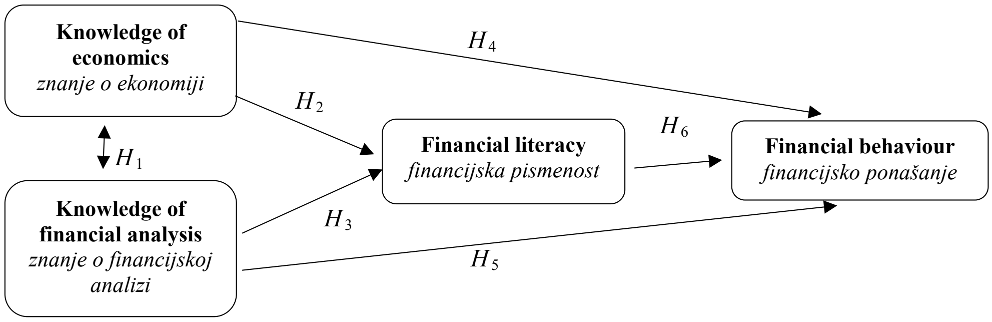

Figure 2 Model used to present correlation between variables
Slika 2. Model primijenjen za prikaz korelacije među varijablama

Depending on the model, the following hypotheses were tested:
H_1: General economic knowledge levels of enterprise owners affect financial analysis knowledge positively.
H_2: General economic knowledge levels of enterprise owners affect financial literacy levels positively.
H_3: Financial analysis information of enterprise owners affects financial literacy levels positively.
H_4: General economic knowledge levels of enterprise owners affect their financial behaviour positively.
H_5: Financial analysis knowledge levels of enterprise owners affect their financial behaviour positively.
H_6: Financial literacy levels of enterprise owners affect their financial behaviour positively.

tive in the furniture manufacturing sector and 42 % of enterprises were active in the wood products sector. The average age of the enterprise owners operating in the wood products and furniture manufacturing sectors was 41.33 and 37.96, respectively. In a similar study, Şahin and Serin (2018) reported that 53.3 % of employees were in the 36 to 45 age range. Our findings regarding the average age of the owners are in line with the values reported by Şahin and Serin (2018). The ratio of micro-sized enterprises surveyed by Şahin and Serin (2018) within the total was 76.7 %. In other words, not all of the enterprises included in their research are micro-scale.

The education levels of enterprise owners by sectors were found as in Table 4. Approximately half of the total number of enterprise owners were high school graduates (44.2 %) and constituted the largest category. Top *et al.* (2014) found in enterprises, where the structural attitudes of forestry products industry in the Gumushane province were examined, that the largest group of enterprise owners had high school education. These two studies are similar in this respect. However, Şahin and Serin (2018) found that 66.7 % of enterprise owners were high school graduates in the study in which the financial literacy level of furniture industry in the Gaziantep province was investigated. This percentage was considerably higher than reported in our study. Özgülbaş and Koyuncugil (2011) reported in a furniture and shoemaking sector analysis study that 91.2 % of the manager positions in the furniture sector were at high school level and under. Of the enterprises studied by Özgülbaş and Koyuncugil (2011), 81.8 % were micro-sized enterprises. The observed difference between our findings may be due to the fact that their study included enterprises in a different sector than the forest products sector, such as shoemaking, and the geographical region differences. Another reason for the huge difference between our and their results (44.2 % and 91.2 %, respectively) is that they gathered primary, secondary and high school graduates under one group as "high school level and under". However, in our study, each school type is considered separately.

The averages of the analysed variables, including financial analysis, economy, financial behaviour and financial literacy knowledge are summarised in terms of sectors in Table 5. Means with a value less than 2.5

Table 3 Some demographic values of enterprise owners
Tablica 3. Neke demografske vrijednosti vlasnika poduzeća

Sectors (sample size) *Sektori (veličina uzorka)*	**Age of enterprise owners** *Starost vlasnika poduzeća*		**Working year in sectors** *Radni staž u sektoru*		**Monthly income, EUR** *Mjesečni dohodak,* EUR	
	Mean *Srednja vrijednost*	**Stdev** *Stand. devijacija*	**Mean** *Srednja vrijednost*	**Stdev** *Stand. devijacija*	**Mean** *Srednja vrijednost*	**Stdev** *Stand. devijacija*
C16 (18)	41.33	11.02	17.61	7.08	761.63	373.64
C31 (25)	37.96	9.23	16.76	8.71	559.57	328.92

Table 4 Level of education of enterprise owners by sectors
Tablica 4. Razina obrazovanja vlasnika poduzeća prema sektorima

Sectors *Sektori*	**School type graduated** / *Završena škola*				**Total** *Ukupno*
	Primary *Osnovna*	**Middle** *Srednja*	**High** *Visoka*	**More** *Više*	
C16	0	6	7	5	18
C31	5	3	12	5	25
Total	5	9	19	10	43

are interpreted as high level of knowledge and the correct answer rate to the questions. The knowledge of financial analysis showed the highest average values and the level of economic knowledge the lowest. In a study investigating financial literacy in the furniture industry, Şahin and Serin (2018) used the 5 point Likert scale and interpreted their findings as percentage of data frequency. In our study, the results were interpreted using means. The level of the economic knowledge was found to be the lowest with mean values of 2.611 and 2.421 among the other variables. In their study, Şahin and Serin (2018) reported a higher level of economic knowledge of enterprise owners. The difference may be due to the fact that approximately 25 % of the enterprises in their study were large-sized and not micro-sized enterprises. All of the enterprises investigated in our study are micro-scale. Agyapong and Attram (2019) report that surveys conducted before revealed that few owner managers of SMEs were able to understand basic financial concepts. This result is not in line with our findings. In our survey, only the level of economic knowledge of owners in the furniture sector was found below the average. Topimin and Hashim (2020) revealed that micro-scale businesses have a low financial literacy level and that the majority of them are not familiar with the basic financial terminology. These results are not in line with ours and Topimin and Hashim (2020) provided no information on the sector in question in their survey.

Tests were performed to see if the difference between the sector means of each variable in Table 5 was statistically significant. For this, we first tested whether the variable data followed a normal distribution. The results are presented in Table 6. Since the sub-sector degrees of freedom (*df*) were less than 30, the decision was made according to the Shapiro-Wilk Test result (Bursal, 2017). Accordingly, at least one of the p-values of economic (p=0.021) and financial behaviour knowledge (p=0.014) belonging to sectors was less than 0.05, and therefore did not meet the normal distribution condition. Since the p-values of financial analysis and financial literacy data were p>0.05, they were found to meet the normal distribution requirement.

Data of financial analysis and financial literacy variables, which comply with the normal distribution between sectors, should secondly meet the condition of homogeneous variances between sectors. If this condition was met, an Independent-sample T-test could be

Table 5 Means and standard deviations of variables by sectors
Tablica 5. Srednje vrijednosti i standardne devijacije varijabli prema sektorima

Sectors (sample size) *Sektori (veličina uzorka)*	**Knowledge of** / *Znanje*							
	Financial analysis *O financijskoj analizi*		**Economics** *O ekonomiji*		**Financial behaviour** *O financijskom ponašanju*		**Financial literacy** *O financijskoj pismenosti*	
	Mean	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**
C16 (18)	1.715	0.406	2.421	1.054	1.793	0.453	2.065	0.555
C31 (25)	1.685	0.401	2.611	0.741	2.087	0.704	1.900	0.644

Table 6 Normality analysis for sub-sectors
Tablica 6. Analiza normalnosti za podsektore

	Sectors *Sektori*	**Kolmogorov-Smirnov**			**Shapiro-Wilk**		
		Statistic	***df***	**Sig.**	**Statistic**	***df***	**Sig.**
Knowledge of financial analysis *Znanje o financijskoj analizi*	C16	0.133	18	0.200*	0.951	18	0.436
	C31	0.122	25	0.200*	0.968	25	0.589
Knowledge of economics *Znanje o ekonomiji*	C16	0.165	18	0.200*	0.874	18	0.021
	C31	0.125	25	0.200*	0.958	25	0.368
Knowledge of financial behaviour *Znanje o ekonomskom ponašanju*	C16	0.144	18	0.200*	0.933	18	0.216
	C31	0.167	25	0.072	0.894	25	0.014
Knowledge of financial literacy *Znanje o financijskoj pismenosti*	C16	0.213	18	0.030	0.930	18	0.196
	C31	0.122	25	0.200*	0.936	25	0.120

Table 7 Equality test of financial analysis and financial literacy and *T*-test
Tablica 7. Test jednakosti financijske analize i financijske pismenosti te *T*-test

		Levene's test for equality of variances *Levinov test jednakosti varijanci*		**T test for equality of means** / *T-test jednakosti srednjih vrijednosti*						
		F	Sig.	*t*	*df*	Sig. (2-tailed)	Mean difference	Std. error difference	95 % confidence interval of the difference	
									Lower	Upper
Financial analysis *Financijska analiza*	Equal variances *jednake varijance*	0.245	0.623	0.243	41	0.809	-0.0303	0.1245	-0.2818	0.2212
	Not Equal *različite varijance*			-0.243	36.458	0.810	-0.0303	0.1248	-0.2833	0.2228
Financial literacy *Financijska pismenost*	Equal variances *jednake varijance*	0.937	0.339	-0.876	41	0.386	-0.1648	0.1881	-0.5446	0.2150
	Not Equal *različite varijance*			-0.898	39.588	0.374	-0.1648	0.1835	-0.5358	0.2061

applied (Pallant, 2017). The test result showing that the variances of the sectors for these two variables were homogeneous are summarised in Table 7. The Levene's Test resulted in a $p>0.05$ for the knowledge of financial analysis ($p=0.623$) and $p>0.05$ for the knowledge of financial literacy ($p=0.339$). Therefore, the condition of homogeneity of variances was met.

According to the T-test values in Table 7, the equality of means under the H_0 hypothesis was accepted since the p value of financial analysis ($p=0.809$) was $p>0.05$ and the *p* value ($p=0.386$) of financial literacy was $p>0.05$. There was no further significant difference between the financial analysis knowledge and financial literacy averages of the sectors. In other words, the differences between the financial analysis knowledge mean of the furniture manufacturing enterprise owners and the financial analysis knowledge mean of the wood products manufacturing enterprise owners were not statistically significant. The same result was true for financial literacy.

The economic and financial behaviour knowledge variables of the sectors did not show a normal distribution. Therefore, a Mann-Whitney U-Test was used to investigate whether there were differences between the means of these variables and results are shown in Table 8. According to these results, neither economic knowledge ($p=0.261$) nor financial behaviour knowledge ($p=0.152$) in terms of sector were statistically significant ($p>0.05$).

According to the results of the Independent-Sample T-test and Mann-Whitney U-Test, the difference between the means of financial analysis, financial literacy, financial behaviour and economic knowledge of furniture and wood products enterprises' owners was not statistically significant. In other words, the owners of the enterprises in the furniture and wood products sectors are similar in terms of the knowledge mentioned above or they belong to the same population.

Correlation analyses between financial analysis, financial literacy, economy and financial behaviour knowledge variables were also conducted. The correlation between financial analysis and financial literacy knowledge, both following a normal distribution, were tested using the Pearson's correlation coefficient. Non-normally distributed variables were analysed by Spearman correlation as shown in Table 9.

Correlation analysis between financial analysis and financial behaviour resulted in $p=0.013$. Therefore, the H_5 hypothesis was accepted and it was concluded that there was a significant relationship between these two variables. According to the Spearman's correlation coefficient $r_s= 0.376$, the relationship was positive and of medium strength. In addition, due to $p=0.002$ for the relationship analysis between economics and financial behaviour knowledge, the H_4 hypothesis was accepted. This means that there was a significant relationship between these two variables. According to the Spearman's correlation coefficient $r_s=0.450$, the relationship was positive and of medium strength. According to the

Table 8 Significance test of the difference between means
Tablica 8. Test značajnosti razlika među srednjim vrijednostima

	Economic knowledge *Znanje o ekonomiji*	**Financial behaviour knowledge** *Znanje o ekonomskom ponašanju*
Mann-Whitney U	179.500	167
Wilcoxon W	350.500	338
Z	-1.123	-1.433
Asymp. Sig. (2-tailed)	0.261	0.152

Table 9 Spearman's correlation test results between variables
Tablica 9. Spearmanova korelacija među varijablama

			Financial analysis *Financijska analiza*	**Economic information** *Ekonomske informacije*	**Financial behaviour** *Financijsko ponašanje*	**Financial literacy** *Financijska pismenost*
Spearman's rho *Spearmanov koeficijent korelacije*	Financial analysis information *Informacije o financijskoj analizi*	Correlation Coefficient	1.000	0.255	0.376*	0.359*
		Sig. (2-tailed)	.	0.099	0.013	0.018
		N	43	43	43	43
	General economic knowledge *Osnovno ekonomsko znanje*	Correlation Coefficient	0.255	1.000	0.450**	0.151
		Sig. (2-tailed)	0.099	.	0.002	0.333
		N	43	43	43	43
	Financial behaviour knowledge *Znanje o financijskom ponašanju*	Correlation Coefficient	0.376*	0.450**	1.000	0.221
		Sig. (2-tailed)	0.013	0.002	.	0.154
		N	43	43	43	43
	Financial literacy knowledge *Znanje o financijskoj pismenosti*	Correlation Coefficient	0.359*	0.151	0.221	1.000
		Sig. (2-tailed)	0.018	0.333	0.154	.
		N	43	43	43	43

Table 10 Pearson correlation test of financial analysis and financial literacy
Tablica 10. Pearsonova korelacija između financijske analize i financijske pismenosti

		Financial analysis *Financijska analiza*	**Financial literacy** *Financijska pismenost*
Financial analysis *Financijska analiza*	Pearson correlation	1	0.402
	Sig. (2-tailed)		0.008
	N	43	43
Financial literacy *Financijska pismenost*	Pearson correlation	0.402	1
	Sig. (2-tailed)	0.008	
	N	43	43

Spearman's correlation coefficients between financial analysis and economic knowledge (p=0.099), financial literacy and economic knowledge (p=0.333) and financial literacy and financial behaviour knowledge (p=0.154), no relation was found for these parameters (p>0.05). For this reason, the H_1, H_2 and H_6 hypotheses were rejected.

The relationship between financial analysis and financial literacy variables was determined according to Pearson's correlation coefficient, since these two variables met the normality requirement. As summarised in Table 10, the value of p=0.008 was smaller than 0.05 and for this reason, the H_3 hypothesis was accepted. It was concluded that there was a significant positive relationship between these two variables. According to correlation coefficient r_s=0.402, the relationship was positive and of medium strength.

It was also tested whether there was a significant relationship between variables and sectors. The Spearman correlation test was used to investigate the effect of the sector on the variable, since the sector variable is of the ordered data type. There was no significant relationship between sector and financial analysis (p>0.05); sector and financial literacy (p> 0.05); sector and economy (p>0.05) and sector and financial behaviour (p>0.05). Mashizha et al. (2019) found that there was a significant difference in the mean scores between sector and financial literacy. These findings are different from our study, which may be due to the fact that Mashizha *et al*. (2019) surveyed SMEs operating in 10 different sectors.

Business owners were asked for a simple interest account and 95.3 % of the participants chose the correct answer. 32.6 % of enterprise owners answered correctly the question of whether or not investing in different assets would increase the risk of losing money. 44.2 % of the enterprise owners indicated that this would increase the risk. In a circle where the annual inflation rate is 10 %, the question about the purchasing power of money invested in the bank for one year with 6 % interest, 83.7 % of the participants correctly chose to decrease the purchasing power of the money. Mashizha *et al.* (2019) revealed that ratios of respondents' knowledge of interest, risk reduction and inflation were 74.5 %, 68.7 %, and 71.6 % respectively. Considering the sector and scale differences, it can be said that these rates are close to our values. In addition, the fact that the knowledge of interest calculation is the highest and the risk distribution is the lowest is the common point of our and their results.

4 CONCLUSIONS
4. ZAKLJUČAK

Scarce resources require economic units to be cautious in their decisions related to finance. Therefore, especially micro-scale enterprises need to be more sensitive to working environment and analyse this environment well. The financial skills of business managers are important in outsourcing and capital procurement, inventory management and determining real needs.

In the current study, financial literacy levels of business owners operating in the forest products sector were determined, while knowledge of financial analysis and general economic and financial behaviour patterns were evaluated. The mean of financial analysis knowledge levels of business owners was the highest. The mean of general economy knowledge levels was the lowest among other factors. However, if the mean of general knowledge levels was less than 2.5, this would mean that the knowledge level of the business owners operating in the micro-scale forest products sector was sufficient. Therefore, it can be concluded that the lack of knowledge of business owners was not the basis of the financing problems common in the forest products sector in literature.

It was investigated whether the differences among the averages of financial analysis, economy, financial behaviour and financial literacy knowledge levels between wood products and furniture sub-sectors were significant and whether there was a correlation between these knowledge levels and the sectors. It was concluded that the differences between knowledge levels by sectors were not significant. In other words, there was no difference between the financial analysis, economy, financial behaviour and financial literacy knowledge of the furniture and wood products sector business owners. It can be concluded that business owners in both sectors belong to the same universe. In addition, no correlation was observed between knowledge levels and sectors. In other words, there was no correlation between, for example, the knowledge means of the financial behaviour of the wood products industry and the furniture industry. The same results were valid for knowledge means of the general economy, financial analysis and financial behaviour.

When correlations among knowledge levels were investigated, regardless of sectors, positive and moderate correlations were obtained between some of the variables. There was no correlation between some variables. Financial analysis information of the business owners positively affects their financial literacy and financial behaviour. Again, economic information of business owners has a positive effect on their financial behaviour. However, there was no relationship between financial literacy and financial behaviour. Financial literacy of business owners is not always reflected on their financial behaviour.

Business owners can accurately calculate the simple interest calculation and the depreciation of money against inflation at a very high rate. However, the ability to analyse requires the basic knowledge, and knowledge is one of the most important components of financial literacy. If it is stated that business owners within the scope of our study have an average of 17 years of work experience, showing that they can obtain enough information about their market. Therefore, this information gained through experience affects positively both financial literacy levels and financial behaviour pattern of business owners. Considering that financial behaviour and financial literacy are affected by two channels such as education and financial socialization, it can be concluded that micro-scale business owners operating in the forest products sector have strong financial socialization aspects. Enterprises surveyed by this study were able to analyse their environment well while continuing their activities and made the right financial decisions with this analysis capability.

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Diagonal Tension Performance of Impregnated Woodworking Corner Joints

Svojstva dijagonalnog naprezanja impregniranih kutnih spojeva od drva

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ABSTRACT • *In this study, the effects were examined of wood species, processing types and processing time on diagonal tension performance of woodworking corner joint with double tenon and mortise. Test samples were prepared by using Scots pine (Pinus sylvestris Lipsky), sessile oak (Quercus petreae Lipsky) and black locust (Robinia pseudoacacia L.). Poly vinyl acetate (PVAc) adhesive was used to join the tenon and mortise corner joints. The samples were impregnated by using the method of immersion for 20 and 40 min with a mixture of wax / linseed oil (3 % paraffin, 10 % linseed oil, 87 % white spirit) and Imersol-Aqua. The test of diagonal compression was used to test 120 samples. In this study, the minimum strength decrease of around 68 % was obtained for Scots pine impregnated with Imersol-Aqua for 40 min and the highest strength increase of around 10 % was obtained for sessile oak samples impregnated with Imersol-Aqua for 40 min. The highest diagonal tension performance of 879.734 N·m was obtained for oak samples impregnated with Imersol-Aqua for 40 min., the lowest diagonal tension performance of 189.111 N·m was obtained for Scots pine samples impregnated with Imersol-Aqua for 40 min.*

KEYWORDS: *paraffin; linseed oil; Imersol-Aqua; diagonal tension; woodworking corner joints*

SAŽETAK • *U radu je prikazano istraživanje utjecaja vrste drva te postupka i vremena njegove obrade na dijagonalno naprezanje kutnog spoja od drva s dvostrukim čepom i rupom. Uzorci su pripremljeni od drva bora (Pinus sylvestris Lipsky), drva hrasta kitnjaka (Quercus petreae Lipsky) i drva bagrema (Robinia pseudoacacia L.). Za lijepljenje spojeva upotrijebljeno je polivinilacetatno ljepilo (PVAc). Uzorci su impregnirani 20-minutnim i 40-minutnim uranjanjem u smjesu voska i lanenog ulja (3 % parafina, 10 % lanenog ulja, 87 % white spirita) te u Imersol-Aqua. Na 120 uzoraka provedeno je tlačno ispitivanje u dijagonalnom smjeru. Istraživanjem je utvrđeno najmanje smanjenje čvrstoće (od oko 68 %) na borovini impregniranoj u Imersol-Aqua u trajanju 40 minuta, a najveće povećanje čvrstoće (oko 10 %) postignuto je na uzorcima drva hrasta kitnjaka impregniranima 40 minuta u Imersol-Aqua. Najveće dijagonalno naprezanje od 879,734 N·m izmjereno je na uzorcima hrastovine impregniranima 40 minuta u Imersol-Aqua, a najniže dijagonalno naprezanje od 189,111 N·m ustanovljeno je na uzorcima borovine impregniranima 40 minuta u Imersol-Aqua.*

KLJUČNE RIJEČI: *parafin; laneno ulje; Imersol-Aqua; dijagonalno naprezanje; kutni spojevi od drva*

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1 INTRODUCTION
1. UVOD

Wood has many good qualities, including its thermal properties, high resistance, easy processing, and ability to accept paint and varnish and to absorb sound. It creates a warm and pleasant atmosphere where it is used aesthetically, which makes it a popular material to use both naturally and with the necessary preservatives. Wood is used intensively as auxiliary material with other building materials in addition to its individual use in all kinds of outdoor conditions. Therefore, applications for turning wood into a durable material by using it in suitable conditions have gained traction. However, wood is a hygroscopic, anisotropic biopolymer, mainly formed by cellulose, hemicellulose, and lignin (Yang *et al.,* 2019; Wang *et al*., 2014). In such products, leaving the material unprotected against the effects of open-air leads to defects, such as loss of color, caused by factors such as sunlight (UV rays), rain, wetting and drying, fiber loss due to cracks, and the gradual erosion of the damaged surface. It is important to reduce these negative effects by rationally using the appropriate wood species under suitable outdoor conditions, extending the life of the wood material with appropriate impregnation methods, and applying top surface treatments. Extending the life of the wood material might help meet the country's needs and provide foreign currency input by exporting these wood materials. Removing water from wood with water repellent treatments is one of the methods to extend the life of wood.

Water repellent treatments could increase water repellency and dimensional stability of wood, as well as reduce wood checking increased by outdoor weathering. Paraffin wax is the most common water repellent applied in the wood industry (Schultzet *et al.,* 2007). The paraffin wax deposited in wood capillaries can reduce water penetration by capillary action, thus limiting dimensional swelling (Evans *et al*., 2009). However, the failure of protection is associated with the nonbond between the cell wall and deposits (Humar *et al*., 2013). A super hydrophobic surface provided by microstructure could resist the contact between water and the wood surface (Wang *et al*., 2011). The waterproof effect relies entirely on the fabrication of the structure on the wood surface, but this microstructure might be damaged when exposed to environmental weathering. Furthermore, the hygroscopicity can be minimized by the decreased or covered hydroxy achieved via chemical modification of wood, such as acetylation, esterification, furfurylation, and so on. However, the most commonly used impregnations contain inorganic toxic substances in chemical modification, such as copper, chromium, arsenic, and their compounds. Currently, increasing cases of cancer and negative environmental effects have spurned a push for organic wood preservatives that will not negatively affect the environment and health, while the chemical modifications might be environmentally unfriendly (Pilgård *et al*., 2010). It is well-known that there is an increasing need for green and renewable materials, such as waxes and oils, derived from plants (He *et al*., 2019- Chen *et al*., 2020).

One of these preservatives is linseed oil. Linseed oil, traditionally used as a surface coating, is a natural, organic chemical that can be used as a wood preservative. It can penetrate the cell walls well enough during the impregnation process, reduce hygroscopic movements in the wood, act as a stabilizer, and since it is considered hydrophobic, it is regarded as a unique chemical. At the same time, during impregnation, linseed oil fills gaps such as tracheid lumens, rays, and cracks caused by the drying process (Olsson *et al.*, 2001).

The effects of bio-oil and epoxidized linseed oil on water absorption, tangential swelling, decay and insect resistance, thermo-gravimetric analysis, and mechanical properties of treated wood samples were studied and it was reported that, in terms of wood strength, the impregnated bio-oil generally reduced the mechanical properties of wood except for modulus of elasticity (Temiz *et al*., 2013).

The strength of Scots pine, fir, chestnut and flat tongued, smooth-tongued dowel, secret tongue, hidden tongue-dowel corner joints, manufactured by Taurus cedar, against the tensile forces was examined and the highest tensile strength was obtained on joints with smooth and grooved pine material in the merge, while the lowest tensile strength was obtained on chestnut material in the flat-tongued merge (Tokgöz *et al.*, 2005).

According to the test results of the diagonal tension performance based on PVAc glue assembly with 2nd Class poplar, chestnut and pine timber, which are widely used in house interiors and door joinery works, the best tensile strength was obtained by pine timber (1.1009 N/mm^2), then chestnut (0.5467 N/mm^2) and poplar (0.5620 N/mm^2) timber. It was reported that the values of chestnut and poplar timber diagonal tensile strength are statistically significant (Gökdemir and Yıldız, 2001).

In their study, Tokgöz and Uzer (2007) used three different types of barefaced corner joints, three different species of wood (Scotch pine, chestnut, fir), and polyvinyl acetate (PVAc) glue in their assembly. As a result of the pressure and tensile tests, Scotch pine was observed to be the strongest material, the best tensile strength in terms of the joint could be obtained with a concealed barefaced tenon, and there was no significant difference between the joints in terms of compressive strength. In his study, User examined the diagonal compressive and tension performance by combining three different wood species (Scots pine, chestnut, fir) of specific humidity level (u = 12 %) with a slip corner joint, haunched stub tenon corner joint and diagonal haunched stub tenon corner joint. The resulting construction showed that the highest diagonal tensile strength was obtained with haunched stub tenon corner joint (Scotch Pine: 73.5 kg/cm^2, chestnut: 64 kg/cm^2, fir: 42.5 kg/cm^2), followed by diagonal haunched stub tenon corner joint (Scotch Pine: 64.5 kg/cm^2, chestnut: 57.5 kg/cm^2, fir: 38 kg/cm^2) and the least with slip corner joint (Scotch Pine: 59 kg/cm^2, chestnut: 52.5 kg/cm^2, fir: 35.5 kg/cm^2). The highest diagonal compressive strength was obtained with diagonal haunched stub tenon corner joint (Scotch pine: 73.5 kg/cm^2, chestnut: 64 kg/cm^2, fir: 42.5 kg/cm^2), followed by slip tenon corner joint (Scotch pine: 64.5 kg/cm^2, chestnut: 57.5 kg/cm^2, fir: 38 kg/cm^2) and the least with haunched stub tenon corner joint (Scotch pine: 59 kg/cm^2, chestnut: 52.5 kg/cm^2, fir: 35.5 kg/cm^2) (Uzer, 1999).

In a study on "The effects of tree species, pressing direction and glue type on diagonal direction (diagonal) pull performance in single-and double-tongued wooden chopping wood type corner joints", diagonal tension performance was obtained on double-tongued Scots pine samples that were glued with PVAc-D_4 glue. On the other hand, the lowest diagonal tensile strength was reported on single-tongued fir samples that were glued with PVAc glue (Altınok *et al.*, 2009).

Laminate test samples, obtained by pasting oak, chestnut, beech and pine veneers with resorcinol formaldehyde, melamine formaldehyde, PVAc-D_4 and VTKA glue, were impregnated with paraffin solution of 3 % concentration (3 % paraffin, 10 % linseed oil, 87 % white spirit). The prepared experimental samples were exposed to outdoor weather conditions for a year and the performance of impregnation process against the atmosphere was investigated (Doruk, 2009).

In the study of Altınok *et al*. (2016), Scots pine and chestnut woods were glued with polyurethane based vinyl tree ketonol acetate (VTKA) and Polyvinyl PVAc-D_4, and double-tongued wood joinery was made. Impregnation was carried out with a 5 % solution of tannin and oak with a natural pine cone resin. Samples were kept for one year in outdoor conditions, diagonal test was performed and it was reported that the natural form treated and untreated samples and comparison of window wings holding the external environment gained strength during the degradation and the reasons for this deterioration were detected against the impregnated material.

In the study of Arslan *et al*. (2006), in which the tensile strength and sag values of the tongued joints applied on wooden window sashes were investigated, those with dowel joints were found to give better results than those without dowel joints in terms of tensile strength and sag data in lower and upper tongued joints of wooden window sashes.

To examine the effects of wood species and impregnation (procedure types and process time) in performance of window frames corner joint with double tenon, "L corner joint" type samples (in total 120) were manufactured by using Scots pine, oak and black locust. PVAc-D_4 adhesive was used to bond tenon and mortise corner joints. The samples were impregnated by using the method of immersion for 20 and 40 min with a mixture of wax and linseed oil (3 % paraffin, 10 % linseed oil, 87 % white spirit) and Imersol Aqua. The diagonal compression test was applied to test samples (to determine performance of the window frames corner joint) according to ASTM-D 143-83 1983 standards. Finally, the highest diagonal compression performance was obtained on black locust samples (7480.016 N) impregnated with Imersol Aqua for 40 min. The lowest diagonal compression performance was observed on oak samples (2572.706 N), which were impregnated for 40 min with a mixture of wax / linseed oil (Altınok *et al*., 2013).

In their study, Onduran *et al*. (2017) investigated the effects of wood modification (thermo-processing and impregnation) and outdoor conditions of storage (natural aging) on the mechanical performance of industrial woodwork. For this purpose, Scots pine (*Pinus sylvestris* L.) and chestnut (*Castanea sativa* Mill) wood were used. Experimental examples were applied in actual size. The samples were prepared using the double tenon-mortise corner joints, commonly used in construction, and polyurethane based VTKA and PVAc-D_4 as glue. Diagonal woodwork test samples were prepared by Thermo S class (185 °C temperature with a thermo-vapor process protection). After applying the heat treatment, the test samples were impregnated with a solution of 95 % natural pine cone resin and 5 % pine tannin by dip method (2 hours). Then, the untreated samples (control), only heat-treated samples and heat treated + impregnated samples were kept for 1 year in outdoor conditions (aging). At the end of the aging process, the samples were tested and it was reported that the performance of woodwork was lower after aging in untreated and heat treated pieces. On the other hand, after aging - heat treated + impregnated materials increased the values. The deformation value of woodwork increased after aging in most untreated materials, while heat treated and heat treated-impregnated materials reduced the effects of aging.

When wood material was left unprotected, it could be easily damaged under the corrosive effect of the external environment. This creates irreparable damages or can only be repaired at high costs. It became a necessity to protect wood with various materials in order to prevent the deterioration of unprotected wood.

In this study, after preparing the double-tongued Scotch pine, white oak and black locust wood chopping half frame (corner) samples were impregnated with Imersol-Aqua and a mixture of paraffin-linseed oil-spirit according to 20 and 40-minutes immersion method.

Practitioners stated that dip impregnation subsequently applied in gluing completed wood works corner joint samples would result in decay of glue joints. Therefore, it was aimed to determine the diagonal tension performance of these prepared samples.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Scotch pine (*Pinus sylvestris* L.), sessile oak (*Quercus petrea* L.) and black locust (*Robinia pseudoacacia* L.) wood species were used in the experiments. Wood materials were obtained by the method of random selection from the site of Ankara Furnishers. Wood materials of natural color, free of insect and fungi damage, clean, free of decay, without growth defects, smooth parallel to grain and part of the sapwood were ensured. Some of the technical characteristics of wood species used in the experiment are given in Table 1.

2.1 Impregnation process
2.2. Postupak impregnacije

As impregnation material, Imersol-Aqua and paraffin linseed oil with the melting point of 56 °C, as organic solvent, colorless (white) spirit was used. Paraffin solution of 3 % on the weight basis (3 % paraffin, 10 % linseed oil, 87 % colorless spirit) was prepared (Yıldız and Hafızoğlu, 1990). Imersol-Aqua (I-A), used in the impregnation process, was supplied by HEMEL (Hemel Hicson Timber Product Ltd.), Istanbul, Turkey. I-A is available on the market in the form of odorless, non-flammable, light straw color, water-based solvent having a pH of 7 and a density of 1.03 g/cm^3; it is entirely soluble in water and does not create corrosion on the metal surfaces. I-A contains 0.5 % w/w tebuconazole, 0.5 % w/w propiconazole, 0.1 % w/w 3-iodo-2-propynyl-butyl carbamate, 0.5 % w/w cypermethrin, etc. (Örs *et al*., 2003).

After dipping in Imersol-Aqua and paraffin solution, the test samples were impregnated by being kept in the solution for 20 and 40 minutes. At the end of each period, the surfaces of samples were removed from the solution and dried. The impregnated samples were kept in air-conditioning fridge at the temperature of (20±2) °C and relative humidity of (65±5) % until reaching moisture balance (Voulgaridis, 1986). Impregnated samples, the retention rate of which was to be determined, were dried in the oven at 55 °C until they reached constant weight, cooled in desiccator and weighed. Thus, the amount of net impregnation of each sample, whose exact dry weight was determined after impregnation, was calculated from Eq. 1.

$$ANI = ((M_s - M_o)/M_o) \times 100 \quad (1)$$

Where:
ANI - Amount of Net Impregnation (%)
M_s - exact dry weight after impregnation (g)
M_o - exact dry weight before impregnation (g)

2.2 Glue
2.2. Ljepilo

Polyvinyl acetate PVAc-D_3 (single component) and polyvinyl acetate PVAc-D_4 (two-component), which was strengthened by adding 5 % hardener (Turbo hardener 303.5), were used for gluing the experimental samples. PVAc-D_3 glue is marketed as single component according to BS EN 204 (BS EN 1991) and as ready for use for D_3 class of service. In practice, it is applied on the surface as follows: 120-180 g/m². The

Table 1 Some technical characteristics of wood species used in the experiment (Bozkurt, 1987)
Tablica 1. Neka tehnička svojstva vrsta drva obuhvaćenih istraživanjem (Bozkurt, 1987.)

Wood species *Vrsta drva*	**Density (*MC*=0 %)** *Gustoća (MC=0 %)* g/cm^3	**Density (*MC*=12 %)** *Gustoća (MC=12 %)* g/cm^3	**Bending strength (*MC*=12 %)** *Čvrstoća na savijanje (MC=12 %)* kg/cm^2	**Compression strength parallel to grain (*MC*=12 %)** *Čvrstoća na tlak paralelno s vlakancima drva (MC=12 %)* kg/cm^2
Scotch pine *borovina*	0.496	0.52	648.7	379.2
Sessile oak *drvo hrasta kitnjaka*	0.675	0.69	1185.0	606
Black locust *drvo bagrema*	0.720	0.76	1361	730

open standby time for 20 °C is 10 minutes (Anonim, 2009). According to BS EN 204, PVAc- D_4 can be aligned with the pasting quality of D_4 by increasing the moisture durability by adding 5 % hardener to the PVAc-D_3 glue solution (Söğütlü and Döngel, 2007).

2.3 Preparation of test samples
2.3. Priprema ispitnih uzoraka

In this study, wood species (3), impregnation types (2), impregnation time (2) and a total of 120 (3x2x2x10) samples, 10 of which were used in each sample, and diagonal tension performance test samples (with slip corner joint) were prepared (Figure 1). So, these tests were repeated ten times for each sample and their averages were used for the analysis.

Sample sizes, cut from rough drafts, were dried naturally in ventilated conditions and away from direct sunlight by putting fir slats in between. After that, they were kept in air-conditioning fridge at the temperature of (20±2) °C and relative humidity of (65±5) % until they reached 12 % humidity equilibrium. After discontinuing the sample stubs, that have reached equilibrium humidity, of the net size, mortise and equivalents were opened at the ends of the components in the milling machine. Afterwards, the mortises were pressed by applying 160 g/m^2 of glue. Pressed samples were held until their glue combinations were fully hardened (4 weeks). The pressure is applied to the tenon surface of test samples according to industrial applications and in the same amount (about 2 N/mm^2) (Selbo, 1975). Equal pressure was tried to be achieved by making equal number of rotations for each sample after taking compression gap hooks by using compression lugs during the application of pressure. Impregnation was applied to prepare tensile test specimens as described above.

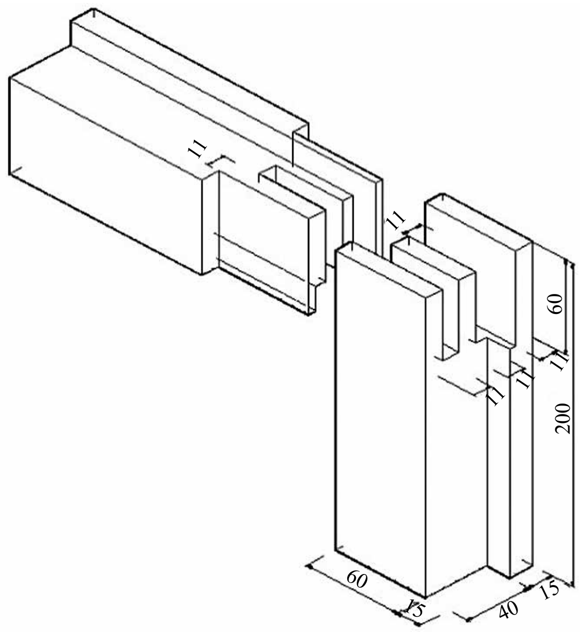

Figure 1 Diagonal tension performance test sample (dimensions in mm)
Slika 1. Izgled uzorka za ispitivanje dijagonalnog naprezanja (dimenzije u mm)

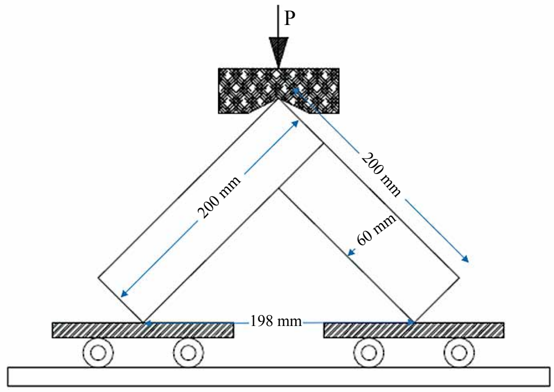

Figure 2 Diagonal tension performance test
Slika 2. Dijagonalno tlačno ispitivanje

2.4 Diagonal compression performance on L-Type samples
2.4. Dijagonalno tlačenje L-uzoraka

The diagonal compression test experiments and deformation value of woodwork examples were held according to the ASTM 1037 standard, in 800 Kp stage of Universal Testing Machine with a capacity of 5 tons. The experimental device was set to increase the compression with a speed of 2 mm/min[1]. The maximum force, read from the machine, was recorded in the unit (Figure 2). The maximum force, read from the machine, was recorded in N.

In the diagonal tensile test, the moment (M_{dt}) inserted to corner is calculated by Eq. 2 (Figure 2):

$$M_{dt} = 0.5 \cdot P_{maxTn} \cdot Lx \text{ (N·m)} \quad (2)$$

Where:
M_{dt} - moment of inertia (N·m),
P_{maxTn} - maximum force at the moment of displacement (N),
Lx - torque distance (198/2= 99 mm).

2.4 Data analysis
2.4. Analiza podataka

Multiple analysis of variance was made in wood chopping corner joints in order to determine the effects of wood species, impregnation type and impregnation period. In case of mutual interactions of sources of variance, significant at α = 0.05, Duncan test was used to identify which factors made the difference.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Table 2 shows the amount of impregnation (retention rates) of test samples, which was recorded by using the immersion method of 20 and 40 minutes.

Table 2 Amount of net impregnation obtained from test samples (%)
Tablica 2. Količina neto impregnacije dobivene iz ispitnih uzoraka (%)

	Scots pine / *Borovina*		**Black locust** / *Drvo bagrema*		**Sessile oak** / *Drvo hrasta kitnjaka*	
	Imersol-Aqua	Paraffin linseed oil *Parafinsko laneno ulje*	Imersol-Aqua	Paraffin linseed oil *Parafinsko laneno ulje*	Imersol-Aqua	Paraffin linseed oil *Parafinsko laneno ulje*
20 min	0.402	0.372	0.730	0.723	0.614	0.610
40 min	0.406	0.402	0.742	0.751	0.651	0.657
Increase / *Povećanje*	0.004	0.03	0.012	0.028	0.037	0.047

Observing the amount of net impregnation obtained from test samples, a little increase was seen in the amount of impregnation within the experimental samples. However, this increase in retention rate was very low, around 1 % in all wood species and impregnation articles (40 min). As in other studies, in order to reduce the water or moisture intake of wood material obtained from Beech, Alder, Spruce and Scotch Pine tree species, Var (2001) impregnated the samples by immersing them in impregnation solution (3 % paraffin wax / 10 % linseed oil / 87 % white spirit) for a duration of 1/3, 3 and 24 hours and reported that the amount of retention increased with the immersion time.

Oriental beech, European oak, Scots pine, Uludag fir, Oriental spruce and Lombardy poplar wood samples were prepared and impregnated with Imersol-Aqua, commonly being used in construction wood materials by the method of short, medium and long-term of dipping, and different amounts of retention were found depending on wood species and impregnation period. Retention is the highest in beech and lowest in pine. Retention was found higher in hard woods than soft woods. As the period of dipping increased, retention increased and the highest was found in long-term dipping, as reported by Keskin *et al*. (2008).

Statistical averages of diagonal tension performance in terms of wood species, process type and processing time are given in Table 3.

In this case, differences have been found to occur between the values obtained by the variation of wood species, process type and processing time on diagonal tension performance of chopping at corner joints and that of control samples.

By applying multiple variance analysis of the averages of diagonal tension performance obtained from variation of wood species, process type and processing time on diagonal tension performance of chopping at corner joints, results are given in Table 4.

According to the results of variance analysis, it can be seen that values in terms of diagonal tension performance of wood species, process type, processing time, and their binary and triple comparisons are different at $\alpha = 0.01$ significance level. Accordingly, this difference can be considered important in terms of level of importance. Duncan test of multiple comparison tests at $\alpha = 0.05$ significance level was applied in order to determine the differences between these groups. The results of binary comparison done in terms of wood species, processing time and process type that were thought significant are given in Table 5. According to the results, the performance of sessile oak was 59 % better than that of Scots pine, and 36 % better than that of black locust. In general, the results showed poor performance of both impregnating agents because gluing was applied before impregnation. The reason of lower diagonal tension performance of samples that were impregnated with paraffin linseed oil is possibly the result of the liquid solvent (spirit) that reduces the bonding strength by decomposing the glue line. Additionally, the mechanical resistance of the linseed oil showed a 75 % and 105 % weight gain decrease, and microstructural changes were reported to occur. Cracks in the tracheid cell wall were observed in these loadings. This was the result of the increase in the internal pressure in the cell wall due to the application of the mechanical oil loading. This pressure leads to micro-cracks in the

Table 3 Statistical averages of diagonal tension performance based on wood species, process type and processing time (N·m)
Tablica 3. Statistički prosjeci dijagonalnog naprezanja s obzirom na vrstu drva te na vrstu i trajanje obrade (N·m)

	Scots pine / *Borovina*		**Black locust** / *Drvo bagrema*		**Sessile oak** / *Drvo hrasta kitnjaka*	
	Imersol-Aqua	Paraffin linseed oil *Parafinsko laneno ulje*	Imersol-Aqua	Paraffin linseed oil *Parafinsko laneno ulje*	Imersol-Aqua	Paraffin linseed oil *Parafinsko laneno ulje*
20 min	696.059	534.713	446.274	244.049	739.065	837.795
40 min	461.807	387.347	189.111	461.224	879.734	808.768
Control *Kontrolni uzorci*	862.465		592.548		798.114	

Table 4 Variance analysis of diagonal tension performance (N·m)
Tablica 4. Analiza varijanci dijagonalnog naprezanja (N·m)

Source of variance *Izvor varijance*	**Sum of squares** *Zbroj kvadrata*	***SD***	**Average of squares** *Prosjek kvadrata*	**Value of *F*** *Vrijednost F*	***P* ≤ 0.01**	**Confidence level** *Razina značajnosti*
Wood species (A) *vrsta drva (A)*	2356535.75	2	1178267.875	2266.147	0.000	0.990
Processing time (B) *trajanje obrade (A)*	40028.88	1	40028.88	76.987	0.000	0.616
Process type (C) *vrsta obrade (C)*	7951.75	1	7951.75	15.293	0.000	0.242
A × B	159570.72	2	79785.356	153.450	0.000	0.865
A × C	68615.265	2	34307.632	65.983	0.000	0.733
B × C	63866.466	1	63866.466	122.834	0.000	0.719
A × B × C	262777.716	2	131388.858	252.698	0.000	0.913
Error	24957.275	48	519.943			
Sum	21608189.146	60				

cell wall layers. Micro-cracks in the S1 layer cause a decrease in resistance. Tomak and Yıldız (2012) also reported some decreases in the compressive strength, parallel to the fibers of vegetable oil-impregnated wood. Increasing of waiting time from 20 min to 40 min generally decreased the strength by 22 to 29 %. 20 min impregnation time with Imersol-Aqua caused a 17 % reduction in strength whereas 40 min time caused a 32 % reduction based on the impregnating agent as compared to control samples. 20 min and 40 min impregnation times with paraffin linseed oil caused 28 % and 26 % strength reductions, respectively. So, it was determined that strengths were reduced with regard to increased waiting time. On the basis of tree species, 6 % and 31 % reduction in tensile strength was observed with Scots pine and black locust, respectively, and a 7 % increase in tensile strength with sessile oak.

Table 5 clearly shows that the ranking can be done from the worst to the best as follow: Scots pine, black locust, and sessile oak in terms of tensile strength. So, sessile oak can be suggested for woodworking since the best tensile strength was obtained. The results of binary comparison made based on tree species, process type and processing time interaction level, which were found to be significant, are given in Table 6. 20 min waiting time can be suggested for woodworking materials since the 19 % improvement was achieved in tensile strength in comparison to 40 min waiting time.

Regarding the amount of reduction in performance against control samples in terms of process type, it was 24 % for Imersol-Aqua impregnated samples, and 27 % for samples impregnated with paraffin linseed oil.

The decrease of diagonal tension performance of treated wood might be because of bio-oil complex chemistry and reactions with wood. Bio-oils are composed of a mixture of water, guaiacols, catecols, syringols, vanillins, furan-carboxaldehydes, isoeugenol, pyrones, acetic, formicandcarbox-ylicacid, hydroxyalhydes, hydroxyketones, sugars and phenolics (Mohan *et al*., 2008; Dubey, 2010; Temiz *et al*., 2013). Due to their amphoteric properties, some bio-oil components may penetrate into the cell wall and change the mechanical properties. The strength losses of wood caused

Table 5 Results of comparison of the average diagonal tension performance by factors (N·m)
Tablica 5. Rezultati usporedbe srednjih vrijednosti dijagonalnog naprezanja prema faktorima (N·m)

Factors / *Činitelji*		**Tensile strength, N·m** *Vlačna čvrstoća,* N·m	**Difference, %** *Razlika, %*	**HG**
Wood species *Vrsta drva*	Black locust / *bagremovina*	519.981	-39.71	B
	Scots pine / *borovina*	335.164	-43.44	C
	Sessile oak / *drvo hrasta kitnjaka*	816.340	2.28	A*
	LSD: 153.88 A*: The highest value / *najveća vrijednost*			
Processing time *Trajanje obrade*	20 min	582.992	-22.38	A*
	40 min	531.331	-29.25	B
	Control	751.042	-	-
	LSD: 197.57 A*: The highest value / *najveća vrijednost*			
Process type *Vrsta obrade*	Imersol-Aqua	568.674	-24.28	A*
	Linseed oil / *laneno ulje*	545.649	-27.35	B
	Control / *kontrolni uzorak*	751.042	-	-
	LSD: 162.20 A*: The highest value / *najveća vrijednost*			

Table 6 Results of binary comparison of diagonal tension performance made based on process type, processing time and tree species interaction level (N·m)
Tablica 6. Rezultati binarne usporedbe dijagonalnog naprezanja na razini interakcije vrste obrade, trajanja obrade i vrste drva (N·m)

Processing time *Trajanje obrade*	**Tree species** *Vrsta drva*	**Black locust** *Bagremovina*			**Scots pine** *Borovina*			**Sessile oak** *Drvo hrasta kitnjaka*		
	Process type *Vrsta obrade*	Tensile strength *Vlačna čvrstoća*	Diff. %	HG	Tensile strength *Vlačna čvrstoća*	Diff. %	HG	Tensile strength *Vlačna čvrstoća*	Diff. %	HG
20 min	Imersol-Aqua	696.059	-19.29	E	446.274	-24.69	G	739.065	-7.40	D
	Paraffin linseed oil *parafinsko laneno ulje*	534.713	-38.00	F	244.049	-58.81	I	837.795	4.97	B
40 min	Imersol-Aqua	461.807	-46.46	G	189.111	-68.09	İ	879.734	10.23	A
	Paraffin linseed oil *parafinsko laneno ulje*	387.347	-55.09	H	461.224	-22.16	G	808.768	1.33	C
Control / *kontrolni uzorak*		862.466	-	-	592.548	-	-	798.114	-	-

LSD: 37.88 A*: The highest value / *najveća vrijednost*

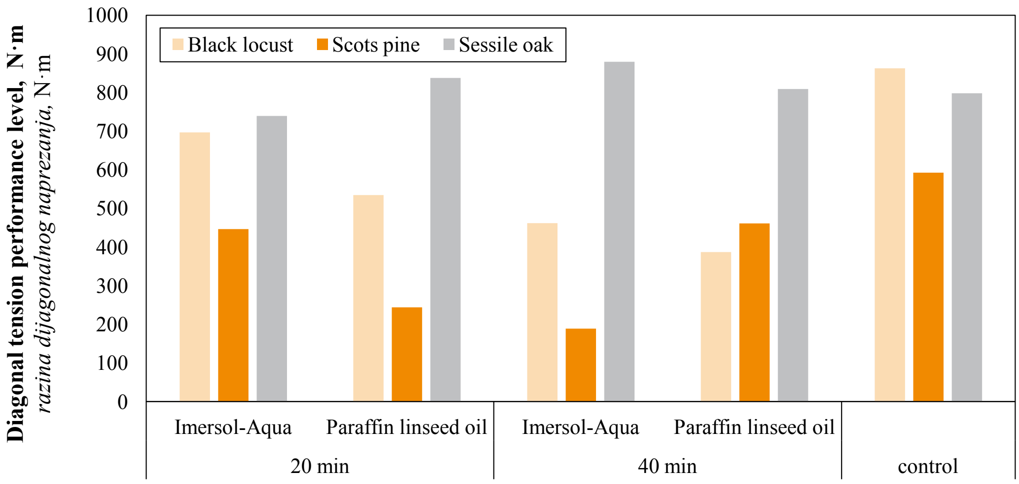

Figure 3 Interaction of tree species, process type and processing time
Slika 3. Interakcija vrste drva te vrste i trajanja obrade

by wood preservatives are directly related to its chemistry and severity of its fixation/precipitation reaction with wood (Temiz *et al*., 2013).

The highest average diagonal tension performance in terms of process type, processing time and tree type interaction was obtained for sessile oak test samples that were processed with Imersol-Aqua for 40 min (879.734 Nm), while the lowest was obtained on Scots pine test samples that were impregnated with Imersol-Aqua for 40 min (189.911 Nm), as shown in Figure 3.

4 CONCLUSIONS
4. ZAKLJUČAK

This study has been conducted in order to determine the effect of the short-term dip impregnation method with paraffin linseed oil and Imersol-Aqua on diagonal tension performance. The following conclusions can be drawn from this study.

The amount of retention in the long-term dipping (40 min.) of Scots pine, sessile oak and black locust was found to be higher than that of short-term dipping (20 min). On the other hand, the amount of retention was observed as sufficient in pine and higher than expected in black locust. The lowest amount of retention was found in pine and oak woods. This may be due to pit aspiration in pine and tyloses in oak. In a similar research, it was reported that, in the impregnation of Scots pine and oriental beech, the retention increased with the increase of impregnation time (Ör *et al*., 2006; Keskin *et al*., 2008).

In this study, the minimum strength decrease of around 68 % was obtained by Scots pine impregnated with Imersol-Aqua for 40 min and the highest strength increase of around 10 % was obtained for sessile oak samples impregnated with Imersol-Aqua for 40 min.

Finally, the highest diagonal tension performance of 879.734 Nm was obtained for oak samples impregnated with Imersol Aqua for 40 min., and the lowest diagonal tension performance of 189.11Nm was obtained for Scots pine samples impregnated with Imersol-Aqua for 40 min.

As a result, if the 5 % performance difference obtained after 20 minutes of paraffin linseed oil impregnation and 40 minutes of Imersol-Aqua impregnation is negligible, paraffin linseed oil treated stemless sessile oak can be recommended, especially since the production time is an important factor in mass production and due to the fact that it is made of organic material.

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The Effect of Sheathing Material on Racking Performance of Plywood Shear Wall

Utjecaj materijala za oblaganje na svojstva posmičnog zida od furnirske ploče

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ABSTRACT • *Wooden buildings are intensely preferred especially in earthquake regions due to their many advantages such as lightness, durability, environmental friendliness, insulation and aesthetics. Shear walls provide the lateral resistance needed for light-frame wood structures to withstand earthquake loads. When sheathed with wooden structural panels such as plywood, shear walls can be strong, stiff, and ductile. This study focuses on the effects of production factors (wood species, thickness of panels) of plywood and fibre direction of sheathing material on the racking performance of the shear wall. The displacement at ultimate load decreased with increasing the thickness of plywood panels. It was also concluded that the black pine plywood panels were the best sheathing materials for the shear walls among wood species in terms of ductility. Scots pine plywood panels are the best sheathing materials for the shear walls among wood species in terms of load carrying capacity. Moreover, it was found that the wall formed perpendicular to fibre direction of sheathing materials could carry more load than the wall formed parallel to fibre direction.*

KEYWORDS*: shear wall; structural plywood; racking performance, fibre direction*

SAŽETAK • *U potresnim su područjima osobito zastupljene drvene građevine zbog njihovih brojnih prednosti kao što su lakoća, trajnost, ekološka prihvatljivost, izolacija i estetika. Posmični zidovi osiguravaju bočnu otpornost kako bi lagane drvene konstrukcije izdržale potresna opterećenja. Kada su obloženi drvenim strukturnim pločama kao što je furnirska ploča, posmični zidovi mogu biti jaki, kruti i duktilni. Ovo je istraživanje fokusirano na učinke proizvodnih čimbenika furnirske ploče (vrstu drva, debljinu ploče) te na smjer vlakanaca materijala za oblaganje na svojstva posmičnog zida. Pokazalo se da se s povećanjem debljine furnirske ploče smanjuje pomak pri krajnjem opterećenju. Također je zaključeno da su sa stajališta duktilnosti furnirske ploče od drva crnog bora bolji izbor za oblaganje posmičnih zidova nego furnirske ploče od ostalih istraživanih vrsta drva. Sa stajališta nosivosti, za oblaganje posmičnih zidova najboljima su se pokazale furnirske ploče od drva bijelog bora. Osim toga, utvrđeno je da zid formiran okomito na smjer vlakanaca materijala za oblaganje može nositi veće opterećenje nego zid formiran paralelno sa smjerom vlakanaca materijala za oblaganje.*

KLJUČNE RIJEČI: *posmični zid; strukturna furnirska ploča; svojstva nosača; smjer vlakanaca*

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1 INTRODUCTION
1. UVOD

In recent devastating earthquakes around the world, many buildings suffered severe damage, leading to huge social and economic losses (Li *et al.,* 2018). Because of the unique structural characteristics of wood, the use of wood construction has been becoming widespread in the world. Wooden buildings are intensely used especially in earthquake regions due to their many advantages such as lightness, durability, environmental friendliness, insulation and aesthetics. They have also traditionally performed well during past earthquakes and provided a good performance during earthquakes. The investigation on performance of platform-frame wood construction showed a remarkably low fatality level (only 34 people) in the 1964 Alaska earthquake (Magnitude-M: 6.4), 1971, 1989 and 1994 California earthquakes (M: 6.7, 7.1 and 6.7, respectively), 1987 New Zealand earthquake (M: 6.3), 1988 Quebec earthquake in Canada (M: 5.7), 1995 Kobe earthquake in Japan (M: 6.8). Also, a few buildings collapsed, but many buildings (about 375.000) survived strong shaking almost unscathed or with various degrees of superficial and structural damage (Rainer and Karacabeyli, 2000). In addition, Carrero *et al.* (2018) analysed in detail the damage level of light-framed timber buildings during three major contemporary earthquakes, namely the 1994 Northridge Earthquake (M: 6.7), the 2010 Chile Earthquake (M: 8.8), and the 2011 Christchurch Earthquake (M: 6.3), all happening in regions with significant stock of platform-framing timber buildings. They stated that light-framed timber buildings can withstand severe earthquakes with low collapse risk (Carrero *et al.,* 2018). Contrarily, the 1999 Izmit earthquake in Turkey (M: 7.4) unfortunately caused 18 000 deaths, mostly from building collapse, and nearly 300 000 buildings damaged, since concrete and masonry are the primary building materials in Turkey. Therefore, focus has been placed on the awareness of earthquake and development of earthquake-resistant structures in Turkey since 1999. In the last 10 years, approximately 70 earthquakes with the magnitudes between 5 and 7 have occurred in Turkey (AFAD, 2019). The officials predict that there might be a big earthquake in the near future, especially in the Marmara region. Even though Turkey is an earthquake country, the new developments and studies about the wooden buildings have not been sufficiently followed in the country. One of the reasons for that is insufficient research on wood construction in Turkey (Caliskan *et al.,* 2019).

The most important components affecting the structural performance of wooden buildings are shear walls and horizontal diaphragms (Skaggs and Martin, 2004). The shear walls are commonly used to provide stiffness and strength to the structure to resist lateral wind and seismic forces in wood-frame buildings. As a shear wall transfers the wind and earthquakes loads from the roof to the foundation, the wall-to-foundation connection is a critical component in transferring the loads from the wall to the foundation. Failures of this connection can occur due to overturning or sliding of a structure (Shadravan and Ramseyer, 2018). A wood shear wall consists of dimensional lumber sheathed with plywood, oriented strand board (OSB), or other sheathing material (van de Lindt and Walz, 2003). Sheathing material has considerable in plane shear strength. Plywood is a good product as sheathing material in wood shear wall because it is much more rigid when loaded along the thin edge (in plane) as opposed to the large flat surface (out of plane) (Bott, 2005). Additionally, plywood is the best for resisting earthquake loads, since it is able to tolerate the greatest amount of displacement before failing (Demirkir *et al.,* 2013). Li *et al.* (2007) also determined that plywood performs well as a sheathing material in terms of stiffness. There are some studies about the performance of plywood, OSB or other sheathing materials used in different shear wall types (Guíñez *et al.,* 2019; Shadravan *et al.,* 2019; Xiao *et al.,* 2015). However, there are few studies about how plywood manufacturing factors affect structural performance of shear wall sheathed with them. It is known that manufacturing factors of the panels such as wood species, adhesive types, number of layers and pressing parameters affect the mechanical properties of plywood (Bal and Bektas, 2014). It should not be ignored that this might be causing the changing of structural performance of shear wall.

The aim of the study is to investigate the effects of some production factors (wood species, thickness of panels) of plywood and fibre direction of sheathing material on the racking performance of the shear wall.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Wood materials and manufacturing of plywood
2.2. Drvni materijali i proizvodnja furnirskih ploča

Three coniferous tree species were used in this study: Scots pine *(Pinus sylvestris),* black pine (*Pinus nigra*) and spruce (*Picea orientalis* L.). The logs for veneer manufacturing, with an average size of 40 cm, were supplied by Trabzon, located at the northern point of the Black Sea Region of Turkey.

The production of plywood was planned to be carried out in a facility capable of producing large size panels that can be used in shear wall construction. For this aim, veneer peeling, veneer drying, gluing and pressing were carried out in a factory under controlled conditions. A rotary peeler with a maximum horizontal holding capacity of 80 cm was used for veneer manufacturing. The logs were steamed for 12-16 hours at a temperature of 80 °C before the peeling process and veneer sheets with dimensions of 120 cm by 240 cm by 2 mm were clipped. The vertical opening was 0.5 mm and the horizontal opening was 85 % of the veneer thickness in the veneer manufacturing process. After rotary peeling, the veneers were dried at 110 °C in a veneer dryer until reaching 6-7 % moisture content.

The Eurocode 5 states that the minimum thickness of the plywood boards to be used in shear walls should be 9 mm EN 1995-1, -2:2004). Therefore, five and seven-ply plywood panels, 10 mm and 14 mm thick, were manufactured by using phenol formaldehyde (PF) glue resin with 47 % solid content. The glue was applied at a rate of 160 g/m^2 to each surface of veneer by using a four-roller spreader. The assembled samples were pressed in a hot press at a pressure of 8 kg/cm^2 (785 kPa) and at 140 °C for 10 min (five-ply plywood) and 14 min (seven-ply plywood). Five replicate plywood panels were manufactured from each group. Before the tests, the density of plywood panels was determined according to EN 323:1993. The results of density according to wood species are given in Table 1.

Table 1 Density results of plywood panels
Tablica 1. Gustoća ispitivanih furnirskih ploča

Wood species *Vrsta drva*	**Thickness of panel, mm** *Debljina ploča, mm*	**Density, g/cm³** *Gustoća,* g/cm³	
		X	***S***
Scots pine *drvo bijelog bora*	10	0.59	0.03
	14	0.66	0.04
Black pine *drvo crnog bora*	10	0.57	0.14
	14	0.61	0.07
Spruce *smrekovina*	10	0.51	0.07
	14	0.49	0.03

2.2 Modelling and sheathing of shear wall
2.2. Modeliranje i oblaganje posmičnog zida

Standard wood frame dimensions for each group of panels and the positioning, mounting and fastening of the produced plywood in this frame are given in Figure 1 according to ASTM E 72 (2014) standard.

All shear walls, 2.4 m x 2.4 m in size were constructed with 50 mm x 100 mm spruce framing members. The upper element and the edges were made of twin pieces of timber beam. Two repetitive frame systems were installed for each group. Each frame was nailed by 2 plywood panels in size of 1.2 m x 2.4 m. Power driven nails (6d) of 3.1 mm in diameter and 63

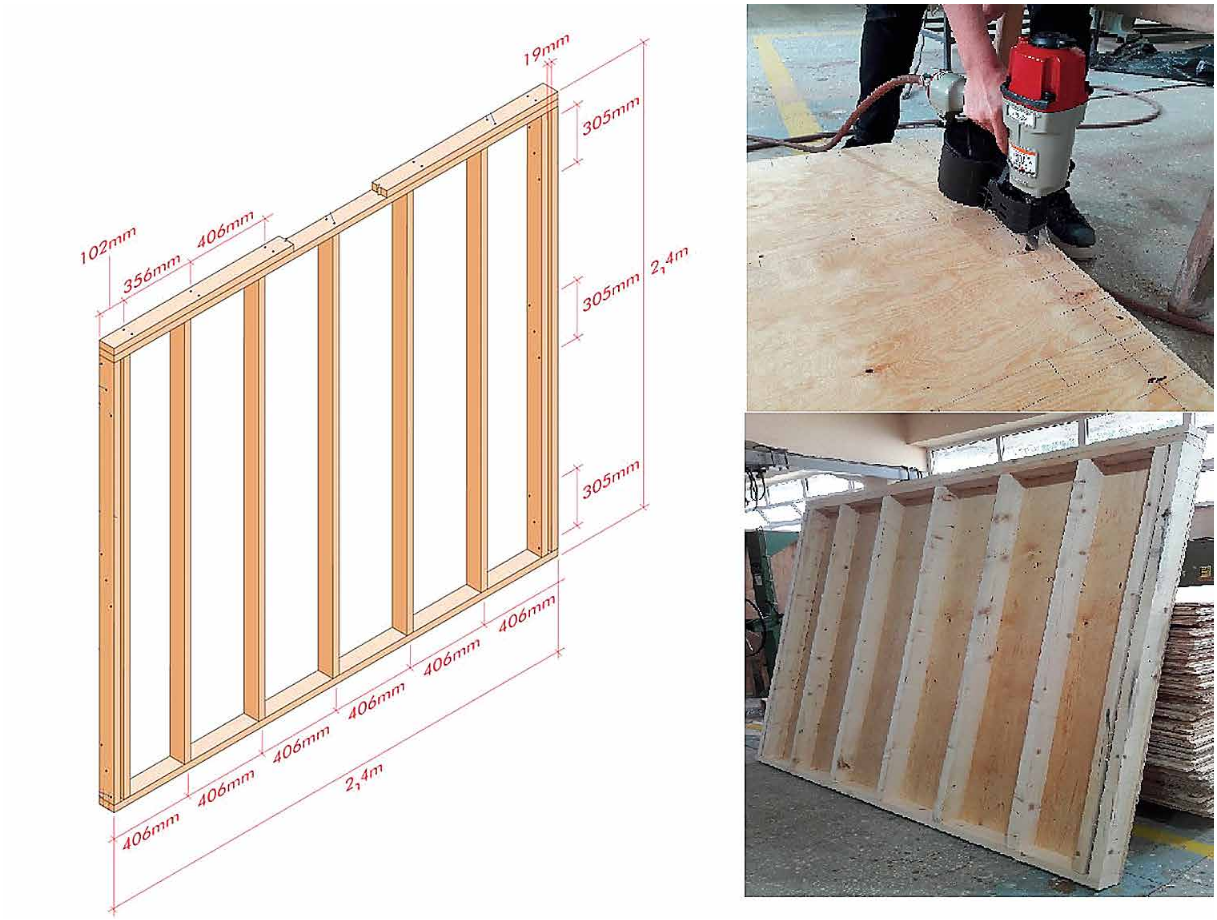


Figure 1 Standard wood frame (ASTM E 72, 2014) and shear wall sheathing with plywood
Slika 1. Standardni drveni okvir (ASTM E 72, 2014) i posmični zid obložen furnirskom pločom

Figure 2 Shear walls formed according to fibre direction (a: perpendicular, b: parallel)
Slika 2. Posmični zidovi formirani prema smjeru vlakanaca (a: okomito, b: paralelno)

Figure 3 Mounting of shear wall to floor
Slika 3. Montaža posmičnog zida na pod

mm in length were used to connect the framing material and the plywood panels. 76 mm nail spacing along the panel edges and 152 mm spacing along the interior studs were used. The plywood of each frame group was tested in two different fibre directions (Figure 2). Connections to the floor of the frame system were made with fittings suitable for concrete floors (Figure 3).

In order to achieve the aim of the study, the description of the shear wall models formed according to the wood species, thickness of plywood and fibre direction of shear wall is given in Table 2.

2.3 Determining racking performance of shear walls
2.3. Utvrđivanje svojstava posmičnih zidova

Shear wall analysis test was carried out under linear load according to ASTM E 72 (2014) standard. The experimental test setup is given in Figure 4.

The shear walls were loaded in three stages to 3.5 kN, 7 kN and 10.5 kN at a uniform rate. After the load of 3.5 kN was placed on the walls, all of the load was removed and any residual displacement in the panel was noted. Then the walls were loaded to 7 kN and again the load was removed and any additional displacement was noted; after this the loading was increased to 10.5 kN, the load was removed again, and the displacement was noted. After the shear wall was loaded as specified to 3.5 kN, 7 kN and 10.5 kN, it was loaded again to failure or until the total displacement of the panel reached 100 mm. As a result of the analysis, maximum load and displacement values were obtained to determine the racking performance of each shear wall group.

Multivariate analysis of variance was performed for statistical evaluation of the changes in the maximum loads and displacements at ultimate load depending on the wood species, thickness of panel and fibre directions of the shear wall. After multivariate analysis, Student–Newman–Keuls test with 95 % confidence level was used to compare the mean values of variance sources.

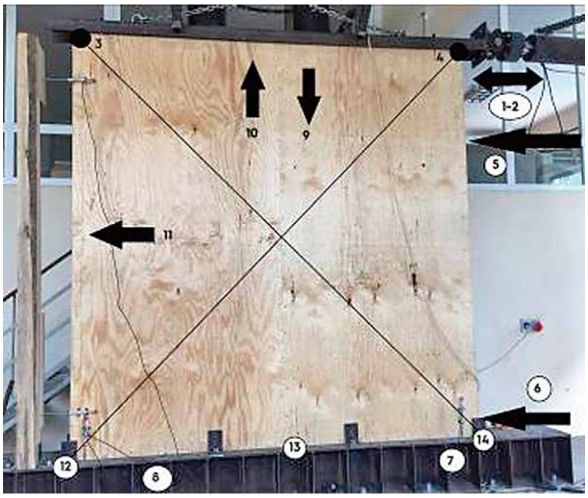
3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Racking performance of shear walls
3.1. Svojstva posmičnih zidova

The wall groups were tested according to ASTM E 72 (2014) and some calculations were made for the racking performance of the walls in the current study.

Table 2 Description of models formed within scope of study
Tablica 2. Opis modela izvedenih u sklopu istraživanja

Wall number *Broj zida*	**Wood species** *Vrsta drva*	**Thickness of panel, mm** *Debljina ploče,* mm	**Fibre direction** *Smjer vlakanaca*
Wall 1	Scots pine *drvo bijelog bora*	10	Perpendicular / *okomito*
Wall 2			Parallel / *paralelno*
Wall 3		14	Perpendicular / *okomito*
Wall 4			Parallel / *paralelno*
Wall 5	Black pine *drvo crnog bora*	10	Perpendicular / *okomito*
Wall 6			Parallel / *paralelno*
Wall 7		14	Perpendicular / *okomito*
Wall 8			Parallel / *paralelno*
Wall 9	Spruce *smrekovina*	10	Perpendicular / *okomito*
Wall 10			Parallel / *paralelno*
Wall 11		14	Perpendicular / *okomito*
Wall 12			Parallel / *paralelno*



1: Applied load / *Primijenjeno opterećenje*
2: Applied load / *Primijenjeno opterećenje*
3: Diagonal displacement / *Dijagonalni pomak*
4: Diagonal displacement / *Dijagonalni pomak*
5: Displacement at the top / *Pomak na vrhu*
6: Sliding on the floor / *Pomak na podu*
7-8: Upward movement in floor connections / *Kretanje prema gore u podnim spojevima*
9-11: Plywood movements / *Kretanja furnirske ploče*
12-14: Displacement of beams / *Pomak greda*

Figure 4 Experimental test setup
Slika 4. Postavka eksperimenta

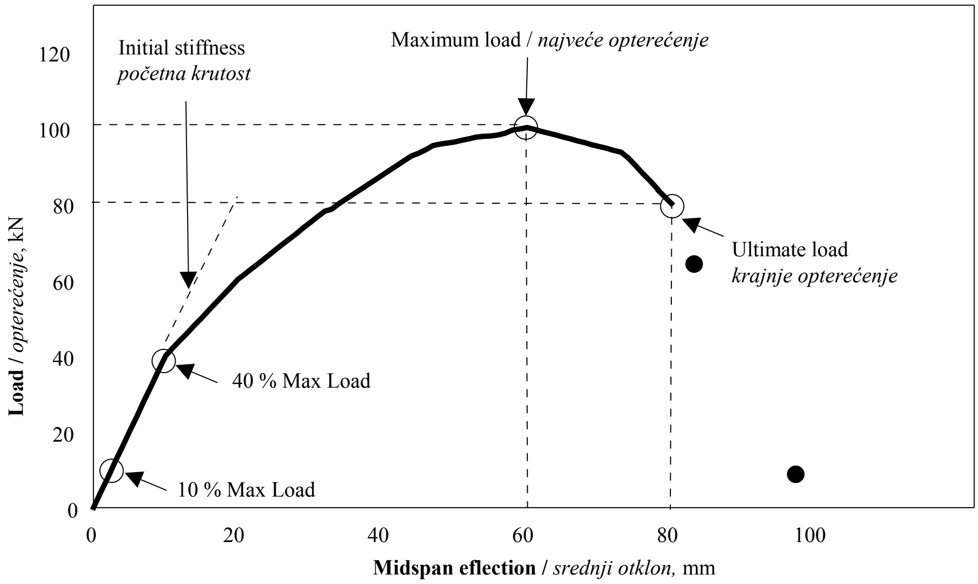


Figure 5 Analysis of a load-displacement curve (Pirvu, 2008)
Slika 5. Analiza krivulje opterećenje – pomak (Pirvu, 2008.)

The following properties shown in Figure 5 were calculated according to Figure 6 for each wall tested and the results are given in Table 3 together with the maximum load and displacement at the maximum load:

- Initial stiffness, by selecting the points closest to 10 % and 40 % of the maximum load and fitting a straight line to the intervening points;
- Ultimate load, as 80 % of the maximum load;
- Displacement at ultimate load; identified based on the calculated ultimate load.

Stiffness is one of the most important parameters for structural panels. If the panels are used as sheathing material in a shear wall that has higher stiffness, they will be more resistant to earthquake loads (Demirkir and Colakoglu, 2015). As shown in Table 3, Wall 3 manufactured with Scots pine seven ply-plywood perpendicular to the fibres showed the highest stiffness, whereas Wall 10 manufactured with spruce five ply-plywood parallel to the fibres showed the lowest stiffness value. In addition to stiffness, ductility is also an important factor, being defined as the ability to deform structures especially under the effect of load. The displacement values at ultimate load can be compared in determining the ductility properties of the walls. According to Table 3, Wall 8 manufactured with black pine seven ply-plywood perpendicular to the fibres showed the highest displacement value at ultimate load, whereas Wall 3 manufactured with Scots pine seven ply-plywood perpendicular to the fibres showed the lowest value. Xiao *et al.* (2015) examined the shear walls sheathed with bamboo plywood at 9 mm thickness and they found stiffness values between 0.89 kN/mm and 1.09 kN/mm. In another study on shear walls sheathing plywood panels, the stiffness value of

Table 3 Results of racking performance of shear walls
Tablica 3. Izmjerene vrijednosti svojstava posmičnih zidova

Wall number *Broj zida*	**Maximum load, kN** *Najveće opterećenje,* kN	**Displacement at maximum load, mm** *Pomak pri najvećem opterećenju,* mm	**Ultimate load, kN** *Krajnje opterećenje,* kN	**Displacement at ultimate load, mm** *Pomak pri krajnjem opterećenju,* mm	**Stiffness, kN/mm** *Krutost,* kN/mm
Wall 1	44.80	75.95	35.84	89.99	0.88
Wall 2	42.98	84.98	34.38	87.26	0.69
Wall 3	39.99	48.24	32.00	64.99	1.48
Wall 4	42.26	66.17	33.81	67.23	0.73
Wall 5	42.06	75.84	33.65	89.98	1.15
Wall 6	39.73	95.77	31.78	99.96	0.97
Wall 7	42.01	74.65	33.61	89.98	1.13
Wall 8	39.88	94.78	31.91	100.17	0.98
Wall 9	27.01	84.99	21.60	85.02	0.93
Wall 10	30.69	80.44	24.55	87.75	0.61
Wall 11	37.68	85.65	30.15	87.68	0.93
Wall 12	26.51	63.25	21.21	87.75	0.70

1.3 kN/mm was found (FEMA, 2001). Okabe *et al.* (2000) found the stiffness of shear walls sheathing Canadian Softwood Plywood between 0.38 and 0.7 kN/mm. In this study, the stiffness values were found in between 0.61 and 1.48 kN/mm, which is similar to those of literature studies.

As a result of the statistical analysis, the effects of wood species, thickness of panel and fibre directions of the wall groups on the maximum load and displacements at ultimate load were found significant. Student–Newman–Keuls test with 95 % confidence level was used to compare the mean values of variance sources and the results are given in Table 4.

When the effect of wood species on the maximum load carried by the walls is examined, the walls sheathing Scots pine plywood gave higher results than other species (Table 4). It can be explained by density values of plywood panels. As can be seen from Table 1, Scots pine has the highest values in density among all wood species. Demir *et al.* (2019) stated that there was a positive correlation between the maximum load carried by the shear wall and density.

Table 4 Racking performance results of Student–Newman–Keuls test at 95 % confidence level
Tablica 4. Rezultati Student-Newman-Keulsova testa za svojstva posmičnog zida pri razini značajnosti od 95 %

Properties *Svojstva*	**Factors** *Činitelji*	**LS Mean** *Srednja vrijednost LS*	**Homogenous groups*** *Homogene grupe**
Maximum load, kN *najveće opterećenje,* kN	Wood species of plywood / *vrsta drva furnirske ploče*		
	Scots pine / *drvo bijelog bora*	42.51	c
	Black pine / *drvo crnog bora*	40.92	b
	Spruce / *smrekovina*	30.47	a
	Thickness of panel, mm / *debljina ploče,* mm		
	10	37.88	a
	14	38.01	a
	Fibre direction of wall / *smjer drvnih vlakana na zidu*		
	Perpendicular / *okomito*	38.93	b
	Parallel / *paralelno*	37.00	a
Displacement at ultimate load, mm *pomak pri krajnjem opterećenju,* mm	Wood species of plywood / *vrsta drva furnirske ploče*		
	Scots pine / *drvo bijelog bora*	77.37	a
	Black pine / *drvo crnog bora*	95.02	c
	Spruce / *smrekovina*	87.05	b
	Thickness of panel, mm / *debljina ploče,* mm		
	10	89.99	b
	14	82.97	a
	Fibre direction of wall / *smjer drvnih vlakana na zidu*		
	Perpendicular / *okomito*	84.61	a
	Parallel / *paralelno*	88.35	b

*Different letters denote statistically significant differences. / *Različito slovo označuje statistički značajnu razliku.*

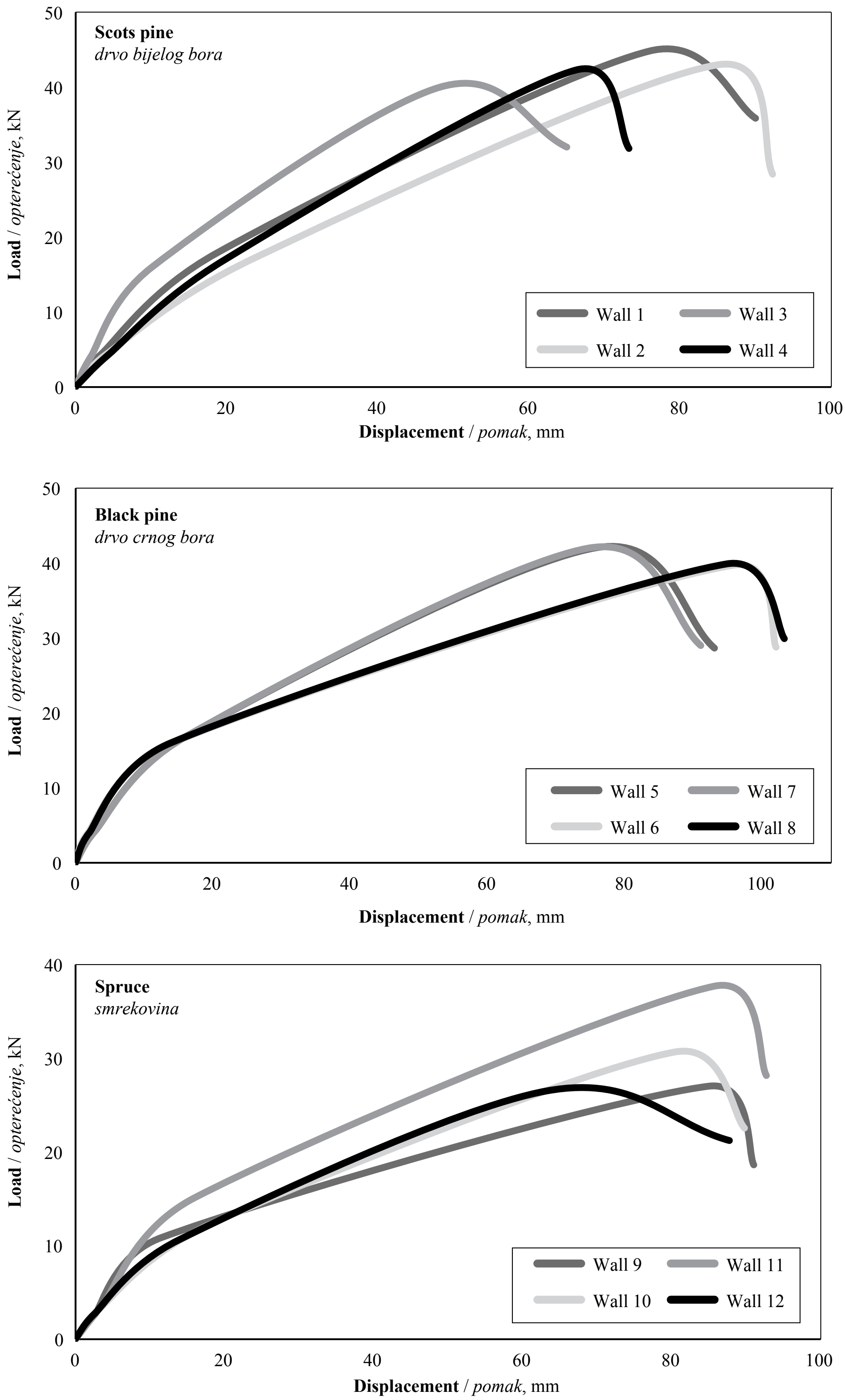


Figure 6 Load-displacement relationship for shear walls sheathed with plywood
Slika 6. Odnos opterećenje – pomak za posmične zidove obložene furnirskom pločom

It is stated that the lateral load resistance of a timber frame system depends on the rigidity of the timber, the sheathing material and the connecting elements used on the shear wall (Li *et al.,* 2007). Demirkir *et al.* (2013) stated that the effect of veneer wood species on maximum load was significant and the difference in wood species was determined to have a small but significant effect on resistance and stiffness. The highest

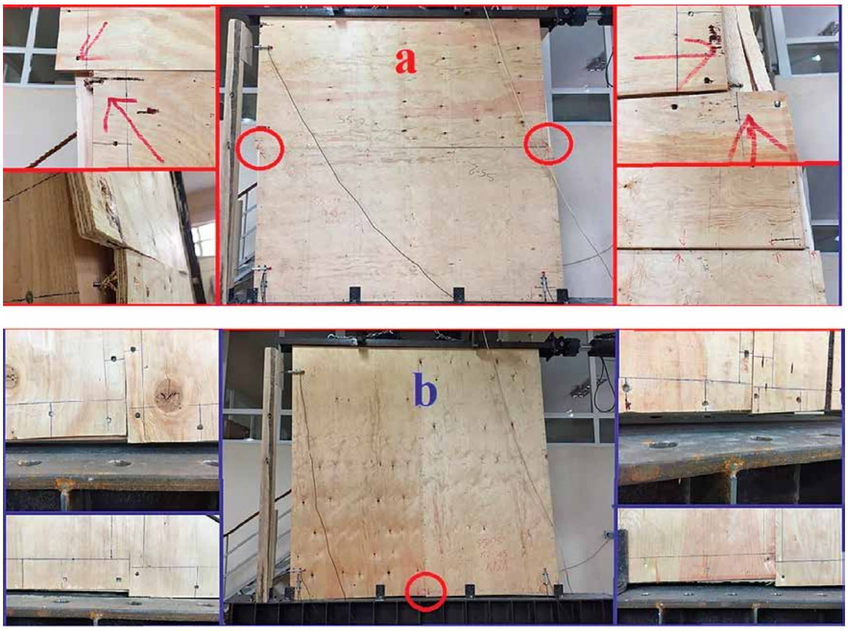


Figure 7 Failure modes of shear walls formed according to fibre direction (a: parallel, b: perpendicular)
Slika 7. Načini loma posmičnih zidova nastali s obzirom na smjer drvnih vlakanaca (a: paralelno, b: okomito)

displacement value at ultimate load was obtained from the shear wall sheathing black pine plywood as compared to other groups (Table 4).

There is no statistically significant difference between the maximum load value of the shear walls with seven and five ply-plywood panels. However, the mean of maximum load of the seven ply-plywood panels was slightly higher than that of the five ply-plywood panels. Han *et al.* (2018) stated that thicker sheathing panels could bear larger lateral shearing loads compared with thinner ones. Also, plywood thickness tends to increase the load carry capacity and stiffness of the hybrid system (Kho *et al.,* 2018). In Table 4, the highest displacement value at ultimate load was obtained from the shear wall sheathing five ply-plywood. Wang *et al.* (2017) examined the lateral loading performance of two different thickness bamboo plywood (6 mm and 9 mm) and they found that increases in thickness of sheathing panels increased the deformability of some groups of shear walls. The size, thickness and material property of the sheathing material have to be designed for effectively resisting the lateral forces and they are critical in providing enough resistance, stiffness and ductility to the system when subjected to earthquake ground motions (Jayamon, 2017).

As shown in Table 4, the maximum load values of shear wall sheathing perpendicular to the fibre directions were higher than those parallel to the fibre directions. Similar results were obtained in the study by Kho (2018). In Table 4, the highest displacement value at ultimate load was obtained from the shear wall sheathing parallel to fibre directions. Similarly, it was found that displacement values of shear wall produced parallel to face grain were larger than those of shear wall produced perpendicular to face grain (Han *et al.,* 2018). The connections nailed perpendicular to grain had significantly lower ultimate displacement due to the tendency of plywood splitting, thus leading to 12 – 45 % lower ductility than the connections nailed parallel to grain (Kho, 2018).

3.2 Failure modes of shear walls
3.2. Načini loma posmičnih zidova

As shown in Figure 9, with the monotonic loading process going on, the nail joints failed as consequence of relative displacement between the sheathing panels and the timber frame. The wall formed perpendicular to fibre direction was less deformed than that formed parallel to fibre direction. Especially, the failure mode of the wall formed parallel observed in all the walls was due to the cutting of sheathing nails, pull out of the nails in the edges of the wall sheathing and crushing of plywood panel by nails head (Figure 7a). The walls formed parallel to fibre direction were displaced more at ultimate load. The main failure mode of the wall formed perpendicular included the dislocation of the panels (Figure 7b). When the loading exceeded the maximum bearing capacity of the nail joints between studs and bottom plate, the relative displacement uplifted the studs and shear walls were wrecked when the nails were withdrawn from the adjacent studs (Han *et al.,* 2018).

The predominant failure mode of the walls was the failure of sheathing to framing nail connections on either side of the wall. The failure never occurred simultaneously on both ends of the wall. The shear wall sheathed with spruce plywood panels failed more than the walls sheathed with other species. Moreover, the wall covered with five ply-plywood was damaged more, because it had larger displacement at ultimate load than the wall covered with seven ply-plywood panels.

4 CONCLUSIONS
4. ZAKLJUČAK

The effects of production factors (wood species, thickness of panel) of plywood and fibre direction of sheathing material on the racking performance of the shear wall were investigated in this study. The maximum load capacity of the wall increased with increasing the density values of plywood panels. It was determined that the Scots pine plywood panels are the best sheathing materials for the shear walls among wood species in terms of load carrying capacity. Moreover, it was found that the wall formed perpendicular to fibre directions sheathing materials can carry more load than the wall formed parallel to fibre directions. The thickness of panel had no statistically relevant impact on the maximum load capacity. The displacement at ultimate load of the wall is significant for determining the ductility of the shear walls. It was also concluded that the black pine plywood panels were the best sheathing material for the shear walls among wood species in terms of ductility. In addition, the wall formed parallel to fibre directions sheathing materials could carry more load than the wall formed perpendicular to fibre directions. The displacement at ultimate load decreased with increasing the thickness of plywood panels. When analysing the failures modes at the end of the test, it was determined that the walls formed parallel to fibre directions were more damaged than the walls formed perpendicular to fibre directions. However, it was seen that the walls were able to withstand loads undergoing displacement for a long time.

This study shows that plywood panels manufactured from softwood species growing in Turkey can be used in wood frame buildings as a sheathing material in shear walls designed to withstand lateral loads such as earthquakes.

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Multivariate Hotelling T^2 Control Chart for Monitoring Some Quality Characteristics in Medium Density Fiberboard Manufacturing Process

Multivarijatni kontrolni dijagram *Hotelling T^2* za praćenje nekih svojstava kvalitete u proizvodnji ploča vlaknatica srednje gustoće

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ABSTRACT • *Statistical process control tools are of great importance in terms of controlling manufacturing processes and improving product quality. In this study, the manufacturing process of medium density fiberboards manufactured in a company operating in the forest products industry was monitored by using multivariate Hotelling T^2 statistical process control chart in terms of some quality characteristics. The T^2 values of the signals detected by the Hotelling T^2 control chart were also decomposed. By the decomposition of T^2 values, it was determined which quality characteristics contributed more to each signal. It was seen that the process was not in control for Hotelling T^2 control chart, which reveals the shift level in the mean of quality characteristics. As a result, the application of Hotelling T^2 allowed fast detection of possible abnormalities in the process. The decomposition of T^2 values successfully revealed which quality characteristics contributed significantly to the signals. Besides, it was concluded that, for monitoring, the Hotelling T^2 chart was able to employ simultaneously different quality characteristics of medium density fiberboard. The current application study also contributed to the emergence of the root causes of the large shifts in the process. In conclusion, the findings of the study enabled the company to ensure the process stability and to facilitate decision-making on actions to be taken for quality improvement.*

KEYWORDS: *wood based panel industry; Hotelling T^2; quality improvement; process control*

SAŽETAK • *Statistički alati za praćenje procesa vrlo su važni za kontrolu proizvodnih procesa i poboljšanje kvalitete proizvoda. U ovom su istraživanju praćena neka obilježja kvalitete procesa proizvodnje ploča vlaknatica srednje gustoće primjenom multivarijatnoga kontrolnog dijagrama Hotelling T^2. Napravljena je dekompozicija T^2 vrijednosti signala detektiranih kontrolnim dijagramom Hotelling T^2. Dekompozicijom T^2 vrijednosti utvrđeno je koja obilježja kvalitete više pridonose pojedinom signalu. Iz kontrolnog dijagrama Hotelling T^2 vidjelo se da proces nije pod kontrolom, što dovodi do pomaka srednjih vrijednosti karakteristika kvalitete. Kao rezultat toga, primjena kontrolnog dijagrama Hotelling T^2 omogućila je brzo otkrivanje eventualnih abnormalnosti u procesu proizvodnje. Dekompozicijom vrijednosti T^2 uspješno je otkriveno koja su svojstva kvalitete značajno pridonijela*

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signalima. Osim toga, zaključeno je da se kontrolni dijagram Hotelling T^2 može primijeniti za istodobno praćenje različitih obilježja kvalitete ploča vlaknatica srednje gustoće. Trenutačna primjena studije također je pridonijela otkrivanju temeljnih uzroka velikih pomaka u procesu. Zaključno, nalazi studije omogućili su promatranoj tvrtki da stabilizira proces proizvodnje i olakša donošenje odluka o postupcima za poboljšanje kvalitete ploča vlaknatica.

KLJUČNE RIJEČI: *industrija drvnih ploča; Hotelling T^2; poboljšanje kvalitete; kontrola procesa*

1 INTRODUCTION
1. UVOD

Manufacturers continuously strive to improve the quality of product and production processes by reducing the variability in their processes. However, the fact is that there is no such a manufacturing process capable of repeatedly producing the same products with all features. In other words, there are always sources of variability that can cause differences between the final characteristics of the products manufactured in almost every manufacturing process. The main reason of the differences between the characteristics of the products coming from the same process is natural or chance and special or assignable causes (Rogalewicz, 2012). The natural variability is cumulative effect of lots of small and inevitable causes. A process that operates only with the effect of natural causes of variation is statistically accepted under control. In other words, these causes are considered as an inherent part of the process. Besides, another kind of variability, called assignable causes, may occur occasionally in the output of a process. This variation in key quality characteristics is generally larger than natural variation and often represents an unacceptable degree of process performance. That is, if a manufacturing process operates in the presence of the assignable causes of variation, it is considered to be an out of control process (Montgomery, 2012). It is clear that the assignable causes of variation that can be present in the process remarkably affect product quality. Hence, it is vital to separate the variation sources from each other to keep the process in a state of control by eliminating assignable causes and manufacture high quality products (Öberg and Åstrand, 2017). One of the most widely used methodologies for this goal is to monitor constantly the process together with statistical process control applications, which are of great importance in terms of the final product quality and customer satisfaction (Kurt and Karayılmazlar, 2019).

Statistical process control, a tool of quality control, uses various statistical approaches to monitor and control any process (Sivasubramanian *et al.*, 2015). Thanks to statistical process control, the occurrence of assignable causes of shifts in the process can be quickly identified. Thus, it is possible to investigate the process and carry out necessary corrective actions before a great number of nonconforming products are manufactured (Montgomery, 2009). One of the most popular procedures for achieving the statistical control of any process is control charts, originally developed by Walter Shewhart in the early 1920s (Darestani and Aminpour, 2014). However, Shewhart control charts were univariate charts with some serious limitations. They allow monitoring only one quality characteristic on the chart at the same time. In addition, the overall probability of a false alarm may be inflated since any correlation between the quality characteristics of the product is ignored as the univariate charts are used (Waterhouse *et al.*, 2010) Further, in many manufacturing processes, it is necessary to consider a great number of different quality characteristics or process parameters in making a decision on the quality of a product or making an assessment of the process. In such cases, practitioners should control and monitor all of them to keep the process stable and ensure its high quality (Rogalewicz, 2012). However, as stated above, it is not possible to control or monitor more than one quality characteristic or parameter related to the process simultaneously with univariate charts. To deal with the limitations of traditional univariate charts, multivariate statistical process control charts were recommended (Djekic *et al.*, 2015; Hossain and Masud, 2016). The rapid rise of demands and requirements of consumers from a product increased the interest in multivariate methods and made these methods popular (Hajlaoui, 2011).

Hotelling T^2 chart is the most familiar multivariate statistical process control procedure. This chart is often employed to monitor the process mean of multiple quality characteristics simultaneously (Hossain and Masud, 2016). It is worth mentioning that the Hotelling T^2 chart only uses the information from the most recent sample. As a result, it is possible to say that it is a very effective tool for capturing large shifts in the process mean vector (Ghute and Shirke, 2008). On the other hand, the multivariate statistical process control procedures like Hotelling T^2, as used alone, can create a serious drawback in terms of interpretation. As the T^2 statistic shows that a process is out of control, it does not give precise information about which quality characteristic, or characteristics, is out of control (Gonzalez-de la Parra and Rodriguez-Loaiza, 2003). Some methods were developed to solve this drawback, that is to detect which quality characteristic, or a set of quality characteristics, contributes to the out of control signal (Bersimis *et al.*, 2005).

A comprehensive literature review showed that Hotelling T^2 chart has been widely used to detect the shifts in quality characteristics or to control the process in various manufacturing processes out of wood based panel industry. However, although Hotelling T^2 chart is one of the best known multivariate statistical process control tools for monitoring the process mean vector in multivariate processes, it has been rarely employed in wood based panel industry. In a previous study, Young *et al*. (1999) tried the T^2 statistic for monitoring the vertical density profile in the manufacturing of medium density fiberboard (MDF) and oriented strand board (OSB). To the authors' knowledge, there is no application study that involves the analysis of the MDF manufacturing process in terms of quality characteristics considered in the current study using both Hotelling T^2 and decomposition of T^2 methods. It is clear that increasing the number of such studies for improving the quality of the products and processes is of great importance.

With this application study, it was aimed to use multivariate Hotelling T^2 chart in order to determine the shift level in the process mean vector of quality characteristics considered in the MDF manufacturing process of a forest products company. Another goal of the study was to detect the contribution of each quality characteristic to the signals encountered in Hotelling T^2 chart by decomposing the T^2 values. Thus, with the current study, an exhaustive statistical process control application has been performed in a forest products company and an important contribution has been made to the literature.

2 HOTELLING T² CHART
2. ANALIZA *HOTELLING T²*

The first original application in multivariate statistical process control was done by Hotelling (1947). This method, developed to monitor processes with two or more quality characteristics, is based on the T^2 statistic and is known as the Hotelling T^2 control chart (Mason and Young, 2002). The chart is one of the most well-known multivariate process control methods and is commonly employed in a wide variety of industries because of its ease of implementation and simplicity (Yeong *et al*., 2016). Hotelling T^2 is sometimes adopted as a multivariate version of the univariate Shewhart chart (Jamaluddin *et al*., 2018). The Hotelling T^2 chart can be applied to processes by following two different procedures. In other words, the chart can be employed either for subgroup data or for individual data. The Hotelling T^2 statistic for subgrouped data is as in Eq. 1 (Montgomery, 2009).

$$T^2 = n\left(\bar{x}-\bar{\bar{x}}\right)' S^{-1}\left(\bar{x}-\bar{\bar{x}}\right) \quad (1)$$

There are two phases, generally phase 1 and phase II, in creating control charts. In phase I, historical data are employed to detect whether a process is in control and to estimate process parameters in control as well as control limits. In phase II, control limits are used to check the data taken from the process (Alfaro and Ortega, 2008). The goal of phase I is to reach a data set in control, which is vital for detecting control limits for phase II. The phase I limits for the T^2 chart are as formulated in Eq. 2 and 3 (Montgomery, 2012).

$$UCL = \frac{p(m-1)(n-1)}{mn-m-p+1} F_{\alpha,\text{p},\text{mn}-\text{m}-\text{p}+1} \quad (2)$$

$$LCL = 0 \quad (3)$$

Where *UCL* is upper control limit, *LCL* is lower control limit, *p* is the number of quality characteristics, *m* is the number of samples, *n* is the sample size, and $F_{\alpha,p,mn\text{-}m\text{-}p+1}$ means a *F*-distribution with a degree of freedom for *p* numerator and *mn-m-p+1* denominator (Aparisi *et al*., 2004). The chart created in phase II is used to monitor future production. The *UCL* for phase II is calculated by Eq. 4 (Mitra, 2016). The *LCL* is taken as zero as in the phase I (Montgomery, 2012).

$$UCL = \frac{p(m+1)(n-1)}{mn-m-p+1} F_{\alpha,\text{p},\text{mn}-\text{m}-\text{p}+1} \quad (4)$$

$$LCL = 0 \quad (5)$$

The analysis of the equations shows that the *UCL* used for phase II in equation (4) is multiplied by (m+1)/(m-1) of *UCL* used for phase I in equation (2) (Montgomery, 2012).

3 MATERIALS AND METHODS
3. MATERIJALI I METODE

3.1 Materials
3.2. Materijali

In this study, a medium-sized company operating in the forest products industry in Turkey was selected as application domain. The panels with 2440 mm × 2800 mm × 18mm dimensions were used as experimental material. The manufacturing process of these panels was investigated in terms of some quality characteristics. Pine is mostly used in the MDF manufacturing process, followed by beech and eucalyptus species. These wood species are generally employed in certain proportions in the manufacturing process. The fibers obtained from the wood species for the manufacture of MDFs are subjected to drying in order to remove their moisture and they are dried to about 8-12 %. The dried fibers are mechanically laid to form the panels. The formed panel mats are compressed by using very high pressure to convert them into panels of the required thickness. Urea formaldehyde adhesive, which has a solids content of 45 % and is frequently employed in the manufacture of wood based panels, is used for the manufacture of panels. The panels manufactured were then kept under suitable conditions. The targeted density of MDFs is 720 kg/m³.

3.2 Methods
3.2. Metode

3.2.1 Quality characteristics
3.2.1. Obilježja kvalitete

It is of great importance to decide which quality characteristics of the product are to be examined prior to the plot of control charts. The quality characteristics considered in the scope of the current study were the mechanical or strength properties of MDF. For this purpose, the tests related to the modulus of rupture (*MOR*) (N/mm^2), modulus of elasticity (*MOE*) (N/mm^2), surface screw holding capability (*SSHC*) (N) and edge screw holding capability (*ESHC*) (N) characteristics, quite important in making a decision on the quality of MDF, were performed in the quality control laboratory of the relevant company.

3.2.2 Data acquisition process
3.2.2. Proces prikupljanja podataka

In this study, the MDF panels were taken from the manufacturing process randomly. In order to obtain reliable information about the manufacturing process, the number of samples or data should be accurately determined in the creation of the control charts. Montgomery (2012) reported that choosing the data number of 20-25 is accepted as a widely referenced approach and it is desirable to reach this number in the calculation of trial control limits. In Vardeman and Jobe (2016), it was mentioned that taking 20-25 samples is generally sufficient. Çetin and Birgören (2007) recommended increasing this number in case of using multivariate charts. Considering this situation, the number of samples was kept above the recommended limits. As a result, 137 data groups for three shifts of day were obtained with 5 measurement values for each quality characteristics considered for the evaluation of the process in the 4-month period between 1 February 2017 and 31 May 2017. In other words, each data group or sample consisted of five measurements.

3.2.3 Tests for quality characteristics
3.2.3. Ispitivanje obilježja kvalitete

In order to plot control charts, the data of previously detected quality characteristics should be obtained. For this purpose, the panels were taken from endless band during the manufacture in each shift, and test samples were prepared from the panels for each quality characteristics. Five samples were prepared for each characteristics from each panel in order to perform the tests of the quality characteristics. All these experimental activities were carried out by the IMAL IB 600 test machine with a capacity of 10 tons in the quality control laboratory of the company.

The *MOR* and *MOE* tests were carried out in accordance with the TS-EN 310:1999 standard. The sizes of the samples were taken as 20k + 50mm. In order to perform the tests, 5 samples were prepared from each experimental panel. In the tests, the force was applied at a constant speed throughout the experiment and the speed of the loading head was adjusted to reach the maximum force in (60±30) seconds. The tests for the *SSHC* and *ESHC* were also conducted, and then the results were recorded. The detection of screw holding capability of the samples was performed in accordance with the TS EN 320 (1999) standard. The samples with 50 mm × 50 mm dimensions were employed to obtain the *SSHC* and *ESHC* values. In the detection of SSHC and *ESHC* values, the samples were drilled with (2.7±0.1) mm crochet and screw holding apparatus with 4.2 mm × 38 mm screw was fixed to the samples with the help of a drill. Afterwards, the apparatus was attached to the test device and the screw was pulled out at a speed of (10±1) mm/min until it was completely removed from the test sample.

3.2.4 Chart design
3.2.4. Dizajn dijagrama

After selecting the control chart to be used for the investigation of the MDF manufacturing process, the charting operation was started using the data obtained from the process. Yeong *et al*. (2016) reported that the choice of design parameters has a great impact on the performance of the chart. Hence, special attention was paid to the design phase. As mentioned earlier, the charting of the T^2 statistic is considered in two stages: phase I and phase II (Yang and Trewn, 2004; Montgomery, 2009). Accordingly, in the current study, a total of 137 data obtained as a result of the data acquisition process were divided into two groups, 50 for phase I and 87 for phase II, respectively. In phase I, a set of data in control, often referred to as historical data set (HDS), was created. The main goal in this phase is to provide a basis for detecting initial control limits and to estimate the unknown parameters, in other words, to determine the design parameters of the chart to be drawn for phase II (Mason *et al*., 2003; Yang and Trewn, 2004). In addition, it is important to emphasize that at this phase all data points with T^2 values greater than the *UCL* are regarded as outliers and therefore they are removed from the data set (Talib *et al.,* 2014). As a consequence, the unknown parameters were estimated for phase II using the HDS brought into a state of statistical control in phase I. Phase II involves chart creation for T^2 statistic. In this phase, the Hotelling T^2 chart was generated with 87 new measurements taken from the MDF manufacturing process and the actual state of the process was observed. The control limits for phase II were calculated by using the HDS obtained with the Hotelling T^2 chart. Further, in the calculation of the limits for both phase I and phase II, α was taken into account as 0.0027.

3.2.5 Chart interpretation
3.2.5. Interpretacija dijagrama

Since univariate statistical process control charts are considered a single quality characteristic, the relationship between quality characteristics is neglected. Hence, the interpretation of out of control data is easy. Unlike univariate control charts, in multivariate control charts, it is not straightforward to decide which quality characteristic, or a set of quality characteristics, causes the problem since the chart generated is associated with more than one quality characteristic and the correlations between these quality characteristics are taken into account (Bersimis *et al*., 2005). Therefore, as a multivariate chart, a major problem encountered in the use of the Hotelling T^2 chart is that it is difficult to interpret a signal that occurs in the process (Mason *et al*., 1997). In such a case, the standard practice is to plot univariate $\bar{x}$ control chart on quality characteristics individually. However, it was notified that this approach may not be successful because of the loss of information about quality characteristics. On the other hand, a useful practice is to decompose the T^2 values into components that reflect the contribution of quality characteristics individually (Montgomery, 2012). In the present study, in order to contribute to the solution of the problem related to the interpretation of the out of control signals in the T^2 chart, the T^2 values were decomposed. In this way, the degree of the contribution of all quality characteristics to the out of control signals on the chart was successfully determined, together with their significance levels. All charting application and the decomposing of the T^2 values were carried out by using Minitab software.

3.2.6 Assumptions
3.2.6. Pretpostavke

It is useful to examine some assumptions in the application of control charts. The assumptions were applied to the HDS reached as a result of phase I and without any out of control data point. For this goal, it was investigated whether the data was normally distributed as well as the correlation analysis revealing the relationship between the data. Kolmogorov-Smirnov test was employed to determine whether the data showed normal distribution. On the other hand, the compatibility of data to multivariate normal distribution was also tested by an analytical method based on Mahalanobis distance. It was notified that the first step for this method is to calculate squared Mahalanobis distance of each data. In addition, it was mentioned that if the population is normal and sample size is large enough ($n \geq 25$), the distances fit the chi-square distribution. This property can be used to obtain a chi-square plot. Finally, the ordered squared Mahalanobis distance and chi-square values are plotted. The fact that the plot demonstrates a linear structure is considered as a sign that the multivariate normality assumption is provided (Sharma, 1996). The Kolmogorov-Smirnov test and correlation analysis were carried out by using the SPSS (Statistical Package for the Social Science).

4 RESULTS AND DISCUSSION
4. REZULTATI I RASPRAVA

4.1 Evaluation of phase I results
4.1. Evaluacija rezultata I. faze

In this study, phase I was applied to test retrospectively whether the MDF manufacturing process was in control as the subgroups were being drawn. In other words, the Hotelling T^2 chart in this phase was used to bring the process into a state where it is statistically in control. In order to analyze the process with this chart, a data set with sample size 5 ($n = 5$), quality characteristic number 4 ($p = 4$) and sample repeat number 137 ($m = 137$) was obtained, and it was divided into two groups for phase I and phase II. The first 50 data were employed in order to achieve a process in control by the Hotelling T^2 chart in phase I, while the remaining 87 data were used to view the future status of the manufacturing process in phase II.

Before proceeding to the plotting application for phase I, the statistical summary of the data to be used in this phase was calculated as presented in Table 1.

As stated above, trial control limits were calculated to achieve a process or data set in control in the implementation of phase I using the Hotelling T^2 chart. This application was repeated until there was no data point beyond control, in other words, above the *UCL*. As the process was completely in control, phase I was finished, and thus a data set in control was obtained.

Table 1 Statistical summary of phase I dataset
Tablica 1. Statistički sažetak skupa podataka I. faze

Quality characteristics *Obilježja kvalitete*	Number of data *Broj podataka*	Minimum *Najmanja vrijednost*	Maximum *Najveća vrijednost*	Mean *Srednja vrijednost*	Standard deviation *Standardna devijacija*	Variance *Varijanca*
MOR	50	32.69	37.05	34.696	1.053	1.11
MOE	50	2958.88	3531.50	3258.820	110.976	12315.72
SSHA	50	1403.20	1834.60	1606.128	91.521	8376.02
ESHA	50	904.20	1155.20	1046.628	53.339	2845.06

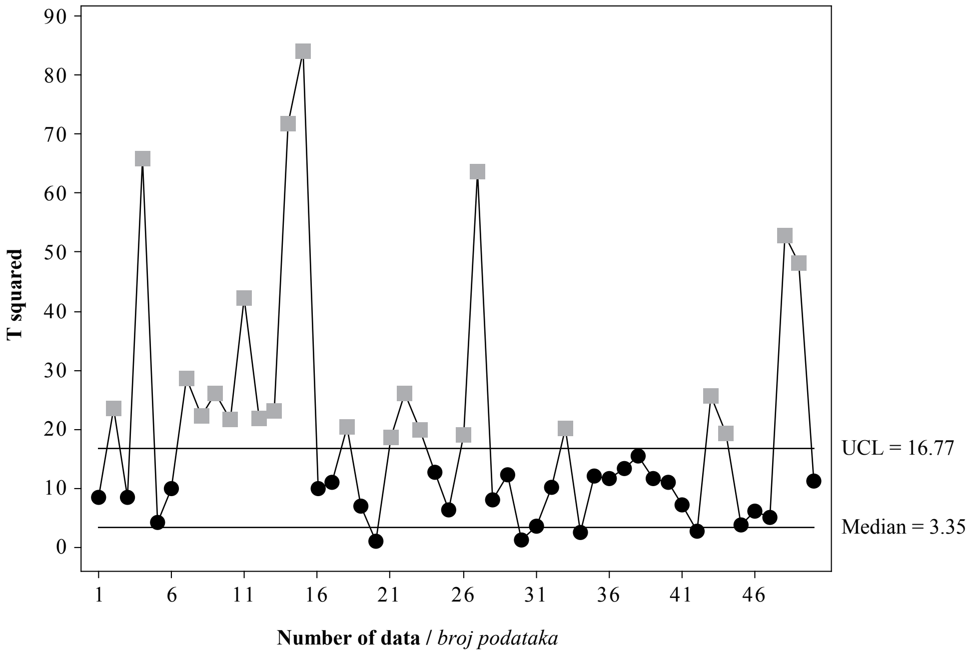

Figure 1 Hotelling T^2 control chart for 50 data
Slika 1. Kontrolni dijagram *Hotelling T^2* za 50 podataka

Accordingly, the process was brought into a state of statistical control by following the steps below:

Firstly, the Hotelling T^2 chart for all data of phase I was generated, and the resulting chart is given in Figure 1.

As the Hotelling T^2 chart obtained in the first step of phase I was examined, it was seen that the *UCL* was 16.77, and 22 data exceeded the *UCL* value. As mentioned earlier, in such a case, in order to obtain a data set in a state of control, the data above the *UCL* must be removed from the data set. Therefore, the analysis was continued with the remaining 28 data after removing the data points whose T^2 value was above the *UCL*. The Hotelling T^2 chart was then generated with the remaining 28 data in the second step of phase I, and the resulting chart is given in Figure 2.

The Hotelling T^2 chart drawn in the second step of phase I showed that all of the T^2 values or 28 data were smaller than the *UCL*. It is possible to say that the MDF manufacturing process is in control since there is no data above the *UCL*. Thus, the chart now clearly shows that the process is statistically stable. All steps of phase I are briefly summarized in Table 2.

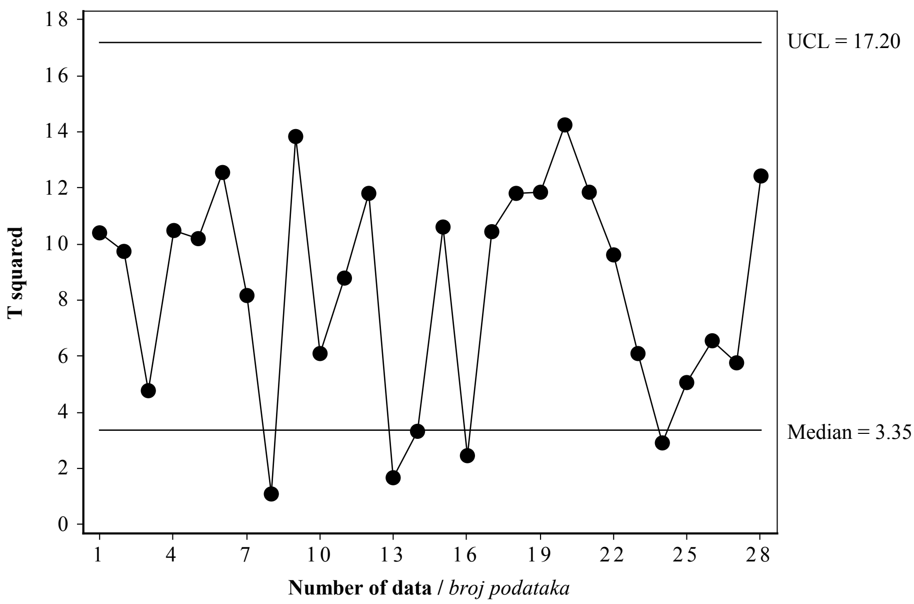

Figure 2 Hotelling T^2 control chart for 28 data
Slika 2. Kontrolni dijagram *Hotelling T^2* za 28 podataka

Table 2 Summary of phase I for Hotelling T^2 chart
Tablica 2. Sažetak I. faze za dijagram *Hotelling* T^2

Application of phase I *Provedba I. faze*	**UCL**	**Number of out of control data** *Broj podataka izvan kontrole*	**Removed data** *Uklonjeni podatci*	**Number of remaining data** *Broj preostalih podataka*
Phase I - Step I	16.77	22	2, 4, 7-15, 18, 21-23, 26-27, 33, 43-44, 48-49	28
Phase I - Step II	17.20	0	-	28

Table 3 Statistical summary of HDS
Tablica 3. Statistički sažetak HDS-a

Quality characteristics *Obilježja kvalitete*	**Number of data** *Broj podataka*	**Minimum** *Najmanja vrijednost*	**Maximum** *Najveća vrijednost*	**Mean** *Srednja vrijednost*	**Standard deviation** *Standardna devijacija*	**Variance** *Varijanca*
MOR	28	33.37	36.77	34.756	0.838	0.70
MOE	28	3171.57	3353.13	3256.634	57.362	3290.37
SSHA	28	1511.40	1756.40	1609.900	70.887	5024.92
ESHA	28	975.20	1137.40	1041.743	33.698	1135.53

The sets consisting of 28 data were accepted as the HDS. The statistical summary of the HDS is given in Table 3.

After obtaining the HDS, phase II should be started to test the future performance of the MDF manufacturing process. However, before proceeding to this stage, some assumptions were investigated for the HDS, which is the basis for phase II.

4.2 Evaluation of assumptions results
4.2. Evaluacija rezultata pretpostavki

It was stated that the unknown parameters for phase II must be estimated from a normally distributed data group that does not include outliers. It was also notified that multivariate data analysis is based on linear correlation. Hence, the significant relationships between quality characteristics are sought (Montgomery, 2012). On the other hand, neglecting the assumptions could negatively influence the reliability of the results (Abo-Hawa *et al*., 2016). Table 4 shows the matrix of the correlation coefficients calculated with 28 data of the quality characteristics.

As the correlation matrix in Table 4 was examined, it was seen that there is a significant relationship between the *MOR* and *MOE*, and also *MOE* and *SSHA*. In addition, although it was not significant at a p = 5% level, there was a notable relationship between the *SSHA* and *ESHA*, with a correlation coefficient of 0.305. When a literature search was conducted, it was seen that there are some studies in which coefficients similar or lower than the correlation coefficients reached in the current study were statistically significant (Gonzalez-de la Parra and Rodriguez-Loaiza, 2003; Haridy and Wu, 2009). This may be due to the characteristics of the datasets considered in the studies. It was noted that very small correlation coefficients

Table 4 Matrix of correlation coefficients for 28 data
Tablica 4. Matrica koeficijenata korelacije za 28 podataka

Quality characteristics *Obilježja kvalitete*		***MOR***	***MOE***	***SSHA***	***ESHA***
MOR	Pearson correlation	1	0.451	-0.204	-0.079
	P	-	0.016	0.297	0.688
	N	-	28	28	28
MOE	Pearson correlation	-	1	-0.380	-0.009
	P	-	-	0.046	0.964
	N	-	-	28	28
SSHA	Pearson correlation	-	-	1	0.305
	P	-	-	-	0.114
	N	-	-	-	28
ESHA	Pearson correlation	-	-	-	1
	P	-	-	-	-
	N	-	-	-	-

with large datasets can be statistically significant (Schober *et al*., 2018).

Following the investigation of the relationships between quality characteristics, regardless of whether the characteristics were normally distributed or not, they were analyzed by applying Kolmogorov-Smirnov test. The results of the Kolmogorov-Smirnov test are given in Table 5.

Table 5 Kolmogorov-Smirnov test results for 28 data
Tablica 5. Rezultati Kolmogorov-Smirnova testa za 28 podataka

Quality characteristics *Obilježja kvalitete*	Kolmogorov-Smirnov		
	Test statistic	*df*	*P*
MOR	0.079	28	0.200
MOE	0.138	28	0.184
SSHA	0.163	28	0.054
ESHA	0.136	28	0.197

When Table 5 was examined, it was understood that the significance level of all quality characteristics were greater than 5 %, in other words, all quality characteristics showed normal distribution.

Since the Hotelling T^2 control chart is a multivariate analysis, in some cases, providing the univariate normal distribution assumption may not produce sufficient and reliable results. Therefore, multivariate normal distribution assumption was also investigated in this study. For this test, the Mahalanobis distance values were calculated using SPSS software and the values were ordered. The chi-square values corresponding to Mahalanobis values were then obtained. In order to see the relationship between ordered Mahalanobis values and chi-square values, a plot was created using Microsoft Excel software and the correlation analysis was performed. The plot showing the relationship between the ordered Mahalanobis values and the chi-square values is presented in Figure 3.

Figure 3 demonstrates that there is a linear relationship between the Mahalanobis values and chi-square values. In addition, a correlation analysis was performed to reveal the power of the relationship between the Mahalanobis and the chi-square values. The result of the analysis showed that the Pearson Correlation coefficient was very close to 1 and the coefficient was at the 1 % level of significance. This means that the multiple normal distribution assumption was provided.

4.3 Evaluation of phase II results
4.3. Evaluacija rezultata II. faze

As seen above, the manufacturing process was successfully brought into a state of statistical control by applying the phase I procedure. This part of the study includes the application of phase II to test whether the process remains in control when future subgroups are drawn. It was notified that the charts created in this phase help the practitioners to monitor the process for any deviation from an in-control state (Bersimis *et al*., 2007). In addition, in the literature, it has been noted that Hotelling T^2 chart is a very popular tool used to simultaneously monitor quality characteristics in multivariate processes (Shabbak and Midi 2012; Hossain and Masud, 2016). On the other hand, attention was drawn to some disadvantages of the chart. As stated earlier, one of the disadvantages of this chart is that the quality characteristics causing an out of control signal cannot be detected easily (Bersimis *et al*., 2005). In the current study, all T^2 values that generate the signal were decomposed to deal with this difficulty. By applying this method to the out of control signals, one or more responsible quality characteristics for each signal were determined.

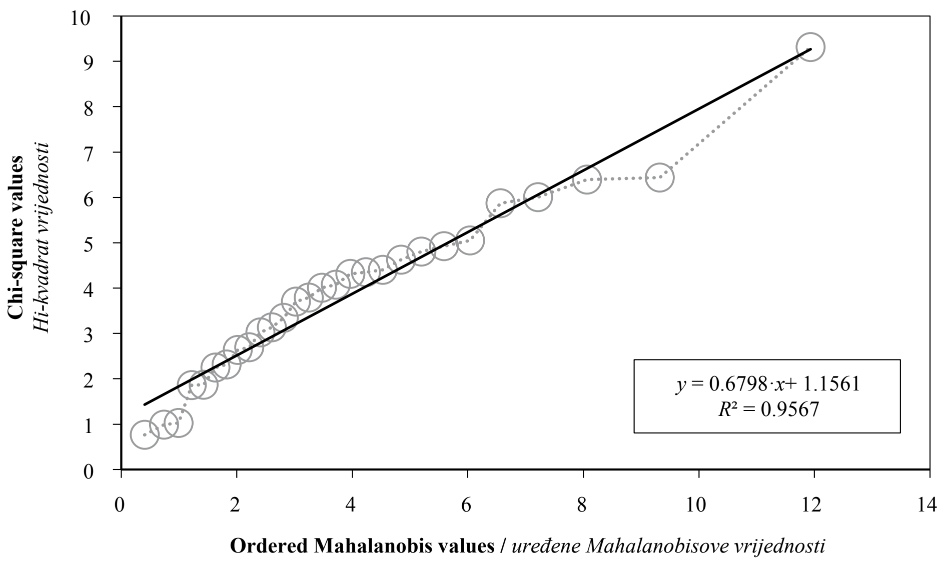

Figure 3 The plot showing the relationship between Mahalanobis values and chi-square
Slika 3. Grafikon koji prikazuje odnos između Mahalanobisovih vrijednosti i Hi-kvadrata

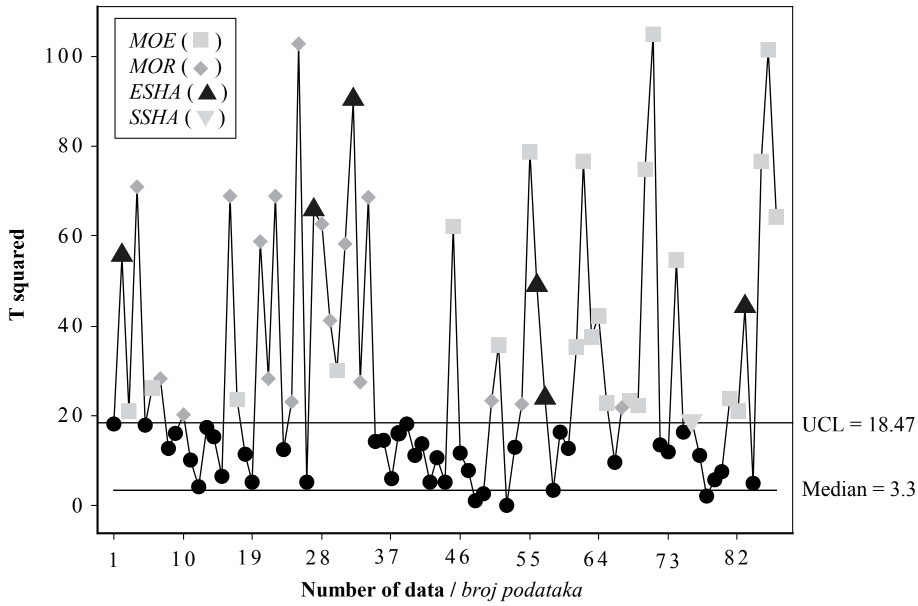

Figure 4 Hotelling T^2 chart for phase II and quality characteristics that contribute most to each signal as a result of T^2 decomposition
Slika 4. Dijagram *Hotelling* T^2 za II. fazu i obilježja kvalitete koja najviše pridonose svakom signalu kao rezultat T^2 dekompozicije

Figure 4 presents the T^2 control chart created for phase II. It also shows the quality characteristics that contribute the most to each signal as a result of T^2 decomposition.

A summary of phase II created to reveal the future state of the process is presented in Table 6.

As Figure 4 and Table 6 were examined, 46 out of control signals were identified for the MDF manufacturing process. In other words, 46 out of control data points with T^2 values greater than an *UCL* of 18.47 were observed. The Hotelling T^2 chart generated for phase II demonstrated that there were major shifts in the process and that the process was not in control. This revealed that the variability in the mean vector of the process subject to the research was high.

Figure 4 also showed that the *MOE* to 22 signals, the *MOR* to 17 signals, the *ESHA* to 6 signals and the *SSHA* quality characteristic to 1 signal provided the maximum contribution. It should be noted that the quality characteristics marked in Figure 4 are not the only factor that leads to the signal or signals in most cases. In general, more than one quality characteristics to each signal make the contribution at different significance levels. The significance levels of the contribution of the quality characteristics to the signals encountered in the Hotelling T^2 chart are given in Table 7.

As can be seen in Table 7, in many circumstance, more than one quality characteristics contributed significantly to the signals observed in the T^2 chart. For example, it was found that the 45th data point on the T^2 chart was detected as the 22nd data point out of control. At this point, all quality characteristics were found to be effective in signal formation. On the other hand, it was understood that only the *MOE* contributed to the signal at the 35th data point out of control (68th data point on the chart).

In brief, it was seen that the MDF manufacturing process was out of control in terms of the process mean vector calculated by taking into account all quality characteristics. In other words, significant shifts were observed from time to time in the process. In order to reveal the reasons of these major shifts in the manufac-

Table 6 Summary of phase II for Hotelling T^2 chart
Tablica 6. Sažetak II. faze za dijagram *Hotelling* T^2

Application of phase II *Provedba II. faze*	**UCL**	**Number of out of control data** *Broj podataka izvan kontrole*	**Out of control data** *Podatci izvan kontrole*	**Number of data in control** *Broj podataka pod kontrolom*	**Data in control** *Podatci pod kontrolom*
Phase II	18.47	46	2-4, 6, 7, 10, 16, 17, 20-22, 24, 25, 27-34, 45, 50, 51, 54-57, 61-65, 67-71, 74, 76, 81-83, 85-87	41	1, 5, 8, 9, 11-15, 18, 19, 23, 26, 35-44, 46-49, 52, 53, 58-60, 66, 72, 73, 75, 77-80, 84

Table 7 Significance levels of contribution of quality characteristics to signals generated in Hotelling T^2 chart
Tablica 7. Razine značajnosti doprinosa obilježja kvalitete signalima generiranim u dijagramu *Hotelling* T^2

Quality characteristics *Obilježja kvalitete*		**Out of control data** *Podatci izvan kontrolne vrijednosti*																						
		2	3	4	6	7	10	16	17	20	21	22	24	25	27	28	29	30	31	32	33	34	45	50
Significance level (p) *razina značajnosti (p)*	*MOR*	NS	NS	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	MOE	**	**	**	**	**	**	**	**	**	**	**	NS	**	NS	*	**	**	**	NS	NS	**	**	**
	SSHA	*	*	NS	*	NS	**	NS	NS	NS	NS	**	NS	NS	**	NS	NS	**	NS	**	**	**	*	NS
	ESHA	**	*	**	NS	*	NS	*	NS	NS	*	**	**	**	**	**	*	NS	NS	**	NS	NS	**	NS

Quality characteristics *Obilježja kvalitete*		**Out of control data** / *Podatci izvan kontrolne vrijednosti*																						
		51	54	55	56	57	61	62	63	64	65	67	68	69	70	71	74	76	81	82	83	85	86	87
Significance level (p) *razina značajnosti (p)*	*MOR*	**	**	**	NS	NS	**	**	**	**	NS	**	NS	NS	**	**	**	NS	**	**	*	**	NS	**
	MOE	**	NS	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
	SSHA	NS	NS	NS	*	NS	NS	NS	NS	**	**	NS	NS	NS	NS	NS	*	**	NS	NS	NS	NS	**	NS
	ESHA	NS	**	**	**	**	NS	**	**	NS	*	NS	NS	*	NS	**	NS	*	*	NS	**	**	**	**

**$p < 0.01$, * $p < 0.05$, NS: Statistically not significant. / *Statistički nije značajno.*

turing process and contribute to the improvement of quality, great efforts have been made to identify the factors that may cause the poor quality or out of control signal. It is a clear fact that the quality of the MDFs manufactured is affected by many manufacturing parameters in the process. Hence, information about the wood species used in the manufacture and their usage rates, adhesive type, moisture content, the density of MDF panels and the pressing parameters such as press time and press pressure etc. were comprehensively evaluated.

As a result of the comparative analysis of the data points on the charts and the values of the manufacturing parameters corresponding to these points, it was thought that one of the main reasons for variation in the quality characteristics or strength values of MDF was the use of the different wood species during the manufacture and especially major variation in the usage rate of these species from time to time. As stated in the materials and methods section of the present study, both coniferous and deciduous wood species were generally used in different rates in MDF manufacture. Wood species might have a significant effect on the strength values of MDF due to their different anatomical structures. Akbulut and Ayrılmış (2001) mentioned that more than 90 % of MDF is made up of wood material and thus wood species have a great impact on MDF properties. Another important factor that can be effective on the quality characteristics in the MDF manufacturing process was the variation in press parameters. İstek (2006) reported that an increase in the value of the press pressure applied during the manufacturing increased the *MOR* and *MOE* of the fiberboard. Balkız (2006) notified that an increase in the press time and pressure generally improved the *MOR*, *MOE* and *SSHA* properties of MDF manufactured by using *Rhododendron Ponticum* L., however, it had no important effect on the *ESHA*. Sihag *et al*. (2017) evaluated the effect of the press pressure on the strength values of MDF made from bamboo (*Dendrocalamus strictus*). They observed that an increase in the pressure value improved the *MOR*, *SSHA* and *ESHA*. Aisyah *et al*. (2013) stated that the impact of press pressure and time on some strength values of MDF varied. As a result, it was concluded that the press parameters had generally an important influence on the strength values or quality characteristics of MDF. On the other hand, considering the complexity of the MDF manufacturing process, in addition to the main factors identified in the present study, other factors might have affected in different ways the variability in quality characteristics.

5 CONCLUSIONS
5. ZAKLJUČAK

This study presented an application of Hotelling T^2 chart to monitor simultaneously the *MOR*, *MOE*, *SSHA* and *ESHA* quality characteristics and contribute to the improvement of quality in the MDF manufacturing process of a medium-size forestry products company. For this aim, the Hotelling T^2 chart was applied to the data obtained from the process. In order to determine the contribution level of the quality characteristics to the signals encountered in Hotelling T^2 chart, the T^2 values were also decomposed. The main conclusions that may be drawn from the study are as follows.

In phase I, the MDF manufacturing process was brought into a state of control using the Hotelling T^2 chart. Then, in phase II, the chart was again created for 87 new data and it was seen that 46 data points were out of control. This revealed that the process was out of control with respect to the considered quality characteristics of MDF.

As a result of the decomposition of T^2 values of the signals detected by employing the Hotelling T^2 chart, it was understood that the *MOR* and *MOE* contributed more to out of control signals when compared to other quality characteristics. On the other hand, it was also determined that in most cases more than one quality characteristics contributed significantly to each signal.

In the examination of the manufacturing process, it was concluded that the major reason of the signals or high variability in strength values was that the usage rates of the wood species used in the manufacture indicated major differences sometimes. The press parameters were other important factors that contribute to out of control signals.

In this respect, it is obvious that the studies to be carried out by using statistical process control methodologies to keep the processes in control will make major contributions to the companies. The results of the study demonstrated that the Hotelling T^2 chart allows practitioners to control and monitor the MDF quality characteristics simultaneously.

Finally, using these methodologies, it is possible to identify quality problems, act in time against the problems, reduce the costs of poor quality and thus manufacture competitive high quality products in international markets.

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Reinforcement of Joints Between LVL Members with GFRP and Finite Element Analysis

Ojačanje spojeva između LVL elemenata polimerima ojačanim staklenim vlaknima i analiza metodom konačnih elemenata

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ABSTRACT • *The goal of this study was to investigate the effect of glass fiber reinforced polymer (GFRP) on joints made of laminated veneer lumber (LVL), through experimental data and evaluation by ANSYS finite element (FE) software. In order to fabricate LVL, veneer from poplar (Populus deltoides Bartr. ex Marsh) with 2.5 mm thickness and PVA adhesive were used. T-shape joints out of LVL were made and two wooden dowels were incorporated as well. Then GFRP was applied to reinforce the joints. GFRP in three grammages (100, 200 and 300 g/m²) was adhered to joints with epoxy resin. Joints reinforcement was performed by a two-layer reinforcing agent. For comparing the effectiveness, half of the specimens were reinforced on sides and the other half on edges. Specimens were tested in static bending. The results have shown that GFRP had a significant effect on the strength of joints. Reinforced joints on both sides were stronger than those reinforced on edge. Joints reinforced with 300 g/m² GFRP were improved by 35 % and 43 %, respectively, compared to 100 and 200 g/m² grammage. Failure modes of specimens are dependent on GFRP grammage. The results of FE have shown that the highest concentration of stress and elastic strain was generated in the tension and compression zones of joints.*

KEYWORDS: *veneer lumber; glass fiber reinforced polymer; finite element method; failure modes*

SAŽETAK • *Cilj rada bio je na temelju eksperimentalnih podataka i analize konačnih elemenata (FE) te uz pomoć softvera ANSYS istražiti utjecaj polimera ojačanog staklenim vlaknima (GFRP) na spojeve od lamelirane drvne građe (LVL). Za izradu LVL-a upotrijebljen je furnir drva topole (Populus deltoides Bartr. ex Marsh) debljine 2,5 mm i PVA ljepilo. Izrađeni su T-spojevi od LVL-a i ugrađena su dva drvena moždanika. Zatim je za ojačanje spojeva primijenjen GFRP u tri gramature (100, 200 i 300 g/m²) tako da je epoksidnom smolom zalijepljen na spojeve. Ojačanje spojeva izvedeno je dvoslojnim armaturnim sredstvom. Radi usporedbe učinkovitosti, polovica uzoraka ojačana je sa strane, a druga polovica na rubovima. Uzorci su ispitani na statičko savijanje. Rezultati su pokazali da GFRP ima značajan utjecaj na čvrstoću spojeva. Spojevi ojačani s obje strane bili su jači od onih ojačanih na rubu. Spojevi ojačani GFRP-om od 300 g/m² poboljšani su za 35 % odnosno za 43 % u usporedbi s GFRP-om gramature100 i 200 g/m². Načini loma uzoraka ovisili su o gramaturi GFRP-a. Rezultati analize konačnih elemenata pokazali su da se najveća koncentracija naprezanja i elastične deformacije pojavljuje u vlačnoj i tlačnoj zoni spojeva.*

KLJUČNE RIJEČI: *drvna građa; polimer ojačan staklenim vlaknima; metoda konačnih elemenata; načini loma*

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1 INTRODUCTION
1. UVOD

An appropriate solution for utilizing low diameter logs and defects prone wood, developed during past decades, is to convert them into structural composite lumber (SCL). Mechanical properties of SCL products are improved by removing randomly scattered growth defects, thus substantially recovering dimensional stability (Williamson, 2002).

SCL products are increasingly replacing the use of solid wood in construction practices (Harrison and Hindman, 2007). Among these products, LVL has gained more popularity than other SCL items (Aydm *et al.,* 2004; Subhani *et al.,* 2017). LVL seems to be a potential material for replacing solid wood in the construction industry. These types of structure joints on load bearing members meet the requirements of the applicable standards. Uses of connecting hardware for increasing stress carrying capacity of joints made on LVL members in construction has limitations due to the size of the member cross-section. Considering these facts, it seems worthwhile to treat such joints by making use of other technologies for increasing their strength, tensile in particular. Hence, many researchers have studied the effect of using fiber-reinforced polymer on the mechanical properties of engineered wood products.

The application of fiber-reinforced polymer (FRP) composites is a promising solution to upgrade/strengthen LVL (Khelifa *et al.,* 2015). Applications of Glass Fiber Reinforced Polymers (GFRP) elements have grown continuously during the last years, as they became very popular in different areas of the aerospace, automotive, marine, oil and gas and civil construction industries, namely (fiberglass structures): ladders, platforms, handrail systems tank, pipe and pump support and or as a reinforcer in wood productions such as glulam and LSL (Osmannezhad *et al.,* 2014; Landesmann *et al.,* 2015; Moradpour *et al.,* 2018; Zor and Kartal, 2020). Many researchers have investigated the operation of FRP materials for strengthening timber elements in the case of increased service (Triantafillou and Deskovic, 1992; Gentile *et al.,* 2002; Micelli *et al.,* 2005; Dempsey and Scott, 2006; Osmannezhad *et al.,* 2014; Raftery and Whelan, 2014; Rautenstrauch, 2007; Moradpour *et al.,* 2018; Reis *et al.,* 2018; Schober and Rautenstrauch, 2007). Using bonded fiber-reinforced polymer laminates for the strengthening and repair of wooden structural members is an effective and economical method (Schober *et al.,* 2015).

According to Kim and Harries (2010), timber beams strengthened with CFRP improved load-carrying capacity and energy absorption capacity when compared to non-strengthened timber.

Khelifa *et al.* (2015) indicated that the increases of flexural strength for the two different reinforcement schemes with 2 and 3 layers of CFRP composite sheets were 41.82 % and 60.24 %, respectively, with respect to the unreinforced timber beams.

D'Ambrisi *et al.* (2014) found that the application of CFRP plates is very effective for repairing both new and old timber beams and it allows to completely restore and to increase their flexural strength, so CFRP can be used for restoring historical building beams. Also, CFRP can increase the load-carrying capacity of timber beams in bending (De Jesus *et al.,* 2012; Nowak *et al.,* 2013; Khelifa and Celzard, 2014; Andor *et al.,* 2015; Rescalvo *et al.,* 2018) and, it shows a significant increase in ultimate strength, stiffness (Borri *et al.,* 2005; Micelli *et al.,* 2005; Nadir *et al.,* 2016; Yang *et al.,* 2016), and energy absorption capacity (Alhayek and Svecova, 2012). Wei *et al.* (2017) investigated the flexural performance of bamboo scrimber beams strengthened with FRP and observed that the strengthening method had a beneficial effect on promoting the compression behavior in the compression zone of the cross-sections of bamboo beams. Ferreira *et al.* (2017) investigated the failure behavior and repair of delaminated glulam beams; their results indicated that the preventively repaired beams showed significant improvements in resistance and stiffness compared to unrepaired beams, although they failed to achieve the performance of healthy beams. Basterra *et al.* (2017) described internal reinforcement of laminated duo beams of low-grade timber with GFRP sheets and presented it by using relatively low reinforcement ratios (1.07 %, 1.6 %) in the tension zone. They found an average improvement of 12.1 % and 14.7 % in stiffness, and an increase of up to 23 % in moment capacity. Hernandez *et al.* (1997) investigated strengthening of laminated beams of *Liriodendron tulipifera* L. (yellow poplar) with external GFRP reinforcements placed in tension, as well as in tension and compression; these authors determined that tensile reinforcement increased flexural strength, whereas double reinforcement increased flexural stiffness. Qi *et al.* (2017) obtained GFRP-wood sandwich beams with lattice-web reinforcement and tested bending in flatwise and sidewise directions. The results showed that the composite sandwich beams in flatwise bending tests failed under a lower load but yielded a larger deflection than those in sidewise bending tests. It was also shown that with the increase in the number of lattice-webs, pseudo-ductility was found to increase in the flatwise directions but decrease in the sidewise directions. The flexural behavior of glulam beams reinforced with fiberglass and steel wire nets was studied by Uzel *et al.* (2018). The results showed that the use of reinforcement nets at the lamination surfaces increased the ultimate load capacities of the tested beams. Investigation of the sandwich beams reinforced with GFRP as surface skins and inner lattice-webs indicated that implementation of GFRP webs in the sandwich beams considerably improved their flexural performance, in association with a pseudo-ductile failure process and certain residual load-carrying capacity (Shi *et al.,* 2017). The strength and stiffness of glulam beams reinforced with glass and basalt fibers were studied by Thorhallsson *et al.* (2017) and they found that the reinforced glulam beams on the tension side allow a possible reduction of the cross-section or lower timber grade while maintaining the same bending strength and stiffness as for the unreinforced beam. Corradi *et al.* (2017) investigated uncertainty analysis of FRP reinforced timber beams and observed that the FRP reinforcement was effective for both enhancing the beam load-carrying capacity and for reducing strength uncertainties. There are also several studies, which indicate that FRP could be increasing mechanical properties of LVL (Wei *et al.,* 2013; Bal, 2014a, 2014b, Wang *et al.,* 2015; Percin and Altunok, 2017; Subhani *et al.,* 2017).

Many studies examined the effect of FRP on the strengthening of engineering wood products i.e. LVL, LSL, glulam. However, the literature does not provide any significant research results related to reinforcing joints fabricated with engineering wood products. Hence, the aims of this study were as follows: 1) to investigate the effect of GFRP on the bending moment capacity joints made of LVL; 2) to compare the density of GFRP in three levels (100, 200 and 300 g/m^2) on the bending moment capacity of these joints; 3) to compare two reinforcing methods using two layers on the sides and two layers in the edge of joints applied in the connection area between two members; 4) to simulate finite element method for investigating the distribution of stress and strain in these joints.

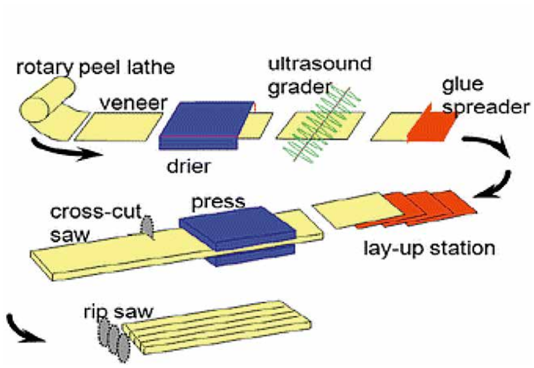


Figure 1 Manufacturing steps of LVL (Buchanan, 2007)
Slika 1. Koraci u proizvodnji LVL-a (Buchanan, 2007.)

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Material
2.1. Materijal

2.1.1 Veneer preparation and LVL manufacturing
2.1.1. Priprema furnira i proizvodnja LVL-a

Rotary cut veneers of poplar logs *(Populus deltoides Bartr. ex Marsh)* were collected from an industrial-scale production. The thickness of the test veneer was 2.3 mm. Veneers were cut into pieces of 2400 mm × 200 mm (length × width), then dried to 6–7 % moisture content. Polyvinyl acetate adhesive was applied to the dried veneer by a manual spreader. The amount of glue per unit area was approximately 200 g/m^2. Nine pieces of glued veneer were stacked with their grain parallel to each other, and then pressed. Press pressure of 1 MPa was applied for 60 minutes. Figure 1 illustrates the process of LVL production.

Some strength properties of experimental LVL, important to this study, were measured according to EN 310 standard, and others were predicted through an existing relationship. Table 1 presents the measured and predicted strength information associated with LVL.

2.1.2 Adhesive
2.1.2. Ljepilo

Two types of adhesives were used in this research, polyvinyl acetate for fabricating LVL and epoxy resin to apply GFRP on target points of test joints. The epoxy consisted of two parts, resin and hardener, which need to be mixed at a ratio of 2:1 in volume. Table 2 presents the strength properties of the adhesive used.

Table 1 Basic properties of wood used in this study
Tablica 1. Osnovna svojstva drva upotrijebljenoga u istraživanju

Parameter *Parametar*	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	v_{LR}	v_{LT}	v_{RT}	v_{TR}	v_{RL}	v_{TL}
	MPa			MPa								
LVL	11103	1216	599	799	688	133	0.37	0.50	0.67	0.33	0.04	0.027
Hornbeam dowel *moždanik od grabovine*	11215	1212	605	807	695	134	0.37	0.50	0.67	0.33	0.04	0.027

E_L, E_R and E_T – Modulus of elasticity in longitudinal, radial, and tangential directions, respectively / *moduli elastičnosti u uzdužnome, radijalnome i tangentnom smjeru*
V_{LR}, V_{RT} and V_{LT} – Poisson's ratio on longitudinal-radial, radial-tangential, and longitudinal-tangential direction, respectively / *Poissonov omjer za uzdužno-radijalni, radijalno-tangentni i uzdužno-tangentni smjer*
G_{LR}, G_{LT} and G_{RT} – Shear modulus on longitudinal-radial, longitudinal-tangential, and radial-tangential direction, respectively / *modul smicanja za uzdužno-radijalni, radijalno-tangentni i uzdužno-tangentni smjer*

Table 2 Strength properties of adhesives used for making LVL and reinforce joints
Tablica 2. Svojstva čvrstoće ljepila upotrijebljenih za izradu LVL-a i za ojačanje spojeva

Parameter *Parametar*	***E*, MPa**	***G*, MPa**	ν
PVA	400	153	0.3
Epoxy	3500	1346	0.3
GFRP	29000	9615	0.3

E – Modulus of elasticity / *modul elastičnosti*, G – Shear modulus / *modul smicanja*, ν – Poisson's ratio / *Poissonov omjer*

2.1.3 GFRP
2.1.3. GFRP

Woven glass fiber reinforced polymer (GFRP) was provided by Mandegar Basbar Company in Karaj, Iran. Three weight intensities of GFRP were applied on test joints, including 100, 200 and 300 g/m^2. GFRP was cut into two pieces, 140 mm × 100 mm and 140 mm × 20 mm, according to the points of application (joint depths and edges).

2.1.4 Dowel
2.1.4. Moždanik

Commercially available dowel out of hornbeam wood was purchased to incorporate in fabrication test joints, as it is a common joint reinforcer in furniture manufacturing. The dowel was 10 mm in diameter and 80 mm in length with a smooth surface.

2.2 Fabrication of test joints
2.2. Izrada ispitnih spojeva

Produced LVL panels were stored for a two-week period to restore and dissipate any strain energy imposed during pressing. Then panels were cut into stacks 300 mm × 100 mm × 21 mm (length × width × thickness) to be utilized as test joint members. Each joint member received two predrilled holes, 40 mm apart on center for installing dowels. The distance between the centers of the two holes was 50 mm and the diameter of the holes was 0.1 mm larger than the dowel diameter. Dowels were dipped in the adhesive prior to being inserted in holes. The adhesive was applied to the cross-section of joints members as well. T-shape assembled joint remained under clamp pressure for 24-h to let adhesive cure well enough. In total 35 T-shape joints were made. For reinforcing test joints with GFRP, a 2-layer GFRP was glued on the depth sides, and top and bottom edges of each joints. Epoxy was the means to apply GFRP with the weight intensity of 100, 200 and 300 g/m^2 (Figure 2). Five replicates were made for each treatment.

2.3 Method of test loading
2.3. Način opterećenja

All specimens were tested by a computer-controlled Instron testing machine (model 4486). The loading rate was set at 5 mm/min. A point load was

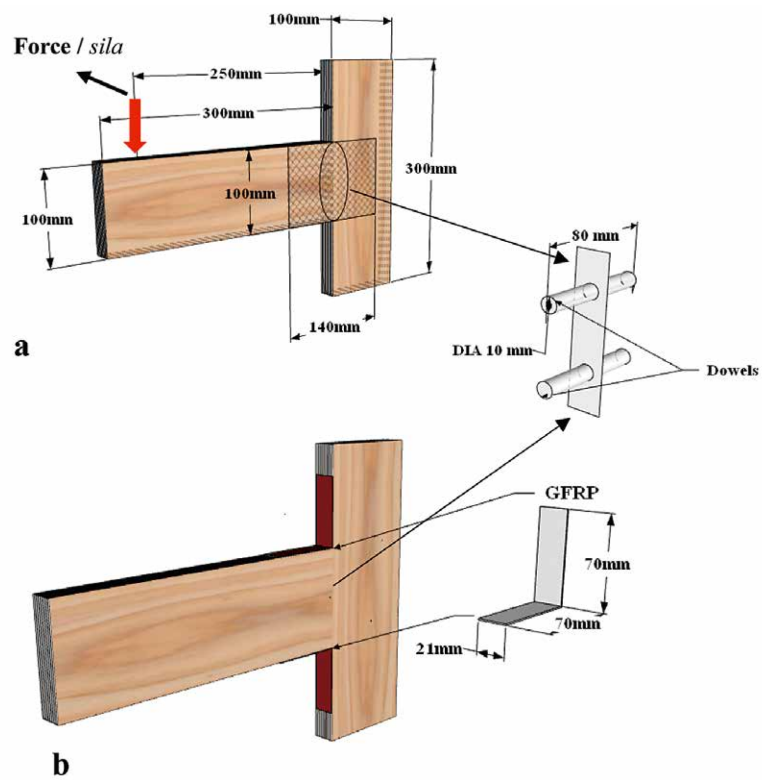


Figure 2 a) Joint reinforced with GFRP by 2 layers on sides (2S), b) joint reinforced with GFRP by 2 layers on upper and bottom edge (2E)
Slika 2. a) Spoj ojačan dvama slojevima GFRP-a sa strane (2S), b) spoj ojačan dvama slojevima GFRP-a na gornjemu i donjem rubu (2E)

applied to the rail member of the joint with the moment arm of 250 mm.

Loading under $M = 0.25 \times P$ (N·m) moment was continued until the joint failure.

2.4 Data analysis
2.4. Analiza podataka

Collected data were first checked for their normal distributions by SPSS software and then refined to determine the effects of variables (grammage, location of applied GFRP), by comparing discrepancies found in mean and standard deviation.

2.5 Finite element modeling
2.5. Modeliranje konačnih elemenata

Ansys workbench 19.1 was used to establish finite element modeling FEM. The geometric size of the FEM was the same as the experimental specimen. For completing strength properties of LVL, relationships between stress and strain were used to calculate others not measured. For mechanical properties of dowels from hornbeam species, average values given in the Wood handbook were adopted (Eqs. 1-9) (Ross, 2010).

$$\sigma_i = E_i \times \varepsilon_i \quad (1)$$

$$\tau_{ij} = G_{ij} \times \gamma_{ij} \quad (2)$$

Where for wood:

$$\varepsilon_L = \frac{1}{E_L}(\sigma_L - \nu_{LR} \cdot \sigma_R - \nu_{LT} \cdot \sigma_T) \quad (3)$$

$$\varepsilon_R = \frac{1}{E_R}(\sigma_R - \nu_{RL} \cdot \sigma_L - \nu_{RT} \cdot \sigma_T) \quad (4)$$

$$\varepsilon_T = \frac{1}{E_T}(\sigma_T - \nu_{TL} \cdot \sigma_L - \nu_{TR} \cdot \sigma_R) \quad (5)$$

$$\gamma_{LT} = \frac{\tau_{LT}}{G_{LT}} \quad (6)$$

$$\gamma_{TR} = \frac{\tau_{TR}}{G_{TR}} \quad (7)$$

$$\gamma_{RL} = \frac{\tau_{RL}}{G_{RL}} \quad (8)$$

Whereas

$$\frac{\nu_{LR}}{E_L} = \frac{\nu_{RL}}{E_R}, \frac{\nu_{LT}}{E_L} = \frac{\nu_{TL}}{E_T}, \frac{\nu_{RT}}{E_R} = \frac{\nu_{TR}}{E_T} \quad (9)$$

Where: E is modulus of elasticity (L: longitudinal, R: radial and T: tangential), G is shear modulus (G_{LR}, G_{LT} and G_{RT}), υ is Poisson's ratio (υ_{LR}, υ_{LT} and υ_{RT}), ε is linear strain in material directions (orthotropic axis), γ is shear strain in material planes (orthotropic planes), σ is linear stress and τ is shear stress.

GFRP and glue lines were referred to as isotropic substances with properties given in Table 2.

Figure 3 illustrates the simulation model of the joint. The tetrahedron method was applied to generate the mesh for joint assembly (Figure 3b$_1$). The developed model included 29735 elements with 124216 nodes. Specific areas of joint such as GFRP, dowel and glue line were meshed with sweep method which is a dense mesh (Figure 3b$_{2,3}$). Interfaces between dowels and hole and between GFRP and joint members were incorporated too.

Boundary conditions reflected experimental specimens, i.e., the force was applied at a point 250 mm on the rail member. Supports were placed in the top, bottom and back of the posting member (Figure 3c).

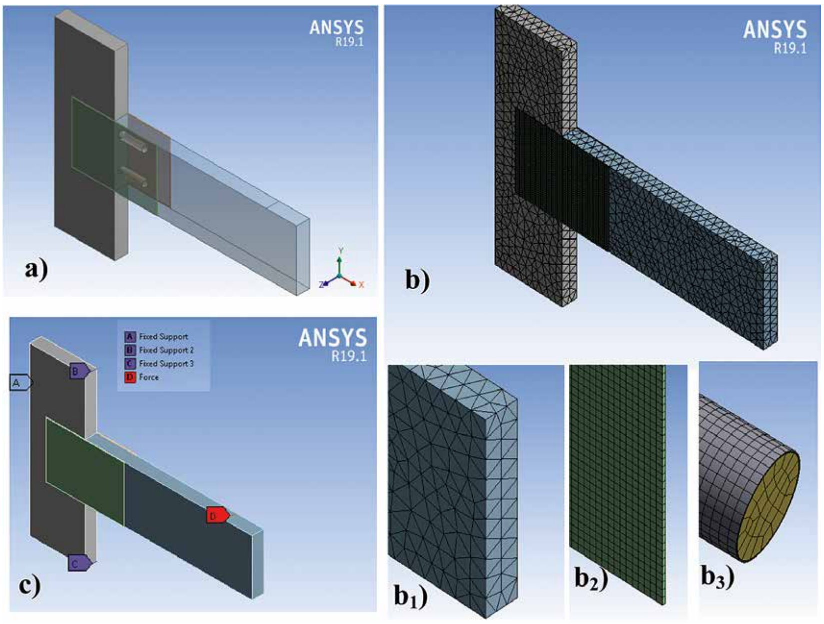


Figure 3 a) Joint modular design, b) FE mesh used for joint, b$_1$) Mesh of joint members, b$_2$) Mesh of GFRP, b3) Mesh of dowel and glue line, c) Boundary conditions

Slika 3. a) Modulirani dizajn spoja, b) FE mreža upotrijebljena za spoj, b$_1$) mreža za spojni element, b$_2$) mreža za GFRP, b$_3$) mreža za moždanik i ljepilo, c) granični uvjeti

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Experimental results
3.1. Eksperimentalni rezultati

The average values of the moment resistance with their standard deviation for types of GFRP and two methods of reinforcing are given in Table 3. This table shows that the highest strength was obtained in joints that were reinforced by GFRP with 300 g/m^2 grammage, while the lowest bending moment resistance was recorded in joints that were not reinforced. The results of multivariable variance analyses of GFRP grammage types, method of reinforcement, and interaction effect between GFRP grammage and the method of reinforcement are given in Table 4.

The analysis of results has indicated that the effects of the main factors (GFRP grammage and method of reinforcement) and their interaction on bending moment resistance were statistically significant at the 1 % significance level.

3.2 Effect of GFRP grammage on bending moment resistance
3.2. Utjecaj gramature GFPR-a na otpor momentu savijanja

Figure 4 shows that the bending moment resistance of joints reinforced with GFRP is significantly higher than that of non-reinforced joints according to Duncan's test. As it can be seen, the bending moment resistance increased with an increase in GFRP grammage. Previous studies in this field have shown that using GFRP materials improves the mechanical properties of timber and the strength of joints (Schober and Rautenstrauch, 2007; De Jesus *et al.,* 2012; Nowak *et al.,* 2013; Raftery and Whelan, 2014; Yildirim *et al.,* 2018).

The highest bending moment resistance was measured for joints reinforced with 300 g/m^2 grammage of GFRP (713 N·m). Average increase in bending moment resistance of joints reinforced by 300 g/m^2 GFRP was 35 % - 43 % as compared to bending moment resistance of joints reinforced by 100 and 200 g/m^2 GFRP, respectively. There were no significant differences between joints reinforced with 100 and 200 g/m^2 GFRP.

3.3 Effect of reinforcing method on bending moment capacity
3.3. Utjecaj metode ojačanja na kapacitet momenta savijanja

As shown in Figure 5, it is obvious that the location of GFRP in reinforced joints had an influence on bending strength and it can be said that the strength of reinforced joints is dependent on the reinforcing method. So, the highest strength was observed in joints reinforced with 2S, the joints being reinforced in depth. Joints reinforced in depth were stronger by 46 % than those reinforced on edges. The main reason for this should be related to the increasing contact zone in the 2S method.

3.4 Failure modes
3.4. Načini loma

In all of the reinforced joints, the fracture was observed in the GFRP zone between two members. An analysis of the failure modes in reinforced joints was investigated and the fracture phenomena observed were divided into three categories. Failure mode in reinforced joints with 100 g/m^2 GFRP grammage oc-

Table 3 Mean bending moment resistance with its standard deviation
Tablica 3. Srednja vrijednost otpora momentu savijanja sa standardnom devijacijom

GFRP grammage *Gramatura GFRP-a*	**Number of specimens** *Broj uzoraka*	**Methods of reinforcement** *Metode ojačanja*	**Bending moment resistance, N m** *Otpor momentu savijanja,* N·m	**Standard deviation** *Standardna devijacija*
100	5	2E	332.150	42.592
	5	2S	392.550	31.631
200	5	2E	369.700	57.453
	5	2S	397.050	53.938
300	5	2E	324.100	46.350
	5	2S	713.100	40.459
Nonreinforced *Neojačan*	5	-	250.000	19.628

Table 4 Univariate analysis of variance for bending moment resistance
Tablica 4. Univarijatna analiza varijance otpora momentu savijanja

Source / *Izvor*	**Sum of squares** *Zbroj kvadrata*	*df*	**Mean square** *Srednja vrijednost kvadrata*	*F*	**Sig.**
Grammage of GFRP / *gramatura GFRP-a*	143806.379	2	71903.190	33.678	0.000*
Methods of reinforcing / *metoda ojačanja*	189408.802	1	189408.802	88.716	0.000*
Grammage of GFRP * Methods of reinforcing *gramatura GFRP-a * metoda ojačanja*	199884.154	2	99942.077	46.811	0.000*

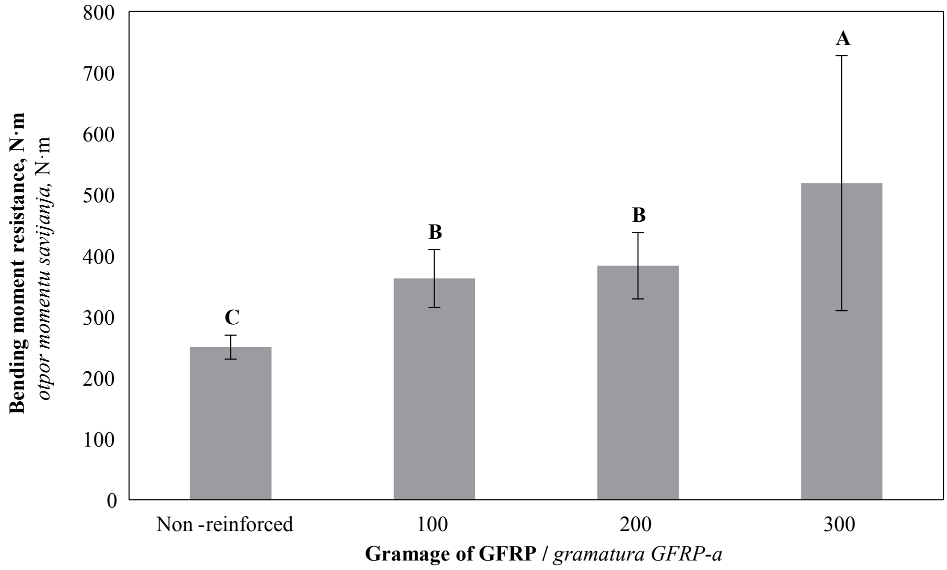


Figure 4 Effect of GFRP grammage on bending moment resistance (bars marked by the same letter are not significantly different according to Duncan's test P < 0.01)
Slika 4. Utjecaj gramature GFRP-a na otpor momentu savijanja (stupci označeni istim slovom ne razlikuju se značajno prema Duncanovu testu uz *P* < 0,01)

curred in tensile mode in GFRP (Figure 6a), and for those reinforced with 300 g/m^2, fracture mode was observed as cracks in GFRP zone (Figure 6c). In the case of reinforced joints with 200 g/m^2 grammage, GFRP combined fracture of two previous modes (tensile mode and fracture mode) was observed (Figure 6b). Mode of failure in reinforced joints by method 2S occurred around the upper connection zone between two members, where it was under tensile stress and the cracking developed along with the connection between two members until the middle of the connection (Figure 7a). However, observations of the mode of failure in reinforced joints by method 2E have shown that the crack occurred at the upper edge of joints exposed to tensile stress. (Figure 7b).

3.5 Finite element modelling
3.5. Modeliranje konačnih elemenata

Since the greatest resistance was obtained from reinforced joint with GFRP of 300 g/m^2 by method 2S, it was selected for the simulation. The analysis of equivalent von Mises stress and elastic strain distribution in reinforced joints revealed that the biggest concentration of stress and elastic strain were generated in the zone of connection between two members. As shown in Figure 8, it can be seen that stress and strain

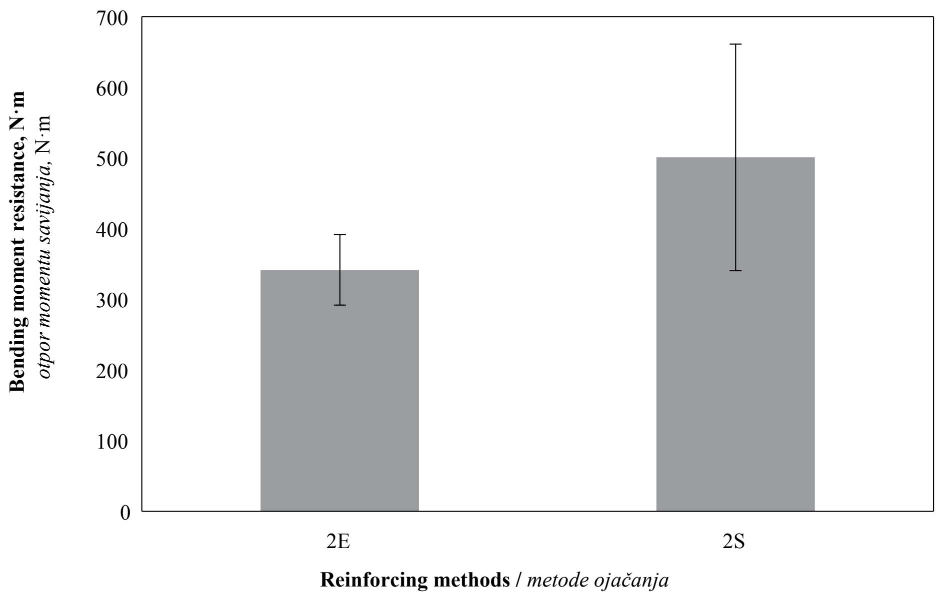
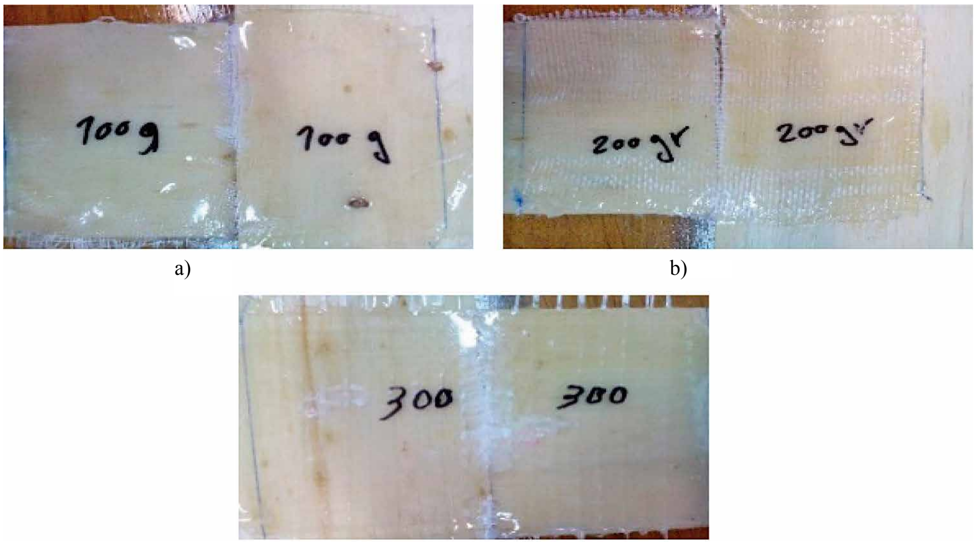


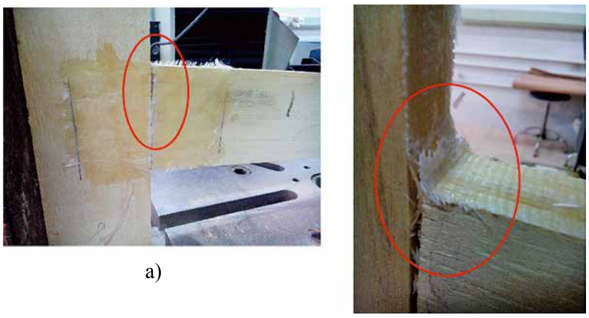
Figure 5 Effect of reinforcing methods on bending moment resistance
Slika 5. Utjecaj metoda ojačanja na otpor momentu savijanja



a) b)

c)

Figure 6 Failure modes, a) tensile mode in GFRP (100 g/m^2), b) combined fracture (tensile mode and fracture mode) in GFRP (200 g/m^2), c) fracture mode in GFRP (300 g/m^2)
Slika 6. Načini loma: a) vlačni lom u GFPR-u (100 g/m^2), b) kombinirani lom (vlačni lom i puknuće spoja) u GFPR-u (200 g/m^2), c) puknuće spoja u GFPR-u (300 g/m^2)



a) b)

Figure 7 Failure modes, a) Fracture in reinforced joints by method 2S, b) Fracture in reinforced joints by method 2E
Slika 7. Načini loma: a) lom u spoju ojačanome metodom 2S, b) lom u spoju ojačanome metodom 2E

are concentrated at the extreme fibers at the top and bottom of the joint. The overall simulated stress and strain of the reinforced joints have shown good agreement with the experimental observations.

Also, based on figures extracted from FEM, one can say that failure occurs when principal tensile stress exceeds the ultimate tensile of GFRP. Therefore, it can be concluded that in joints reinforced with GFRP, tensile strength is essential.

This statement is confirmed by the results obtained from the experimental observations made in this study. The stress and strain distribution of GFRP is illustrated in Figure 8. It can be seen that the highest stress and strain occurred in the top middle of GFRP where the fracture initiated in the experiments. According to the results, joints reinforced by GFRP with higher grammages were stronger than those reinforced with lower grammages. This result can be described as increasing tensile strength in GFRP with increasing grammage. In other words, the tensile strength of GFRP is dependent on the grammage and the type of glass fiber, so the higher grammage of GFRP, the higher is the strength. (De la Rosa García *et al.,* 2013; Clausen *et al.,* 2018,).

Stress and strain distribution in the length of the dowels is shown in Figure 9. It can be seen that the distribution of stress and strain was different for each dowel. The highest stress concentration occurred in the upper part of the top dowel and lower part of the bottom dowel. In order to better illustrate the distribution of stress and strain in dowels, a cross-section of dowels is presented (Figure 9) (glue lines are hidden). The upper and bottom dowel received the tensile and compression stress, respectively (Figure 9).

4 CONCLUSIONS
4. ZAKLJUČAK

Results of the experimental investigations have shown that GFRP reinforcing improves the bending moment strength in T-shape joints. In terms of GFRP grammage, results have shown that 300 g/m^2 GFRP had more effect on the strength of joints than 100 and 200 g/m^2 GFRP. Also, the reinforcing method was important for the strengthening of joints, so that joints reinforced by method 2S achieved better results those reinforced by 2E method.

Failure modes of reinforced joints were different, and three modes of failure were observed: tensile modes in 100 g/m^2 GFRP, fracture modes in 300 g/m^2 GFRP, combined fracture (tensile mode and fracture mode) in 200 g/m^2 GFRP.

According to the finite element analysis of reinforced joints, the highest concentration of stress and

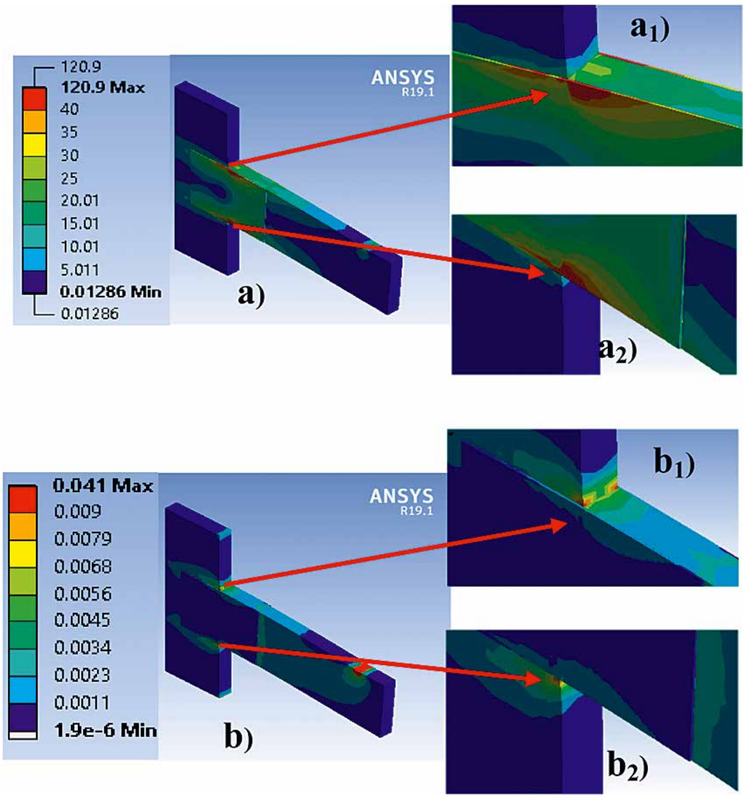


Figure 8 a, b) Distribution of stress and strain in reinforced joint; a_1, b_1) Distribution of stress and strain at the edge of joint; a_2, b_2) Distribution of stress and strain at bottom edge of joint
Slika 8. a), b) Raspodjela naprezanja i deformacija u ojačanom spoju; a_1), b_1) raspodjela naprezanja i deformacija na rubu spoja; a_2), b_2) raspodjela naprezanja i deformacija na donjem rubu spoja

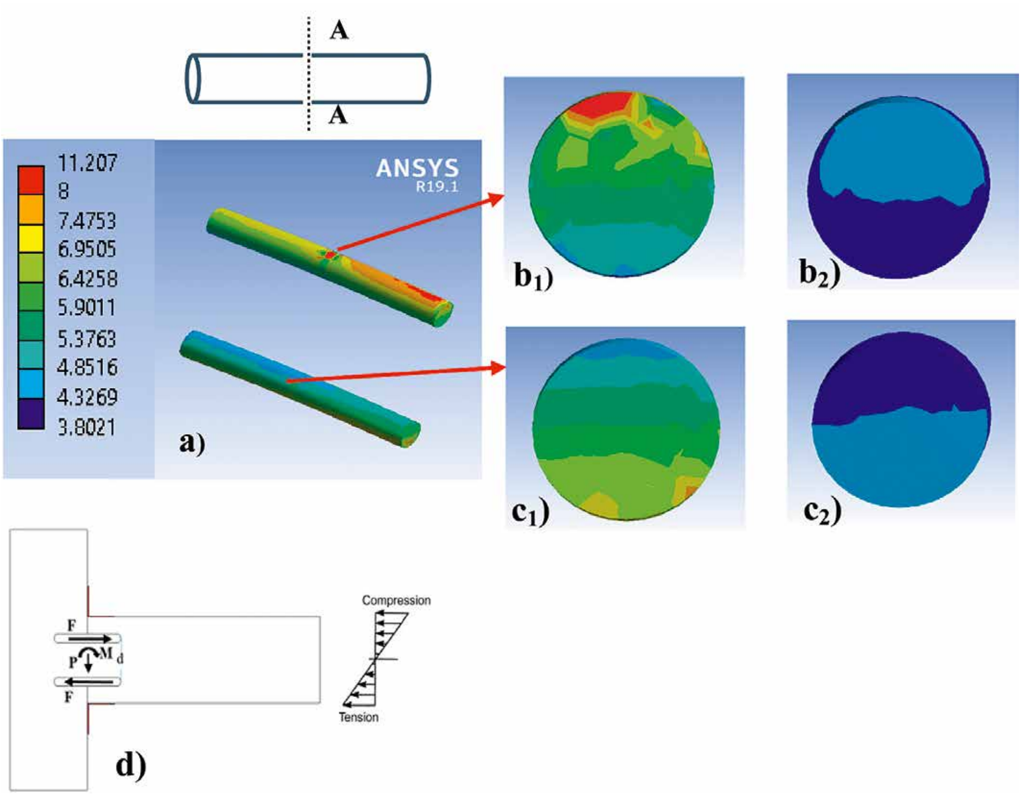


Figure 9 a) Distribution of stress and strain in dowels, b_1, b_2) Distribution of stress and strain in top dowel, c_1, c_2) Distribution of stress and strain in bottom dowel, d) Position of dowels
Slika 9. a) Raspodjela naprezanja i deformacija u moždanicima; b_1), b_2) raspodjela naprezanja i deformacija u gornjem moždaniku; c_1), c_2) raspodjela naprezanja i deformacija u donjem moždaniku; d) položaj moždanika

elastic strain were generated in the zone of connection between two members. In the GFRP zone, the highest stress and strain occurred in the top and bottom middle, which was the main cause of fracture in reinforced joints. The distribution of stress and strain in dowels showed that dowels were affected by different types of stress. Thus, the dowel inserted in the upper part of the joint was stressed in tension, while the bottom dowel was stressed in compression. According to the results of this research, the overall simulated stress and strain of the reinforced joints have shown good agreement with the experimental observation. Further research in this field should focus on studying the performance of the reinforced joints under different loading including tension and compression and different materials i.e., other engineered wood materials and different connectors, such as screws, nails, etc.

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Long-Term Hygroscopic Thickness Swelling Rate of Hydrothermally Treated Beech Wood / Polypropylene Composites

Brzina dugotrajnoga higroskopskog debljinskog bubrenja kompozita od polipropilena i hidrotermički tretirane bukovine

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ABSTRACT • *Long-term hygroscopic thickness swelling rate of polypropylene (PP) composites filled with thermally treated wood flour was investigated. The beech wood chips were heat treated at 120 °C, 150 °C or 180 °C for 30 or 120 min using saturated steam in a digester. The composites based on PP, beech wood flour (BF), and coupling agents (PP-g-MA) were made by melt compounding and injection molding. The weight ratio of BF to PP was controlled at 50/47 for all blends. The amount of coupling agent was fixed at 3 wt.% for all formulations. Further study was conducted to model thickness swelling of the composites, a swelling rate parameter (*K_{SR}*). The thickness swelling of thermally-treated samples at 120 ºC for 30 min and at 150 ºC for 30 min were lower than that of control samples, followed by thermally-treated samples at 180 ºC for 120 min, at 180 ºC for 30 min, at 120 ºC for 120 min, and at 150 ºC for 120 min, respectively. Furthermore, the thickness swelling of the BF/PP composites decreased with increasing time and temperature of the thermal-treatment. In addition, at 120 ºC for 30 min, the composites showed a lower swelling rate than control samples. The *K_{SR}* *of the composites was influenced both by the time and temperature of thermal treatment.*

KEYWORDS: *thickness swelling rate; thermal-treatment; lignocellolusic filler; polypropylene*

SAŽETAK • *U radu je istražen dugotrajni stupanj higroskopskoga debljinskog bubrenja polipropilenskih (PP) kompozita punjenih toplinski obrađenim drvnim brašnom. Iverje od bukovine bilo je toplinski tretirano na 120, 150 ili 180 °C tijekom 30 ili 120 minuta uz pomoć zasićene pare u digestoru. Kompoziti na bazi PP-a, brašna od bukovine (BF)-a i veziva (PP-g-MA) izrađeni su taljenjem i injekcijskim prešanjem. Maseni je omjer BF/PP*

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za sve smjese bio 50/47. Količina veziva za sve formulacije bila je na 3 wt.%. Nadalje, provedeno je modeliranje debljinskog bubrenja kompozita i parametra brzine bubrenja (KSR). Debljinsko bubrenje uzoraka toplinski tretiranih 30 min na 120 ºC i 30 min na 150 ºC bilo je niže nego na kontrolnim uzorcima, zatim slijede uzorci toplinski tretirani 120 min na 180 ºC, 30 min na 180 ºC, 120 min na 120 ºC, odnosno 120 min na 150 ºC. Nadalje, debljinsko bubrenje BF/PP kompozita smanjivalo se s povećanjem vremena i temperature toplinskog postupka. Osim toga, kompoziti su pri 30 min na 120 ºC pokazali niži parametar brzine bubrenja od kontrolnih uzoraka. Na parametar brzine bubrenja kompozita utjecali su vrijeme toplinskog tretmana i temperatura.

KLJUČNE RIJEČI: *stupanj debljinskog bubrenja; toplinski tretman; lignocelulozno punilo; polipropilen*

1 INTRODUCTION
1. UVOD

Thermal treatment has been used by many researchers to improve dimensional stability of wood and wood-based composites (Kazemi Najafi *et al.*, 2007; Kaboorani *et al.*, 2008). It decreases the water absorption of wood by the crystallization of cellulose and extraction of hemicelluloses from wood (Wallenberger and Weston, 2004; Yildiz and Gümüşkaya, 2007; Hosseinihashemi *et al.*, 2016). The enhancement of the dimensional stability, reduction of the swelling, and alteration of the chemical composition of wood have been found in thermally modified wood (Tjeerdsma *et al.*, 2000; Militz and Tjeerdsma, 2001; Yildiz *et al.*, 2004; Temiz *et al.*, 2006; Rezayati Charani *et al.*, 2007; Koubaa *et al.*, 2011; Hadi *et al.*, 2016).

Under high-temperature conditions, a series of complex chemical reactions takes place in the wood cell wall, such as degradation and condensation reactions (Yin *et al.*, 2010). This leads to changes in the amount of the components of wood and also in its physical and chemical properties. After the heat-treatment process, the dimensional stability and the durability of wood increase, which is strongly associated with the reduction in hygroscopicity (Bekhta and Niemz, 2003; Cao *et al.*, 2012; Olarescu *et al.*, 2014).

Amorphous region of cellulose by heating of wood at high temperature results in an increase in the degree of crystallinity of this polymer. A cross-linkage between the lignin and the polymers occurs because of the thermal degradation of wood, which is responsible for the decrease in the hygroscopicity of wood and the improvement of its dimensional stability (Jämsä and Viitaniemi, 2001; Waskett and Selmes, 2001; Bekhta and Niemz, 2003; Wikberg and Maunu, 2004; Metsä-Kortelainen *et al.*, 2006; Calonego *et al.*, 2010).

The improvement in the hygroscopic and micromechanical properties of heat-treated wood occurred with an elevation in the steam temperature, which correlated well with this pattern of degradation in the constituents of the biocomposite matrix in the cell wall (Yin *et al.*, 2010). Also, the improvement in the dimensional stability of thermally treated wood could be related to a reduction in the number of free hydroxyl groups with chemical reactions (Dale Ellis, 1994; Zhang *et al.*, 2006; Deka and Saikia, 2000). This could also be related to the chemical modification in the cell wall of the fiber during the hydrothermal treatment (Yildiz *et al.*, 2004; Hadi *et al.*, 2016; Rowell and LeVan-Green, 2005). Hemicelluloses degraded by thermal treatment positively affect the dimensional stability of wood (Garrote *et al.*, 1999; Tjeerdsma and Militz, 2005). In addition, the reduction of the thickness swelling could be related to the increase of the crystalline regions in the cellulose microfibrils (Wallenberger and Weston, 2004; Yildiz and Gümüşkaya, 2007). Previous studies reported that the swelling loss could occur as a result of esterification of the cellulose microfibrils (Tjeerdsma and Militz, 2005; Boonstra and Tjeerdsma, 2006). In general, the degradation of wood components and particularly of hemicelluloses negatively affects the mechanical properties of wood (Yildiz *et al.*, 2006; Korkut *et al.*, 2008). Although the effect of heat treatment of wood on thickness swelling of wood plastic composites were investigated by previous studies (Ayrilmis *et al.*, 2011; Tufan *et al.*, 2016), the long term thickness swelling has not been extensively investigated. In the present study, the effect of thermal-treatment of beech wood on the long-term thickness swelling of the thermoplastic composites was investigated.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

The polymer matrix comprised of V30S polypropylene (PP), with a melt flow index of 16 g/10 min and a density of 0.87 g/cm^3, was supplied by Marun Petrochemical Co. (Mahshahr, Iran). The lignocellulosic material used as the reinforcing filler in the composites was beech (*Fagus orientalis* L.) wood flour, which was ground by a grinder. A maleic anhydride grafted polypropylene (MAPP) as a coupling agent, which was PPG101, was provided by Kimia Javid Sepahan Co. (Tehran, Iran), with a melt flow index of 64 g/10 min, and a density of 0.91 g/cm^3. The amount of the MAPP in all the specimen groups was 3 wt.%.

2.2 Thermal-treatment of wood chips
2.2. Toplinski tretman drvnog iverja

Before the preparation of the composites, beech logs were chipped by a drum-type chipper. Prior to the heat treatment, the wood chips were dried at room temperature for 24 h. After cooling in a desiccator containing silica gel powder, the wood chips were heat treated for 30 or 120 min at different temperatures (120 °C, 150 °C, or 180 °C) using saturated steam in a digester. Then beech wood flour (BWF) was prepared from the treated chips using laboratory type grinder. The wood flour was dried until 0 to 1 % moisture content in an oven at (103±2) °C for 24 h. Polypropylene, beech wood flour, and the coupling agent were then weighed and bagged according to the formulations given in Table 1.

2.3 Preparation and testing of WPCs
2.3. Priprema i ispitivanje WPC-a

The mixing of raw materials was carried out with a counter-rotating intermeshing twin-screw extruder (Model T20, 1990, Dr. Collin GmbH, Germany), with its barrel temperature ranging from 180 °C at six zones, from feeding zone to the die zone, at a screw speed of 60 rpm for 14 min. The pasty compound produced was cooled to room temperature and then grinded to produce suitable granules for further processing. Grinding was carried out in a laboratory mill (Wieser, WGLS 200/200 Model, Germany) and the granulated materials were dried at 105 °C for 4 h. Test specimens were prepared by injection molding machine (Model EM80, Aslanian Co., Iran) set at a temperature ranging from 160 to 180 °C. A complete set of specimens for different tests were produced for each molding operation. Finally, the specimens were conditioned at a temperature of 23 °C and relative humidity of 50 % for at least 40 h, according to ASTM D 618-99 prior to testing. The water absorption (WA) was determined according to ASTM D 570 standard.

2.4 Morphological analysis of WPCs
2.4. Morfološka analiza WPC-a

The morphology of WPCs was characterized using scanning electron microscopy (SEM, Model LEO 440i, Oxford, UK) at 15 kV accelerating voltage. Specimens were first frozen in liquid nitrogen and fractured to ensure that the microstructure remained clean and intact, and then coated with a gold layer to provide electrical conductivity.

2.5 Physical test
2.5. Ispitivanje fizičkih svojstava

Water absorption studies were performed following the ASTM D 570 standard. The water absorption of the WPC specimens with nominal dimensions of 5 mm x 11 mm x 80 mm was determined after 2, 4, 6, 8, 10, 12, 24, 48, 72, 168, 336, 504, 720, and 1440 h immersion in distilled water at room temperature. Three specimens of each type of WPC were dried in an oven for 24 h at (103±2) ºC. The dried specimens were weighed with a precision of 0.001 g and then they were placed in distilled water. At the end of immersion periods, the specimens were removed from the distilled water and the surface water was wiped off using blotting paper. Weight of the specimens was measured at different time intervals during the long-time immersion. The measurements were terminated after the equilibrium weights of the specimens were reached. The values of the water absorption and thickness swelling in percentage were calculated using Eq. 1 and 2:

$$WA\ (t) = [\frac{W(t) - W(o)}{W(o)}] \cdot 100 \qquad (1)$$

Where, $WA(t)$ is the water absorption at time t, $W(o)$ is the initial weight of specimens, and $W(t)$ is the weight of specimens at time t (Equation 1).

$$TS\ (t) = [\frac{T(t) - T(o)}{T(o)}] \cdot 100 \qquad (2)$$

Where, $TS\ (t)$ is the thickness swelling at time t, $T(o)$ is the initial thickness of specimens, and $T(t)$ is the thickness of specimens at time t (Eq. 2).

Further study was conducted to model long-term thickness swelling behavior of the composites. The swelling rate parameters in the model were obtained by fitting the model predictions with the experimental

Table 1 Composites of the evaluated WPC (wood plastic composite) formulations
Tablica 1. Formulacije istraživanih WPC-ova (drvoplastičnih kompozita)

WPC code *Oznaka WPC-a*	**Treatment type** *Vrsta tretmana*	**Beech wood flour, wt.%** *Drvno brašno od bukovine*, wt.%	**Polypropylene (PP), wt.%** *Polipropilen (PP)*, wt.%	**MAPP[a] wt.%**
A	WPC-30 min-120 ºC	50	47	3
B	WPC-30 min-150 ºC	50	47	3
C	WPC-30 min-180 ºC	50	47	3
D	WPC-120 min-120 ºC	50	47	3
E	WPC-120 min-150 ºC	50	47	3
F	WPC-120 min-180 ºC	50	47	3
G	WPC-control	50	47	3

[a] MAPP – maleic anhydride grafted polypropylene / *polipropilen graftiran anhidridom maleinske kiseline*

data. Shi and Gardner (2006) studied to quantify the thickness swelling rate of WPCs for more convenient comparisons. They developed a swelling model describing the hygroscopic swelling process of wood based composites. In this model, a swelling rate parameter (K_{SR}), as determined using the test data, can be used to quantify the swelling rate. The swelling model is described by the following Eq. 3:

$$T(t) = \frac{T_s}{1 + \left(\frac{T_s}{T_o} - 1\right) e^{-K_{SR}\, t}} \quad (3)$$

Where, $T(t)$ is the thickness swelling at time t. T_o and T_s are the initial and equilibrium board thickness, respectively. K_{SR} is a constant referred to as the initial (or intrinsic) relative swelling rate.

The values of K_{SR} in Eq. 3 depend on how fast the composites swell and also on their equilibrium thickness swelling. Non-linear curve fitting was used to find the swelling rate parameter (K_{SR}) that provided the best fit between the equation and the experimental data. This algorithm seeks the parameter values that minimize the sum of the squared differences between the observed and predicted values of the dependent variable as seen in Eq. 4,

$$ss = \sum_{i=1}^{n} \left(y_i - \overline{y_i}\right)^2 \quad (4)$$

Where, SS is the sum of squared difference and y_i, and $\bar{y}_i$ are the observed and predicted values of the dependent variable, respectively.

2.6 FT-IR analysis
2.6. FT-IR analiza

FT-IR measurements were carried out in an Equinox instrument (Bruket Co., Germany) by direct transmittance using KBr pellet technique. Each spectrum was recorded at a rate of 10 scans, in the range from 3500 to 800 cm^{-1} with a resolution of 4 cm^{-1}.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Long term water absorption and thickness swelling behavior
3.1. Dugotrajno upijanje vode i debljinsko bubrenje

Long-term water absorption and thickness swelling of the composites after 1440 h immersed in water are presented in Figures 1 and 2. Generally, water absorption and thickness swelling increased with immersion time, reaching a certain value beyond which weight and thickness increased no more. At the early stage of the water uptake test, as compared with the long term test, the composites clearly absorbed more water as well as faster. The composites containing thermally treated beech wood flour had longer equilibrium time (time to reach the equilibrium water absorption and thickness swelling) (Figures 1 and 2). Furthermore, the composites containing thermally treated beech wood flour swelled and gained weight very slowly.

The independent effects of thermal-treatment temperatures and durations on the long-term thickness swelling of WPCs are presented in Figures 3 and 4. A significant correlation was found between the treatment time and long term thickness swelling. A similar relationship was determined for the treatment temperature.

Exposure duration and temperature are two important factors affecting hemicelluloses degradation (Ayrilmis *et al.* 2011; Militz and Tjeerdsma, 2001). Cumulative thermal exposure in the hot-press alters the hemicelluloses structure because arabinan and galactan, each a side-chain component of the hemicelluloses, tend to be more degraded as the chip size decrease (Winandy and Krzysik, 2007). These changes in the chemistry of hemicelluloses seem to reduce the hygroscopicity of the flakes. A lower internal void vol-

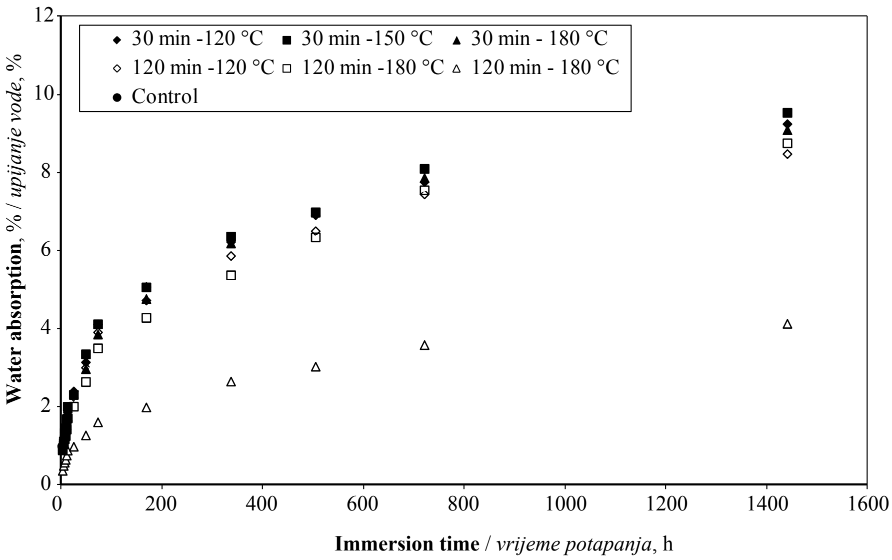

Figure 1 Effect of thermal-treatment severity on long-term water absorption of WPCs
Slika 1. Utjecaj jačine toplinskog tretmana na dugotrajno upijanje vode WPC-a

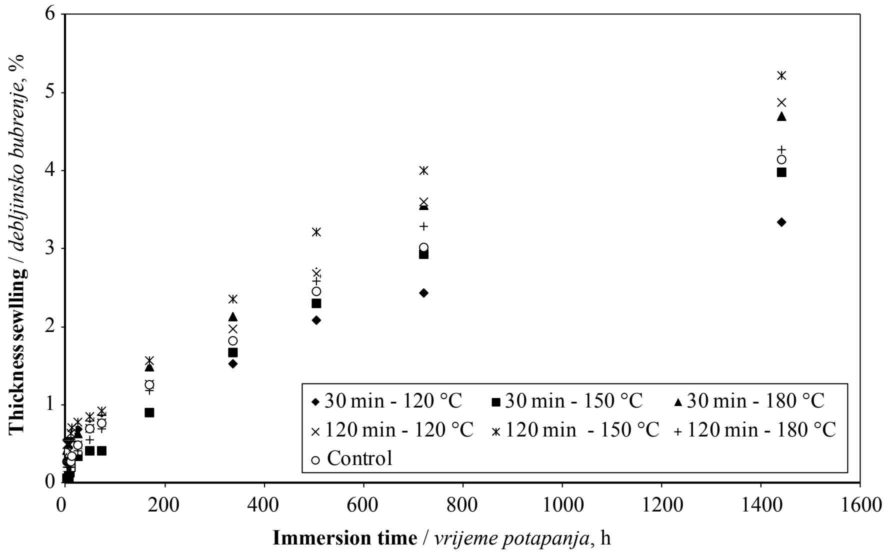

Figure 2 Effect of thermal-treatment severity on long-term thickness swelling of WPCs
Slika 2. Utjecaj jačine toplinskog tretmana na dugotrajno debljinsko bubrenje WPC-a

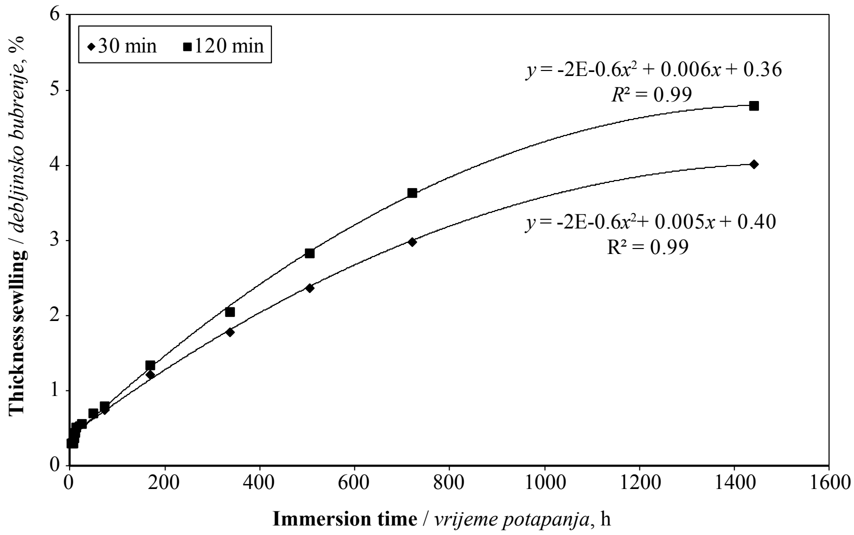

Figure 3 Independent effect of thermal-treatment times on long-term thickness swelling of WPCs
Slika 3. Neovisni učinak trajanja toplinskog tretmana na dugotrajno debljinsko bubrenje WPC-a

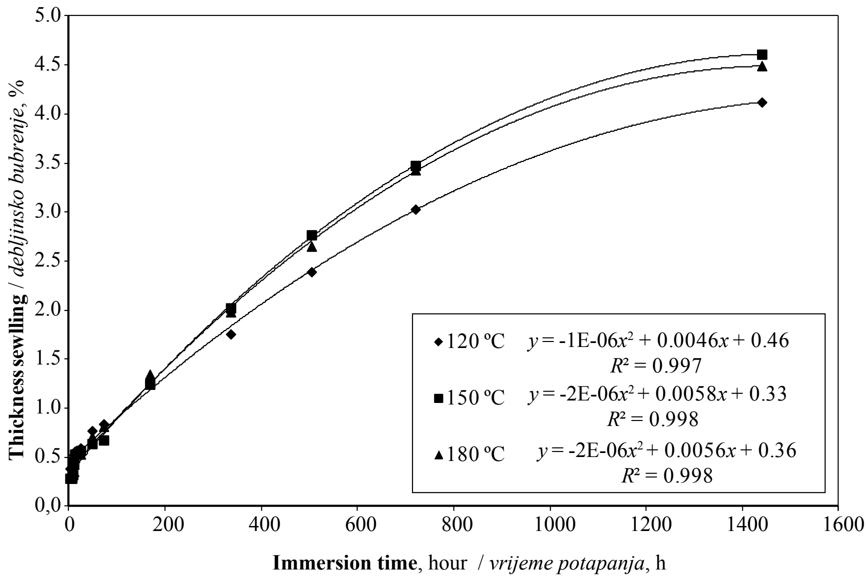

Figure 4 Independent effect of thermal-treatment temperatures on long-term thickness swelling of WPCs
Slika 4. Neovisni učinak temperature toplinskog tretmana na dugotrajno debljinsko bubrenje WPC-a

Table 2 Swelling rate parameters for studied composites
Tablica 2. Parametri brzine bubrenja istraživanih kompozita

WPC code *Oznaka WPC-a*	**Maximum thickness swelling, %** *Najveće debljinsko bubrenje, %*	**Maximum value of $K_{sr}\times 10^{-3}$, h^{-1}** *Najveća vrijednost $K_{sr}\times 10^{-3}$, h^{-1}*	**Sum of squared** *Zbroj kvadrata*
A	3.35	0.0023	2.51
B	3.99	0.0018	0.27
C	4.70	0.0021	1.74
D	4.88	0.0019	0.99
E	5.23	0.0021	2.08
F	4.27	0.0021	0.44
G	4.15	0.0020	0.73

ume might obstruct the migration of moisture and diminish the convective effect. The decrease of hemicellulose content results in a decrease of hydroxyl groups, which also include free hydroxyl groups, thus decreasing the water absorption capacity of wood. Water absorption of untreated wood was the greatest. The greater water uptake of samples with greater weight loss could be due to the possible presence of larger and more numerous pores in these samples, resulting in increased capillary action of water.

The swelling rate parameter (K_{SR}) and maximum values of thickness swelling of the composites are given in Table 2.

The composites produced by a 120 min / 150 °C treatment had the highest thickness swelling. The minimum K_{SR} was calculated for the composites produced with beech wood flour treated at 120 °C for 30 min. The maximum value of K_{SR} was found in the composites produced with wood flour at 150 °C for 30 min. It is important to note that in the swelling model K_{SR} was obtained considering the whole thickness process until it was equilibrated. It is dependent not only on the initial rate of swelling but also on the equilibrium thickness swelling of the composites (Shi and Gardner, 2006; Kord, 2013). Less time was required to reach the equilibrium thickness for thermally treated beech wood flour/PP composites (Figure 2). This can be explained by very high K_{SR} value determined in the wood flour filled composites. The correlation between predicted and experimental thickness swelling is given in Table 3.

Table 3 Correlation between predicted and experimental thickness swelling
Tablica 3. Korelacija između predviđenoga i eksperimentalnoga debljinskog bubrenja

WPC code / *Oznaka WPC-a*	R^{2*}
A	0.98
B	0.99
C	0.99
D	0.99
E	0.99
F	1.00
G	0.99

* R – squared / *R – kvadrat*

Table 4 Relationship between long-term water absorption (*WA*) and thickness swelling (*TS*) in studied composites
Tablica 4. Odnos između dugotrajnog upijanja vode (*WA*) i debljinskog bubrenja (*TS*) ispitivanih kompozita

WPC code *Oznaka WPC-a*	**Equation** *Jednadžba*	R^{2*}
A	TS= 0.30 WA + 0.02	0.92
B	TS= 0.42 WA – 0.63	0.92
C	TS= 0.47 WA – 0.32	0.93
D	TS= 0.53 WA – 0.56	0.90
E	TS= 0.57 WA – 0.34	0.95
F	TS= 1.05 WA – 0.56	0.96
G	TS= 0.46 WA – 0.25	0.98

* R – squared / *R – kvadrat*

Figures 5 and 6 indicate fitting predicted thickness swelling with the experimental data obtained from thermally treated beech wood flour/PP composites for calculating the swelling rate.

The relationship between long-term water absorption and thickness swelling in the composites is given in Table 4. Thickness swelling is a response to absorbed water in the composites. The R-squared values of all the composites were found to be 0.90 (Table 4).

3.2 FT-IR analysis
3.2. FT-IR analiza

FT-IR spectroscopy is a simple technique applied to determine the effect of various applications used in order to obtain information about the structure of wood components causing changes in the chemical structure of wood. It is preferred because it needs only a small sample size and short analysis time for test application, as well as because it does not disrupt wood structure. Due to their complex nature, spectra are considered as two regions for examination. The first region is expressed as 2700-4000 cm^{-1} band where the OH and C-H stretching vibrations are included, while the second region is defined as the “Fingerprint” region between at 1100-1800 cm^{-1} where different vibration extension regions of wood components are identified.

Band assignment of wood material in the 4000-800 cm^{-1} region is presented in Table 5 (Li *et al*., 2015). FT-IR spectroscopy of the test specimens treated at 120

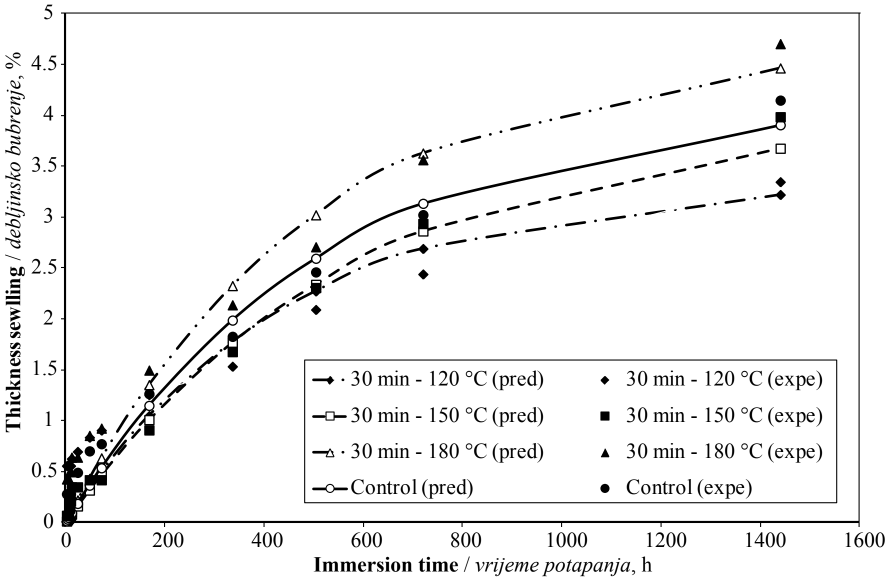

Figure 5 Fitting predicted thickness swelling with experimental data for WPC specimens produced with thermally treated wood particles at different temperatures for 30 min
Slika 5. Uparivanje predviđenoga debljinskog bubrenja s eksperimentalnim podatcima za WPC uzorke proizvedene s toplinski tretiranim drvnim **česticama** 30 min na različitim temperaturama

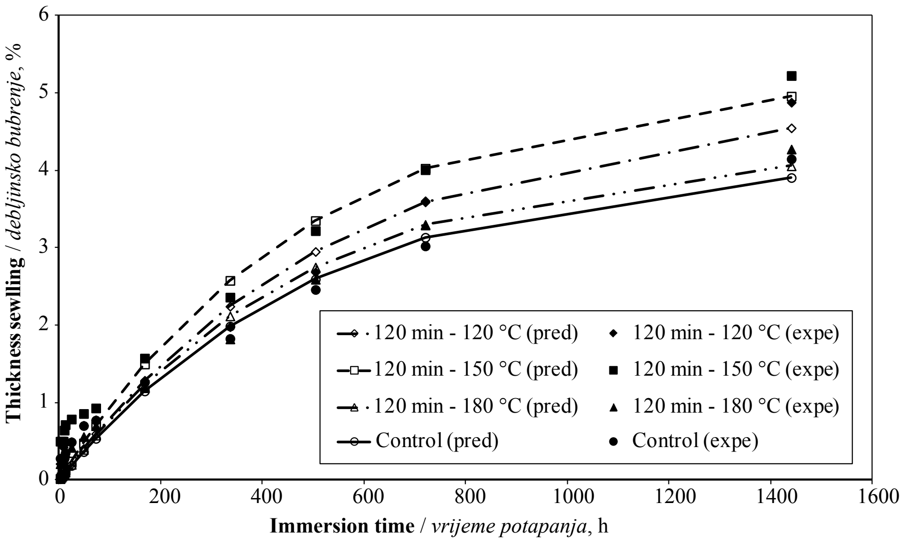

Figure 6 Fitting predicted thickness swelling with experimental data for WPC specimens produced with thermally treated wood particles at different temperatures for 120 min
Slika 6. Uparivanje predviđenoga debljinskog bubrenja s eksperimentalnim podatcima za WPC uzorke proizvedene s toplinski tretiranim drvnim **česticama** 120 min na različitim temperaturama

°C and 180 °C with control samples was recorded. As shown in Figure 7, the peak intensity of the OH stretches at about 3400 cm^{-1} in test specimens exposed to temperatures of 180 °C and 120 °C reduced as compared to the control sample. The C-H deformations in lignin and carbohydrates were observed around 1462 cm^{-1}. When the exposure time of the test specimens at 180 °C increased, aromatic and aliphatic C-H (methylene groups) stretches were determined between 2800 and 2920 cm^{-1}. Similarly, the C=O carboxyl groups were observed between 1731 and 1737 cm^{-1}. In 1596 cm^{-1} C=C aromatic skeletal vibration (lignin) peak value, peak intensity showed an increase due to the temperature increase. The intensity of the C-O stretching peak of lignin at 1250 cm^{-1} decreased with the effect of temperature. The C-O stretching vibration in cellulose and hemicelluloses formed at 1054 cm^{-1} was slightly degraded. The cellulose and hemicellulose C-H deformations and C-O-C stretches formed at 1377 cm^{-1} and 1169 cm^{-1}, respectively.

As a result, the IR peaks were not affected by the heat treatment temperature. However, the intensities of the functional groups, in particular for –OH stretches, decreased at 180 °C as compared to the control samples at lower temperature (150 °C and 180 °C). Thus, it can be said that some functional groups such as –OH or

Table 5 Band assignment of wood samples in 4000-800 cm^{-1} region (Li *et al*., 2015)
Tablica 5. Vrpce pripisane uzorcima drva u području 4000 – 800 cm^{-1} (Li *et al*., 2015.)

Wavenumber, cm^{-1} *Valni broj,* cm^{-1}	**Band assignment** *Pripisane vrpce*
3399	O-H stretching in hydroxyl groups
2921	C-H asymmetric stretching in methylene groups
1736	C=O stretching vibration of carbonyl, carboxyl and acetyl groups
1659	Conjugated C-O in quinines coupled with C=O stretching of various groups
1594	C=C stretching of aromatic skeletal in lignin
1508	C=C stretching of aromatic skeletal in lignin
1463	C-H deformation in lignin and carbohydrates
1423	C-H deformation in lignin and carbohydrates
1374	C-H deformation in cellulose and hemicellulose
1328	C-H vibration in cellulose and C-O vibration in syringyl derivatives-condensed structures in lignin
1266	C-O stretching in lignin
1234	C-O stretching vibration of Ph-O-C coupled with aromatic ring vibration in lignin and C-O stretching vibration in xyloglucan
1157	C-O-C stretching vibration in cellulose and hemicelluloses
1055	C-O stretching vibrations in cellulose and hemicelluloses
1034	C-O ester stretching vibrations in methoxyl and β-O-4 linkages in lignin
897	Character of cellulose P-chains, C-H stretching out of plane of aromatic ring

carboxylic acid C=O groups reacted with each other at 180 °C and formed new ester or etheric groups in addition to –OH or C=O stretches.

3.3 Morphological analysis
3.3. Morfološka analiza

The morphological analysis of the composites is presented in Figure 8. The SEM images revealed that there was some distortion and modification of the cell walls of wood due to the hydro-thermal treatment. The cracks in the cell walls of wood increased with increasing the treatment temperature and time. The melted PP polymer filled the cracks in the cell walls of wood based on the SEM images, thus decreasing the thickness swelling.

4 CONCLUSIONS
4. ZAKLJUČAK

The composites produced with thermally treated beech wood flour swelled and gained weight very slowly. The thickness swelling of the composites decreased with increasing time and temperature of the thermal-treatment. In addition, at 120 ºC for 30 min, the composites showed a lower swelling rate than control samples. The K_{SR} of the composites was influenced by both the time of thermal treatment and temperature. A strong correlation was found between the long-term water absorption and thickness swelling in the composites. Based on the findings obtained from the present study, it can be said that thermal treatment of the

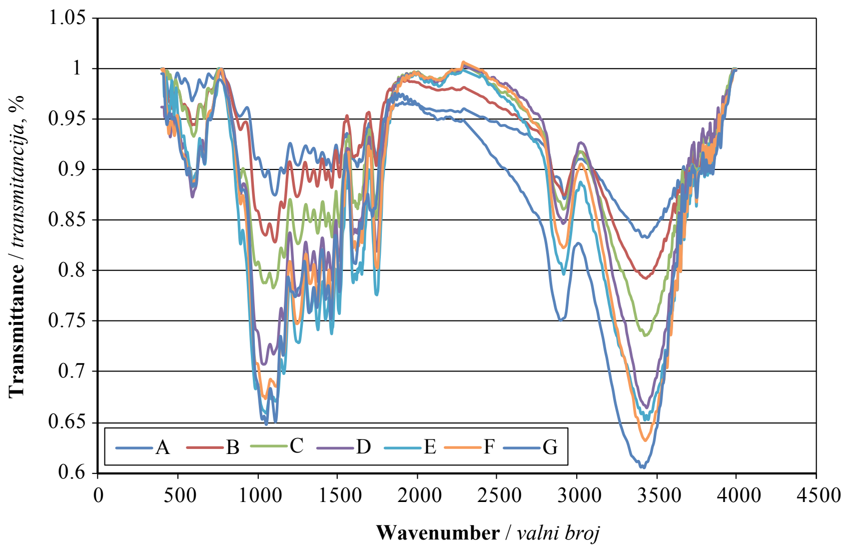

Figure 7 FT-IR spectrum of heat treated and untreated test samples (A, B, C, D, E, F and G according to Table 2)
Slika 7. FT-IR spektri toplinski tretiranih i netretiranih uzoraka (A, B, C, D, E, F i G prema tablici 2.)

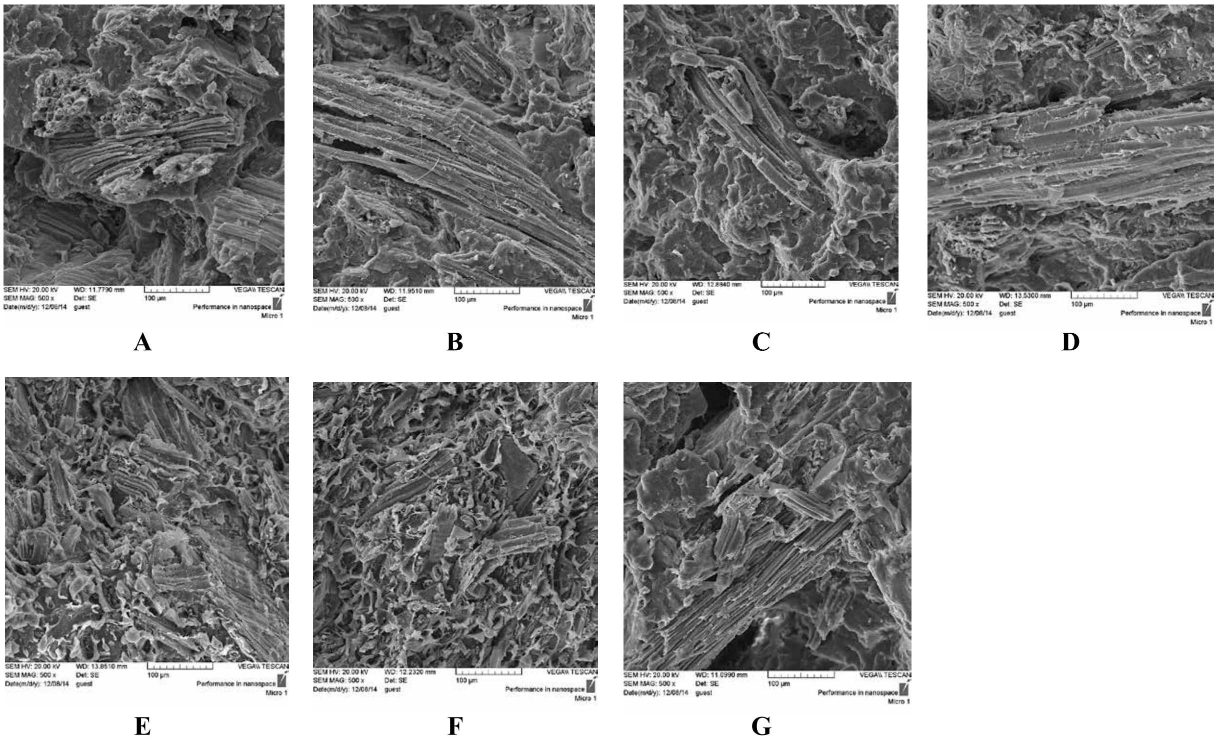

Figure 8 SEM micrograph of fracture surfaces in WPC specimens produced with thermally treated wood particles at different times and temperatures (A, B, C, D, E, F, and G according to Table 2)
Slika 8. SEM mikrografije lomnih površina u WPC uzorcima proizvedenim s toplinski tretiranim drvnim česticama pri različitom vremenu i temperaturi tretiranja (A, B, C, D, E, F i G prema tablici 2.)

wood chips at 150 °C for 30 min result in optimal parameters for the wood flour reinforced polypropylene composites, as they have higher water resistance than other treatment groups.

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Tensile Performance of Traditional and Modern Corner Joints in Wooden Structures

Vlačna svojstva tradicionalnih i modernih kutnih spojeva u drvnim konstrukcijama

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ABSTRACT • *Corner joints are critical points of wooden structures not only in furniture construction but also in traditional wooden architecture, especially in constructions without nails. This study was performed to determine the effects of particular factors such as the axis of assembly, types of material, and adhesive on the tensile performance of various modern and traditional types of wooden corner joints. For this purpose, various corner joint specimens were prepared with three different wooden materials: Scots pine (Pinus sylvestris Lipsky) wood, Lombardy poplar (Populus nigra Lipsky) wood, and Medium Density Fibreboard (MDF) using two different adhesives: polyvinyl acetate (PVAc) and polyurethane (Desmodur-VTKA) glues; and five different wooden joint types: dowel, tongue-and-groove, half-blind dovetail, screw, and eccentric screw joints. Tensile performance tests, vertical and parallel to the axis of assembly, were carried out according to ASTM D 1037 guidelines. Experiments indicated that, while the tensile performance of MDF specimen connected with a screw and PVAc adhesive was the highest under loading parallel to the axis of assembly (4592 N); it was the lowest under loading parallel to the axis of assembly in MDF specimen connected with tongue-and-groove joint and PVAc adhesive (260 N), respectively. As a result, it may be advantageous to apply screwed joints in corners for high tensile strength in parallel to the axis of the assembly.*

KEYWORDS: *tensile performance; construction materials; corner joints; wooden joints*

SAŽETAK • *Kutni su spojevi kritične točke drvnih konstrukcija ne samo u proizvodnji namještaja nego i u tradicionalnoj drvnoj arhitekturi, posebice u konstrukcijama bez čavala. Ovo je istraživanje provedeno kako bi se utvrdili učinci specifičnih čimbenika kao što su os montaže, vrsta materijala i vrsta ljepila na vlačna svojstva različitih modernih i tradicionalnih vrsta drvnih kutnih spojeva. Za tu su svrhu pripremljeni različiti uzorci kutnih spojeva od tri vrste drvnog materijala: od drva bijelog bora (Pinus sylvestris Lipsky), drva lombardijske topole (Populus nigra Lipsky) i od srednje guste ploče vlaknatice (MDF), uz uporabu dvaju različitih ljepila: polivinilacetatnoga*

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(PVAc) i poliuretanskoga (Desmodur-VTKA) te uz pet različitih vrsta drvnih spojeva: moždanika, pera i utora, poluzatvorenog lastina repa, vijka i ekscentra. Ispitivanja vlačnih svojstava okomito i paralelno s osi montaže provedena su u skladu s normom ASTM D 1037. Rezultati su pokazali da su najbolja vlačna svojstva MDF uzorka spojenoga vijkom i PVAc ljepilom pod opterećenjem paralelno s osi montaže (4592 N), a najlošijima su se pokazala vlačna svojstva MDF uzorka spojenoga perom i utorom te PVAc ljepilom pod opterećenjem paralelno s osi montaže (260 N). Prema tome, primjena vijaka u kutnim spojevima može biti dobar izbor za postizanje visoke vlačne čvrstoće paralelno s osi montaže.

KLJUČNE RIJEČI: *vlačna svojstva; konstrukcijski materijali; kutni spojevi; drvni spojevi*

1 INTRODUCTION
1. UVOD

Wood is a sustainable, environmentally friendly and renewable material that has good strength compared to its density. Moreover, it is compatible with other building materials and can be very long-lasting when used properly (Bozkurt, 2011). With these features, it was used as a basic building material in traditional Turkish architecture from furniture to building elements such as: lateral and vertical bracing elements, roof trusses, door-window frames, etc. The widespread use of wood in Anatolia has led to the development of various jointing techniques, generally called "Çantı" (Figure 1).

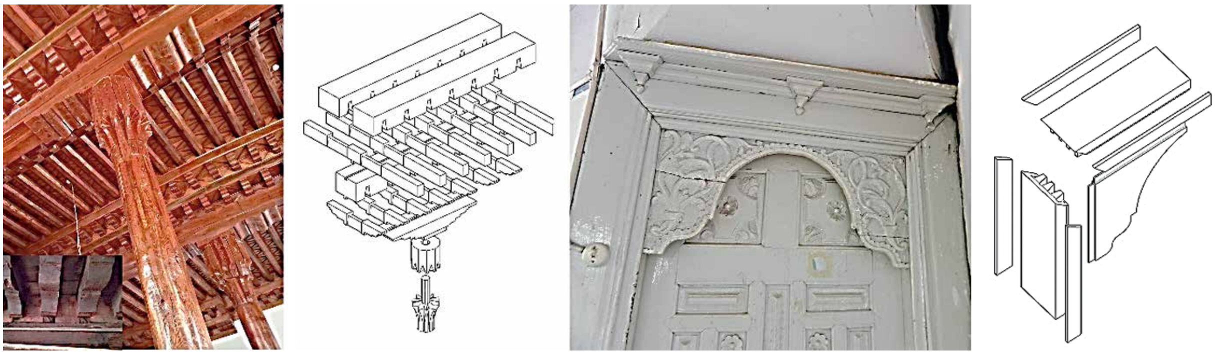
Finger jointing (Kurtboğaz Geçme) is one of the popular techniques of the "Çantı" in the Eastern Black Sea region and is implemented by interdigitating pieces together with dowels instead of nails. These elements are used to carry the load of the building, to create windows and door frames and they provide room corners (Akbaş and Özcan, 2018). The dovetail technique (Kırlangıç Kuyruğu) is another common type of interdigitating, frequently used in floor and corner jointing. In the dovetail, the male tongue does not come out of the female groove as a result of its special "V-shaped" tapering structure.

The dovetail joint is an ancient technique, the first examples of which were found in Ancient Egypt used in sleds carrying heavy stones in the pyramid construction (Arnold, 1991; Edwards, 2010). It has been widely used in simple carpentry, sophisticated decorative joints, basic building techniques, and the highest standards of cabinet making. Hence, as Edwards (2010) conveyed, dovetail jointing can represent the history of furniture and timber building construction and production. Another example where wood is interdigitated without using nails is found in the structure of the historical hypostyle wooden mosques of Anatolia (Figure 1a). In these mosques, wooden beams are connected by tapered grooves tightly together like a single dovetail. These kinds of joints provide flexible jointing that increased the strength of the structures against lateral and vertical loads. Thanks to this strength, these structures survived today as an important work of traditional building art (Develi, 2019). However, as steel and concrete replaced the wood material in contemporary Turkish architecture, currently, these traditional wooden details are not used by modern construction. Nevertheless, the experiences gained from these structures in terms of construction techniques are still used in the construction of wooden doors, windows, and furniture.

Since ancient times, narrow pieces have been widely used with tongue-and-groove, and dowel joints in wooden interdigitating furniture constructions (Küreli, 1988). Nevertheless, the invention of finger jointing had strengthened the joints in wooden corners – such as window and door frames, furniture, and various wooden structural bearing elements (columns, beams)- 60-80 % more than the use of dovetail and tongue-and-groove jointing (Örs,1987; Altınok, *et al.*, 2010). Today, many connections and bonding techniques have been developed with increasing wooden sectors especially furniture production. It is important for carpenters to know which type and size of loads will be applied during the use of the wooden element. To ensure efficient use conditions, the elements and joints of furniture must be designed to meet these expected loads. Moreover, new materials and techniques may advance the details and may help carpenters to strengthen the wooden corners.

In addition to traditional techniques, there are also detachable connecting fittings (threaded bolt with a pivot pin (so-called Minifix), Lamello Clamex P 15, Lamello Invis Mx, Clamex P14, Tenso P14), which have been spreading rapidly in recent years (Kasal, 2004). Although there are many separate or comparative studies on the structural capacity of wooden corners of these joints in the literature (Gou *et al*., 2019; Atar *et al*., 2017; Simeonova, 2016; Jivkov and Marinova, 2016; Smardzewski *et al*., 2014), those related to the relatively new Clamex P14 and Tenso P14 fasteners are few in number (Saar *et al*., 2015; Karaman, 2019; Prekrat *et al*., 2019; Karaman, 2020, Karaman, 2021).

The strength of a wooden corner depends not only on the materials but also on the joint types. This study surveyed the rigidity of edge-to-edge joints in wooden corners. Edge-to-edge joints are statically critical points of box-type wooden elements such as door and window frames (Figure 1b), cabinets, chests, etc.



a) b)

Figure 1 a) Photo and detail of "Çantı" technique in a traditional Turkish wooden hypostyle mosque; Ulucami in Ayaş-Ankara b) Photo and detail of a wooden corner of a door frame in a traditional Turkish house; Kızılcabölük – Denizli
Slika 1. a) Fotografija i detalj tehnike *çantı* u tradicionalnoj turskoj drvnoj hipostilnoj džamiji Ulucami u Ayaş-Ankari, b) fotografija i detalj drvnog kuta dovratnika u tradicionalnoj turskoj kući (Kızılcabölük – Denizli)

Moreover, additional mechanical forces may occur in kinetic box-type wooden elements such as drawers. Whether it is static or kinetic, compelling forces in the corners may cause deformation over time in box-type wooden elements. To determine these deformations, various researches have been carried out on the effects that a corner can be exposed to.

In box-type construction, the strength and durability of the structure depend on the torsional stiffness and rigidity of the plates. Box-type constructions are mostly four-sided, forming a frame with a backplate. If the main box carries other frames, such as drawers and cabinet doors, then the structure is generally defined as frame-type wooden construction. A bookshelf is an example of a box-type and a laundry cabinet with drawers can be given as an example of the frame-type (Eckelman, 1978).

As a critical point of carpentry both for furniture and building construction, the performance of wooden joints had been a subject of interest for many years. Some of these studies focused on the bending behavior of jointing details (Chen *et al.*, 2016; Kamperidou and Vasileiou, 2012) while others such as Rad *et al.* (2019) focused on tension. Within many studies on tension and compression resistance of wooden corners, most of them were about the resistance of furniture corners. As regards these studies, glued (fixed) and non-glued (disassembled) joints for corners used in the production of box-type furniture, fiberboards have better results than particleboards, and also, non-glued (disassembled) joints have better performance than glued (fixed) joints (Atar, 2006; İmirzi, 2000; Efe, *et al.*, 2003; Hrovatin and Zupančič, 2013; Kasal, *et al.*, 2006; Şakacı, 2010; Efe, *et al.*, 2012). Efe and Kasal stated that multifix fasteners are more successful than minifix fasteners (Efe, *et al.*, 2000). Şafak (2000) indicated that corner joints with non-glued multifix have the best performance. As a result of the literature review, it is seen that studies mostly focused on the comparison of two-factor affecting the tensile strength of wooden corners. Nevertheless, this study aims to analyze the tensile performance of wooden corner joints under 4-factor interaction: the jointing technique, the type of material, the axis of assembly, and the type of adhesive.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

The test specimens for analysis of wooden corner joints were prepared by using Scots pine (*Pinus sylvestris* Lipsky), Lombardy poplar (*Populus nigra* Lipsky), and medium density fiberboard (MDF), which were preferred due to their wide use in furniture and construction industry. Two kinds of adhesives - polyvinyl acetate (PVAc) and polyurethane (Desmedur-VTKA), and 5 kinds of joinery techniques - 8x35 mm dowel joint, tongue-and-groove joint, half-hidden dovetail joint, 4 mm × 60 mm philips-headed flat screw joint, and eccentric joints, were selected. Additionally, the assembly of the plates was done in two different axes, parallel and perpendicular to the axis of the assembly. Hence; 300 (2 × 5 × 3 × 2 × 5) different tests were executed with 2 adhesives, 5 joinery techniques, 3 materials, 2 axes of assembly with 5 specimens each.

Each test specimen consisted of two plates, A and B, and the thickness of all the specimens was chosen as 16 mm. A is in 100 mm × 109 mm dimensions while B is 100 mm × 125 mm, and their placement is shown in Figure 2. In the test specimen with dowel joint, wedge dowels of 8 mm in diameter and 35 mm in length were used. Dowel holes were drilled in the beveled combination with two centers 8 mm in diameter and 23 mm in depth and 8 mm in diameter and 12 mm in depth on the face of the plate B, so that the center of the dowel on plate A would be symmetrical to the center of the

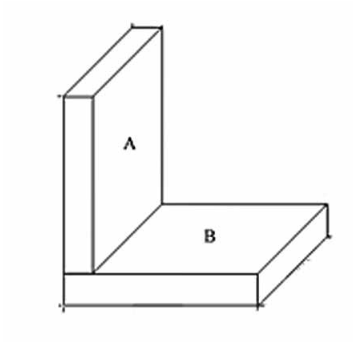


Figure 2 Dimensions of test specimen (dimensions in mm)
Slika 2. Izgled ispitnog uzorka (dimenzije u mm)

hole and directly fit in. The dimensions of the wooden dowel joint specimen are shown in Figure 3a. Approximately 150 g of adhesive was applied with a brush on the overlapping surfaces of plates A and B and the dowel holes; afterward, a torsion force at a pressure of 0.2-3 N/mm^2 was applied to assemble the test specimens. Assembly of test specimens was carried out under (20±2) °C temperature and (65±3) % relative humidity in the conditioning chamber and they were heated until they reached the counterweight.

The dimensions of the test specimen, which was produced by circular saw cutting on the principles of the tongue-and-groove joint, are shown in Figure 3b. The test specimen was assembled by applying a pressure of 0.2-3 N/mm^2 with clamp after applying with a brush approximately 150 g of adhesive to the overlapping surfaces of plates A and B. The assembled samples were allowed to reach constant weight in the conditioning chamber under the temperature of (20±2) °C and relative humidity of (65±3) %.

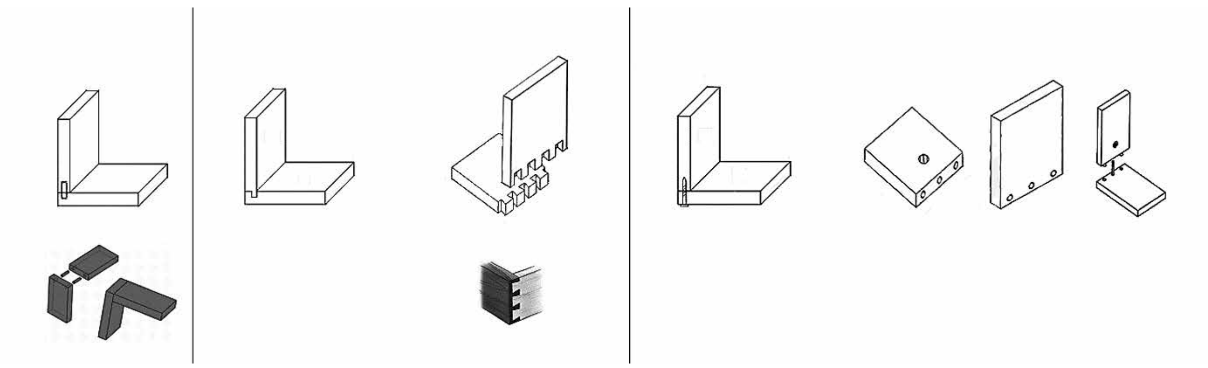
The pins and tails of the test specimen with a half-blind dovetail joint were cut in a threading machine. The dimensions of the specimen are shown in Figure 3c. Test specimens were assembled by applying a pressure of 0.2-3 N/mm^2 on the tacked planes after applying approximately 150 g of adhesive with a brush to the overlapping surfaces of plates A and B. The assembled samples were stored until reaching a constant weight in the conditioning chamber under the temperature of (20±2) °C and relative humidity of (20±2) %.

In the test specimen with the screw joint, the screw pilot holes were drilled by using the horizontal and vertical drilling machines. In the preparation of the specimen, the principles stated in TS EN 326-1 were respected (TS EN 326-1, 1999). Accordingly, a pilot hole, with a diameter of about 60 % of the thread diameter of the connecting screw, was drilled in the edges of panels. The depth of the pilot hole was 5 times its diameter. The connections of the screws complied with the recommendations of ASTM 1037 and the manufacturers (ASTM D 1037, 2006). Accordingly, the screws were connected to the pilot slots and the screw axis, so that they were perpendicular to the edges of the plates (TS EN 13446, 2005). The screws used in the experiments (4 mm × 60 mm) had a diameter of 4mm, while the hole diameter was (2.5±0.5), the pilot hole diameter was (12.5±0.5), and the screwing depth was (20.5±0.5) mm (Figure 3d).

For the test specimen with eccentric joint, the operations on the plate were carried out with the hole drilling machine. The dimensions of the test specimen are shown in Figure 3e. After drilling the holes, the parts of the eccentric connecting joint were assembled so that the plates A and B were mounted following the specified principles for the non-adhesive eccentric connecting. The assembled test specimens were stored until reaching a constant weight in the conditioning chamber with a temperature of (20±2) °C and relative humidity of (65±3) %.

2.2 Testing and data analyzing procedure
2.2. Ispitivanje i analiza podataka

After the selection of the wood material as defined in TS 2470, TS 64-3, and EN 622-3, the prepared



a) b) c) d) e)

Figure 3 Test specimens: a) Wooden dowel jointed test specimen - DJ, b) Test specimen with tongue-and-groove joint - TGJ, c) Test specimen with half-blind dovetail joint – DTJ, d) Test specimen with screw joint – SJ, and e) Test specimen with eccentric (Minifix) joint – MJ
Slika 3. Ispitni uzorci: a) drvni ispitni uzorak spojen moždanikom – DJ, b) ispitni uzorak spojen perom i utorom – TGJ, c) ispitni uzorak spojem poluzatvorenim lastinim repom – DTJ, d) ispitni uzorak spojen vijkom – SJ, e) ispitni uzorak spojen ekscentrom (Minifixom) – MJ

Table 1 Measured tensile stress values as Kgf
Tablica 1. Izmjerene vrijednosti vlačnog naprezanja kao Kgf

Joinery tech. *Tehnika spajanja*	Test	Parallel to the axis of assembly (I) *Paralelno s osi montaže (I)*						Vertical to the axis of assembly (II) *Okomito na os montaže (II)*					
	Wood *Drvo*	Scots Pine (Sp) *Borovina (Sp)*		Poplar (Po) *Topolovina (Po)*		MDF		Scots Pine (Sp) *Borovina (Sp)*		Poplar (Po) *Topolovina (Po)*		MDF	
	Adh.	PVAc	PU	PVAc	PU	PVAc	PU	PVAc	PU	PVAc	PU	PVAc	PU
DJ	max.	162	140	152	130	192	202	260	302	246	265	300	302
	min.	150	120	130	106	164	157	219	256	205	190	252	276
	s	5.02	7.12	7.98	8.87	11.43	18.9	16.54	17.72	17.64	31.4	19.51	10.6
	v	25.2	50.8	63.8	78.8	130.8	358	273.8	314	311.5	986	380.8	113
	x	155.8	129.4	140.6	119.6	178.4	176	241.4	277	224	234	274.6	289
TGJ TGJTG	max.	95	195	60	150	31	73	126	182	116	142	102	126
	min.	58	158	30	100	22	58	89	103	72	110	68	98
	s	15.36	14.97	11.45	19.38	3.67	5.97	14.72	32.91	17.72	11.9	14.2	11.4
	v	236.2	224.2	131.2	375.8	13.5	35.7	216.7	1083	314	143	201.8	130
	x	74.2	175.8	45.8	130.6	26	63.8	105.2	141.4	95	126	85.4	113
DTJ	max.	243	273	243	263	330	355	234	283	233	263	212	217
	min.	218	235	190	223	276	320	208	230	196	220	187	192
	s	10.08	14.84	21.01	15.17	22.71	13.1	9.98	29.03	14.69	16.9	11.56	9.39
	v	101.7	220.3	441.7	230.3	516	171	99.7	401.5	216	288	134.5	88.3
	x	232.8	253.4	211.8	242.6	301	336	221.2	255	215	242	198	202
SJ	max.	380	350	374	334	471	460	350	338	332	321	460	395
	min.	345	309	300	296	450	436	316	296	297	285	514	349
	s	14.81	15.82	28.6	15.17	8.22	9.94	13.01	16.51	14.42	13.9	17.12	20.2
	v	219.5	250.3	818.3	230.2	67.7	98.8	169.3	272.8	208.2	195	293.3	410
	x	362	331.4	338.4	313.8	459.2	446	333.6	315.4	312.2	304	435.6	371
MJ	max.	205		182		155		223		184		340	
	min.	148		136		122		200		159		300	
	s	22.34		18.29		14.01		8.98		10.84		15.3	
	v	499.3		334.8		196.3		80.7		117.7		234.2	
	x	177.6		157.6		134.4		212.8		173.2		322.2	

s – Standard deviation / *standardna devijacija*, *v* – Variance / *varijanca*, *x* – Average / *srednja vrijednost*, DJ – Dowel joint / *spoj moždanikom*, TGJ – Tongue-and-groove joint / *spoj perom i utorom*, DTJ – Half-blind dovetail joint / *spoj poluzatvorenim lastinim repom*, SJ – Screw joint / *spoj vijkom*, MJ – Eccentric (Minifix) joint / *spoj ekscentrom (Minifixom)*, PVAc – Polyvinyl acetate adhesive / *polivinilacetatno ljepilo*, Pu – Polyurethane adhesive / *poliuretansko ljepilo* specimens were tested with 3000 kp capacity SEIDNER test device in the laboratory of Gazi University, Faculty of Technology, Department of Wood Products Industrial Engineering. By using the standard procedure of ASTM D 1037, an axial tension test was conducted under 2 mm/min in the pressure arm. The forces on the test specimens were recorded as Newton. In this research, the effects of various factors - such as types of material, adhesive, and load cases - on the tensile performance of defined corner joints in box-type wooden structures were studied. Multiple variance analysis (MANOVA) was conducted to determine the effects of these factors on tensile performance, and the DUNCAN test was used to indicate the level of significance with a 5 % margin of error.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Measured tensile stress values of different joinery techniques according to the types of material and adhesive under two different load cases are given in Table 1, and the results of the multivariate analysis of the tensile performance of the different joinery techniques according to the types of material, and adhesive, and under two different load cases are given in Table 2. The analysis indicated that the difference between the factors – joinery techniques, types of material, axis of assembly, and types of adhesive – are statistically significant ($\alpha = 0.05$). The Duncan test results are used to determine which groups of differences are significant and they are given in the comparison of interactions.

The average values of tensile performance in terms of joinery techniques are given in Table 3. The tensile strength of the screwed joint (SJ) (3603 N) is maximum for all test specimens, while the tongue-and-groove joint (TGJ) (986 N) is minimum. Regarding the joinery technique, the tensile strength performance of the screw joint is followed by the half-blind dovetail joint (DTJ), dowel joint (DJ), and the minifix joint (MJ), respectively. In terms of material, the tensile strength results from the highest to the lowest value are in order of Medium-Density Fiberboard (MDF) (2436 N), Scots pine wood (Sp), and Poplar wood (Po) (1979 N). This higher strength can be explained by the high density and homogeneous structure of MDF material, and test results draw a parallel between the obtained results and the material densities.

The tensile performance of the vertical load case (2343 N) gives better performance than the parallel one (2061 N). This higher tensile strength of vertical loading can be explained by the shear force resistance of all joints. These higher results of non-axial performance in tensile strength than axial can be explained by the shear force resistance of types of jointing. And finally, the tensile strength performance of polyurethane-based adhesive (Pu) (Desmodur-VTKA) is higher (2257 N) than that of polyvinyl acetate (PVAc) adhesive (2148 N). This result can be explained by the higher mechanical adhesion of polyurethane.

The mean values of the tensile performance of the binary interactions are given in Table 4. The highest tensile performance in terms of the binary interaction is found to be in the interaction of joinery technique and type of material pairing. Maximum tensile strength is observed in the MDF + screw joint (SJ) (4282 N) pair, while the minimum in the MDF + tongue-and-groove joint (TGJ) (722 N). As seen in Table 4, the tensile per-

Table 2 Multivariate analysis of tensile performance
Tablica 2. Multivarijatna analiza vlačnih svojstava

Source *Izvor*	**Degrees of freedom** *Stupnjevi slobode*	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednja vrijednost kvadrata*	***F* value** *F-vrijednost*	***P*<5 % (Sig)**
Joinery techniques (A) / *tehnika spajanja (A)*	4	2146354.447	536588.612	2109.121	0.0000
Types of material (B) / *vrsta materijala (B)*	2	104485.127	52242.563	205,3452	0.0000
AxB	8	139201.273	17400.159	68.3933	0.0000
Axis of assembly (C) / *os montaže (C)*	1	59643.000	59643.708	234.4335	0.0000
AxC	4	253630.833	1079.13	249.2311	0.0000
BxC	2	2158.260	18020.951	4.2416	0.0155
AxBxC	8	144167.607	8899.853	70.8334	0.0000
Types of adhesive (D) / *vrsta ljepila (D)*	1	8899.853	13513.928	34.9819	0.0000
AxD	4	54055.713	866.923	53.118	0.0000
AxBxD	8	3546.687	337.08	1.7426	0.0494
AxCxD	4	11999.620	615.97	11.7915	0.0000
BxCxD	2	1231.940	89.408	2.4211	0.0210
AxBxCxD	8	7123.260	254.413	3.4998	0.0008
Error / *pogreška*	240	61059.200			
Total / *ukupno*	299	2999627.747	-	-	

Table 3 Average tensile performances in terms of joinery techniques (N)
Tablica 3. Srednja vlačna svojstva s obzirom na tehnike spajanja (N)

Joinery techniques* / *Tehnike spajanja**	*X*	HG
Screw joints (SJ) / *spoj vijcima (SJ)*	3603	A
Half-blind dovetail joints (DTJ) / *spoj poluzatvorenim lastinim repom (DTJ)*	2426	B
Dowel joints (DJ) / *spoj moždanikom (DJ)*	2034	C
Eccentric (Minifix) joints (MJ) / *spoj ekscentrom (Minifixom) (MJ)*	1963	D
Tongue-and-groove joints (TGJ) / *spoj perom i utorom (TGJ)*	986	E
Type of material** / *vrsta materijala***		
MDF (MDF)	2436	A
Scots pine (Sp) / *borovina (Sp)*	2192	B
Poplar (Po) / *topolovina (Po)*	1979	C
Axis of assembly***/ *os montaže****		
Tensile strength vertical to the axis of assembly (non-axial) (IIV) *vlačna čvrstoća okomito na os montaže (neaksijalno) (IIV)*	2343	A
Tensile strength parallel to the axis of assembly direction (axial) (IP) *vlačna čvrstoća paralelno s osi montaže (aksijalno) (IP)*	2061	B
Type of adhesive**** / *vrsta ljepila*****		
Polyurethane (Pu) / *poliuretan (Pu)*	2257	A
Polyvinyl acetate (PVAc) / *polivinilacetat*	2148	B

**LSD*=5.731, ***LSD*=4.432, ****LSD*=3.625, *****LSD*=3.625, HG – Homogeneity groups / *homogenost grupa*, *X* – Mean / *srednja vrijednost*

formance in terms of jointing technique and the axis of assembly interaction is the highest in the screw joint (SJ) (3752 N), and the lowest in the tongue-and-groove joint (TGJ) (863 N) both in axial tensile loading. In screw joint (SJ) under the tensile loading in the axial direction, no deformation was caused in plate A and B. The only deformation occurred in the form of burying the head of the screw into the plate. In some of the test specimens, it is observed that the screw broke under tension. During the non-axial (vertical) tensile loading, fiber-debonding in plate A and deformation of the fibers in plate B are observed.

When the tensile performance of the jointing technique and types of adhesive interaction is considered, screw joint (SJ) + PVAc adhesive (3735 N) pair has the maximum strength, while tongue-and-groove joint (TGJ) + PVAc adhesive (719 N) has the minimum. The observations during the performed tests demonstrated that in SJ+ PVAc joint the adhesive lost its performance at 200-250 kgf/m loading, whilst the performance of the screw was maintained up to 450-500 kgf/m loading. Hence, it can be concluded that this type of jointing can be applied without glue, which does not have a function.

Tensile performance in terms of material type and the axis of assembly interaction is found to be the highest in MDF + non-axial loading (2615 N) and the lowest in poplar (Po) + axial loading (1858 N). During the tests, no deformation was observed in the plates in tensile loading parallel to the axis of the assembly. In the direction vertical to the axis of assembly, it was observed that the MDF, which is a composite material, was deformed in the form of breakage, while the pine and poplar were deformed in the form of peeling. When tensile performance in terms of the type of material and type of adhesive interaction is considered, the polyurethane adhesive (Pu) adhesive + MDF (2457 N) pair has the highest performance and the PVAc adhesive + poplar (Po) wood (1914 N) pair has the lowest. As shown in the last part of Table 4, the tensile performance in terms of load cases and type of adhesive interaction is found to be the highest in the polyurethane adhesive (Pu) (2387 N) + vertical to the axis of the assembly pair and the lowest in the polyvinyl acetate adhesive (PVAc) (1996 N) + parallel to the axis of assembly pair.

The average values of the tensile performance of triple interactions are given in Table 5. As MDF + axial tensile loading pair is similar in both the highest and the lowest tensile performance rates of the triple interaction between joinery technique, type of material, and axis of assembly, the joinery technique is found as a critical variable; hence, the tensile strength of screw joint technique (SJ) is the highest (4529 N), while tongue-and-groove joint technique (TGJ) is the lowest (449 N). In traditional half-blind dovetail jointing, which took the second place in the ranking of test specimens, the joint was peeled off. It is thought that this may be related to the form and dimensions of the teeth of the dovetail joint. However, to obtain more detailed information on this issue, it would be beneficial to carry out further studies in this direction. The dowel jointing took third place in the tensile performance rankings. During the tests, it was observed that no deformation occurred in the plates under the axial (parallel) tensile loading, and the dowels remained on the plate A side. Under non-axial (vertical) tensile loading, plate B (female) appeared to be deformed by the failure of the fibers. In some of the test specimens, the deformation was observed as the breakage of the dowel.

Table 4 The average value of tensile performance of binary interactions (N)
Tablica 4. Srednja vrijednost vlačnih svojstava u binarnoj interakciji (N)

Jointing technique + Type of material* *Tehnika spajanja +vrsta materi-jala**	*X*	HG	**Jointing technique + Axis of assembly**** *Tehnika spajanja + os montaže***	*X*	HG	**Type of material + Axis of assembly***** *Vrsta materi-jala + os montaže****	*X*	HG	**Joinery technique + Type of adhesive****** *Tehnika spajanja + vrsta ljepila*****	*X*	HG	**Type of material + Type of adhesive******* *Vrsta materi-jala + vrsta ljepila******	*X*	HG	**Axis of assembly + Type of adhesive******** *Os montaže + vrsta ljepi-la*******	*X*	HG
SJ+MDF	4282	A	SJ+IP	3752	A	MDF+IIV	2615	A	SJ+ PVAc	3735	A	MDF+PVAc	2415	A	IIV+PVAc	2300	B
SJ+ Sp	3356	B	SJ+IIV	3454	B	MDF+IP	2257	B	SJ+ Pu	3471	B	MDF+Pu	2457	A	IP+ Pu	2127	C
SJ+Po	3171	C	DTJ+IP	2629	C	Sp+IIV	2316	B	DTJ+ Pu	2554	C	Sp+ Pu	2269	B	IP+PVAc	1996	D
DTJ+MDF	2595	D	DJ+IIV	2568	C	Po+IIV	2100	C	DTJ+PVAc	2298	D	Sp+PVAc	2116	C			
DTJ+ Sp	2404	E	MJ+IIV	2361	D	Sp+IP	2069	C	DJ+PVAc	2025	E	Po+Pu	2045	D			
MJ+MDF	2283	F	DTJ+IIV	2223	E	Po+IP	1858	D	DJ+Pu	2044	E	Po+ PVAc	1914	E			
DJ+MDF	2298	F	DJ+IP	1501	F				MJ+ PVAc	1963	E						
DTJ+Po	2279	F	MJ+IP	1565	F				MJ+ Pu	1963	E						
MJ+ Sp	1952	G	TGJ+IIV	1112	G				TGJ+Pu	1253	F						
DJ+Sp	2009	G	TGJ+ IP	863	H				TGJ+PVAc	719	G						
DJ+Po	1796	H															
TGJ+Po	995	K															
TGJ+MDF	722	L															
MJ+Po	1654	I															
TGJ+ Sp	1242	J															

**LSD*=9.926, ***LSD*=8.105, ****LSD*=6.278, *****LSD*=8.098, ******LSD*=6.273, *******LSD*=5.122, HG – Homogeneity groups / *homogenost grupa*, *X* – Mean / *srednja vrijednost,* DJ – Dowel joint / *spoj moždanikom*, TGJ – Tongue-and-groove joint / *spoj perom i utorom*, DTJ – Half-blind dovetail joint / *spoj poluzatvorenim lastinim repom*, SJ – Screw joint / *spoj vijkom*, MJ – Eccentric (Minifix) joint / *spoj ekscentrom (Minifixom)*, IP – Axis I-parallel to the axis of assembly / *os I – paralelno s osi montaže*, IIV – Axis II-vertical to the axis of assembly / *os II – okomito na os montaže*, Sp – Scots pine / *borovina*, Po – Poplar / *topolovina*, MDF – Medium density fiberboard / *srednje gusta ploča vlaknatica*, PVAc – Polyvinyl acetate adhesive / *polivinilacetatno ljepilo*, Pu – Polyurethane adhesive / *poliuretansko ljepilo*

Table 5 Mean values of tensile performance of triple interactions (N)
Tablica 5. Srednja vrijednost vlačnih svojstava u trostrukoj interakciji (N)

***Jointing technique + Type of material + Axis of assembly** / **Tehnika spajanja + vrsta materijala + os montaže*					
Factors	*X*	HG		*X*	HG
DJ+MDF+IIV	2820	F	SJ+MDF+IP	4529	A
DJ+Sp+IIV	2592	G	SJ+MDF+IIV	4035	B
DTJ+Po+IP	2272	H	SJ+Sp+IP	3467	C
DJ+Po+IIV	2292	H	SJ+Sp+IIV	3245	D
DTJ+Sp+IIV	2381	H	SJ+Po+IP	3261	D
DTJ+Sp+IP	2426	H	DTJ+MDF+IP	3188	DE
DJ+MDF+IP	1775	J	MJ+MDF+IIV	3222	DE
DJ+Sp+IP	1426	L	SJ+Po+IIV	3082	E
DJ+Po+IP	1301	LM	DTJ+Po+IIV	2286	H
TGJ+Sp+IP	1250	MN	DTJ+MDF+IIV	2002	I
TGJ+Sp+IIV	1233	MN	MJ+Sp+IIV	2128	I
TGJ+Po+IIV	110	NO	MJ+Po+IIV	1732	J
TGJ+MDF+IIV	995	OP	MJ+Sp+IP	1776	J
TGJ+Po+IP	882	P	MJ+Po+IP	1576	K
TGJ+MDF+IP	449	Q	MJ+MDF+IP	1344	LM
****Jointing technique + Type of material + Type of adhesive** / ***Tehnika spajanja + vrsta materijala + vrsta ljepila*					
DTJ+Sp+Pu	2542	G	SJ+MDF+PVAc	4474	A
DJ+MDF+Pu	2330	HI	SJ+MDF+Pu	4090	B
DJ+MDF+PVAc	2265	IJ	V+Sp+PVAc	3478	C
DTJ+Sp+PVAc	2265	IJ	SJ+Sp+Pu	3234	D
DJ+Sp+Pu	2032	KL	SJ+Po+PVAc	3253	D
DJ+Sp+PVAc	1986	L	SJ+Po+Pu	3090	E
DTJ+Po+PVAc	2134	L	DTJ+MDF+Pu	2695	F
DJ+Po+ PVAc	1823	MN	DTJ+MDF+Pu	2495	G
DJ+Po+Pu	1770	NO	DTJ+Po+Pu	2424	GH
TGJ+Sp+Pu	1586	P	MJ+MDF+PVAc	2283	HIJ
TGJ+Po+Pu	1285	Q	MJ+MDF+Pu	2283	HIJ
TGJ+Sp+PVAc	897	R	MJ+Sp+PVAc	1952	LM
TGJ+MDF+Pu	887	R	MJ+Sp+Pu	1952	LM
TGJ+Po+PVAc	704	S	MJ+Po+PVAc	1654	OP
TGJ+MDF+PVAc	557	T	MJ+Po+Pu	1654	OP
*****Joinery technique + Axis of assembly + Type of adhesive** / ****Tehnika spajanja + os montaže + vrsta ljepila*					
DJ+IIV+Pu	2669	D	SJ+IP+PVAc	3865	A
DTJ+IP+Pu	2775	D	SJ+IIV+PVAc	3605	B
DTJ+IP+PVAc	2482	E	SJ+IP+Pu	3639	B
DJ+IIV+PVAc	2467	EF	SJ+IIV+Pu	3303	C
DJ+IP+PVAc	1583	I	MJ+IIV+PVAc	2361	FG
DJ+IP+Pu	1419	J	MJ+IIV+Pu	2361	FG
TGJ+IP+Pu	1234	K	DTJ+IIV+Pu	2332	G
TGJ+IIV+Pu	1271	K	DTJ+IIV+PVAc	2114	H
TGJ+IIV+PVAc	952	L	MJ+IP+PVAc+	1565	I
TGJ+IP+PVAc	486	M	MJ+IP+Pu	1565	I
******Type of material + Axis of assembly + Type of adhesive** / *****Vrsta materijala + os montaže + vrsta ljepila*					
Sp+IIV+Pu	2403	B	MDF+IIV+Pu	2598	A
Sp+IIV+PVAc	2228	CD	MDF+IIV+PVAc	2632	A
Sp+IP+Pu	2135	D	MDF+IP+Pu	2316	BC
Sp+IP+PVAc	2003	EF	Po+IP+Pu	2161	D
Po+IP+Pu	1928	F	MDF+IP+PVAc	2198	D
Po+IP+PVAc	1788	G	Po+IIV+PVAc	2039	E

**LSD*=14.04, ***LSD*=14.03, ****LSD*=11.45, *****LSD*= 8.871 HG – Homogeneity groups / *homogenost grupa*, *X* – Mean / *srednja vrijednost*, DJ – Dowel joint / *spoj moždanikom*, TGJ – Tongue-and-groove joint / *spoj perom i utorom*, DTJ – Half-blind dovetail joint / *spoj poluzatvorenim lastinim repom*, SJ – Screw joint / *spoj vijkom*, MJ – Eccentric (Minifix) joint / *spoj ekscentrom (Minifixom)*, IP – Axis I-parallel to the axis of assembly / *os I – paralelno s osi montaže*, IIV – Axis II-vertical to the axis of assembly / *os II – okomito na os montaže*, Sp – Scots pine / *borovina*, Po – Poplar / *topolovina*, MDF – Medium density fiberboard / *srednje gusta ploča vlaknatica*, PVAc – Polyvinyl acetate adhesive / *polivinilacetatno ljepilo*, Pu – Polyurethane adhesive / *poliuretansko ljepilo*

Likewise, in the triple interaction between joinery technique, type of material, and type of adhesive, the joinery technique appeared as a critical factor since MDF + PVAc pair is similar in both the highest and lowest combinations. Hence, the tensile strength of the screw joint (SJ) is found to be the highest (4474 N), while the tongue-and-groove joint (TGJ) is the lowest (557 N). Although the tongue-and-groove joint had the worst performance due to the tensile performance rankings, no deformation was observed on the glued surfaces of tongue or groove. In the tensile loading both parallel and vertical to the axis of assembly, it is seen that the deformation does not occur in the plate A which is broken by 8 mm; and the broken part is left on the plate B. The reason for the low values may be due to the rupture of the fibers during the preparation of the tongue and groove. It is not recommended to use this joinery technique at the wooden corners as its strength is very low and it is easy to deform.

In triple interaction of joinery technique, the axis of assembly, and type of adhesive in terms of tensile performance, the axis of tensile force applied parallel to the axis of assembly appeared similar in both the highest and the lowest tensile performance rates. As the axis of assembly is the same in both cases, the highest combination is found to be in screw joint (SJ) + PVAc pair (3865 N), while tongue-and-groove joint (TGJ) + PVA is the lowest (486 N). In terms of the type of material, axis of assembly, and type of adhesive interaction, the highest tensile performance was found to be in MDF + IIV + PVAc trio (2632 N), while the lowest in Po+IP+PVAc (1788 N).

When the 4-factor (type of material, joinery technique, type of adhesive, and axis of assembly) effects on the tensile performance are considered, SJ + MDF + PVAc + IP is the highest (4592 N), while TGJ + MDF + PVAc + IP is the lowest (260 N).

The Duncan test results for 4-factor interaction of the jointing technique, the type of material, the axis of assembly, and the type of adhesive, affecting the tensile performance of wooden corner joints are given in Table 6.

According to the test results, the screw joint has increased the tensile performance by 49 % of half-blind dovetail jointing (DTJ), 77 % of dowel joint (DJ), 84 % of the eccentric joint (MJ) with minifix apparatus, and 265 % of tongue-and-groove joint (TGJ). In terms of types of material, the MDF has increased the tensile performance by 11 % of Scots pine wood (Sc) and 23 % of Poplar wood (Po). According to the tests on the effect of the types of adhesive on the tensile performance, the polyurethane glue is 5 % higher than the polyvinyl acetate glue. The tensile performance in terms of the axis of assembly shows that the non-axial (vertical) tensile performance value is 14 % higher than the axial (parallel) tensile performance in the assembly direction. The results on PVA adhesives are compatible with the study of Taghiyari *et al*. (2017) and the results on the effects of types of materials on the tensile performance of corner joints are in accordance with the study of Yıldız and Çavuş (2008).

4 CONCLUSIONS
4. ZAKLJUČAK

Thanks to the developments in building materials and chemicals, many new details regarding wooden corner joints have been produced in the last century. Parallel to these developments, traditional wooden construction details tend to be abandoned. Nevertheless, the wisdom of traditional know-how may still be valid. The results of testing traditional and modern jointing details, with natural and artificial materials, revealed interesting information that can guide us to better design wooden corners.

The existing literature is mostly focused on the comparison of two-factor affecting the tensile strength of wooden corners; hence, they do not draw a holistic frame for the evaluation of corner joints. In this respect, this study is original as it analyzes the tensile performance of wooden corner joints under multiple factor interactions. This study contributes to the current literature by examining the interaction of four different factors: the jointing technique, the type of material, the axis of assembly, and the type of adhesive.

Upon considering the tensile performance results, the screwed joint, which is thought to be low-cost and easy to work with, can be recommended for wooden corner joints. The traditional half-blind dovetail jointing technique took the second place in the performance rankings, followed by the dowel joint and then the contemporary eccentric joint. Due to the tensile performance rankings, the worst performance is observed in the tongue-and-groove joint. Therefore, it is not recommended to use this joinery technique for the wooden corners as its strength is very low and it is easy to deform. Consequently, it can be stated that for wooden corner joints, it may be advantageous to apply screw joint, MDF, and PVAc glue under tension parallel to the assembly axis.

As seen from the results, the contemporary materials and techniques are not always better than the traditional ones, as the traditional half-blind dovetail jointing technique took the second place in the performance rankings among all joints. Although it is the most historic technique, its performance is still compatible with the modern ones and applicable in carpentry. Nevertheless, the advantage of modern techniques and materials, such as screw joint and MDF is undeniable, so that the wisdom gained by experience in tradi-

Table 6 Duncan test results on 4-factor interaction (joinery technique, type of material, axis of assembly, and type of adhesive) affecting tensile performance
Tablica 6. Rezultati Duncanova testa za četverostruku interakciju (tehniku spajanja, vrstu materijala, os montaže i vrstu ljepila) koji utječu na vlačna svojstva

Joinery technique + Type of material + Axis of assembly + Type of adhesive *Tehnika spajanja + vrsta materijala + os montaže + vrsta ljepila*	*X*	HG	**Joinery technique + Type of material + Axis of assembly + Type of adhesive** *Tehnika spajanja + vrsta materijala + os montaže + vrsta ljepila*	*X*	HG
SJ + MDF + IP+ PVAc	4592	A	DTJ + Sp + IIV + Pu	2128	NOP
SJ + MDF + IP+ Pu	4466	AB	DTJ + Po + IP + PVAc	2118	NOP
SJ + MDF + IIV + PVAc	4356	B	YK + MDF + IIV + Pu	2024	OP
SJ + MDF + II V+ Pu	3714	C	DTJ + MDF + IIV + PVAc	1980	PQ
SJ + Sp + IP + PVAc	3620	C	DJ + MDF + IP + PVAc	1784	QR
SJ+ Po + IP + PVAc	3384	D	MJ + Sp + IP + PVAc	1776	QR
DTJ + MDF + IP + Pu	3366	D	MJ + Sp + IP + Pu	1776	QR
SJ + Sp + IIV + PVAc	3336	DE	DJ + MDF + IP + Pu	1766	QR
SJ + Sp + IP+ Pu	3314	DEF	TGJ + Sp + IV + Pu	1758	QR
MJ+ MDF + IIV + PVAc	3222	DEFG	MJ + Po + IIV + PVAc	1732	R
MJ + MDF + IIV + Pu	3222	DEFG	MJ + Po + IIV + Pu	1732	R
SJ + Sp + IIV + Pu	3154	EFG	MJ + Po+ IP + PVAc	1576	RS
SJ + Po + IP + Pu	3138	EFG	MJ + Po + IP + Pu	1576	RS
SJ + Po + IIV + PVAc	3122	FG	DJ + Sç + IP+ PVAc	1550	RS
SJ + Po + II + Pu	3042	GH	TGJ + Sp + IIV + Pu	1414	ST
DTJ + MDF + IP + PVAc	3010	GH	DJ + Po + IP + PVAc	1406	ST
DJ + MDF + IIV + Pu	2894	HI	MJ + MDF + IP + PVAc	1344	TU
DJ + Sp + IIV + Pu	2770	I	MJ + MDF+ IP+ Pu	1344	TU
DJ + MDF + IIV + PVAc	2746	IJ	TGJ + Po + IP + Pu	1306	TU
DTJ + Sp + IIV + Pu	2550	JK	DJ + Sp + IP + Pu	1294	TU
DTJ+ Sp + IP + Pu	2534	KL	TGJ + Po + IIV + Pu	1264	TUV
DTJ + Po + IIV+ Pu	2426	KLM	DJ + Po + IP + Pu	1196	TUV
DTJ + Po + IP + Pu	2422	KLM	TGJ + MDF + IIV + Pu	1136	UVW
DJ + Sp + IIV + PVAc	2414	KLM	TGJ + Sp + IIV + PVAc	1052	VWX
DJ + Po + IIV + Pu	2344	KLMN	TGJ + Po + IIV + PVAc	950	WXY
DTJ+Sp + IP + PVAc	2318	LMN	TGJ + MDF + IIV + PVAc	854	XY
DJ + Po + IIV + PVAc	2240	MNO	TGJ + Sp + IP + PVAc	742	YZ
DTJ + Sp + IIP + PVAc	2212	MNO	TGJ + MDF + IP + Pu	638	Za
DTJ + Po+ IIV + PVAc	2150	NOP	TGJ + Po + IP + PVAc	458	ab
MJ +Sp + IIV + PVAc	2128	NOP	TGJ + MDF + IP + PVAc	260	bc

**LSD*=14.04, ***LSD*=14.03, ****LSD*=11.45, *****LSD*=8.871, HG – Homogeneity groups / *homogenost grupa*,*X* – Mean / *srednja vrijednost*, DJ – Dowel joint / *spoj moždanikom*, TGJ – Tongue-and-groove joint / *spoj perom i utorom*, DTJ – Half-blind dovetail joint / *spoj poluzatvorenim lastinim repom*, SJ – Screw joint / *spoj vijkom*, MJ – Eccentric (Minifix) joint / *spoj ekscentrom (Minifixom)*, IP – Axis I-parallel to the axis of assembly / *os I – paralelno s osi montaže*, IIV – Axis II-vertical to the axis of assembly / *os II – okomito na os montaže*, Sp – Scots pine / *borovina*, Po – Poplar / *topolovina*, MDF – Medium density fiberboard / *srednje gusta ploča vlaknatica*, PVAc – Polyvinyl acetate adhesive / *polivinilacetatno ljepilo*, Pu – Polyurethane adhesive / *poliuretansko ljepilo*

tional carpentry can be evolved by contemporary technological advances to get higher performance in wooden details.

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Analysis of Operational Efficiency of Wooden Chair Manufacturing Companies in Serbia using DEA

Analiza učinkovitosti poslovanja tvrtki za proizvodnju drvenih stolica u Srbiji primjenom DEA metode

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ABSTRACT • *This paper deals with the operational efficiency of companies engaged in the production of wooden chairs using selected statistical and DEA (Data Envelopment Analysis) methods. Indicators that typically characterise the supply chain in the production of selected companies were taken as input and output variables for the DEA method. They included three input variables: inventories, material costs and production services costs and one output variable: company's net profit. The obtained coefficients of correlation pointed to a high degree of correlation between the variables, which justified the performance of an efficiency analysis using the DEA method. The study included 12 companies engaged in the production of wooden chairs. The results of the conducted analyses show that only one company had a relatively satisfactory operational efficiency (efficiency coefficient of 0.83) for the nine-year period. All other companies, especially micro and small enterprises, had unsatisfactorily low operational efficiency. Micro enterprises had the lowest operational efficiency, with an efficiency coefficient of only 0.14. Small enterprises reached the value of 0.3, and large companies 0.67. Medium companies had the most favourable efficiency coefficient of up to 0.83.*

KEYWORDS: *value chain; chair; suppliers; DEA; efficiency; operation; enterprises*

SAŽETAK • *U radu je analizirana učinkovitost poslovanja tvrtki za proizvodnju drvenih stolica primjenom odabranih statističkih metoda i DEA (Data Envelopment Analysis) metode. Kao ulazne i izlazne varijable za DEA metodu izabrani su tipični pokazatelji koji su karakteristični za lanac opskrbe u proizvodnji odabranih tvrtki. To obuhvaća tri ulazne varijable: zalihe, materijalne troškove i troškove proizvodnih usluga te jednu izlaznu varijablu – neto dobit tvrtke. Dobiveni koeficijenti korelacije pokazali su visok stupanj međusobne povezanosti odabranih varijabli, što potvrđuje opravdanost primjene DEA metode za analizu učinkovitosti poduzeća. Istraživanje je obuhvatilo 12 tvrtki koje se bave proizvodnjom drvenih stolica. Rezultati provedene analize pokazuju da je samo*

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jedna od njih u posljednjih devet godina imala relativno zadovoljavajuću učinkovitost poslovanja (koeficijent učinkovitosti 0,83). Sve ostale tvrtke, posebice mikropoduzeća i mala poduzeća, imale su nezadovoljavajuće nisku učinkovitost poslovanja. U mikropoduzećima je zabilježena najmanja učinkovitost poslovanja, s koeficijentom učinkovitosti 0,14. Mala poduzeća postigla su koeficijent učinkovitosti od 0,3, a velika poduzeća od 0,67. Srednja poduzeća imala su najbolji koeficijent učinkovitosti: 0,83.

KLJUČNE RIJEČI: *lanac vrijednosti; stolica; dobavljači; DEA metoda; učinkovitost; poslovanje; poduzeće*

1 INTRODUCTION
1. UVOD

The wood industry is one of the most developed industries in Serbia, thanks, among other things, to the domestic raw material resources on which it builds its production.

Due to the dramatic growth in the demand for raw wood material in the world's leading centres for the production of furniture and other final wood products, its exports from Serbia in the form of sawlogs and sawn timber have risen substantially (Glavonjić *et al.,* 2020). This growth has particularly marked the last six years. Analyses and calculations related to the wood and wood products flows in Serbia for 2015 showed that only 48 % of the total quantities of hardwood sawlogs were processed into high-value-added products, and 52 % were exported as low-value-added products, i.e., sawlogs and sawn timber. One of the conditions to be met to change this situation is to increase the finalisation of raw wood materials that Serbia has at its disposal. (Glavonjić, 2016). Due to increased exports, domestic producers of final wood products have been increasingly facing a lack of good-quality raw wood material, especially oakwood. As a result, many of them are forced to import sawn timber. Considering the mentioned problems faced by the companies in the wood industry of Serbia, the research presented in this paper aimed to analyse the segment of the value chain that relates to suppliers (hereinafter referred to as the supply chain) in wooden chair manufacturing companies. We chose the manufacturers of wooden chairs because chairs are high-value-added products. Another reason is that Serbia was an internationally recognised manufacturer of wooden chairs thirty years ago and is aspiring to regain this reputation in the global trade of these products in the coming years.

Every company strives to achieve maximum efficiency in production and business processes. In order to be successful in the market and increase competitiveness, the main role of a company is to come up with product innovations. An economic aspect is another non-negligible challenge, too (Potkány *et al.,* 2019). The economic mission of every company, including companies in the wood industry, stems from the requirement to use the limited resources carefully to meet the ever-growing needs of customers. According to the general principle of the economy, the value of needs being satisfied should exceed the value of resources being used (Stevanović *et al.,* 2007). In this regard, the value chain has recently come into the focus of experts in practice due to the need to optimise and improve all its segments in order to increase the competitiveness of companies in the market and achieve better business results. According to Porter (2007), value-creating activities are interconnected within the value chain, as the way one of such activities is performed may affect the costs or performance of other activities.

Given the complexity of the value chain in the production of wooden chairs, the analysis presented in this paper focuses on the supply chain as the initial segment of the value chain. The main reason to choose the supply chain (supplier) as the subject of the research lies in the fact that the efficiency of the entire value chain largely depends on the quality of raw materials procured, security of delivery, prices, payment deadlines and other elements that suppliers are responsible for. To assess the efficiency of the supply chain, the following two key indicators were selected: the accounts payable turnover ratio and the number of days a company needs to cover the liabilities to suppliers.

Having this in mind, the main goal of the research presented in this paper was to create a model to quantify parameters that can be used to assess the efficiency of companies for the production of wooden chairs in Serbia using the DEA method. Another goal of the research was to select and apply appropriate tools that can be used to answer the question of how much it is necessary to increase the efficiency of the supply chain in order to achieve a satisfactory level of operational efficiency.

The analyses cover the period from 2011 to 2019. This is the period for which data from balance sheets and income statements of selected companies were available. There are 25 companies engaged in the production of wooden chairs in Serbia, 12 of them of which submit financial reports to the appropriate institution. The largest number of selected companies belong to the categories of micro, small and medium enterprises, while one company belongs to the category of large enterprises. Small and medium enterprises (SMEs) represent a significant part of the economy and industrial system of every country (Buehlmann *et al*., 2013; Bumgardner *et* *al*., 2011). This is certainly the case with the companies in the wood industry in Serbia.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The research presented in this paper used official data from the balance sheets and income statements of selected companies for the period from 2011 to 2019 obtained from the Business Registers Agency of Serbia, as follows: the value of inventories, costs to suppliers in the country and abroad, material procurement costs, production services costs and net profit.

The collection of data in the selected companies was performed in a period of one year. The data collected using the technique of interviews and direct recording were processed using qualitative content analysis of documents.

The collected data formed the basis for the application of appropriate scientific methods and techniques for the analysis of supply chain efficiency. They were used to calculate the values of the accounts payable turnover ratio and the number of days needed to cover the liabilities to suppliers as selected indicators. The accounts payable turnover ratio also shows how many times a year the company pays off its suppliers. Suppliers can be in the country and abroad. This ratio determines the period a company is "credited" by the supplier, i.e., how long it usually takes the company to cover the liabilities to suppliers after the material / goods have been procured. The following Eq. (1) was used to calculate the accounts payable turnover ratio:

$$APT = \frac{(Ix - Iy) + (Cm + Cp)}{\left[\dfrac{(Lsx + Lasx) - (Lsy + Lasy)}{2}\right]} \quad (1)$$

Where:
APT – accounts payable turnover ratio; *I*x – inventories at the end of the year; *I*y – inventories at the beginning of the year; *C*m – material procurement costs; *C*p – production services costs; *L*sx-liabilities to suppliers in the country at the end of the year; *L*asx – liabilities to suppliers abroad at the end of the year; *L*sy – liabilities to suppliers in the country at the beginning of the year; *L*asy – liabilities to suppliers abroad at the beginning of the year

The following formula was used to calculate the number of days needed to cover the liabilities to suppliers:

Number of days needed to cover the liabilities to suppliers = 365 / *APT*

Where: *APT* – accounts payable turnover ratio.

The collected data that relate to inventories, material costs, production services costs and company's net profit were used to calculate the operational efficiency coefficient (*C*e) of companies engaged in the production of wooden chairs in Serbia.

The supply chain efficiency coefficient was calculated for each company individually and each year in the selected period using the DEA method (*Data Envelopment Analysis*). DEA is a linear programming technique for evaluating the efficiency of decision-making units (DMUs) under multiple inputs and outputs (Kropivšek *et al*., 2019). This method is based on mathematical and operational research methods. The Data Envelopment Analysis (DEA) is a nonparametric approach based on linear programming, which allows for the calculation of the efficiency of decision-making units within a group of organizations (Mimović and Krstić, 2016). Therefore, DEA is considered one of the most successful methods of operational research used in business analysis of economic entities (Popović and Martić, 2005).

According to Tekić *et al*. (2020) DEA (*Data Envelopment Analysis*) is used in efficiency analysis when data is available on several inputs and outputs for each of the *n* DMU (*Decision Making Units*). For each DMU, the maximum performance score is calculated relative to all other units in the observed sample that must meet the condition of being at or below an extreme limit called the efficiency limit (Savić, 2016).

The measure of efficiency provided by the DEA method is relative because it depends on the kind and number of DMUs included in the analysis, as well as the number and structure of inputs and outputs (Vukelić, 2014). In the output-oriented DEA model, which was used in the analysis presented in this paper, the analysis is aimed to determine the input and output weights at which a DMU unit has the highest relative efficiency and the weighted sum of inputs of the observed DMU unit is equal to one. The input and output units do not have to be uniform. They can include the number of working hours, the area of the workplace, the degree of utilisation of a resource, monetary values, etc.

This paper analysed the efficiency of 12 companies as DMUs out of 25 companies engaged in the production of wooden chairs. We analysed 12 instead of all 25 companies because some companies did not submit financial reports to the Agency for Business Registers of Serbia. These are companies that belong to the category of micro companies that are not obliged to have the double-entry bookkeeping system.

Indicators that characterise the supply chain in the production of selected companies to the greatest extent were chosen as input and output variables for the DEA method. These indicators included:

- three input variables: inventories (x_1), material costs (x_2) and production services costs (x_3),
- one output variable: company's net profit (y).

Before the DEA model was created, we had established the correlation between the selected variables by testing the statistical significance of their correlation coefficients.

We used the econometric modelling methods to project future net income values depending on the changes in selected independent variables. The obtained values of indicators were analysed and discussed using the methods of analysis, induction and synthesis.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The research results are presented through the obtained values of selected indicators by applying the methods and techniques described above with accompanying analyses and evaluations.

Before creating the DEA model, the statistical significance of the correlation between the selected variables (inputs and outputs) had been examined by calculating their correlation coefficients at the level of statistical significance $p<0.01$. The obtained results are shown in Table 1.

Based on the obtained values of correlation coefficients, it could be concluded that there was a high degree of correlation between the selected variables, and the DEA analysis was justified. The second step in conducting the analyses was to calculate the key indicators of descriptive statistics of selected variables. The obtained values of the variables are shown in Table 2.

The average value of inventories in selected companies in the study period was 5,773,131.7 RSD, material costs 112,765,231.5 RSD, and production services costs 18,179,465.7 RSD. The average net profit amounted to 23,980,933.3 RSD.

Most companies have the values of selected variables below the average, which can be observed by looking at the minimum values of the variables and high values of the coefficient of variation. High values of the coefficient of variation in all variables indicate that they are highly variable, i.e., there are substantial differences in the business of selected companies. The value of the coefficient of variation in the variable related to inventories is markedly high.

The results of the analysis of operational efficiency of companies engaged in the production of wooden chairs in Serbia using the DEA method are presented through the values of the efficiency coefficient (*Ce*) individually for each year of the study period (Table 3). The standard values of the efficiency coefficient range from 0 to 1. The values closer to 1 point to higher efficiency and vice versa. The software MaxDEA 8 Basic

Table 1 Correlation coefficients of selected variables and net profit
Tablica 1. Korelacijski koeficijenti promatranih varijabli i neto dobiti

	Inventories (x_1) *Zalihe (x_1)*	**Material costs (x_2)** *Materijalni troškovi (x_2)*	**Production services costs (x_3)** *Troškovi proizvodnih usluga (x_3)*	**Net profit (y)** *Neto dobit (y)*
Inventories (x_1) / *Zalihe (x_1)*	1.000***	0.433***	0.267***	0.283***
Material costs (x_2) / *Materijalni troškovi (x_2)*	0.433***	1.000***	0.933***	0.917***
Production services costs (x_3) *Troškovi proizvodnih usluga (x_3)*	0.267***	0.933***	1.000***	0.900***
Net profit (y) / *Neto dobit (y)*	0.283***	0.917***	0.900***	1.000***

***The correlation is significant at the level of 0.01. / ****Korelacija je značajna pri razini od 0,01.*

Table 2 Indicators of descriptive statistics for selected variables of enterprises engaged in the production of wooden chairs in Serbia in the study period
Tablica 2. Pokazatelji deskriptivne statistike za ispitivane varijable poduzeća za proizvodnju drvenih stolica u Srbiji u promatranom razdoblju

Indicator / *Pokazatelj*	**Inventories, RSD*** *Zalihe*, RSD*	**Material costs, RSD*** *Materijalni troškovi,* RSD*	**Production services costs, RSD*** *Troškovi proizvodnih usluga,* RSD*	**Net profit, RSD*** *Neto dobit,* RSD*
Average / *srednja vrijednost*	5,773,131.7	112,765,231.5	18,179,465.7	23,980,933.3
Minimum / *minimum*	50,000.0	37,000.0	92,000.0	12,000.0
Maximum / *maksimum*	122,457,000.0	758,295,000.0	85,687,000.0	216,075,000.0
Coefficient of variation *koeficijent varijacije*	114.73	52.81	52.63	67.61

*The Serbian dinar/ *srpski dinar*

Table 3 Coefficient of operational efficiency of companies for the production of wooden chairs in Serbia in 2011-2019 (Authors' calculations based on the data from the balance sheets and income statements of selected companies)
Tablica 3. Koeficijent učinkovitosti poduzeća za proizvodnju drvenih stolica u Srbiji za razdoblje 2011. – 2019. (izračuni su utemeljeni na podatcima iz bilance i računa dobiti i gubitka odabranih tvrtki)

Enterprise / *Poduzeće*	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**Average** *Srednja vrijednost* **2011-2019**
E1	0.15	0.08	0.16	0.00	0.00	0.00	0.00	0.24	0.06	0.08
E2	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.02	0.05
E3	0.79	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.31
Average micro enterprises *srednja vrijednost za mikropoduzeće*	0.35	0.36	0.06	0.00	0.00	0.00	0.33	0.18	0.03	0.14
E4	0.00	0.00	0.00	0.00	0.00	0.11	0.01	0.00	0.09	0.02
E5	0.72	1.00	0.99	0.00	1.00	1.00	0.09	1.00	0.96	0.75
E6	0.23	0.10	0.02	0.24	0.50	0.30	0.01	0.02	0.03	0.16
E7	0.59	0.71	1.00	0.00	0.00	0.74	0.06	0.40	0.22	0.41
E8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.34	0.08
E9	0.02	0.05	0.23	0.26	0.39	0.40	0.18	1.00	0.90	0.38
E10	0.46	0.63	0.51	0.00	0.50	0.59	0.07	0.00	0.03	0.31
Average small enterprises *srednja vrijednost za malo poduzeće*	0.29	0.36	0.39	0.07	0.34	0.45	0.06	0.40	0.37	0.30
E11 (medium enterprise *srednje poduzeće*)	0.85	0.76	1.00	1.00	0.78	0.79	0.25	1.00	1.00	0.83
E12 (large enterprise *veliko poduzeće*)	0.50	0.77	0.99	0.99	1.00	0.73	0.08	0.00	1.00	0.67

was used to analyse the efficiency of companies. The analysis of the company efficiency in the study period is structured by company categories because, in that way, the changes in the operational efficiency and the impact of the supply chain (supplier) on the net profit can be best seen.

The obtained values of the efficiency coefficient were analysed separately for each enterprise category. When it comes to micro enterprises, it can be concluded that their business operation was very variable in the study period. This conclusion applies even to those companies that had the maximum value of the efficiency coefficient in certain years, while in the following years, their efficiency was equal to zero because they were operating at a loss. Most companies in the micro category had serious business problems in most years of the study period because they were operating at a loss (efficiency equal to zero). The situation was a little better from 2017 to 2019 when two companies from this category made a profit. However, the profit accounted for a small percentage of the total revenue due to extremely high costs, primarily material and production services costs, in the total expenditures.

Due to the above, the average efficiency coefficient of micro enterprises in the study period was only 0.14. It was 2.1 times smaller than the average efficiency coefficient of small enterprises and 5.9 than the medium enterprise. Such a low coefficient of efficiency of micro enterprises revealed that these enterprises were still far from satisfactory and very far from maximum efficiency.

The key recommendation for micro enterprises derived from the obtained DEA analysis is that they must significantly improve the efficiency of procurement and consumption of materials and reduce production services costs in the total operating costs. However, an important characteristic of these companies, which is also a positive aspect of their business, is the small share of inventories. This is somewhat logical having in mind that micro-companies procure the necessary raw materials in small quantities, usually as needed for each contracted job. The reason for this approach is the lack of working capital since most of these companies procure materials with the money customers pay in advance after they have made an order. In such a situation, the prices at which materials are procured in small quantities are significantly higher than the prices when materials are purchased in bulk.

The companies categorized as small enterprises had slightly better business results than the companies in the category of micro enterprises as their average efficiency coefficients ranged from 0.02 to 0.75. The total average efficiency coefficient for this group of companies was 0.30 for the study period. Out of seven companies in this category, one company had a satisfactory level of efficiency coefficient that amounted to 0.75. All other companies had an average efficiency coefficient below 0.5, which shows that the average efficiency coefficient in this category was still far from a satisfactory level. The analysis results show that material costs were the main cause of low efficiency in most small enterprises. The efficiency was less affected by the production services costs, while most small enterprises had inventories significantly above optimum values. High material costs indicate a low degree of their utilisation, on the one hand, and high prices at which they were procured on the other hand.

Observed by years, the average value of the efficiency coefficient shows that 2017 was the most difficult year for the companies in this category because their average efficiency coefficient was as small as 0.01. The highest value of the efficiency coefficient in that year was only 0.18 for one company in this category. In all other years, the average efficiency coefficient was relatively stable and ranged from 0.37 (2019) to 0.45 (2016). As with companies in the category of micro enterprises, the basic conclusion that can be drawn from the results obtained is that small enterprises also have room to increase the efficiency of the supply chain, especially in the segment of reducing material costs.

The situation was significantly better in the only medium enterprise engaged in the production of wooden chairs in terms of efficiency compared to micro and small enterprises. In the study period, its efficiency ranged from 0.25 (2017) to 1.00. The average efficiency coefficient in this category of companies was 1.00 in as many as four out of nine years of the study period. Consequently, its average efficiency coefficient was 0.83, representing the highest average efficiency for all observed categories of companies. This result indicates that this company had significantly lower values of inventories, as well as material and production services costs compared to micro and small companies. One of the reasons is that this company had a larger production volume, which enabled the procurement of a larger amount of required material at more reasonable prices. Considering that this medium enterprise used, in most cases, beechwood for the production of its products, there was no need to form large stocks because this type of wood is available in the domestic market at any time. However, although the average efficiency of 0.83 is the best for all categories of companies, there is still room to reduce costs in order to increase its efficiency and thus raise the profit as the ultimate goal of every company.

With regard to the only large company that manufactures wooden chairs in Serbia, 2017 and 2018 were very difficult years. In 2017, its efficiency coefficient was 0.04, and in 2018, this company operated at a loss.

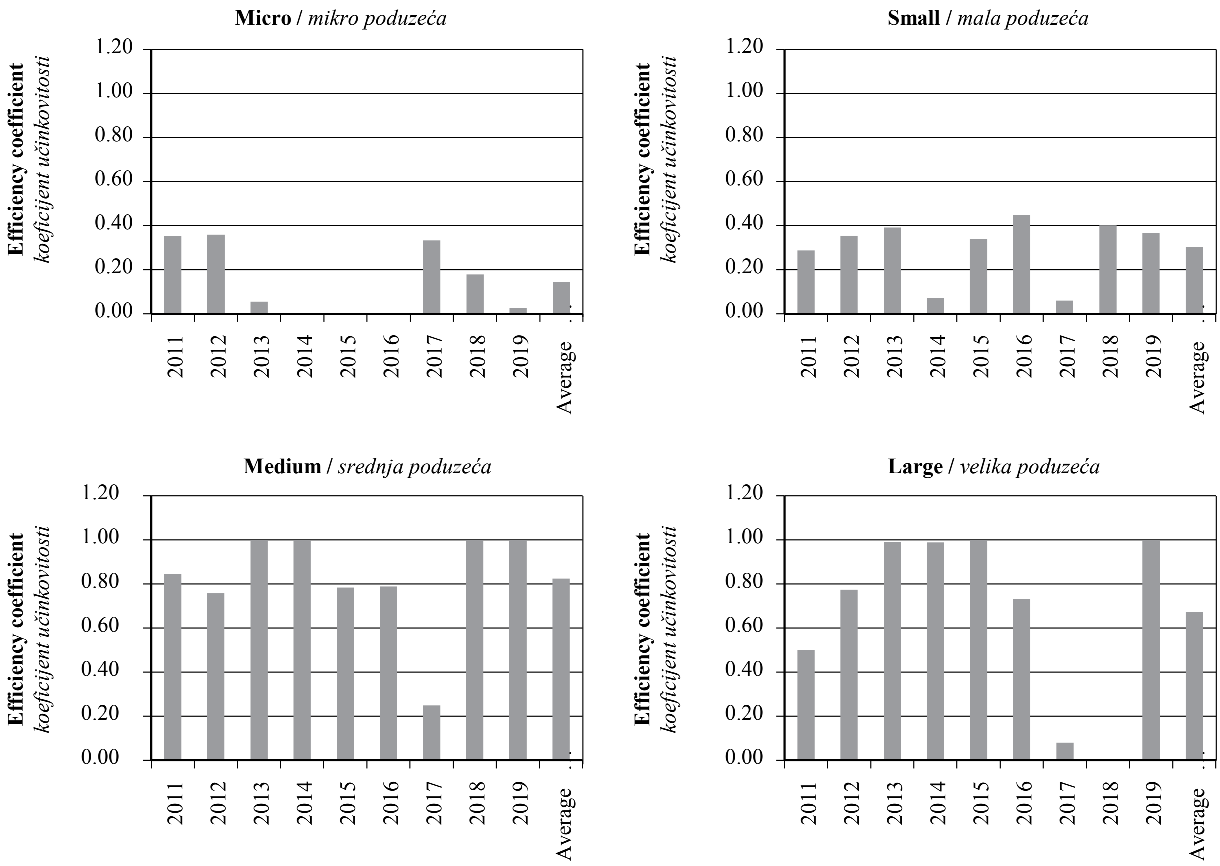

Figure 1 Average values of efficiency coefficient of certain categories of wooden chair manufacturing companies in Serbia from 2011 to 2019
Slika 1. Srednje vrijednosti koeficijenta učinkovitosti pojedinih kategorija poduzeća za proizvodnju drvenih stolica u Srbiji za razdoblje 2011. – 2019.

Table 4 Average values of output and input variables based on the results of the DEA method in the study period (Author's calculations based on data from the balance sheets and results of the DEA method)
Tablica 4. Srednje vrijednosti izlaznih i ulaznih varijabli prema rezultatima DEA metode u promatranom razdoblju (izračuni su utemeljeni na podatcima iz bilance i rezultata DEA metode)

	Average values / *Srednje vrijednosti*			
	Inventories *Zalihe* (1,000 RSD)	**Material costs** *Materijalni troškovi* (1,000 RSD)	**Production services costs** *Troškovi proizvodnih usluga* (1,000 RSD)	**Net profit** *Neto dobit* (1,000 RSD)
Moderately efficient companies (efficiency coefficient 0.3- 0.7) *Srednje učinkovite tvrtke (koeficijent efikasnosti 0,3 – 0,7)*	10,099.1	184,945.1	27,550.9	41,609.2
Efficient companies (efficiency coefficient 0.7-1) *Učinkovite tvrtke (koeficijent efikasnosti 0,7 – 1)*	1,794.0	65,139.1	15,519.7	25,850.8

Thanks to the good results achieved in 2013, 2014, 2015 and 2019, when its efficiency coefficient was as high as 0.99 and 1.00, the average efficiency coefficient for the observed period of nine years was 0.67. This company had 4.7 times higher efficiency than micro and 2.2 times higher efficiency than small enterprises, but also 1.2 times lower average efficiency than the medium enterprise. The analysis of the efficiency coefficient of this company also indicates that the company increased costs of inventories, as well as material and production services costs. Since this company produces oakwood seating furniture, whose domestic supplies are insufficient, the company was forced to import raw materials. Therefore, there was a need for larger stocks of raw and other materials that are in short supply on the domestic market. Figure 1 shows the average values of the efficiency coefficient by individual categories of enterprises in the study period.

Table 4 provides an overview of the average values of the selected input and output variables for the companies that, according to the results of the DEA method, had a medium efficient and efficient business operation.

It made no sense to make comparisons with the companies that according to the DEA method operated inefficiently, since they had very high average values of the analysed parameters. Companies that according to the DEA method operated efficiently had an average of 5.6 times lower value of inventories, 2.8 times lower value of material costs, and almost 1.8 times lower value of production services costs compared to companies that were determined to operate in the category of medium-efficient companies. On the other hand, the company that operated efficiently had 1.6 times lower net profit compared to the average net profit of the company in the category of medium efficiency.

The general conclusion that can be drawn based on the efficiency coefficients of wooden chair manufacturing companies in Serbia is that only one company had a relatively satisfactory operational efficiency (efficiency coefficient of 0.83), as observed collectively for the nine-year period. All other enterprises, especially in the category of micro and small enterprises, had unsatisfactorily low operational efficiency. In order to increase the efficiency of companies that operated inefficiently, it is necessary to enhance the management of inventories, material costs and production services costs, which points to the need to establish more efficient channels in the supply chains of required materials.

How much it is necessary to increase the efficiency of the supply chain in order to achieve a satisfactory level of operational efficiency is one of the major issues for the management of every company. Regarding the selected companies, the answer to that question is presented below using the results obtained by the DEA method.

The greatest possibility and need to reduce costs is in the category of material costs in all categories of companies, given that these costs are the highest. For instance, according to the DEA results, micro enterprises can reduce material costs by 80.7 % or as much as 99.6 % in some enterprises. This confirms the conclusion that reduced material costs in this category of companies are a crucial factor in increasing their efficiency. It should be noted that a reduction in any category of costs in practice can hardly reach the values obtained by the DEA method. However, every company should strive to get as close as possible to the obtained values. It is these values that represent the target and reference point for the management of the companies to strive for in their future business.

The largest fluctuations in the material costs in the study period were recorded in the category of small enterprises. The results of the DEA method show that material costs in small enterprises should be 73.4 % lower on average in order to obtain a satisfactory coefficient of efficiency. This fact points to the irrational use of materials and thus the high inefficiency of supply chains of most companies in this category. One of the elements that can be enhanced is the utilisation of materials, another being the price at which materials are procured. The material purchase price depends on the market. In the medium and large enterprise, the efficiency exceeds the value of 0.9 and affects the costs that correspond to their production volume.

The production services costs in micro enterprises were higher by an average of 91.1 % and in small enterprises by 72.4 %. As in the category of material costs, there are some possibilities for reducing the production services costs in the medium and large company.

Regarding the value of inventories as the third variable in the observed model, the medium and large enterprise need significantly higher stocks that entail high inventory costs. The results of the DEA analysis show that there is still some room for reducing inventory costs in these two categories of companies. However, the instability of the domestic market in terms of the supply of basic materials forces these companies to keep stocks in order to ensure continuity of production. One of the solutions to this problem could be to stimulate domestic sawn timber producers to be included in the supply chain of domestic companies engaged in the production of final wood products (Glavonjić, 2018). Until the market stabilises in this respect, companies will be forced to build up stocks and have an unsatisfactory level of supply chain efficiency. The cost of inventories in the category of small enterprises was also extremely high. The results of the DEA method show that the same profit could be realised even if the costs of inventories were lower by an average of 68.4 %.

As can be concluded from the results obtained, the values of all three input variables are significantly higher than they really should be for the realised value of net profit as the output variable. This finding confirms the previously stated assessment of the inefficiency of the supply chain in most of the companies engaged in the production of wooden chairs in Serbia. This assessment was further confirmed by analysing the value of two additional indicators: the accounts payable turnover ratio (*APT*) and the number of days needed to cover the liabilities to suppliers for selected companies in the study period.

Companies engaged in the production of wooden chairs in Serbia usually procure raw and other materials from several suppliers to whom they have to cover liabilities within a certain period of time. The analysis of data for selected companies in the nine-year study period shows that the average annual accounts payable turnover ratio amounted to 5.4 for micro enterprises and 15.4 for small enterprises. It means that micro enterprises, on average, covered their liabilities less than six times a year and small enterprises a little less than 15 times, i.e., more than once a month. Although this is not so bad for small enterprises, they should strive for better results and higher turnover ratios. Regarding the medium and large company, the accounts payable turnover ratios were 16.4 and 27.8, respectively. Compared to micro and small enterprises, these results are significantly better.

Looking at the number of days companies need to cover liabilities to suppliers, it can be concluded that micro and small enterprises have very high values of this indicator. In other words, many days pass from the moment they take over the goods from the supplier to the moment when they settle their obligations to them. In micro enterprises, the average value of this indicator exceeds 100 days. It is 60 days on average for small enterprises and 27 and 20 days for medium and large enterprises. The situation was somewhat better with the medium and large company, but they also found it difficult to cover liabilities to the suppliers who sell their goods with maturity below 20 days or advance payment.

Based on the above analysis, the question arises as to what impact the selected independent variables could have on the value of the output variable (net profit). It can be answered by creating a model for each category of selected companies. Having in mind the goals of this study and the limitation in terms of its size, the results of the multifactor econometric model for all selected companies are collectively presented below.

The forecast of the future net profit based on changes in selected independent variables was made using the multiple regression Eq. (1) that included average values of independent variables. The multifactor regression model of average values of inventories, material costs, production services costs and net profit is represented by the following linear logarithmic Eq. (2):

$$\ln y = -4.927 - 0.026 \cdot \ln x_1 + 1.961 \cdot \ln x_2 - 0.840 \cdot \ln x_3$$

or in the transformed form:

$$y = 0.00724 \cdot x_1^{-0.026} \cdot x_2^{1.961} \cdot x_3^{-0.840} \quad (2)$$

The basic statistical parameters of this regression model are presented in Table 5.

The high correlation coefficient (*R*) and its significance, as well as the fact that 92 % of the variation of the dependent variable (y) is explained by changes in the factors entered into the model, clearly show a very large influence of selected factors on net profit. The parameter (x_1) related to inventories shows that a 1 % decrease in the value of inventories can be expected to increase net profit by 0.026 %. As for the parameter (x_2) related to material costs, a 1 % increase in material costs can increase the net profit by 1.9 %. It is understandable, bearing in mind that an increase in the production volume entails an increase in material costs. The parameter (x_3) related to production services costs shows that a 1 % decrease in production services costs is expected to increase net profit by 0.84 %.

Table 5 Model parameters
Tablica 5. Parametri modela

Variables *Varijable*	y **Net profit** *Neto dobit*	x_1 **Inventories** *Zalihe*	x_2 **Material costs** *Materijalni troškovi*	x_3 **Production services costs** *Troškovi proizvodnih usluga*	
Statistical characteristic / *Statistička obilježja modela*					
R	R^2	R^2 cor	F(3,6)	F test $_{(0.05)}$	Sq
0.92	0.85	0.87	11.477	+	0.326

* R – correlation coefficient / *koeficijent korelacije*; R^2 – coefficient of determination / *koeficijent determinacije*; *Sq* – standard error / *standardna pogreška*; *F* – *F*-statistics / *F-statistika*

Based on the results obtained by applying the multiple regression equation, growth can be expected at an average annual rate of 8.02 % for all selected groups of companies in the period 2020-2025. The relatively high value of the growth rate is largely the result of the expected production growth in the categories of medium and large enterprises.

4 CONCLUSIONS
4. ZAKLJUČAK

The results of the analyses of operational efficiency of wooden chair manufacturing companies in Serbia show that in the selected companies in the study period the average value of inventories was 5,773,131.7 RSD, material costs 112,765,231.5 RSD, production services costs 18,179,465.7 RSD and the average net profit amounted to 23,980,933.3 RSD. According to input and output parameters, all analysed companies had significantly higher values of inventories, material costs and production services costs, which reflected the low average efficiency of companies. Observed by categories, the efficiency coefficients of companies by individual categories were as follows: micro 0.14, small 0.30, medium 0.83 and large 0.67. The obtained results of the DEA analysis show that only companies from the category of medium and large companies operated with relatively satisfactory efficiency. The analysed companies that operated efficiently in the study period had an average of 5.6 times lower value of inventories, 2.8 times lower value of material costs and almost 1.8 times lower value of production services costs than the companies that operated in the category of medium-efficient enterprises. Consequently, it can be concluded that medium-efficient companies must significantly reduce operating costs to achieve higher profits and to move from the category of medium-efficient to efficient companies. The same applies to inefficient companies. In order to survive in the market at all, they must significantly reduce operating costs. The above finding was additionally confirmed by analysing two additional indicators: the accounts payable turnover ratio (*APT*) and the number of days needed to cover liabilities to suppliers. The turnover ratio in the study period amounted to 5.4 for micro and 15.4 for small enterprises, while it was 16.4 for the medium and 27.8 for the large enterprise. Regarding the number of days needed to cover liabilities to suppliers, it can be concluded that micro and small enterprises found it very difficult to pay off suppliers on time. The situation was somewhat better with the medium and large company, but it varied significantly from year to year. Based on the obtained results of the multifactor regression analysis, it can be concluded that a 1 % reduction in input variables would significantly increase the net profit of companies. According to the model obtained, if the average values of input variables (inventories and costs) were reduced by only 1 %, the average annual rate of expected net profit growth of selected companies could be 8.02 % from 2020 to 2025.

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Effect of Acetylation and Accelerated Weathering of Nigerian Grown Rubberwood (*Hevea brasiliensis*, Müll. Arg.) on Equilibrium Moisture Content and Colour Change

Utjecaj acetilacije i ubrzanog izlaganja vremenskim utjecajima na ravnotežni sadržaj vode i promjenu boje drva kaučukovca uzgojenoga u Nigeriji (*Hevea brasiliensis*, Müll. Arg.)

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ABSTRACT • *This study was conducted to investigate the effect of acetylation on equilibrium moisture content (EMC) of Nigerian-grown rubberwood and its effect on colour change in exposure of rubberwood to surface degradation through accelerated weathering. The samples were modified to two levels of acetylation, which yielded weight percent gain (WPG) of 7 % and 10 % after 8hr (8-hr Acetyl) and 48hr of acetylation (48-hr Acetyl), respectively. Accelerated weathering of unmodified (Ref) and acetylated wood was done using QUV-Accelerated Weathering Tester for four weeks. The unmodified and acetylated samples (weathered and unweathered) were oven-dried and conditioned in climate rooms at different relative humidity of 50 %, 65 % and 95 %, with samples being moved to each room after 14 days. Results showed that acetylation led to a significant decrease in equilibrium moisture content of rubberwood. After weathering, there was a decrease in EMC of rubberwood due to removal of hemicelluloses alongside the degraded lignin, and a slight increase in EMC of the acetylated wood. In terms of colour change, photo-bleaching of the acetylated samples was higher (10.46 for 48-hr Acetyl) after four weeks of weathering compared to the unmodified samples (6.43). Hence, the outcome of this study has shown that, although acetylation is effective in minimizing moisture ingress into wood, it resulted in photo-bleaching of the weathered samples. Additional surface coating is recommended to serve as a protective layer, preventing partial washing out of the acetyl groups, minimize photo-bleaching during weathering and prolong the aesthetic value of the wood especially in outdoor applications such as wall cladding and façade.*

KEYWORDS: *rubberwood; equilibrium moisture content; moisture ratio; acetylation; accelerated weathering*

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SAŽETAK • *Ova je studija provedena kako bi se istražio utjecaj acetilacije na ravnotežni sadržaj vode (EMC) i na promjenu boje drva kaučukovca zbog površinske razgradnje prouzročene ubrzanim izlaganjem vremenskim utjecajima. Drvo je uzgojeno u Nigeriji, a uzorci su modificirani acetilacijom u dva stupnja, što je nakon osam sati (8-hr Acetyl) odnosno 48 sati acetilacije (48-hr Acetyl) rezultiralo povećanjem mase (WPG) od 7 i 10 %. Ubrzano izlaganje nemodificiranoga (Ref) i acetiliranog drva vremenskim utjecajima provedeno je u QUV uređaju tijekom četiri tjedna. Nemodificirani i acetilirani uzorci (izlagani i neizlagani) sušeni su u sušioniku i kondicionirani u klimatskim prostorijama pri različitim relativnim vlažnostima zraka, od 50, 65 i 95 %, a uzorci su nakon 14 dana premještani u svaku od prostorija. Rezultati su pokazali da je acetilacija dovela do znatnog smanjenja ravnotežnog sadržaja vode u drvu kaučukovca. Nakon izlaganja vremenskim utjecajima EMC drva kaučukovca smanjio se zbog nestajanja hemiceluloze uz razgradnju lignina, a EMC acetiliranog drva blago se povećao. Kad je riječ o promjeni boje, izbjeljivanje je nakon četiri tjedna izlaganja vremenskim utjecajima bilo veće na acetiliranim uzorcima (10,46 za 48-hr Acetyl) nego na nemodificiranima (6,43). Stoga je ovo istraživanje pokazalo da je acetilacija, iako je učinkovita glede smanjenja prodora vlage u drvo, rezultirala izbjeljivanjem uzoraka ubrzano izloženih vremenskim utjecajima. Stoga se preporučuje primjena površinskog premaza koji će služiti kao zaštitni sloj, sprječavati djelomično ispiranje acetilnih grupa, smanjiti izbjeljivanje tijekom izlaganja drva vremenskim utjecajima i dulje očuvati njegovu estetsku vrijednost, posebice u vanjskim uvjetima, primjerice kad je drvo kaučukovca upotrijebljeno kao zidna obloga ili fasada.*

KLJUČNE RIJEČI: *drvo kaučukovca; ravnotežni sadržaj vode; omjer ravnotežnog sadržaja vode; acetilacija; ubrzano izlaganje vremenskim utjecajima*

1 INTRODUCTION
1. UVOD

Hevea brasiliensis (rubberwood), though previously known as an agricultural product, is fast becoming an acceptable raw material for lightweight constructions and in the furniture industry (de Junior *et al*., 2015). Although the major aim of establishing rubber tree plantations is for the production of latex, a raw material in the rubber and tyre industries, wood from rubber trees is also an acceptable source of sawn-timber production. After the period of latex production (usually around 25-30 years), rubber tree plantations become unprofitable for the original purpose. At this point, the trees are previously converted to fuelwood or cleared to start a new plantation. Teoh *et al*. (2012) noted that nowadays, with increasing knowledge about the potentials of rubberwood, the trees are harvested and converted to sawn-timber for various purposes such as construction, furniture production and manufacture of wood-based panel products. In countries such as Malaysia, Indonesia, and Thailand, production of rubberwood has formed a major drive in the success of their wood industries, and this has made a great impact on their economy for several decades (Shigematsu *et al*., 2011, Shigematsu *et al*., 2013). However, in Nigeria, the economic and environmental potential of rubberwood is yet to be explored to its maximum capacity. This is due to the dependence on wood supply from the natural forest, whose resource has been overexplored and many durable species are currently becoming or are already endangered.

Rubberwood is a lightweight material with uniform colour that varies from white to pale cream at harvest, but afterwards may change to light straw or light brown. The sapwood is not distinguished from the heartwood, and its texture is homogeneous but varies from moderately coarse to coarse texture (Killmann and Hong, 2000; Lim *et al*., 2002). The major positive attributes of rubberwood include its ease of sawing, slicing into veneer and turning on lathe machines. On the other hand, rubberwood has quite a number of shortcomings related to its proneness to seasoning defects such as twisting, cupping, bowing and checks; and its non-durability, which makes it susceptible to insects and fungi attacks (Balsiger *et al*., 2000) and surface degradation due to weathering (Olaniran *et al*., 2019) when used outdoor. For this reason, rubberwood requires treatments that can minimize its interaction with moisture, thereby making it hydrophobic, and subsequently influence biotic and abiotic agents and enhance its service life. One of the treatments that have been successfully used in improving the hydrophobic properties of wood for decades is the acetylation process. Previous studies have shown that acetylation enhances the hydrophobic properties and improves the durability of several wood species to biological deterioration and weathering (Larsson-Brelid *et al*., 2000; Chang and Chang, 2001; Mohebby and Militz, 2010).

Acetylation process involves the reaction of acetic anhydride with wood polymers through esterification reactions, where the accessible hydroxyl groups in the wood cell wall undergo a single addition reaction with acetyl groups (Rowell, 1983). This single addition process, where an acetyl group reacts with a hydroxyl group without polymerization (Rowell, 2014), leading to a wood material with higher hydrophobic property and dimensional stability, was compared to the unmodified wood (Gerardin, 2016; Sandberg *et al*., 2017). Aside from its effect on dimensional stability, acetylation of wood has been reported to lower the photodegradation and weathering of wood. In studies by Pandey and Pitman (2002), and Pu and Ragauskas (2005), acetylation was found to improve the weathering performance of wood. This improvement was made possible by the stabilization of lignin, and reduction of coloured chromophore formation and consequently a reduction in photo-yellowing of wood.

To make rubberwood suitable for outdoor applications such as cladding and facades, its susceptibility to surface degradation due exposure of wood to ultraviolet rays, degradation of lignin on rubberwood surface and subsequent washing away of the degraded lignin from the wood surface by water in form of rain or snow can be minimized by acetylation as previously demonstrated for other species in previous studies. Hence, the purpose of this study is to investigate the role that acetylation method of wood modification can play in minimizing the surface degradation of rubberwood essentially through reduction in equilibrium moisture content of rubberwood. This may further help to prevent the attack of rubberwood by fungi, as the moisture content of the treated wood will become too low to support their growth on the wood surface.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The rubber tree used for this study was harvested from a private plantation at Legbogbo village, Ode-Irele Ondo State Nigeria with the following coordinates: Lat. 06.59308°N, Long. 004.89078°E. At the time this study was carried out, the trees in the plantation were well over 30 years old. They yielded no more latex, leading to the abandonment of the plantation. A tree stand was harvested from the plantation at 0.5 m above the buttress, and two boles were selected at diameter at breast height (dbh). The harvested boles were processed into planks of dimension 550 mm × 120 mm × 40 mm, pre-dried in a kiln at 105 °C for three days to lower their moisture content and prepare them for shipping to the laboratory located at Wood Material Science Laboratories at ETH Zurich, Switzerland. On arrival, the wood samples were stacked in the climate room at 65 % relative humidity for a total of 6 months before the commencement of the experiment.

Rubberwood samples were further processed into dimensions of 50 mm × 15 mm × 1mm (L-T-R) to produce 180 samples required for the experiment. Thereafter, the samples were grouped into three groups including the unmodified samples (Ref), samples for 8-hr acetylation (8-hr Acetyl) and samples for 48-hr acetylation (48-hr Acetyl). Each of the three groups were further divided into four groups consisting of 15 samples each for the unweathered samples and samples subjected to accelerated weathering for two, three and four weeks.

The process for chemical modification started with drying of the wood samples at 65 °C for 48 hours. Drying at this low temperature was carried out to prevent rapid drying of the samples and occurrence of drying defects such as cracks on the samples. The dried samples were placed in a flask containing dimethylformamide (DMF) and acetic anhydride (50 v/v%). To enhance homogeneous penetration of the reaction chemicals, a vacuum impregnation was performed for 18 hours, and the mixture was heated to a temperature of 70 °C under reflux; the reaction was maintained for 8 hours and 48 hours. After treatment, the acetylated samples were washed in acetone for five days, with the solution being changed twice a day to remove the excess acetic acid. The treated samples were dried at 65 °C for 48 hours and the weight percent gain was determined. The average weight percent gain for the treated samples was 7 % for samples acetylated for 8 hours and 10 % for samples acetylated for 48 hours.

The treated and reference samples were weathered under accelerated conditions with QUV Accelerated Weathering Tester (Q-Lab Miami, USA), equipped with heating compartments, UV-A 340 lamps and water spray. The procedure for weathering followed a single test cycle of 2hr 30 minutes of UV exposure, 30 minutes of water spray, and a panel temperature of 30 °C. Before and after weathering, colour measurements were performed with Chroma Meter (CR-200), Minolta USA. Colour change in the weathered samples was determined according to CIE standard colour space $L^*a^*b^*$, and the total colour change was calculated according to Eq. 1:

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

Where: L is the lightness in the range of 0 – 100; $+a^*$ and $+b^*$ are the chromatic indices representing red and yellow, respectively, $-a^*$ and $-b^*$ represent green and blue direction, respectively.

The equilibrium moisture content of the weathered and unweathered samples was reached in climate rooms at 50 %, 65 % and 95 % RH after oven-drying the samples to a constant weight at 65 °C for 48 hours. The increase in weight due to moisture sorption in the climate rooms was measured consistently until the samples attained constant weights. After this, the wood samples were moved from one climate room to another after 14 days, and the equilibrium moisture content in each climate room was determined. The moisture ratio of acetylated wood (MR_A) was calculated as a ratio of the equilibrium moisture content of the acetylated rubberwood and the unmodified samples (Thygesen *et al*., 2010). This will help to reveal the percentage of moisture in the unmodified to that in the modified wood, thus revealing the effectiveness of the modifying agent. The data obtained were analysed using the SPSS Software, V20.0 (IBM Corporations, USA) to perform the analysis of variance (ANOVA) and determine the significant differences among the treatments.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Influence of acetylation on equilibrium moisture content of rubberwood in unweathered state
3.1. Utjecaj acetilacije na ravnotežni sadržaj vode neizloženog drva kaučukovca

The equilibrium moisture content of unmodified and acetylated rubberwood is shown in Figure 1. In the unmodified and unweathered state, the moisture content of rubberwood is 5.3 %, 10.2 % and 17.5 % at the relative humidity of 50 %, 65 % and 95 %, respectively. Subsequently, after 8-hour acetylation (8hr-Acetyl/W0), the moisture content of rubberwood decreased to 2.73 %, 5.39 % and 8.74 %. After 48-hour acetylation (48hr-Acetyl/W0), the moisture content of acetylated rubberwood further decreased to 2.49 %, 5.03 % and 8.35 % at the observed relative humidity (Figure 1b and c). The effect of the level of acetylation and varying level of exposure to relative humidity is significant on the equilibrium moisture content of acetylated rubberwood (Table 1). The goal of the acetylation method is to reduce moisture uptake, thereby improving the dimensional stability and enhancing wood durability (Thygesen *et al*., 2010), and to decay fungi and non-biological agencts such as the ultra-violet rays and weathering. According to Rowell (2014), through covalent bond formation, acetyl groups are substituted with hydroxyl groups on the sorption sites in the cell wall; this directly blocks the hydroxyl groups from gaining access to moisture. For the modification of rubberwood, acetylation has proved to be effective in reducing the moisture content of rubberwood even at low weight percent gain after treatment. Comparison of moisture ratio (MR_A) of acetylated rubberwood at two levels of *WPG* showed that the effect on moisture ratio was not significantly different (Table 2). This means that the difference in the *WPG* of acetylated rubberwood does not significantly influence the moisture ratio (0.53 for 8hr-Acetyl, and 0.5 for 48hr-Acetyl). This MR_A is lower (as shown in Table 3) compared to the previous report on acetylation of Corsican pine reported by Papadopoulos and Hill (2003) with *MR* in the range of 0.58-0.60, and even at a higher *WPG* of 15.58 as later reported in the work of Thygesen *et al*., (2010). Moisture ratio was also estimated by Thygesen *et al*. (2010) for furfurylated Norway spruce and found that the moisture ratio of furfurylated wood was 0.80, showing that the modified wood can hold as much water as the untreated wood. This indicated that, although a higher *WPG* can be obtained by furfurylation than by acetylation, the latter is more effective in minimizing moisture

Table 1 Analysis of variance for equilibrium moisture content of acetylated rubberwood
Tablica 1. Analiza varijance ravnotežnog sadržaja vode acetiliranog drva kaučukovca

Equilibrium moisture content (*EMC*) / *Ravnotežni sadržaj vode (EMC)*					
Source of variation *Izvor varijacije*	**Sum of squares** *Zbroj kvadrata*	***df***	**Mean square** *Srednja vrijednost kvadrata*	***F*-crit.**	***p*-value** *p-vrijednost*
Acetylation level *stupanj acetilacije*	572.308	2	286.153	161.488	0.000*
Relative humidity *relativna vlažnost*	966.223	2	483.111	272.640	0.000*
Error / *greška*	150.618		1.772		
Total / *ukupno*	1689.146				

*significant at *p*-value ≤ 0.05 / *značajno pri p-vrijednosti ≤ 0,05*

Table 2 Analysis of variance for moisture ratio (MR_A) of acetylated rubberwood
Tablica 2. Analiza varijance omjera ravnotežnih sadržaja vode acetiliranoga i nemodificiranog drva kaučukovca

Moisture ratio (MR_A) / *Omjer ravnotežnih sadržaja vode* (MR_A)					
Source / *Izvor*	**Sum of squares** *Zbroj kvadrata*	***df***	**Mean square** *Srednja vrijednost kvadrata*	**F-value** *F-vrijednost*	**Significance** *Značajnost*
Acetylation level (AL) *stupanj acetilacije (AL)*	0.013	1	0.013	2.614	0.112 ns
Relative Humidity (RH) *relativna vlažnost (RH)*	0.008	2	0.004	0.835	0.440 ns
AL*RH	0.001	2	0.000	0.087	0.916 ns
Error / *greška*	0.267		0.005		
Total / *ukupno*	0.289				

ns – not significant at *p*-value >0.05 / *nije značajno pri p-vrijednosti > 0,05*

Table 3 Mean values of equilibrium moisture content (*EMC*) and moisture ratio (MR_A) of acetylated rubberwood
Tablica 3. Srednje vrijednosti ravnotežnog sadržaja vode (EMS) acetiliranog drva kaučukovca i omjera ravnotežnog sadržaja vode (MR_A) acetiliranoga i nemodificiranog drva kaučukovca

Acetylation level *Stupanj acetilacije*	**Relative humidity** *Relativna vlažnost*	***EMC*, %**	MR_A
Unmodified *Nemodificirano drvo*	50	5.08 ± 0.41	-
	65	10.03 ± 0.58	-
	95	17.25 ± 0.36	-
8hr-Acetyl (7 % *WPG*)	50	2.73 ± 0.38	0.54 ± 0.07
	65	5.36 ± 0.56	0.54 ± 0.07
	95	8.76 ± 0.47	0.51 ± 0.02
48hr-Acetyl (10 % *WPG*)	50	2.57 ± 0.49	0.51 ± 0.11
	65	4.95 ± 0.49	0.49 ± 0.06
	95	8.33 ± 0.31	0.49 ± 0.02

interaction with wood. Analysis of variance revealed that MR_A of acetylated rubberwood among those observed is also not significantly different, and this is consistent with previous studies.

The implication of this result is that sufficient bulking of the cell wall was achieved for acetylated wood by acetyl group despite the low *WPG*, and consequently a significant difference was observed in reduction in equilibrium moisture content of acetylated rubberwood compared to the unmodified samples.

3.2 Effect of weathering on equilibrium moisture content of unmodified and acetylated rubberwood
3.2. Utjecaj izlaganja vremenskim utjecajima na ravnotežni sadržaj vode nemodificiranoga i acetiliranog drva kaučukovca

Unmodified and modified wood used in outdoor application are subjected to weathering, which involves the exposure of wood to ultraviolet rays. The effect of UV on the wood surface leads to degradation of lignin, which is thereafter washed out with water either in form of rain or snow. In the present study, unmodified rubberwood weathered under accelerated conditions showed continuous decrease in moisture content as the weathering period progressed from two to four weeks (Figure 1a). The equilibrium moisture content of unmodified, weathered rubberwood at the observed relative humidity is 4.1 %, 7.6 % and 14 %, respectiely at the end of the four-week period of weathering. These moisture content values of unmodified, weathered rubberwood decreased from the initial moisture content of unmodified and unweathered rubberwood of 5.3 %, 10.3 % and 17.5 %. The decrease in *EMC* of the unmodified rubberwood after weathering can be attributed to washing out of the degraded lignin alongside hemicelluloses, which is closely associated with lignin in the cell wall. These findings were previously observed by Feist *et al*. (1991), who found out that the exposure of unmodified aspen to weathering for 700 hours led to the degradation of lignin and hemicelluloses, leaving the surface with the inaccessible and moisture resistant cellulose. The attraction of moisture to wood is enhanced by wood polymers (cellulose, hemicelluloses and lignin) due to their ability to form hydrogen bonds with water molecules. Of these wood polymers, hemicelluloses were reported to have the highest proportion of sorption sites. For rubberwood acetylated for 8-hours, moisture content of acetylated rubberwood gradually decreased to 2.9 %, 6.1 %, and 11.3 % at the observed relative humidity after four weeks of exposure to accelerated weathering. These values are higher, compared to rubberwood acetylated for 48 hours with moisture content values of 2.6 %, 5.6 % and 9.9 % at the observed relative humidity. These results indicate that the interaction between moisture and acetylated rubberwood decreased as the acetyl groups blocked the free hydroxyl groups, which should be available to aid weathering of rubberwood surface. However, there seems to be a slight increase in moisture content for weathered acetylated wood compared to the unweathered acetylated wood.

This was clearly observed in rubberwood acetylated for 8-hours, and slightly in samples acetylated for 48-hours, with a higher *WPG* when compared to the equilibrium moisture content of the unweathered samples. Increase in moisture content observed in weathered acetylated wood may occur because a part of the acetylated products is washed out with the UV-degraded lignin, which is closely related to hemicelluloses in the modified cell wall. Previous studies on Fourier Transform Infrared Spectroscopy (FT-IR) of weathered modified and unmodified rubberwood showed decreasing intensities at spectra bands of 1505 cm^{-1} and 1600 cm^{-1} (stretching vibration of aromatic C=C of lignin); and 1740 cm^{-1} corresponding to vibration of unconjugated C=O in xylan (Pandey and Pitman, 2002; Olaniran *et al*., 2019). It can be inferred from these studies that removal of lignin during weathering is often accompanied by a significant loss in hemicelluloses content in the unmodified wood and only slight in the modified samples.

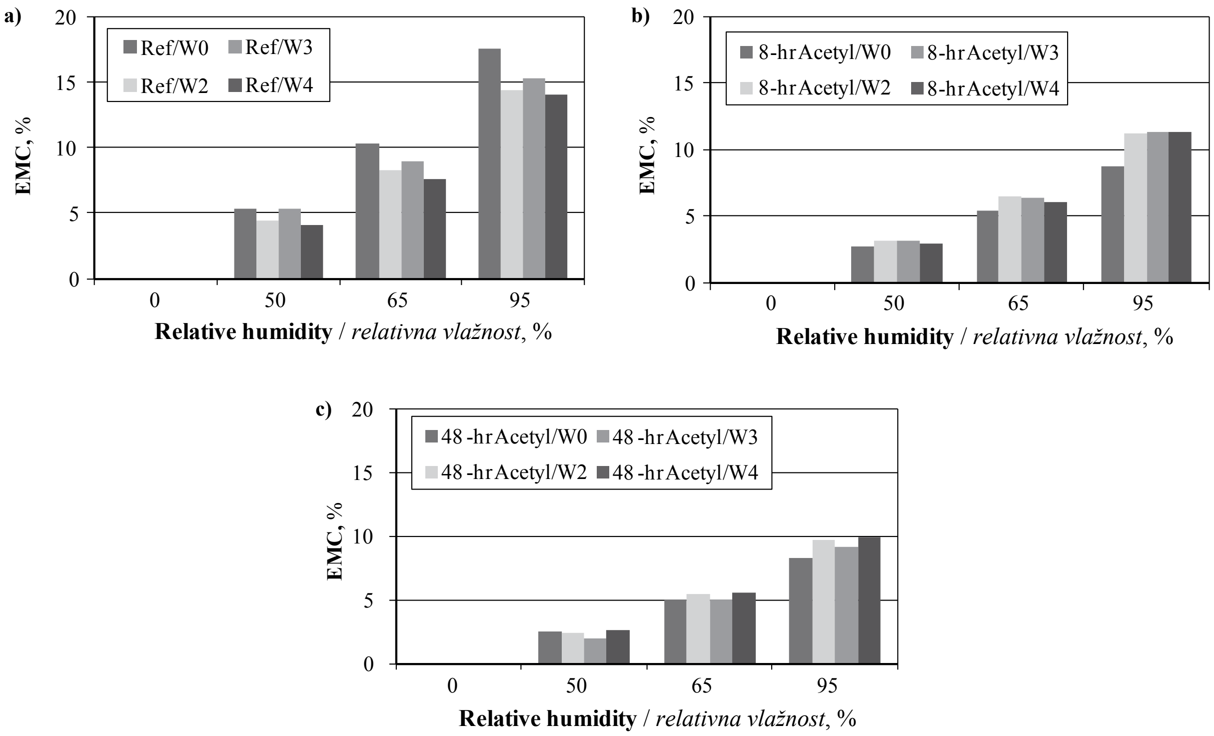

Figure 1 Equilibrium moisture content of (a) unmodified samples, (b) acetylated rubberwood at 8 hours of acetylation, (c) acetylated rubberwood at 48 hours of acetylation after exposure to accelerated weathering (W0 – samples not exposed to weathering, W2 – samples exposed for two weeks, W3 – samples exposed for three weeks, W4 – samples exposed for four weeks)
Slika 1. Ravnotežni sadržaj vode (a) nemodificiranih uzoraka, (b) acetiliranog drva kaučukovca pri 8-satnoj acetilaciji i (c) acetiliranog drva kaučukovca pri 48-satnoj acetilaciji nakon ubrzanog izlaganja vremenskim utjecajima (W0 – neizloženi uzorci, W2 – uzorci izloženi dva tjedna, W3 – uzorci izloženi tri tjedna, W4 – uzorci izloženi **četiri** tjedna)

3.3 Colour change in unmodified and acetylated rubberwood
3.3. Promjena boje nemodificiranoga i acetiliranog drva kaučukovca

Base on the above discussion, there are varying degrees of accessibility of moisture in unmodified wood and acetylated wood. Moisture in form of liquid water is a major factor that aids weathering of wood surfaces. The ultraviolet rays react with and break down the lignin polymer resulting in a colour change of wood surfaces. With the presence of water, the degraded lignin is washed out of the wood surface, leading to a total colour change. As shown in Figure 2 (a, b and c), the lightness index, L^* of the unmodified (Ref) and acetylated samples increased through the four-week exposure to weathering, whereas, acetylated samples recorded higher values of lightness compared to the unmodified samples (Figure 2d). The lightness index was found to decrease in all the exposed samples after the third week of exposure to weathering. Increase in lightness index was reported to be characteristic of acetylated wood in previous studies (Salla *et al.* 2012). Increase in lightness of the unmodified rubberwood observed in this study is contrary to the report of Salla *et al.* (2012), while persistent and higher lightness in acetylated wood is attributed to the photobleaching of the modified surface.

Contrary to the previous observation on the lightness index, no yellowing was found in the reference samples or in the acetylated samples as shown by negative values in Figure 2d. The negative values obtained for yellowing index further confirm that photobleaching occurred in the weathered samples including the reference, contrary to the outcome of previous studies where increased yellowing was observed in the weathered samples all throughout the period of exposure to weathering (Salla *et al.*, 2012; Guo *et al.*, 2017). However, the reason for non-yellowing of the reference samples observed in this study is not yet clear. On the other hand, it is clear as previously reported by Olaniran *et al.* (2019) that surface degradation of rubberwood under accelerated weathering was prevented by acetylation as no crack, twisting or cupping were observed throughout the exposure period when compared to the reference samples. Therefore, this suggests that, though it is possible to limit moisture interaction and consequently surface degradation in weathered rubberwood through acetylation, resistance to photo-bleaching of acetylated wood surface needs to be improved. This may be achieved by adding another protective layer to

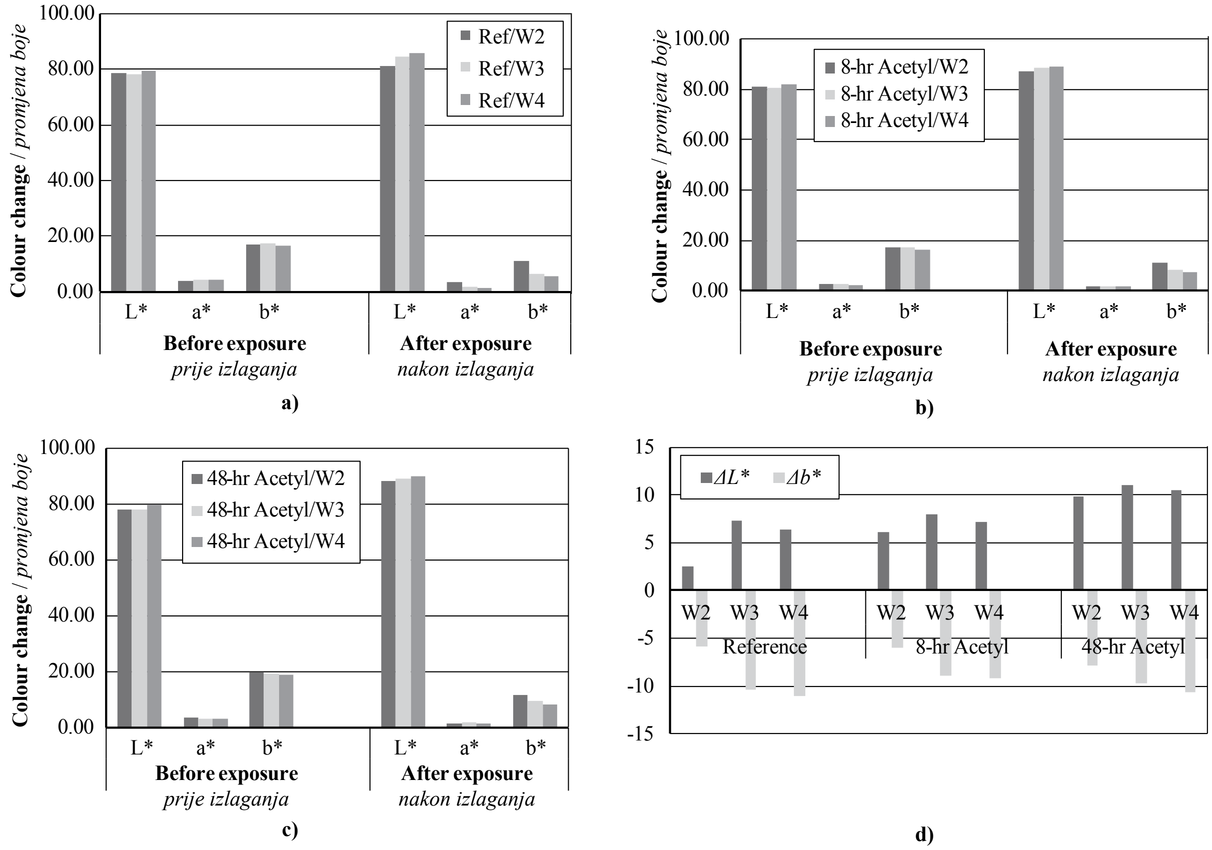

Figure 2 Colour change in rubberwood showing lightness (L^*), redness (a^*), yellowness (b^*) indices for the (a) unmodified samples, (b) samples acetylated for 8 hours, (c) samples acetylated for 48 hours, and (d) shows the change in lightness (ΔL^*) and yellowness (Δb^*)

Slika 2. Promjena boje drva kaučukovca prikazana na temelju parametara svijetljenja (L^*), crvenjenja (a^*) i žućenja (b^*) za (a) nemodificirane uzorke, (b) uzorke acetilirane 8 sati i (c) uzorke acetilirane 48 sati te (d) prikaz promjene svjetline (ΔL^*) i žućenja (Δb^*)

minimize the observed colour change. This additional protection can be achieved by deposition of protective layer on the acetylated wood. Previous researches have experimented on possible layers such as titanium dioxide/cerium (TiO_2/Ce) xerogel and zinc oxide (ZnO) nanostructures (Guo *et al*., 2016; Guo *et al*., 2017), which can be deposited on wood surface to preserve its aesthetic value especially when the wood is intended for outdoor use.

4 CONCLUSIONS
4. ZAKLJUČAK

This study has shown the effectiveness of acetylation on the equilibrium moisture content and colour change in rubberwood exposed to accelerated weathering. The moisture content ratio of the acetylated wood has revealed that even at low *WPG*s of acetylated rubberwood, the modification is still effective in minimizing moisture ingress. In the process of weathering, however, the increasing lightness of weathered acetylated rubberwood gives an indication that its natural aesthetics may not be completely preserved only by acetylation. Hence, it is necessary to apply additional layers of nano-coating with compounds such as ZnO, as demonstrated for other wood species in previous studies, to preserve the natural beauty of rubberwood surface.

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Biomass Pelletizing Process: A Review

Proces peletiranja biomase - pregled literature

REVIEW PAPER
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ABSTRACT • *A review paper was designed as a lab-scale start-up guideline for general pelletizing process and technologies for biomass feedstock. The main body consists of summarized published research on the topic of all main parts of the biomass pelletizing process and technology, including machinery and their parts, optimal feedstock conditions as well as pellet forming processes and principles. This paper is more focused on the specific parameters necessary to obtain optimal pelletizing process that results in desired pellet quality, and less on feedstock preparation, final product post-treatment (e.g. cooling), handling (storage, transportation) or exact quality specifications. A summary of the suggested feedstock, technological and other parameters for the purpose of easier lab-scale start-up of biomass pellets production, which is based on the cited literature throughout this paper, is given in the last section.*

KEYWORDS: *biomass feedstock; pellets; pelletizing technology; pelletizing process; feedstock parameters*

SAŽETAK • *Pregledni rad pripremljen je kao laboratorijski priručni materijal za osnovne procese i tehnologije peletiranja biomase. U njemu su sistematizirane spoznaje iz dostupnih izvora literature o temi glavnih dijelova procesa i tehnologije peletiranja biomase, uključujući strojeve i njihove pripadajuće dijelove, optimalne ulazne parametre sirovine, kao i načela i procese izrade peleta. Ovaj je priručni materijal više usmjeren na specifične parametre nužne za optimalan proces peletiranja radi dobivanja peleta željene kvalitete, a manje na pripremu sirovine, tretiranje proizvedenog peleta (npr. hlađenje), rukovanje peletima (skladištenje, transport) ili na određena kvalitativna svojstva peleta. Sažetak preporučenih tehnoloških parametara i ulaznih parametara sirovine, koji se temelji na informacijama iz navedene i citirane literature, nalazi se na kraju ovoga preglednog rada.*

KLJUČNE RIJEČI: *biomasa/sirovina; pelet; tehnologija peletiranja; proces peletiranja; parametri sirovine*

1 INTRODUCTION
1. UVOD

In the past couple of decades, due to the urge to reduce greenhouse gas emissions and CO_2 footprint, utilization of so far underused biomass, which is considered a renewable energy source together with wind, solar, hydro, geothermal and marine (tidal) energy (Ellabban *et al*., 2014), has gained its popularity in replacing fossil fuels.

Biomass is defined as wood and agricultural residues from the wood industry, crop fields and forests. Even though there are obvious advantages of biomass in the form of clean heat and power generation, there

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are also some disadvantages: ununiformed size and shape, low bulk and energy density as well as high moisture content, which can lead to degradation during storage and transportation (Demirbaş, 2001). All these properties negatively affect the supply chain management both economically and practically.

In order to overcome these obstacles, biomass is pelletized into cylindrical pellets used for both residential (diameter 6mm) and industrial (diameter ≥8mm) heat and power applications. Pelletized biomass has shown improved and more consistent properties over lose biomass, such as low moisture content, high energy content as well as homogenous shape and size (Mobini *et al*., 2014), all positively contributing to the supply chain management and logistics of biomass pellets.

Pelletizing process is described as compression of the feedstock (in this case biomass) that is pelletized. The friction between the biomass and the press channel generates a force which results in compression of biomass, causing the final product, pellets, maintain their shape and density due to bonding that occurs between the particles at high pressure inside press channels (Nielsen *et al*., 2009a; Holm *et al*., 2006).

This process is carried out by the pellet mill. Large scale producers usually use ring or flat die pellet mills, with ring die mills being the most common (Haslinger, 2005). The main parts of the mill are always the die and rollers, with rollers pushing the material through the bore-holes of the die, making an infinite string of pelletized material, breaking up into pieces randomly or getting cut into desired length by knives (Obernberger and Thek, 2010).

And finally, the goal of this paper was to summarize and organize available findings in the area of biomass pelletization in order to provide a pelletizing lab-scale start-up guidelines for the research project "INOPELET", held by Bjelin Ltd. in partnership with the University of Zagreb, Faculty of Forestry and Wood Technology.

2 PELLETIZING PROCESS
2. PROCES PELETIRANJA

Biomass is pelletized in order to achieve improved utilization performance as a solid biofuel, meaning reduced moisture content, increased calorific value and bulk density, and maybe most importantly, uniformed shape, size and density. These, in general more stable and consistent properties, offer lower usage cost in terms of transportation, storage and end use – feeding residential or industrial boilers and finally, burning.

There are multiple explanations and definitions of the pelletizing process available within the published research. In short, the pelletizing process is based on pushing the raw material through the openings of the die (Tica and Djurdjevic, 2007). It is also considered to be a kneading, compressing, heating and forming process where rheological transformations in the material take place (Salas-Bringas *et al*., 2008), as well as a high agglomeration process (Salas-Bringas *et al*., 2010). In general, this paper deals with biomass which can be compressed into pellets during the mechanical process in which pressure is applied to the biomass to crush its cellular structure, increasing its density. Key parameters affecting the cost, technique and dynamics of the process itself, as well as the quality of the final product (biomass pellets), are raw material species, exact plant parts/components used, moisture content and particle size. Additionally, temperature and pelletizing pressure play an important role in the pelletizing process (Stelte, 2011), together with the type of the pellet mill and specifications of the die (Holm *et al*., 2006), all affecting each other directly or indirectly to form a pellet of a certain quality.

2.1 Feedstock parameters
2.1. Parametri sirovine

2.1.1 Types and species
2.1.1. Tipovi i vrste sirovine

For the purpose of this paper, types of feedstocks are divided into two groups: forestry/woody and agricultural/herbaceous. Species refer to specific forest trees and agricultural crops within two feedstock groups. In general, types of forestry and wood industry feedstock species can be divided into hardwood and softwood. Different species have various energy requirements for pelletizing, directly impacting the cost and production capacities (Nielsen *et al*., 2009b). For example, a study showed that hardwood such as European beech required more energy to process than the softwood Scots pine, while producing the pellets of better mechanical properties (strongest) (Nielsen *et al.*, 2009b). This was also confirmed by Holm *et al*. (2006), who were not able to obtain a stable production of pure beech pellets, while pellets from pine shavings gave them a stable production, proving that beech dust is much more difficult to pelletize than pine. They also showed that pellets could be made by mixing pine and beech with the ratio of 60 % (wt) and 40 % (wt). On the other hand, another study done by Föhr and Ranta (2017) showed that pre-treated (torrefied) hardwood (without binders) pelletized better than the softwood. Mechanical durability of softwood pellets was lower than the hardwood ones, as shown in previous studies.

Pelletizing of agricultural type feedstock was investigated by Puig-Arnavat *et.al*. (2016), who studied pelletizing behavior of triticale, fescue, alfalfa and sorghum materials. When pelletized, all materials were of the same quality, except sorghum, which had poorer mechanical properties. Calorific value of these pellets was within 17.46 and 18.02 MJ/kg, which was similar to softwood (19.66 and 20.36 MJ/kg) and hardwood (17.63 and 20.81 MJ/kg) pellets (Telmo and Lousada, 2011). The research proved that investigated agricultural feedstock can have satisfactory pelletizing properties if other parameters, such as adequate moisture content, are met. Furthermore, the addition of softwood (pine) into the agricultural (straw) feedstock can result in improved mechanical properties of produced pellets (Theerarattananoon *et al*., 2011), which was also found by Harun and Afzal (2016), who investigated how particle size and other parameters impact the quality of agricultural pellets. They concluded that blending agricultural biomass with woody biomass to produce pellets can be one of the potential options for the pellet industry, not only because agricultural biomass is economically affordable and profusely available, but also because their research showed that blending agricultural biomass with existing woody biomass improved mechanical and physical properties of the pellet that can meet the quality standard. And finally, this was also confirmed in the study done by Šafran *et al*. (2017), who found a mixture of corn-stalk and fir to be a good option for agro-wood pellet production.

2.1.2 Moisture content
2.1.2. Sadržaj vode

In terms of moisture content (MC), feedstock can be divided into two stages: 1) raw, wet or pre-treated, when the material has not been dried to the desired MC yet and is not ready for pelletizing, and 2) dried to the optimal MC and ready for pelletizing, which is the one considered in this paper. Optimal MC can be described as the one that provides stable fiber compression and desired production performance, while producing the standard quality pellets.

Ungureanu *et al*. (2018) reported the MC of 10 to 15 % to be the most optimal for pelletizing the woody feedstock, while the MC above 20 % did not form any stable pellets. Furthermore, their research revealed that the increase of MC for both woody (beech and spruce) and agricultural (straw) feedstock resulted in a decrease of pelletizing pressure, while MC >14 % started to negatively affect pellets mechanical durability. Similar results were reported by numerous other studies: optimal MC for beech was found to be 6 to 10 % (wt), spruce around 10 % (wt) (Stelte *et al*., 2011a), and pine 6 to 8 % (wt) (Nielsen *et al*., 2009b).

Agricultural feedstock, on the other hand, has showed to require higher MC (barley straw 19-23 %; wheat straw ~15 %) in order to be properly pelletized (Serrano *et al*., 2011; Smith *et al*., 1977), while the increase of optimal MC values, as in woody feedstock, resulted in decreased mechanical durability of pellets produced (Theerarattananoon *et al*., 2011).

2.1.3 Particle size distribution
2.1.3. Distribucija čestica prema veličini

Particle size of biomass feedstock depends on the raw material characteristics as well as on pre-treatment methods of size reduction and equipment (hammers, knives, screens, etc.) specifications (Jensen *et al*., 2011). This paper, as in all other sections of feedstock parameters, deals only with already pre-treated feedstock (in case pre-treatment is necessary in terms of size reduction), meaning that its size is suitable for the pelletizing process.

Particle size, in synchronization with feedstock species and moisture content, plays an important role in the pelletizing process, impacting both production performance and pellet quality.

Research has shown that the decreasing particle size increases friction in the press channel of a pellet mill, while increasing pellet density (Stelte, 2011; Stelte *et al*., 2011a; Kaliyan and Morey, 2009; Mani *et al*., 2006). For example, the efficacy of the pressure agglomeration process directly depends on particle size – the smaller the particles are, the larger the contact surface is. Therefore, the bonds between the particles have higher energy per unit mass (Lisowski *et al*., 2020).

When it comes to the exact feedstock particle size that is adequate for pelletizing and for the production of good quality pellets, Lisowski *et al*. (2020) conducted a brief overview of already investigated size specifications, which were as follows: smaller than 3.2 mm (Mani *et al*., 2003), between 1 and 3 mm in diameter (Stelte *et al*., 2011b), below 5 mm in diameter (Stelte *et al*., 2012; Scatolino *et al*., 2018). Generally, a wide-ranging particle size is the most adequate with respect to the pellet quality; however, a too high amount of fine particles (smaller than 0.5 mm in diameter) has a negative impact on the friction and pellet quality (Stelte *et al*., 2012).

2.2 Pellet mill
2.2. Preša

2.2.1 Pellet mill design and main parts
2.2.1. Vrste preša i njihovi glavni konstrukcijski dijelovi

A typical pellet mill consists of two main parts: die and rollers, where the rollers force the biomass to flow into and through the die cylindrical press channels. These two main parts, which are wearing parts and need to be replaced periodically (Kytö and Äijälä, 1981), are manufactured from wear-resistant materials, mostly from hardened chromium steel (Alakangas and Paju, 2002). When wear and tear of these main parts of the pellet mill become significant, it might be necessary to substantially reduce the production rates (e.g. from 4.5 t/h to 3.5 t/h) in order to maintain the desired

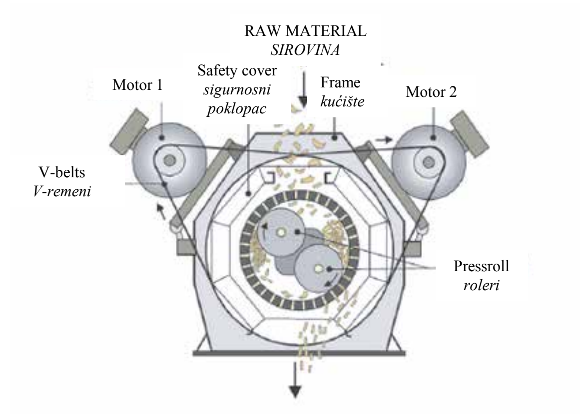

Figure 1 Pellet mill with ring die (source: www.smallpelletmills.net)
Slika 1. Preša s prstenastom matricom (izvor: www.smallpelletmills.net)

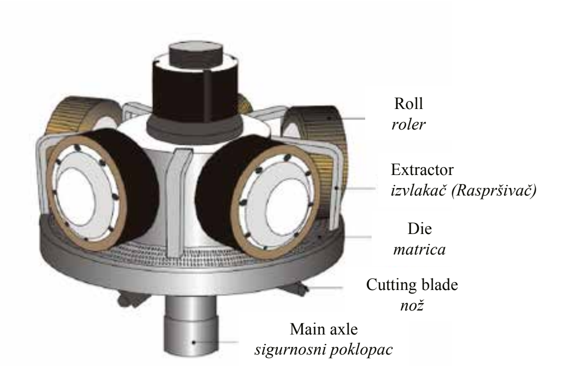

Figure 2 Pellet mill with flat die (source: ww.smallpelletmills.net)
Slika 2. Preša s ravnom matricom (izvor: www.smallpelletmills.net)

pellet quality properties (Sultana *et al*., 2010). This finding suggests that the worn out state of rollers and/or die can have a negative impact on pellet mechanical properties.

Pellet mills usually come in two different designs, which are dictated by the shape of the die. The die can either be in the shape of a ring (Figure 1) or a flat plate (Figure 2) (Alakangas and Paju, 2002). In case of the flat die, rollers are rotated, and in case of a ring die, motors power and rotate the die itself.

Ring dies are commonly used in commercial facilities due to their high throughput, while flat dies manifest more robustness with input biomass and generally require lower capital investment than ring dies (Jackson *et al*., 2016). Apart from the rollers and die, other fundamental parts of every pellet mill are the motor – powering the rollers or the die, usually by belt drive; cutting blades – cutting the infinite string of pelletized material into the desired length; and the axle – delivering the rotation from the motor, while being powered by belts through the gearbox.

2.2.2 Technological and constructional parameters
2.2.2. Tehnološki i konstrukcijski parametri

Tica and Djurdjevic (2007), as well as Tumuluru *et al*. (2010), have summarized some of the main technological and constructional parameters needed for an optimal pelletizing process:

- Temperature
- Circumferential speed of the rollers on the die
- Clearance between the rollers and the die
- Die parameters

Pelletizing process creates friction between the steel surface and feedstock in press channels, causing build-up of a high back pressure, consequently generating heat (Stelte, 2011). Numerous studies have been made on the subject of optimal pelletizing temperature. For example, Serrano *et al*. (2011) found that the temperature of the die under operation at stable conditions is around 90 °C. This was also confirmed in studies by Mostafa *et.al*. (2019) and Tumuluru (2014), who stated that the optimal die temperature for pelletizing biomass feedstock was close to 100 °C. However, Šafran (2015) found that increased temperature (170 to 220 °C) of pelletizing can increase pellet density, consequently increasing calorific value.

As for the circumferential speed of the rollers on the die, Amandus-Kahl Group recommended it to be 2.2 to 2.6 m/s for a flat die, while for a ring die, where the die is turned around the fixed rollers, the speed of the rollers is equal to the speed of the edge of the die, and can be determined by the number of spins of the shaft (Tica and Djurdjevic, 2007).

The distance between the rollers and the die needs to be adjusted before starting the pelletizing process, and it might need to be re-adjusted after certain production time, due to wear and tear of the die and rollers. The distance depends on multiple factors such as type, moisture and particle size of the feedstock, but the general "rule-of-thumb" would be to adjust it to 0.1 to 0.5 mm. One roller, however, which is always lower than the others, by design, in order to push the material through the die, is adjusted to 0.1 to 0.2 mm. Clearance between the rollers and the die greatly affects the mechanical properties of pellets.

Die specifications and dimensions depend on the type of the pellet mill (already discussed in chapter 3.2.1. Pellet Mill Design and Main Parts) and the desired shape and size of the pellet.

Šafran (2015) has summarized some of the key parameters of the die:

- conically recessed opening of the press channel (Figure 3) for easier entry of the material into the die
- inlet angle of indentation (30 ° to 60 °)
- indentation compression ratio (1 to 1.56 for smaller diameter pellets; 1 to 4 for bigger diameter pellets)

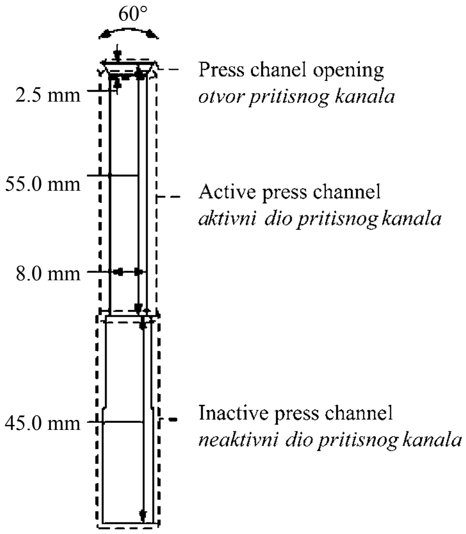

Figure 3 Example of a press channel (source: Nielsen et al., 2009b)
Slika 3. Primjer kanala u matrici (izvor: Nielsen et al., 2009b)

- compression ratio, which is the ratio between length (usually between 6 and 25 mm (Stelte, 2011) and diameter of the press channel (Stelte, 2011) (e.g. softwoods demand 4 to 5 for flat die and 8 to 10 for ring die, while agricultural biomass demands higher ratios) disposition and number of holes (it is necessary to achieve the highest number of holes as possible, without affecting the mechanical integrity of the die itself).

2.3 Pellet forming
2.3. Formiranje peleta

As it can be seen in Figure 4, pellets are formed from the crushed biomass that is compressed inside the press channels.

Mani *et al*. (2004) investigated pellet forming principles for various feedstock and described the forming process in terms of the applied pressure. The initial stage, also called particle rearrangement, of pellet forming happened at low pressures, when particles were moved around and rearranged, while pore spaces were being eliminated. In the second stage, as compressive force progressed, densification was indicated by elastic, plastic deformation and interlocking of particles, where these particles were bound by the cohesion of inner surfaces and their fibrous parts (Alakangas and Paju, 2002). As stated in previous sections, this process creates friction between biomass particles and die channel, generating heat that softens some biomass components, such as natural binding material lignin, due to its relatively low melting point of 140 °C (Mani *et al*., 2004.). Softened and/or melted lignin causes adhesion of biomass particles, forming pellets (Alakangas and Paju, 2002). After the pellets are formed, they are discharged through the die, cut by knives to desired length and, as the last stage, cooled in the cooler in order for pellet particles to form very strong solid bridges (Ghebre-Sellassie, 1989). The pellet particles now being fully interlocked, pellets achieved their final shape and other mechanical properties.

3 DISCUSSION AND CONCLUSIONS
3. RASPRAVA I ZAKLJUČAK

A brief overview of specific feedstock, technological and constructional parameters necessary for optimal pelletizing process was conducted in order to help with lab-scale start-ups designed for scientific research in the area of biomass pellets. Summarized findings and parameters are as follows:

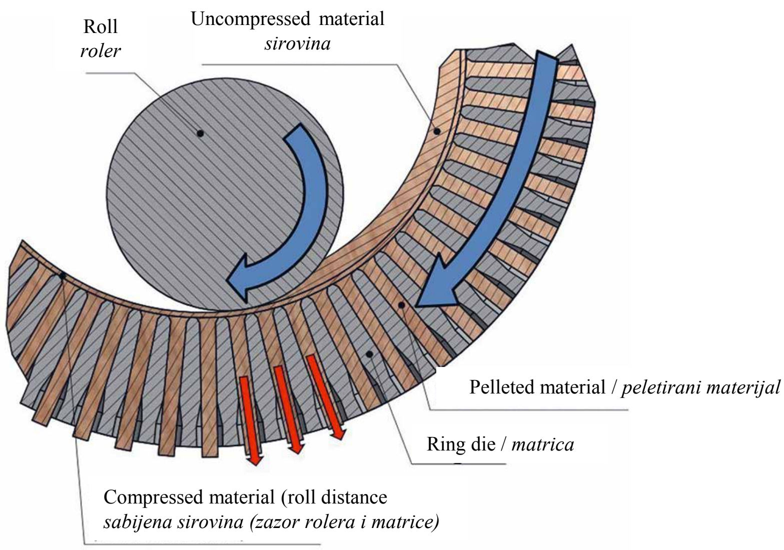

Figure 4 Close-up pelletizing process (source: Nielsen *et al.*, 2020)
Slika 4. Prikaz procesa peletiranja (izvor: Nielsen *et al.*, 2020.)

All key parameters need to be in harmony in order to obtain optimal pelletizing process and pellets of desired quality.

Hardwoods require more energy to be pelletized than softwoods.

Pellets made of hardwood feedstock are often more durable than those made of softwood.

Thermal pre-treatment (e.g. torrefaction, steam explosion) of feedstock can improve pelletizing properties as well as durability and end quality of pellets in general.

Pelletizing agricultural feedstock, as well as mixing different feedstock (hardwood/softwood; wood/agricultural) in various ratios, is possible and can even improve pelletizing properties and pellet quality.

Woody feedstock requires the moisture content of between 10 and 15 % in order to be properly pelletized. The increase of moisture content reduces pellet mechanical durability, while the decrease can amplify energy consumption needed for pelletizing, simultaneously reducing production capacity and increasing the risk of die blockage.

Agricultural feedstock requires the moisture content of around 20 %, which is substantially higher than that of woody feedstock.

The optimal particle size of the feedstock was found to be between 1 and maximum 5 mm, with a not too high amount of particles below 0.5 mm in diameter, due to the negative impact of fines on the mechanical durability of pellets.

The temperature of the die required for biomass pelletizing was found to be around 100 °C. Increased pelletizing temperature can increase pellet density and calorific value.

Roller velocity is recommended to be between 2.2 and 2.6 m/s.

Clearance between the rollers and the die should be between 0.1 and 0.5 mm. One roller that is always closest to the die should be adjusted to 0.1 to 0.2 mm.

Preferable blends of feedstock (woody/agricultural) for achieving optimal parameters (e.g. moisture content and particle size) for the desired pelletizing process and pellet quality is yet to be investigated. However, this paper would suggest to lean towards setting both feedstock and pressing parameters closer to woody feedstock requirements for the purpose of lab-scale research. With the idea of agricultural feedstock being a minority share, gradual introduction and increase of agricultural feedstock into the blend during the process will allow for "real time" adjustments of pelletizing parameters, if necessary.

Replacement of the die and rollers is necessary due to their wear and tear. Frequency of replacement mostly depends on the quality of the die and rollers, type of feedstock, production rates, etc. Lower quality of pellets, in the first place mechanical durability, is usually the first indicator of die and/or rollers wear out (in case all other parameters are in optimal state).

Die parameters depend on the type of the pellet mill as well as on the type of the feedstock. Summarized parameters of the die can be found in the last paragraph of the section 2.2.2. (Technological and Constructional Parameters).

The optimal pelletizing pressure was found to be around 100 MPa. Increased pressure increases pellet density.

After they are discharged from the die and cut to desired length, pellets need to be cooled in order to achieve their final shape and other mechanical properties.

All parameters and findings listed above are solely projected to be a general guideline providing a framework for setting up a lab-scale production for research purposes, and are not intended to represent any definitive claims. Optimal parameters can greatly vary depending on the type of the feedstock and many other factors.

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Drvo obične američke duglazije *Pseudotsuga menziesii* (Mirb.) Franco

OPĆENITO O VRSTI

Pseudotsuga menziesii (Mirb.) Franco vrsta je drva iz porodice *Pinaceae*. Trgovački su nazivi te vrste Douglas Fir, Yellow Fir, Red Fir, Oregon Fir, Oregon Pine i Oregon Spruce (Kanada, SAD, Velika Britanija); Douglasfichte, Douglastanne (Njemačka); Pin de l'Oregon, Douglas (Francuska); Douglasia (Italija). Dominantno je sjevernoamerička vrsta, a raste u svim državama, od gorja Stjenjak do Tihog oceana. Jedna je od najrasprostranjenijih vrsta četinjača u Sjevernoj Americi i čini petinu ukupnih zaliha drva četinjača na kontinentu. U Europu je unesena u 19. stoljeću, najprije u Englesku, a zatim i u druge europske zemlje, gdje se pojačano uzgaja zbog brzog rasta i velikog prirasta drvne mase. Duglazija je jedna od najvažnijih vrsta drveća u svijetu. Iznimno je prilagodljiva i može rasti u vrlo različitim klimatskim uvjetima. Zbog svoje raznovrsnosti drvo duglazije ima široku primjenu, osobito u graditeljstvu. U sklopu mreže EUFORGEN u Europi se provode aktivnosti konzervacije genetskih izvora duglazije. Ta vrsta nije na popisu ugroženih vrsta međunarodne organizacija CITES, a prema IUCN-u, vodi se kao vrsta drva čiji je opstanak najmanje upitan.

RELEVANTNE SPOZNAJE O DRVU DUGLAZIJE (U VEZI S PRIKAZOM NA NASLOVNICI)

Drvo duglazije grube je teksture. Karakterizira ga oštar prijelaz ranog drva u kasno, s postojećim i vidljivim smolenicama.

Pregled ranih istraživanja drva duglazije prema Zobelu i van Buijtenenu (1989.) te Zobelu i Spragueu (1998.) otkriva ove spoznaje: juvenilno drvo obuhvaća prvih 15 godova od srčike; drvo u blizini srčike manje je gustoće u usporedbi sa zrelim drvom sličnog prirasta; gustoća kasnog drva je 2 – 2,5 puta veća od gustoće ranog drva; na gustoću drva neznatno utječe širina goda.

Novija istraživanja te vrste rezultirala su zaključcima (a) o znatnoj neujednačenosti gustoće drva unutar i između godova (Vonnet i dr., 1985.), (b) o znatno manjim varijacijama u gustoći ranog drva, dok se maksimalna gustoća utvrđuje neposredno prije granice goda

GENERAL INFORMATION ON SPECIES

Pseudotsuga menziesii (Mirb.) Franco is a wood species in the *Pinaceae* family. Its common names are: Douglas-fir, Yellow-fir, Red-fir, Oregon-fir, Oregon pine and Oregon spruce (Canada, USA, Great Britain); Douglasfichte, Douglastanne (Germany); Pin de l'Oregon, Douglas (France); Douglasia (Italy). It is a distinctive North American species that grows in all states from the Rocky Mountains to the Pacific Ocean. It is North America's most plentiful softwood species, accounting for one fifth of the continent's total softwood reserves. It was introduced to Europe in the 19th century, first to England and then to other European countries, where it is cultivated due to its rapid growth and large production of wood mass. Douglas-fir is one of the most important timber species in the world. It is a highly adaptable species and able to grow under a wide variety of climatic conditions. Because of great versatility, Douglas-fir wood can be used for a wide range of applications, especially in construction. Activities in the field of conservation of Douglas-fir genetic sources in Europe are carried out within the EUFORGEN network. This wood species is not listed in the international organization CITES Appendices and is reported by the IUCN as a species of least concern.

RELEVANT KNOWLEDGE ABOUT DOUGLAS-FIR WOOD (REGARDING THE IMAGE ON THE COVER)

Douglas-fir wood is considered to be coarse-textured. It is characterized by abrupt transition from earlywood to latewood and resin canals normally occur and are visible.

According to Zobel and van Buijten (1989) and Zobel and Sprague (1998), a review of early research on Douglas-fir wood provides the following information: juvenile wood is formed to the 15th growth ring from pith; wood near the pith is lighter than outer wood of similar growth rate; density of latewood is 2 to 2.5 times heavier than that of earlywood; wood density is considered influenced by annual ring width only to a small extent.

Further research comes to the following conclusions: (a) wood density is characterized by a strong in-

(de Kort i dr., 1991.), (c) o tendenciji veće gustoće zrelog drva kada su godovi u juvenilnom drvu široki, dok prirast i gustoća pokazuju negativnu korelaciju u ranom drvu, a pozitivnu u kasnome (Abdel-Gadir i dr., 1993.), (d) o povećanju gustoće drva kroz god (Rathgeber i dr., 2006.), (e) o kontinuiranom rastu udjela kasnog drva u radijalnom smjeru (Giagli i dr. 2017.), (f) o smanjenju gustoće drva s porastom prirasta (Henin i dr., 2018.).

Uzgojem duglazije ciljano se proizvodi sirovina u obliku građe velikih dimenzija. Drvo duglazije ispunjava sve zahtjeve u kojima je čvrstoća primarni uvjet.

Napomena: podatci o tehničkim i tehnološkim svojstvima drva duglazije dostupni su na web stranicama i u priručnicima navedenima u literaturi na kraju ovog teksta.

VAŽNOST DUGLAZIJE I ISTRAŽIVANJA TE VRSTE U HRVATSKOJ

U nekoliko europskih zemalja (Francuskoj, Njemačkoj, Ujedinjenom Kraljevstvu), duglazija je uzgojno najperspektivnija alohtona vrsta, a u tim se zemljama i detaljno istražuje. Nove spoznaje naglašavaju njezin utjecaj na klimatske promjene, pri čemu se duglazija spominje kao vrsta povoljnih bioloških osobina.

Duglazija je unesena u Hrvatsku prije više od sto godina. Masovnije se počinje iskorištavati u šumarstvu tek nakon 1960. Rana istraživanja rasta i prirasta duglazije na nekoliko lokaliteta u Hrvatskoj počeo je provoditi Klepac (1962.), i to radi određivanja uvjeta u kojima je ta vrsta visokoprinosna. Duglazija kao komercijalna vrsta u Hrvatskoj trenutačno nema veliko značenje. Međutim, istraživanja provenijencija duglazije na pokusnim plohama dugi niz godina provodi Hrvatski šumarski institut, počevši od 1972., kada se uključuje u IUFRO-ov program istraživanja te vrste (neka od tih istraživanja proveli su Orlić i Ocvirek, 1996.; Orlić i Perić, 2005.; Perić i dr., 2005.; Perić i dr., 2011.; Đodan i dr., 2019.). U navedenim se istraživanjima zaključuje o pogodnosti osnivanja kultura duglazije na slobodnim šumskim i nešumskim površinama u Hrvatskoj, posebice duglazija europskih provenijencija – onih iz Bugarske i Danske, ali i onih iz savezne države Washington. Također, duglazija bi mogla postati superiorna običnoj smreki, koja je trenutačno ekonomski najvažnija drvna vrsta središnje Europe. U tijeku su istraživanja strukture i svojstava drva duglazije spomenutih provenijencija na Fakultetu šumarstva i drvne tehnologije Sveučilišta u Zagrebu, kojima će se odrediti kvaliteta proizvedene sirovine.

ter- and intra-tree-ring heterogenity (Vonnet *et al.*, 1985); (b) variation in earlywood density is much less, while maximum density occurs before the ring boundary (de Kort *et al.*, 1991); (c) wide rings in juvenile wood tend to produce mature wood with higher density, and growth rate and density are negatively correlated in earlywood but positively correlated in latewood (Abdel-Gadir *et al.*, 1993); (d) wood density increases along a growth ring (Rathgeber *et al.*, 2006); (e) proportion of latewood steadily increases with age (Giagli *et al.* 2017); (f) wood density decreases due to increase in growth rate (Henin *et al.*, 2018).

The cultivation of Douglas-fir produces raw material in large sizes. It meets all the requirements where strength is the primary factor. Note: data on technical and technological properties of Douglas-fir wood are available on web pages and in manuals listed in literature section.

THE IMPORTANCE OF DOUGLAS-FIR AND ITS RESEARCH IN CROATIA

Douglas-fir is found to be the most promising non-native species in several European countries (France, Germany, the United Kingdom), where it has been fully investigated. New knowledge highlights its significance in terms of climate changes where it is mentioned as a species of beneficial biological features.

Douglas-fir was introduced to Croatia more than 100 years ago. Only after 1960, it began to be used more widely in forestry. Early research on growth and increment of Douglas-fir from several sites in the Republic of Croatia was started by Klepac (1962), with the aim of determining the conditions in which this species is highly productive. Currently, in Croatia Douglas-fir is not considered as a commercially important species. However, research on the provenances has been carried out for many years by the Croatian Forestry Institute, starting in 1972 when it was included in the IUFRO research program of this species (e.g. Orlić and Ocvirek, 1996; Orlić and Perić, 2005; Perić *et al.*, 2005; Perić *et al.*, 2011; Đodan *et al.*, 2019). The above research points to the conclusion on the suitability of establishing Douglas-fir cultures on free forest and non-forest areas in Croatia, particularly provenances from Bulgaria and Denmark, as well as from Washington. Consequently, Douglas-fir could become a superior species to Norway spruce, which is currently the most important economic species in Europe. Research on the structure and properties of Douglas-fir wood from the above provenances is in progress at the Faculty of Forestry and Wood Technology, and is expected to show the quality of the produced raw material.

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Latinska imena trebaju biti pisana kosim slovima (italicom), a ako je cijeli tekst pisan kosim slovima, latinska imena trebaju biti podcrtana.

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Materijal i metode trebaju biti što preciznije opisane da omoguće drugim znanstvenicima ponavljanje pokusa. Glavni eksperimentalni podaci trebaju biti dvojezično navedeni.

Rezultati trebaju obuhvatiti samo materijal koji se izravno odnosi na predmet. Obvezatna je primjena metričkog sustava. Preporučuje se upotreba SI jedinica. Rjeđe rabljene fizikalne vrijednosti, simboli i jedinice trebaju biti objašnjeni pri njihovu prvom spominjanju u tekstu. Za pisanje formula valja se koristiti Equation Editorom (programom za pisanje formula u MS Wordu). Jedinice se pišu normalnim (uspravnim) slovima, a fizikalni simboli i faktori kosima (italicom). Formule se susljedno obrojčavaju arapskim brojkama u zagradama, npr. (1) na kraju retka.

Broj slika mora biti ograničen samo na one koje su prijeko potrebne za objašnjenje teksta. Isti podaci ne smiju biti navedeni i u tablici i na slici. Slike i tablice trebaju biti zasebno obrojčane, arapskim brojkama, a u tekstu se na njih upućuje jasnim naznakama ("tablica 1" ili "slika 1"). Naslovi, zaglavlja, legende i sav ostali tekst u slikama i tablicama treba biti napisan hrvatskim i engleskim jezikom.

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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 (*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".

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Primjer

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Müller, D., 1977: Beitrag zür Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanstalt für Forstund Holzvvirt schaft 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 (pristupljeno 27. siječnja 2010).

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Other publications (brochures, studies, etc.):
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