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Wood Industry Trade Competitiveness of Selected Countries of Southeast Europe

Trgovinska konkurentnost drvne industrije u zemljama jugoistočne Europe

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ABSTRACT • *The paper examines the trade competitiveness of the wood industry as a whole and some of its parts (Cork and wood, Cork and wood manufactures and Furniture and parts) of five countries of South Eastern Europe (Serbia, Croatia, Bulgaria, Romania and Bosnia & Herzegovina) by using six indicators (Revealed Comparative Advantage – RCA, Index of Trade Performance – RCA2, Competitiveness Growth Index – RCA1, Michaely Index – MI, Index of Contribution to the Trade Balance – CTB and Grubel-Lloyd Index – GLI) in the period 2000-2015. On the basis of the results obtained, it was concluded that the wood industry of these countries observed as a whole has great export potential and that it significantly participates in their processing industry. The results of the survey show that companies from the wood industry viewed as a whole are competitive on the domestic market. However, this cannot be said of the international competitiveness of the timber industry of these countries. To be specific, the production of cork and wood from Bulgaria and Serbia, cork and wood manufactures excluding furniture from Bulgaria, Serbia and Croatia, as well as furniture and parts manufacturers from Bulgaria do not have a competitive advantage in the international market. By combining the values of six competitiveness indicators, it can be concluded that there is a statistically significant difference in the competitiveness of the wood industry of the countries observed. It can also be concluded that the degree of wood processing has a positive impact on their export competitiveness, this impact not being statistically significant, and that the level of finalization of production did not have a positive impact on the competitiveness of the wood industry of the selected countries of Southeastern Europe.*

Keywords: *trade competitiveness, trade competitiveness indicators, wood industry, Southeast Europe*

SAŽETAK • *U radu se istražuje trgovinska konkurentnost drvne industrije pet zemalja jugoistočne Europe (Srbije, Hrvatske, Bugarske, Rumunjske te Bosne i Hercegovine), i to u cjelini i po dijelovima (pluto i drvo, proizvodi od pluta i drva, namještaj i dijelovi za namještaj). Istraživanje je provedeno u razdoblju od 2000. do 2015. uz pomoć šest pokazatelja konkurentnosti (utvrđene komparativne prednosti – RCA, indeksa neto poslovanja – RCA2,*

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indeksa rasta konkurentnosti – RCA1, Michaely indeksa – MI, indeksa doprinosa trgovinskoj bilanci – CTB i Grubel-Lloyd indeksa – GLI). Iz dobivenih je rezultata zaključeno da drvna industrija navedenih zemalja, promatrana u cjelini, ima velik izvozni potencijal i da značajno sudjeluje u njihovoj prerađivačkoj industriji. Rezultati istraživanja pokazuju da su poduzeća iz sektora drvne industrije, promatrana u cjelini, konkurentna na domaćem tržištu. Međutim, to se ne može reći i za međunarodnu konkurentnost drvne industrije tih zemalja. Konkretno, proizvodnja pluta i drva iz Bugarske i Srbije, proizvodi od pluta i drva iz Bugarske, Srbije i Hrvatske, kao i namještaj i dijelovi za namještaj iz Bugarske nemaju konkurentsku prednost na međunarodnom tržištu. Kombiniranjem vrijednosti šest pokazatelja konkurentnosti utvrđena je statistički značajna razlika u konkurentnosti drvne industrije promatranih zemalja. Također se može zaključiti da stupanj obrade drva ima pozitivan utjecaj na njihovu izvoznu konkurentnost, ali taj utjecaj ipak nije statistički značajan. Nadalje, uočeno je da stupanj finalizacije proizvodnje nije pozitivno utjecao na konkurentnost drvne industrije promatranih zemalja jugoistočne Europe.

Ključne riječi: *trgovinska konkurentnost, pokazatelji trgovinske konkurentnosti, drvna industrija, jugoistočna Europa*

1 INTRODUCTION
1. UVOD

Competitiveness is one of the most powerful concepts of modern economic thought (Garelli, 2004). However, given the complexity of competitiveness, there is no generally accepted definition of this phenomenon. Broader concept of competitiveness relates to tendency and skill to compete, ability to win and retain market position, and to increase market share and profitability. In other words, the term implies business success.

The concept of competitiveness is the result of a long history of economic thought, which gave rise to various aspects of this complex phenomenon. Apart from company level, competitiveness is increasingly popular at the national level, at the regional level, and at the industry level, as well as between individual sectors (Cvetanović *et al*., 2015).

The paper examines wood industry trade competitiveness in five countries of Southeast Europe (Serbia, Croatia, Romania, Bulgaria, and Bosnia & Herzegovina) and its subsectors (cork and wood, cork and wood manufactures excluding furniture, and furniture and parts) in the period 2000-2015. Wood industry is one of the sectors where national economies can influence the market of Southeast Europe, and to a lesser extent the European market, by using their own resources.

Wood-based production in all five countries involved has a long tradition, having a sufficient amount of high-quality wood raw material that is naturally renewable and closely related to various sectors of the national economy. It contributes to economic, ecological, and social development of the countries and regions, where wood is used as a renewable resource. Wood-based products are biodegradable and can be used as substitutes for materials arising from non-renewable sources.

The need to study wood industry is partly the result of the fact that the European Union is focusing on economic development based on renewable sources. Wood industry is certainly a promising sector, and the EU encourages its development, wishing it to be a highly competitive activity on the world market. Three countries to be analyzed are full members of the EU (Croatia, Romania, and Bulgaria), Serbia is in the accession phase, while Bosnia & Herzegovina is a signatory to the EU Accession Treaty.

The following hypotheses are set.

H1: Wood industry of the selected countries as a whole and considering its parts is competitive on the domestic and foreign markets;

H2: There is a significant difference in the achieved level of trade competitiveness of wood industry in these countries;

H3: Level of trade competitiveness of wood industry in these countries is related to production finalization stage.

Wood industry competitiveness is here seen as the ability of domestic companies to sell products on the domestic and international markets in a competitive struggle with companies from other economies in the same area, through efficient use of production factors. Competitiveness indicators used in the paper are: Revealed Comparative Advantage – RCA, Index of Trade Performance – RCA2, Competitiveness Growth Index – RCA1, Michaely Index – MI, Index of Contribution to the Trade Balance – CTB, and Grubel-Lloyd Index – GLI.

The appropriate statistical methods are used to analyze wood industry competitiveness and its parts in five countries covered. The obtained results are then mutually compared.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Concept of industry trade competitiveness
2.1. Koncept trgovinske konkurentnosti

Competitiveness is a dynamic, multifactorial, and hierarchical phenomenon that encompasses individual companies, company clusters, all companies in a particular sector, and, finally, all companies and sectors in a given country (Jovović, 2017). The past two decades have been abundant in reports, indices, as well as academic and policy debates dealing with national and industry competitiveness and related performance issues. This shows that governments are more and more focusing on their country's competitiveness and grasping its structural drivers. Consequently, all economies, notwithstanding their level of development, struggle to uplift their competitiveness, particularly their manufacturing industry competitiveness, to ultimately raise their country's well-being (Fagerberg *et al*., 2007; UNIDO, 2013).

Since the 1990s, most economists and experts have found that competitiveness has the status of a "natural law of market economy" (Kitson *et al*., 2004). However, since competitiveness does not have a single meaning, it can be analyzed in different ways, i.e. depending on the chosen concept, it can be used with different methodologies and indicators. Also, there are some differences in researching the competitiveness of companies, industries, and countries. In this regard, various institutions monitor the competitiveness of countries using micro and macro competitiveness indicators. The most prominent indicators of competitiveness at the national level are the World Competitiveness Index of the Institute for Management Development – IMD, Global Competitiveness Index of the World Economic Forum, and UNIDO Competitive Industrial Performance Index. Unlike company level, where competitiveness is fundamentally seen as the capacity "to maximize productivity and factor incomes (wages and profits) on a sustained basis" (Hatzichronoglou, 1996), and where foreign trade indicators are used to record companies' individual and overall competitiveness (UNIDO, 2013), the study of competitiveness at the industry level gives some insight into the impact of economic policy on the economy, with data more accessible and internationally more comparable than data at the company level (Toming, 2007).

When it comes to measuring industry competitiveness, productivity and exports are the commonly analyzed variables. Another indicator of industry competitiveness lies in relative prices in that industry, seen in relation to one or more foreign competitors (Siggel, 2006).

Industry competitiveness refers to the country's industry ability to generate profit in relation to identical industries in other countries, the ability to attract production factors in relation to other industries within the same country or in other countries, and the ability to adapt the industry to socio-economic conditions. Therefore, coordination between companies in a particular field and certain socio-economic conditions in which they operate justifies the analysis of competitiveness at the industry level.

UNIDO (2002, 2013) sees industry competitiveness as "the capacity of countries to increase their presence in international and domestic markets whilst developing industrial sectors and activities with higher value added and technological content", pointing to main elements of industry competitiveness – ability to produce and export competitively, technological growth and progress, and, ultimately, impact on world-scale manufacturing industry and exports (UNIDO, 2013). Referring to this approach, Lall (2001) believes that "competitiveness in industrial activities means developing relative efficiency along with sustainable growth", indicating that the rise in industry competitiveness requires abandoning static sources of cost advantage and focusing on diverse industrial activities (climbing the technological ladder). This idea of industry competitiveness is multidimensional by nature, and may be relevant both in 'ex-ante' and 'ex-post' analyses, depending on whether the focus is on 'process assessment' or 'outcome assessment' of co55522 country industry competitiveness. In particular, this perspective may involve both a specific set of 'structural drivers' of industry competitiveness (i.e. process) and the resulting competitive industry performance of nations (i.e. outcome). Industry competitiveness is measured based on perceptible realities. What is more, the idea maintains a 'stochastic' nature, visualizing the possibility of pluralistic industry patterns of progress (UNIDO, 2013).

Although being a subject of various studies, there is no universally valid and generally accepted definition of industry competitiveness in literature. In the case of sectoral competitiveness, it involves macroeconomic assessment of competitiveness of certain sectors, so the analysis of industry competitiveness as a whole overlaps with individual sectors.

Rybakovas (2009) points out that industry competitiveness or sectoral competitiveness depends on the quality of products and services, customer satisfaction, effectiveness of internal processes, innovation, employee satisfaction, etc. It is important to note that most research on industry competitiveness makes no distinction between domestic and international markets, because they believe that, due to trade liberalization, companies are exposed to global competition. However, although this starting point is largely accurate, it still cannot be said that there is a completely unified global market, either in the formal sense (e.g., the existence of various non-tariff barriers), nor in the essential sense (e.g. there is still a need for local adjustment to the requirements and needs of consumers, because the needs and demands of consumers are still far from universal and much more time will pass while consumers' taste and needs become homogenized globally).

A clear and logical basis for measuring competitiveness can be the balance of external trade, as it relies on the analysis of industry comparative advantage. At the sector level, international trade is also taken into account. Sector competitiveness, on the one hand, relates to the company ability to compete on domestic and foreign markets. On the other hand, it is a country ability to support business development because competitiveness is the key determinant of growth, maintenance, and creation of jobs in every economy.

2.2 Indicators of industry and sector trade competitiveness

2.2. Pokazatelji trgovinske konkurentnosti industrije i industrijskih sektora

In this paper, research relies on secondary sources, scientific studies dealing with theoretical and empirical analysis of sector and country trade competitiveness, and foreign trade statistics on wood industry.

The current research on competitiveness is based on the use of statistical methods to assess the detected and expected comparative and competitive advantage.

In fact, there is not a single comprehensive indicator of competitiveness, regardless of whether the study focus is on economy competitiveness as a whole or its parts. Some indicators relate only to the economy as a whole, while others can show both competitiveness at the level of the economy as a whole, and competitiveness at lower levels of economic structure. In practice, a number of indicators for the detection and measurement of competitiveness have been developed and used, and they represent a specific combination of competitiveness characteristics of the selected industry sector and/or countries (Han *et al*., 2009; Dieter and Englert, 2007).

Competitiveness indicators can be classified into two basic groups: result-oriented indicators and determinant-oriented indicators of competitiveness (Dieter and Englert, 2007). Result-oriented indicators help to reveal an ex-post competitive position. They are used to determine competitiveness at the sector level and on the international market. Based on the study of literature and methodologies of international organizations that measure competitiveness at the economy and industry levels, it has been concluded that more indicators are used to assess competitiveness of individual industries and their internal structures.

In reference (or related) works in this field (Sujová and Hlaváčková 2015; Sujová *et al*., 2015a,b), the most frequently used trade competitiveness indicators were:

a) Revealed Comparative Advantage – RCA. There are several variants of this indicator: RCA indicator measures competitiveness at the national level, and is obtained as the logarithm of export and import ratio of the commodity group in total export and import of the observed country. This indicator can be adjusted to reveal competitiveness of commodity groups in the economy, or to determine cross-sectoral competitiveness. Competitiveness Growth Index – RCA1 allows determining economy competitiveness on the regional and global market. It is obtained by comparing the share of certain commodity group export in the total country export in relation to the value of total exports of the observed commodity group and the total global value of exports. Index of Net Business Performance – RCA2 (Balassa, 1965) measures the share of a particular sector in active trade balance. It is obtained as a percentage difference between exports and imports of commodity groups and the sum of exports and imports of these commodity groups.

RCA index of inter-sectoral specialization (in line with the methodology of the United Nations Conference on Trade and Development – UNCTAD, International Trade Center – ITC, World Bank and World Trade Organization – WTO) analyzes the difference between net exports, existing specialization, trade deficit, and theoretical net exports.

b) Michaely Index (Michaely, 1962) shows the degree of country specialization in a commodity group or branch. It measures the share of the commodity group in total national exports.

c) Index of Contribution to the Trade Balance – CTB (Melišek, 2012) measures the contribution of certain sectors to the national trade balance. It is obtained as a difference between the actual and expected balance of the economy.

d) Grubel-Lloyd Index – GLI analyzes the share of goods with inter-sectoral character in foreign trade. Higher share points to a higher level of national competitiveness. GLI measures country capacity to exploit economies of scale (Grubel and Lloyd, 1971).

The actual competitiveness of the wood industry as well as its parts is examined in this paper by using the above-mentioned methods, based on the example of five countries of Southeast Europe (Serbia, Croatia, Romania, Bulgaria, and Bosnia & Herzegovina) in the period 2000-2015.

Indicators used in reference research have been modified and their calculation has been customized to provide inter-sectoral competitiveness analysis. In relation to their use, abbreviations are used as follows:

e_{sc} – value of exports of commodity group “s” in sector “s” and country “c”,
i_{sc} – value of imports of commodity group “s” in sector “s” and country “c”,
E_{sc} – value of exports of sector “s” and country “c”,
I_{sc} – value of imports of sector “s” and country “c”,
E_c – value of total exports from country “c”,
I_c – value of total imports into country “c”,
E_s – global (world) export of commodity group “s”,
E – total global (world) exports

RCA represents a comparative advantage or lack of export and its competitive ability. It is calculated at two levels, national (N-RCA) and sectoral (S-RCA):

$$N-RCA = ln\frac{\frac{e_{sc}}{i_{sc}}}{\frac{E_c}{I_c}} \tag{1}$$

$$S-RCA = ln\frac{\frac{e_{sc}}{i_{sc}}}{\frac{E_{sc}}{I_{sc}}} \tag{2}$$

RCA < 0 indicates comparative disadvantage of products. On the contrary, RCA > 0 implies the existence of a certain comparative advantage in the product export or sector to which the product belongs. Finally, RCA > 1 indicates that the product and industry are internationally competitive.

RCA1 is calculated as follows:

$$RCA1 = \frac{\frac{e_{sc}}{E_c}}{\frac{e_s}{E}} \tag{3}$$

RCA1 > 1 points to comparative advantage of industries on the global market, while RCA1 < 1 means that the product group has no competitive ability on the relevant market.

RCA2 measures the comparative advantage of industry or product export and its competitive ability. It is calculated by using the formula:

$$RCA2 = \frac{e_{sc} - i_{sc}}{e_{sc} + i_{sc}} \tag{4}$$

For RCA2 variables, the following applies: when RCA2 = -1, export does not exist and then $e_{sc} = 0$; $-1 < RCA2 < 0$ points to comparative disadvantages; when RCA2 = 0, export is equal to import, i.e. then $e_{sc} = i_{sc}$; $0 < RCA2 < 1$ indicates the existence of comparative advantage; and when RCA2 = 1, this means that import does not exist, i.e. $i_{sc} = 0$.

MI shows the degree of specialization or lack of specialization in certain commodity groups. The calculation of the index is carried out at two levels, sectoral (S-MI) and national (N-MI):

$$MI = \frac{e_{sc}}{\sum_{s=1}^{n} E_c} - \frac{i_{sc}}{\sum_{s=1}^{n} I_c} \qquad (5)$$

The value of MI indicator ranges from -1 to 1, i.e. $0 < MI < 1$ points to a certain degree of country specialization in the commodity group, while $-1 < MI < 0$ points to insufficient specialization of the country in the commodity group.

CTB is adjusted to determine the competitiveness of wood industry segments and is calculated on the basis of the formulas:

$$N-CTB = \frac{e_{sc} - i_{sc}}{E_c + I_c} - \frac{E_c - I_c}{E_c + I_c} \cdot \frac{e_{sc} + i_{sc}}{E_c + I_c} \cdot 100 \qquad (6)$$

$$S-CTB = \frac{e_{sc} - i_{sc}}{E_c + I_c} - \frac{E_c - I_c}{E_c + I_c} \cdot \frac{e_{sc} + i_{sc}}{E_c + I_c} \cdot 100 \qquad (7)$$

The left part of the equation represents the actual industry trade balance, weighted by its share in the total foreign trade exchange of the country that is cross-sectoral trade. The right part of the equation measures the expected trade balance of the sector (commodity group), provided that each commodity contributes to the total trade balance according to its share in total trade. The difference between the actual and the expected trade balance measures a specific contribution to the total trade balance.

When it comes to CTB index, CTB > 0 means that the actual surplus is higher than expected while the relative trade deficit is lower than expected, so that the sector makes a positive contribution to the overall trade balance; CTB < 0 means that the sector makes a negative contribution to the overall trade balance, and that the actual results, compared with the expected, are negative or insufficient.

GLI measures export capacity at the macroeconomic level. For the assessment at the industry level, the index has been modified and its calculation shows the degree of commodity share in the inter-sectoral foreign trade of the country. The formula for calculating the GLI index is:

$$GLI = 1 - \frac{\frac{e_{sc}}{E_c} - \frac{i_{sc}}{I_c}}{\frac{e_{sc}}{E_c} + \frac{i_{sc}}{I_c}} \qquad (8)$$

The GLI values range from 0 to 1 ($0 < GLI < 1$). Comparable value should be the GLI average for all sectors in the country or the GLI value at EU level or the global value of a given sector (commodity group).

The above mentioned indicators of trade competitiveness are only a suitable basis for further analysis of trade competitiveness. Therefore, MANOVA (Multivariate Analysis of Variance) with one factor of variability was applied, whereby the variability factor is the country. MANOVA is a method of statistical analysis, which is a multidimensional generalization of the ANOVA method. It is applied in order to test the equality of multidimensional random variables across multiple populations. The multidimensional random variable in this case is the trade competitiveness of the wood industry measured with 6 indicators (dimensions). The conclusion about the statistical significance of the difference between populations (countries) is based on the value of Wilks Lambda.

2.3 Data set
2.3. Skup podataka

The calculation of individual indicators is applied in the wood industry and its individual parts. What distinguishes the wood industry is the processing of raw wood and its further processing at different finalization stages. Accordingly, based on the United Nations Statistics Division – UNSTATS: Standard International Trade Classification (SITC Revision 3), wood industry [Wood industry – 24 + 63 + 821] can be broken down into the following sections: 24 – Cork and wood, 63 – Cork and wood manufactures (excluding furniture), and 821 – Furniture and parts.

Input data for assessing the competitiveness of wood industry and its parts for Serbia, Croatia, Romania, Bulgaria, and Bosnia & Herzegovina in the period 2000-2015 was taken from the United Nations Conference on Trade and Development – UNCTAD: UNCTAD stat database: Merchandise trade matrix – detailed products, exports in thousands of dollars, annual, 1995-2015. Based on the selected database, the export and sector competitiveness of wood industry of the selected countries of South East Europe can be analyzed on the basis of data on the value of exports and imports of wood industry and its parts.

Statistical variables for measuring wood industry competitiveness were calculated by using the specially developed MS Excel application. A multivariate analysis of variance made in SPSS 20.0 software (Statistical Package for Social Sciences) was used for data analysis.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Comparative analysis of wood industry competitiveness on the example of five countries of Southeast Europe in the period 2000-2015
3.1. Komparativna analiza konkurentnosti drvne industrije na primjeru pet zemalja jugoistočne Europe u razdoblju 2000. – 2015.

The selection of competitiveness indicators was inspired by the effort to determine whether wood industry in the observed countries, as well as its individual parts, are competitive on the domestic and international markets. For this purpose, the paper analyzes

Table 1 Average value of trade competitiveness indicators of selected countries of Southeast Europe in the period 2000-2015
Tablica 1. Prosječna vrijednost indikatora trgovinske konkurentnosti odabranih zemalja jugoistočne Europe u razdoblju 2000. – 2015.

	RCA	**RCA1**	**RCA2**	**MI**	**CTB**	**GLI**
Serbian wood industry / *Drvna industrija Srbije*	**0.6719**	**2.2525**	**0.0154**	**0.0198**	**0.8419**	**0.6783**
Cork and wood / *Pluto i drvo*	0.5170	0.5786	-0.0608	0.0046	0.2550	0.7496
Cork and wood manufactures / *Proizvodi od pluta i drva*	0.2817	0.6116	-0.1675	0.0026	0.2764	0.8630
Furniture and parts / *Namještaj i dijelovi za namještaj*	1.0389	1.0322	0.1943	0.0117	0.3109	0.5246
Croatian wood industry / *Drvna industrija Hrvatske*	**0.9606**	**4.2556**	**0.1510**	**0.0463**	**1.4070**	**0.5566**
Cork and wood / *Pluto i drvo*	2.0435	1.9332	0.5880	0.0295	0.4590	0.2361
Cork and wood manufactures / *Proizvodi od pluta i drva*	0.4786	0.7346	-0.0840	0.0049	0.3095	0.7663
Furniture and parts / *Namještaj i dijelovi za namještaj*	0.5505	1.5879	-0.0489	0.0118	0.6385	0.7325
Romanian wood industry / *Drvna industrija Rumunjske*	**1.6083**	**4.1456**	**0.5685**	**0.0597**	**0.5975**	**0.3395**
Cork and wood / *Pluto i drvo*	2.9008	1.158	0.8314	0.0199	0.1425	0.1316
Cork and wood manufactures / *Proizvodi od pluta i drva*	0.8635	0.914	0.2707	0.0092	0.1613	0.5993
Furniture and parts / *Namještaj i dijelovi za namještaj*	1.7187	2.074	0.6055	0.0306	0.2937	0.3098
Bulgarian wood industry / *Drvna industrija Bugarske*	**0.9692**	**1.6542**	**0.3118**	**0.0182**	**0.3007**	**0.5575**
Cork and wood / *Pluto i drvo*	2.0425	0.3481	0.6841	0.0055	0.0498	0.2396
Cork and wood manufactures / *Proizvodi od pluta i drva*	0.5162	0.4641	0.1017	0.0033	0.1033	0.7538
Furniture and parts / *Namještaj i dijelovi za namještaj*	1.0039	0.8420	0.3278	0.0094	0.1477	0.5422
B&H wood industry / *Drvna industrija BiH*	**1.7875**	**8.6044**	**0.4218**	**0.1302**	**2.6207**	**0.2884**
Cork and wood / *Pluto i drvo*	3.3771	4.3490	0.8384	0.0779	1.0435	0.0769
Cork and wood manufactures / *Proizvodi od pluta i drva*	0.5296	0.9373	-0.1693	0.0069	0.4748	0.7420
Furniture and parts / *Namještaj i dijelovi za namještaj*	1.5112	3.3182	0.2889	0.0454	1.1024	0.3697

Authors' calculation, based on data taken from the UNCTADstat database / *Izračun autora na temelju podataka iz baze podataka UNCTADstat*

trade competitiveness of wood industry and its parts based on different modifications of RCA, CTB, GLI, and MI coefficients. The obtained results of individual indicators are given in Table 1.

The positive average value of the RCA index indicates that the wood industry of the observed countries as a whole, as well as its individual parts (Cork and wood, Cork and wood manufactures excluding furniture, and Furniture and parts), have a comparative advantage on the national market. The wood industries of Romania and Bosnia & Herzegovina have built significant competitiveness at the international level. The wood industries of Croatia and Bulgaria are becoming internationally competitive, while the wood industry of Serbia is not sufficiently competitive on the international market.

Within wood industry, the highest value of the RCA index, in the field of Cork and wood, is found in companies from Bosnia & Herzegovina. They have a significant level of international competitiveness, and they are followed by companies from Romania, Croatia, and Bulgaria. With Cork and wood manufactures excluding furniture, the situation is significantly different because companies of none of the five countries achieve competitiveness at the international level, but only a certain level of competitiveness within the national economy. The biggest competitors are companies from Romania, followed by companies from Bosnia & Herzegovina and Bulgaria, and the lowest level of competitiveness is found in wood processing companies from Croatia and Serbia. When it comes to Furniture and parts, the situation is significantly more favorable in most of the countries observed. The most competitive Furniture and parts manufacturers are from Romania and Bosnia & Herzegovina, who manage to reach a certain level of international competitiveness, while Furniture and parts manufacturers from Serbia and Bulgaria are on the right track to achieve international competitiveness. The least favorable situation is with Furniture & parts manufacturers from Croatia because they are only competitive within the domestic market.

The average value of the RCA1 index shows that, in all countries observed, there is revealed comparative advantage of wood industry on the global market, with wood industry of Bosnia & Herzegovina having the highest comparative advantage, followed by wood industry of Croatia and Romania, while the lowest comparative advantage is found in wood industry of Serbia and Bulgaria. Analysis of individual parts of wood industry shows that Cork and wood companies from Bulgaria and Serbia, Cork and wood manufactures excluding furniture companies from Bulgaria, Serbia, Croatia, Romania, and Bosnia & Herzegovina, as well as Furniture & parts manufacturers from Bulgaria do not have competing advantage on the relevant market.

The obtained results show that Cork and wood companies from Bulgaria and Serbia, Cork and wood manufactures excluding furniture companies from Bulgaria, Serbia, Croatia, Romania, and Bosnia & Herzegovina, as well as Furniture and parts manufacturers from Bulgaria do not have a competitive advantage on the international market. It follows that the hypothesis H1 is confirmed in the part related to competitiveness of observed countries wood industry on the domestic market. On the contrary, the results do not confirm the second part of the hypothesis H1, which refers to trade competitiveness of all parts of wood industry of these countries.

The analysis of the average value of the RCA2 index shows the existence of a positive contribution of wood industry in the formation of active trade balance in all countries observed. The largest wood industry surplus is recorded in Romania, Bosnia & Herzegovina, and Bulgaria, and to a lesser extent in Croatia, while this contribution is the smallest in Serbia. Great positive contribution to foreign trade also comes from individual parts of wood industry, especially Cork and wood companies from Bosnia & Herzegovina, Romania, Bulgaria, and Croatia, as well as Furniture and parts manufacturers from Croatia, and to a lesser extent Cork and wood manufactures excluding furniture from Romania and Bulgaria, as well as Furniture and parts manufacturers from Bulgaria, Bosnia & Herzegovina, and Serbia. Unlike these companies, Cork and wood companies from Serbia, as well as Cork and wood manufactures excluding furniture from Serbia, Croatia, and Bosnia & Herzegovina and Furniture & parts manufacturers from Croatia, due to comparative disadvantages, record a deficit in foreign trade operations, thereby adversely affecting foreign trade balance trends.

The average MI values indicate that all countries observed achieve a certain degree of wood industry specialization. The highest level of wood industry specialization is achieved in Bosnia & Herzegovina and Romania, and the lowest in Bulgaria and Serbia. In relation to certain parts of wood industry, Cork and wood manufactures excluding furniture companies record the lowest specialization in all countries observed. In Serbia, Romania, and Bulgaria, Furniture and Parts manufacturers have a higher degree of specialization in relation to Cork and wood companies, unlike Bosnia & Herzegovina and Croatia, where there is greater specialization in the field of Cork and wood than Furniture and parts.

The obtained CTB values show that in all countries observed wood industry creates a higher surplus than expected and that the actual trade balance is better than expected, so that wood industry sector contributes positively to the overall trade balance. This contribution is particularly high in Bosnia & Herzegovina and Croatia and least pronounced in Bulgaria and Romania, while Serbia is at the level of the average countries observed. An identical situation is found when the analysis goes down to the level of Cork and wood and Cork and wood manufactures excluding furniture, as well as Furniture and parts companies.

The obtained GLI values show that the capacity to use the economies of scale in the wood industry is mostly used by companies from Serbia, then Bulgaria and Croatia, and the least in companies from Bosnia & Herzegovina and Romania. An almost identical situation is found with companies operating in the Cork and wood area. A somewhat different situation is found with Cork and wood manufactures excluding furniture companies, since, in addition to Serbia, companies from Croatia and Bulgaria widely use economies of scale, and to a lesser extent companies from Romania and Bosnia & Herzegovina. Furniture & parts manufacturers, mostly using economies of scale, come from Croatia, Bulgaria, and Serbia, and companies from Romania and Bosnia & Herzegovina use it the least.

3.2 Multivariate analysis of variance of wood industry trade competitiveness on the example of five countries of Southeast Europe in the period 2000-2015

3.2. Multivarijantna analiza varijance trgovinske konkurentnosti drvne industrije na primjeru pet zemalja jugoistočne Europe u razdoblju 2000. – 2015.

The question that arises here is whether there is a statistically significant difference in terms of the level of wood industry competitiveness among the countries observed. Data in Table 2 (Wilks' Lambda) gives a positive answer to this question. By combining the values of six competitiveness indicators, the WL value obtained is less than 0.05, which proves the existence of a statistically significant difference between the achieved competitiveness levels of the analyzed Southeast European countries, thus confirming the H2 hypothesis.

Table 3 gives more detailed information on competitiveness indicators exhibiting a difference (column Sig.). Data points to the conclusion that the values of all observed indicators are statistically different depending on individual countries. What is more, the table (Partial Eta Squared column) indicates that the highest variance in the degree of competitiveness, produced as a result of the country included in the analysis, is present with RCA1, and the lowest with RCA2 (absolute values in this column are compared), and it

Table 2 Multivariate Tests
Tablica 2. Multivarijantni testovi

Effect *Učinak*		**Value** *Vrijednost*	***F***	**Hypothesis df** *Hipoteze df*	**Error df** *Pogreška df*	**Significance** *Značajnost*	**Partial Eta Squared** *Djelomični eta kvadrat*
Intercept *Odjel*	Pillai's Trace	1.000	43003.352[b]	6.000	95.000	.000	1.000
	Wilks' Lambda	.000	43003.352[b]	6.000	95.000	.000	1.000
	Hotelling's Trace	2716.001	43003.352[b]	6.000	95.000	.000	1.000
	Roy's Largest Root	2716.001	43003.352[b]	6.000	95.000	.000	1.000
Country *Zemlja*	Pillai's Trace	1.851	14.071	24.000	392.000	.000	.463
	Wilks' Lambda	.020	28.904	24.000	332.625	.000	.626
	Hotelling's Trace	14.473	56.384	24.000	374.000	.000	.783
	Roy's Largest Root	12.320	201.234[c]	6.000	98.000	.000	.925

Table 3 Multivariate analysis of variance
Tablica 3. Multivarijantna analiza varijance

Indicator *Pokazatelj*	**Country** *Zemlja*					**F**	***p*-value** *p-vrijednost*	**Partial Eta Squared** *Djelomični eta kvadrat*	**Bonferroni**
	1 SRB	**2 HR**	**3 ROM**	**4 BUG**	**5 BiH**				
RCA	0.722	0.998	1.773	1.047	1.837	69.407	.000	.735	1-2,1-3,1-4,1-5, 2-3,2-5, 3-4,4-5
RCA1	2.482	4.111	4.219	1.562	9.377	189.771	.000	.884	1-2,1-3,1-4,1-5, 2-4,2-5,3-4,3-5,4-5
RCA2	0.047	0.175	0.615	0.364	0.364	43.866	.000	.637	1-3,1-4,1-5,2-3, 2-4,2-5,3-4,3-5
MI	0.025	0.048	0.066	0.019	0.151	92.870	.000	.788	1-2,1-3, 1-5,2-4,2-5,3-4,3-5,4-5
CTB	0.936	1.388	0.625	0.257	3.199	51.032	.000	.671	1-4,1-5,2-3,2-4,2-5,3-5,4-5
GLI	0.657	0.542	0.302	0.528	0.28	68.671	.000	,733	1-2,1-3,1-4,1-5, 2-3,2-5, 3-4,4-5

can be concluded that the largest variations are found with RCA and RCA1 indicators.

Information on which countries are statistically different in terms of individual quality dimensions is found in the Bonferroni column in Table 3. For example, there is a statistically significant difference between Serbia (1) and all other countries in terms of the value of RCA indicator, but there is no statistically significant difference between Croatia (2) and Bulgaria (4) regarding the value of RCA indicator, as there are no differences between Romania (3) and B&H (5).

When looking at RCA1 indicator, there is no significant difference between Croatia and Romania only (2-3). With RCA2 indicator, the difference is not significant between Serbia and Croatia (1-2), or Bulgaria and Bosnia & Herzegovina (4-5). According to MI indicator, there is no significant difference between Serbia and Bulgaria (1-4), or between Croatia and Roma-

Table 4 Competitiveness of countries depending on the finalization stage
Tablica 4. Konkurentnost zemalja u ovisnosti o stupnju finalizacije

		Mean *Srednja vrijednost*	**Std. Deviation** *Stand. devijacija*	**Std. Error** *Stand. pogreška*	**95 % Confidence Interval for Mean** *95 %-tni interval pouzdanosti*	
					Lower Bound *Donja granica*	**Upper Bound** *Gornja granica*
RCA	Cork and wood / *pluto i drvo*	2.17640	1.090346	.487618	.82256	3.53024
	Cork and wood manufactures / *proizvodi od pluta i drva*	.53420	.209624	.093747	.27392	.79448
	Furniture and parts / *namještaj i dijelovi za namještaj*	1.16480	.459735	.205600	.59396	1.73564
	Total / *ukupno*	**1.29180**	**.950174**	**.245334**	**.76561**	**1.81799**
RCA1	Cork and wood / *pluto i drvo*	1.67340	1.616034	.722712	-.33317	3.67997
	Cork and wood manufactures / *proizvodi od pluta i drva*	.73240	.200861	.089828	.48300	.98180
	Furniture and parts / *namještaj i dijelovi za namještaj*	1.77080	.990917	.443152	.54041	3.00119
	Total / *ukupno*	**1.39220**	**1.128338**	**.291336**	**.76735**	**2.01705**
RCA2	Cork and wood / *pluto i drvo*	.57600	.371230	.166019	.11506	1.03694
	Cork and wood manufactures / *proizvodi od pluta i drva*	-.00940	.191644	.085706	-.24736	.22856
	Furniture and parts / *namještaj i dijelovi za namještaj*	.27360	.236692	.105852	-.02029	.56749
	Total / *ukupno*	**.28007**	**.356500**	**.092048**	**.08264**	**.47749**
MI	Cork and wood / *pluto i drvo*	.02756	.029967	.013402	-.00965	.06477
	Cork and wood manufactures / *proizvodi od pluta i drva*	.00546	.002602	.001164	.00223	.00869
	Furniture and parts / *namještaj i dijelovi za namještaj*	.02184	.015686	.007015	.00236	.04132
	Total / *ukupno*	**.01829**	**.020562**	**.005309**	**.00690**	**.02967**
CTB	Cork and wood / *pluto i drvo*	.39020	.396015	.177103	-.10152	.88192
	Cork and wood manufactures / *proizvodi od pluta i drva*	.26480	.144237	.064505	.08571	.44389
	Furniture and parts / *namještaj i dijelovi za namještaj*	.49860	.381936	.170807	.02436	.97284
	Total / *ukupno*	**.38453**	**.319701**	**.082546**	**.20749**	**.56158**
GLI	Cork and wood / *pluto i drvo*	.28700	.268004	.119855	-.04577	.61977
	Cork and wood manufactures / *proizvodi od pluta i drva*	.74480	.094566	.042291	.62738	.86222
	Furniture and parts / *namještaj i dijelovi za namještaj*	.49600	.165528	.074026	.29047	.70153
	Total / *ukupno*	**.50927**	**.261581**	**.067540**	**.36441**	**.65413**

Table 5 ANOVA
Tablica 5. ANOVA test

		Sum of Squares *Zbroj kvadrata*	***Df***	**Mean Square** *Kvadrat srednje vrijednosti*	***F***	**Sig.**
RCA	Between groups / *između grupa*	6.863	2	3.432	7.128	.009
	Within groups / *unutar grupa*	5.777	12	.481		
	Total / *ukupno*	12.640	14			
RCA1	Between groups / *između grupa*	3.289	2	1.644	1.358	.294
	Within groups / *unutar grupa*	14.535	12	1.211		
	Total / *ukupno*	17.824	14			
RCA2	Between groups / *između grupa*	.857	2	.429	5.576	.019
	Within groups / *unutar grupa*	.922	12	.077		
	Total / *ukupno*	1.779	14			
MI	Between groups / *između grupa*	.001	2	.001	1.715	.221
	Within groups / *unutar grupa*	.005	12	.000		
	Total / *ukupno*	.006	14			
CTB	Between groups / *između grupa*	.137	2	.068	.635	.547
	Within groups / *unutar grupa*	1.294	12	.108		
	Total / *ukupno*	1.431	14			
GLI	Between groups / *između grupa*	.525	2	.263	7.284	.008
	Within groups / *unutar grupa*	.433	12	.036		
	Total / *ukupno*	.958	14			

nia (2-3). The average value of CTB indicator in Serbia does not differ significantly from the value of this indicator in Croatia and Romania (1-2 and 1-3). In addition, according to this indicator, there is no significant difference between Romania and Bulgaria (3-4). According to GLI indicator, Croatia and Bulgaria (2-4) do not significantly differ, nor do Romania and Bosnia & Herzegovina (3-5).

Data on the values of these indicators is found in the Countries column (with appropriate sub-columns denoting countries), so it is still possible to compare which of the countries has the highest value of this competitiveness indicator and which the lowest. In the observed period, Bosnia & Herzegovina has the highest indicators of RCA, RCA1, RCA2 (together with Bulgaria), MI, and CTB, while the highest value of GLI indicator relates to Serbia.

In order to prove the H3 hypothesis, the values of the competitiveness indicators are examined according to the finalization stage, with all countries considered as a whole (Table 4).

According to the results of Table 4, the highest average value of RCA, RCA2, and MI indicators is at the lowest finalization stage – Cork and wood. The highest average value of GLI indicator is related to a higher finalization stage, i.e. Cork and wood manufactures excluding furniture, while the highest average value of RCA1 and CTB in the countries observed is achieved at the highest finalization stage – Furniture and parts.

Table 5 gives the results of testing the significance of the difference in the average values of indicators among different finalization stages. The finalization stages are observed as a factor of variability. Based on the results, it can be concluded that the difference in the average value of indicators between the finalization stages is significant with RCA, RCA2, and GLI indicators (Sig. is less than 0.05), while with other indicators of competitiveness there is no significant difference in the average values between different finalization stages.

Based on the results shown in Tables 4 and 5, it can be concluded that, if only RCA1 and CTB indicators are observed, the wood processing stage has a positive impact on trade competitiveness, but this impact is not statistically significant. According to other indicators, the finalization stage has no positive impact on trade competitiveness, i.e. hypothesis H3 cannot be confirmed.

3.3 Overall discussion
3.3. Rasprava

Numerous studies deal with wood industry trade competitiveness in individual countries. For example, Carvalho et al. (2009) use RCA and data on relative market share on a global scale to come to the conclusion on high competitiveness of Brazilian wood pulp processing on the international market. Dieter & Englert (2007) explore the competitiveness of certain parts of the wood-processing industry on a global scale, with emphasis on the wood processing industry of Germany, through revealed comparative advantage and constant market share indices, to conclude that Russia is most competitive with untreated timber, Finland with secondary treated wood, and Poland with final wood production. Mäkelä (2009) studies the competitiveness of the wood processing industry in Russia, and concludes that it is competitive on the international market only in the production of low value added products. In the paper Evaluating the Competitiveness of Wood Processing Industry, Sujová *et al*. (2015a) analyze competitiveness of Czech and Slovak wood industries in relation to the EU wood processing industry taken as a whole in the period 2003-2012. The authors come to the conclusion that competitiveness of the Czech wood industry is low compared to the EU wood industry, while wood industry of Slovakia is on its way to losing its competitiveness in the coming period. Identical results are obtained for wood processing and furniture production. The authors conclude that the success of the wood industry lies in actively finding new comparative advantage, since competitive advantage based on prices and costs obviously disappears. Authors Sujová and Hlaváčková (2015) have come to the identical result in evaluating the level and development of competitiveness of WPI in the Czech Republic in sub-sectoral structure for the period 2003-2012. Paluš *et al*. (2015) analyzes the competitiveness of the wood processing industry in Hungary, Poland, Slovakia, and the Czech Republic, using indicators related to trade specialization, ratio of exports and imports, standard Grubel-Lloyd index, revealed comparative advantage and the change of competitiveness in the period from 2003-2012. Their conclusion is that within the group of analyzed countries, Slovakia shows a comparative advantage in most products, especially in the trade of primarily processed wood, wood-based panels, pulp, paper, and cardboard products. The results of the analysis also show that specialization within the industry increases the level of added value.

The results of the analysis carried out in this paper confirm the hypothesis H1 in the part of wood industry competitiveness of the observed countries in the domestic market. On the contrary, the results do not confirm the second part of the hypothesis H1 that relates to the export competitiveness of all parts of the wood industry of the countries observed. Also, the results of the study showed the existence of statistically significant differences between the achieved levels of competitiveness of the annihilated countries, which confirmed the hypothesis H2. The research also showed that the level of finalization of the wood industry in the work of the countries involved does not have a positive impact on export competitiveness, which means that H3 hypotheses cannot be confirmed. Overall, the results of the research in this paper largely correspond to the results obtained in the aforementioned, comparable, foreign studies. As the survey analyzes the countries of South East Europe with a relatively low degree of specialization in the wood industry, logically the degree of finalization has little impact on their commercial competitiveness. The results of comparable studies show that specialization within the wood industry significantly affects the increase in the added value level only in countries that have achieved a significant degree of specialization. This implies that the countries of South East Europe, in view of increasing the commercial competitiveness of wood industry, or increasing the size of revenues within the business, must significantly raise the level of specialization within the wood industry, so as to increase its overall effect. The current situation suggests that the observed countries of South-Eastern Europe have a subsidiary role within the global value chain of the wood industry and that unless they change, the existing business and development models will be condemned to stagnation and/or decline in the long term on a more demanding and challenging global market.

4 CONCLUSIONS
4. ZAKLJUČAK

Based on the results of the previous analysis, it can be concluded that wood industry has a large export potential in the economy, with a significant share in manufacturing industry in the selected Southeast Europe countries. This is important since it is an activity that does not depend on imported raw materials as timber assortment in these countries is large enough within the national economy.

The obtained results show that wood industry companies in the selected countries, taken as a whole, achieve a competitive position on the national market, but this cannot be said for international competitiveness of these countries. To be specific, Cork and wood companies from Bulgaria and Serbia, Cork and wood manufactures excluding furniture companies from Bulgaria, Serbia, and Croatia, as well as Furniture & parts manufacturers from Bulgaria do not have a competitive advantage on the international market.

By combining the values of six competitiveness indicators, the WL value of less than 0.05 is obtained, which proves the existence of a statistically significant difference between the achieved level of competitiveness of Croatia, Serbia, Romania, and Bosnia & Herzegovina in the period 2000-2015.

Judging by RCA1 and CTB indicators, it can be concluded that the wood processing stage has a positive impact on export competitiveness; however, this impact is not statistically significant. According to other indicators, the wood processing stage has no positive impact on export competitiveness.

5 REFERENCES
5. LITERATURA

1. Balassa, B., 1965: Trade liberalisation and "revealed" comparative advantage. The manchester school, 33(2): 99-123. https://doi.org/10.1111/j.1467-9957.1965.tb00050.x.
2. Carvalho, K.; Silva, M.; Soares, N., 2009: Competitiveness of Brazilian Wood Pulp in the International Market. CERNE, 15 (4): 383-390.
3. Cvetanović, S.; Filipović, M.; Nikolić, M.; Belović, D., 2015: Endogenous growth theory and regional development policy. Spatium, 34: 10-17. https://doi.org/10.2298/SPAT1534010C.
4. Cvetković, M.; Petrović-Ranđelović, M., 2017: The Analysis of Agricultural Products Export Competitiveness of the Republic of Serbia based on the RCA Index. Economic Themes, 55(3): 399-420. https://doi.org/10.1515/ethemes-2017-0022.
5. Dieter, M.; Englert, H., 2007: Competitiveness in the global forest industry sector: an empirical study with special emphasis on Germany. European Journal of Forest Research, 126(3): 401-412. https://doi.org/10.1007/s10342-006-0159-x.
6. Fagerberg, J.; Srholec, M.; Knell, M., 2007: The Competitiveness of Nations: Why Some Countries Prosper While Others Fall Behind? World Development, 35: 1595-1620. https://doi.org/10.1016/j.worlddev.2007.01.004.

7. Garelli, S., 2004: Competitiveness of Nations: The Fundamental. *IMD World* Competitiveness Yearbook 2004, Lausanne, Switzerland, pp. 730-74.
8. Grubel, H.; Lloyd, P., 1971: The Empirical Measurement of Intra-Industry Trade. Economic Record, 47 (120): 494-517. https://doi.org/10.1111/j.1475-4932.1971.tb00772.x.
9. Han, X.; Wen, Y.; Kant, S., 2009: The global competitiveness of the Chinese wooden furniture industry. Forest Policy and Economics, 11(8): 561-569. https://doi.org/10.1016/j.forpol.2009.07.006.
10. Hatzichronoglou, T., 1996: Globalization and Competitiveness: relevant indicators, OECD. https://doi.org/10.1787/885511061376.
11. Jovović, D., 2017: Improving regional competitiveness in the light growth theory recommendations. Economic Themes, 55(3): 319-333. https://doi.org/10.1515/ethemes-2017-0018.
12. Kitson, M.; Martin, R.; Tyler, P., 2004: Regional competitiveness: an elusive yet key concept? Regional studies, 38(9): 991-999. https://doi.org/10.1080/0034340042000320816.
13. Lall, S., 2001: Competitiveness, Technology and Skills. Edward Elgar Publishing. https://doi.org/10.4337/9781781950555.
14. Mäkelä, T., 2009: The Russian Forest Industry: A Case Of Competitiveness And Export Taxes, epub.lib.aalto.fi /fi /ethesis/pdf/12057/hse_ethesis_12057.pdf (Accessed August 07, 2017).
15. Melišek, I., 2012: Meranie a hodnotenie makroekonomických výsledkov zahraničného obchodu. Ekonomické rozhľady, *41*(4): 439-451.
16. Michaely, M., 1962: Multilateral balancing in international trade. The American Economic Review, *52*(4): 685-702.
17. Paluš, H.; Parobek, J.; Liker, B., 2015: Trade Performance and Competitiveness of the Slovak Wood Processing Industry within the Visegrad Group Countries. Drvna industrija 66 (3): 195-203. https://doi.org/10.5552/drind.2015.1431.
18. Rybakovas, E., 2009: Competitiveness of Lithuanian manufacturing industry. Economics and management, 14: 912-918.
19. Siggel, E., 2006: International Competitiveness and Comparative Advantage: A Survey and a Proposal for Measurement. Journal of Industry, Competition and Trade, 6(2): 137-159. https://doi.org/10.1007/s10842-006-8430-x.
20. Sujová, A.; Hlaváčková, P., 2015: Sectoral Analysis of Competitiveness of Wood Processing Industry in the Czech Republic. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 63(1): 293-302. http://dx.doi.org/10.11118/actaun201563010293.
21. Sujová, A.; Hlaváčková, P.; Marcineková, K., 2015a: Evaluating the Competitiveness of Wood Processing Industry. Drvna industrija, 66(4): 281-288. https://doi.org/10.5552/drind.2015.1432.
22. Sujová, A.; Hlaváčková, P.; Marcineková, K., 2015b: The Trade Competitiveness of Furniture Products. Drewno, 58(195): 103-117. doi: 10.12841/wood.1644-3985.104.09.
23. Toming, K., 2007: The Impact of EU Accession on the Export Competitiveness of the Estonian Food Processing Industry. Post-Communist Economies, 19(2): 187-207. https://doi.org/10.2139/ssrn.959212.
24. UNIDO – The United Nations Industrial Development Organization, 2002: Competing through innovation and learning. Industrial Development Report 2002/2003, Vienna. https://doi.org/10.18356/94674506-en.
25. UNIDO – The United Nations Industrial Development Organization, 2013: The Industrial Competitiveness of Nations: Looking Back, Forging Ahead. Competitive Industrial Performance Report 2012/2013, Vienna.
26. ***World bank: Trade Indicators – World Integrated Trade Solution (WITS). http://wits.worldbank.org/WITS/WITS/WITSHELP/Content/Utilities/e1.trade_indicators.htm (Accessed July 13, 2017).
27. *** United Nations Conference on Trade and Development – UNCTAD: UNCTADstat database: Merchandise trade matrix – detailed products, exports in thousands of dollars, annual, 1995 – 2015, http://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=24738 (Accessed July 12, 2017).
28. *** United Nations Statistics Division – UNSTATS: Standard International Trade Classification – SITC Revision 3. https://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=14 (Accessed August 23, 2017).

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The Effect of Mat Layers Moisture Content on Some Properties of Particleboard

Utjecaj sadržaja vode u slojevima ploče iverice na njezina svojstva

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ABSTRACT • *In this study, the effect of mat moisture content on the physical and mechanical properties of particleboard was investigated. The experimental boards were produced by using 40 % softwood, 45 % hardwood chips, and 15 % sawdust. The formaldehyde resin/adhesive was used in three-layers (bottom-top layer 12 %, core layer 8 %). Multi-opening press was used during manufacturing the experimental particleboards. The physical and mechanical properties of boards obtained were identified according to the TS-EN standards. The optimum core layer moisture content was determined as 6 % and 7 % according to the results, whereas the moisture content of bottom and top layers was 14 %. Under these moisture content conditions, the bending strength was found to be 13.3 N/mm², the modulus of elasticity in bending 2466 N/mm², and internal bonding strength 0.44 N/mm². The optimum bottom-top layer moisture content was determined to be between 13 % and 15 % and 6.5 % for the core layer.*

Keywords: *wood-based panels; particleboard; mat moisture content; properties*

SAŽETAK • *U radu je istraživan utjecaj sadržaja vode u slojevima ploča od usitnjenog drva na njihova fizička i mehanička svojstva. Istraživane su ploče proizvedene od iverja mekog drva u udjelu 45 %, iverja tvrdog drva u udjelu 15 % i drvne prašine u udjelu 15 %. Ploče su se sastojale od tri sloja u kojima je upotrijebljena formaldehidna smola/ljepilo (u vanjskim slojevima 12 %, u središnjim slojevima 8 %), a prešanje je obavljeno višeetažnom prešom. Fizička i mehanička svojstva ploča određena su prema TS-EN normama. Iz dobivenih je rezultata utvrđen optimalan sadržaj vode u središnjem sloju od 6 i 7 %, dok je konstantni sadržaj vode u vanjskim slojevima iznosio 14 %. Pri tim sadržajima vode dobiveni su ovi rezultati: čvrstoća na savijanje 13,3 N/mm², modul elastičnosti 2466 N/mm² i međuslojna čvrstoća 0,44 N/mm². Utvrđeno je da je optimalan sadržaj vode u vanjskim slojevima između 13 i 15 %, a u središnjem sloju 6,5 %.*

Ključne riječi: *drvne ploče, ploča od usitnjenog drva, sadržaj vode u slojevima ploče, svojstva*

1 INTRODUCTION
1. UVOD

Particleboards (PB) are manufactured under heat and pressure of mat obtained from wood particles or other lignocellulosic material in particle with the addition of an adhesive. PB properties can be changed with some factors such as adhesive bonding, particle geometry, resin type and density variations due to random particle deposition during mat forming (Sanabria *et al.*, 2013; İstek *et al.*, 2010). The most important factors

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affecting the properties of board at the stage of pressing are the mat moisture, temperature, specific press pressure, press closing speed, and pressing duration. In a previous study, it was determined that, at 11 % mat moisture and mat thickness increased from 20 mm to 40 mm, the duration of core layer temperature increase to 100 °C was prolonged by 4 times (Hata, 1993). It was reported that the mat moisture content plays an important role in properties of MDF produced using phenol formaldehyde (FF) resin, and that the mean characteristics achieved at 12 % mat moisture content were found to be better than those obtained at 6 % and 9 % mat moistures (Chow and Zhao, 1992). The mat moisture contents higher than the limit were reported to cause bursting risk in PB production, while the lower contents caused brittle fracture following the pressing (Bardak, 2010; *Kollmann et al.*, 1975). It was reported that moist PB mat is plasticized under the effects of temperature and pressure in pressing, which results in a stable structure (Güler and Sanca, 2016; Sedano-Mendoza *et. al*., 2010). The moisture of mat PB before the hot pressing is one of the most important factors affecting the heat transfer within mat, as well as the properties of PB (Park *et al*., 1999).

In PB production, the mean mat moisture is calculated by taking the particle concentration and core layer moisture into consideration since the surface layers and core layer have different moisture contents. The mat moisture plays a significant role in the surface smoothness and soundness of PB, the bubbling on surface during the pressing, and the production costs. In case of too low moisture in particles, the resin is absorbed by the particles and there may be insufficient resin in the medium for the required adhesion level (Lynam, 1969; Akbulut, 1998). In this case, no sufficient bond can be established on the surface layers of boards, and the board surface becomes loose and weak. High moisture content, on the other hand, may cause the burst of board after the pressing procedure (Lynam, 1969). During the board production, the water is sometimes sprayed on the mat surfaces in order to shorten the pressing time, to eliminate the pre-hardening, and to improve the surface structure (Kollmann *et al*., 1975). If the mat contained too much moisture, the board would contain visible and open vapor bubbles. As a result of that, the parallel shear resistance of surface decreases, and the moisture content of board increases. In order to prevent or minimize such results, longer pressing is required (Lynam, 1969). It was reported that, prior to the pressing procedure, if the mean mat moisture is higher than 15-16 %, the moisture cannot be vaporized sufficiently by using a short pressing time for the boards with the density of 0.65 gr/cm^3 and, in addition to insufficient vaporization, the board will also burst from the core layer (Huş, 1979). In another study, it was emphasized that the high level of mat moisture content during the hot pressing procedure increased the formaldehyde emission (Kollman *et al*., 1975; Roffael, 1982). Nemli *et al*. (2007) reported that, in PB production, the mat moisture contents higher than 13 % caused lower technological properties in boards. In another study, it was found that the mat moisture content in MDF board production plays an important role in internal bond strength (IB) and thickness (Hague *et al*., 1999).

The aim of this study was to investigate the effects of mat moisture content on the physical and mechanical properties of PB, and to determine the ideal mat moisture content for 3-layered PB production. The ultimate aim was to increase the production quality and to decrease the costs.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The experimental boards used in this study were produced in a company's production line in Kastamonu, Turkey. All of the production parameters used in manufacturing the experimental boards are the same as those used in company's products; the materials consist of 40 % black pine (*Pinus nigra*), 30 % sessile oak (*Quercus petraea*), 15 % poplar (*Populus alba*), and 15 % sawdust (90 % pine-10 % poplar). Particles were dried at 170 °C by using rotary drum dryer to reach the target moisture content (MC) at 1 % – 2 %. Urea formaldehyde (UF), which was used as adhesive, consists of (62 ± 1) % solid matter and its pH is 8.2 pH. This material was also produced in the same facility. As a hardener, 20 % ammonium chloride (NH_4Cl) solution was used based on 2.5 % of resin solid weight for the core layers and 1 % of resin solid weight for the surface layers. The experimental boards were produced in multi opening press, and mat moisture contents are presented in Table 1, while the production conditions are specified in Table 2.

In determining the physical and mechanical properties of experimental boards, the Turkish standards that are compatible with European norms were used, and the results are presented in Table 3.

Table 1 Mat moisture content of experimental boards
Tablica 1. Sadržaj vode u istraživanim pločama

Board type *Vrsta ploče*	**Board replications** *Broj ploča*	**Mat moisture content, %** *Sadržaj vode, %*	
		Core layer *Središnji sloj*	**Outer layers** *Vanjski slojevi*
A	3	5.5	14
B	3	6	14
C	3	6.5	14
D	3	7	14
E	3	7.5	14
F	3	8	14
G	3	6.5	12
H	3	6.5	13
I	3	6.5	14
J	3	6.5	15
K	3	6.5	16
L	3	6.5	17

Table 2 Production conditions of experimental boards
Tablica 2. Uvjeti proizvodnje istraživanih ploča

Characteristics / *Svojstva*	**Production conditions** *Uvjeti proizvodnje*
Board thickness / *debljina ploče*, mm	18
Board width – length / *širina i duljina ploče*, mm	2100- 2800
Board density / *gustoća ploče*, kg/m^3	605
Core layer chip ratio / *udio iverja u središnjem sloju*, %	62
Bottom-top layer chip ratio / *udio iverja u gornjem i donjem sloju*, %	19-19
Press temperature / *temperatura prešanja*, °C	180
Press pressure / *tlak prešanja*, kg/cm^2	30
Total press time / *ukupno vrijeme prešanja*, s	180
Bottom-top layer resin ratio / *udio smole u gornjem i donjem sloju*, %	12
Core layer resin ratio / *udio smole u središnjem sloju*, %	8

Table 3 Test standards used to determine physical and mechanical properties
Tablica 3. Norme prema kojima su određena fizička i mehanička svojstva ploča

Sampling, cutting and inspection / *Uzorkovanje, krojenje i provjera*	TS EN 326-1 (1999)
Determination of density / *Određivanje gustoće*	TS EN 323 (1999)
Determination of swelling in thickness after immersion in water (2 hours) *Određivanje debljinskog bubrenja nakon potapanja u vodi (2 sata)*	TS EN 317 (1999)
Determination of tensile strength perpendicular to the plane of the board *Određivanje vlačne čvrstoće okomito na površinu ploče*	TS EN 319 (1999)
Determination of modulus of elasticity in bending and of bending strength *Određivanje čvrstoće na savijanje i modula elastičnosti čvrstoće na savijanje*	TS EN 310 (1999)
Determination of resistance to axial withdrawal of screws *Određivanje otpora pri okomitom vađenju vijaka*	TS EN 320 (2011)
Surface soundness / *Međuslojna čvrstoća*	TS EN 311 (2005)

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The effects of moisture content changes on the physical and mechanical properties were determined by keeping the mat moisture content of core layer at 6.5 % and by applying various moisture contents of bottom-top layers, and keeping the bottom-top layer moisture at 14 % and applying various moisture contents of core layer. The results are shown in Table 4.

When the mat moisture content of bottom-top and core layers was fixed at 14 % and 8 %, respectively, it was observed that the board generally burst at the end of hot press. Similarly, when the mat moisture of core layer was kept constant at 6.5 % and mat moisture contents of bottom-top layer were adjusted at 17 %, some of the boards burst when leaving the hot press in test production.

The densities of experimental boards were observed to vary between 600 and 609 kg/m^3, and the density differences between the boards were at negligibly low levels. It was reported that the boards with density differences less than 10 % (TS EN 312) would exhibit similar mechanical properties and remain within the same group of boards (İstek and Sıradağ, 2013). The effects of mat moisture content changes in particleboard production on the water absorption and swelling properties are presented in Figures 1 and 2.

As shown in Figure 1, as the top and bottom surface mat moisture contents increased from 12 % to 15 %, the water absorption characteristics of particleboards improved and increased again at 16 and 17 %

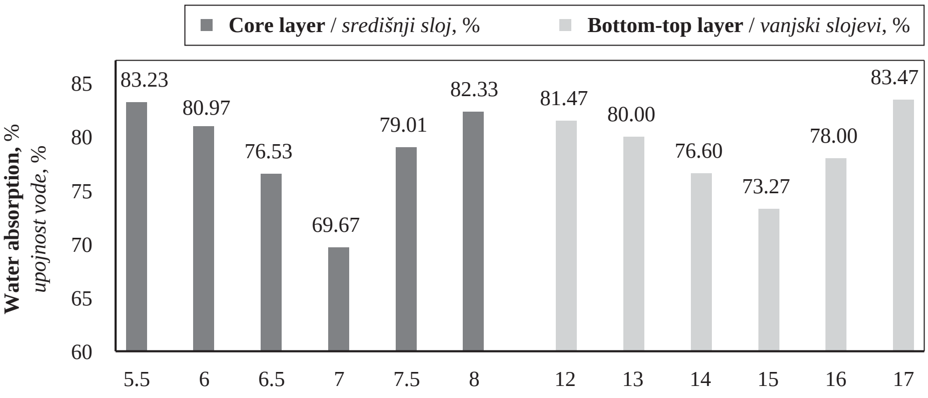

Figure 1 The effects of mat layers moisture content changes on water absorption (2h) characteristics
Slika 1. Utjecaj promjene sadržaja vode u slojevima ploče na upojnost vode (2h)

Table 4 Effects of mat moisture changes on particleboard properties
Tablica 4. Utjecaj promjene sadržaja vode u slojevima ploče na njezina svojstva

Moisture value *Sadržaj vode*, %		**Density** *Gustoća* kg/m³	**Water absorption (2h)** *Upojnost vode* (2h) %	**Thickness swelling (2h)** *Debljinsko bubrenje* (2h), %	**Internal bonding strength** *Čvrstoća raslojavanja* N/mm²	**Bending strength** *Čvrstoća na savijanje* N/mm²	**Modulus of elasticity in bending** *Modul elastičnosti pri savijanju* N/mm²	**Screw withdrawal** *Otpor vađenju vijaka* N/mm²	**Surface soundness** *Međuslojna čvrstoća* N/mm²
Mat moisture changes of core layer / *promjena sadržaja vode u središnjem sloju*	5.5	603 (4.58)	83.23 (1.66)	14.20 (0.17)	0.34 (0.02)	11.83 (0.15)	2140 (61.85)	526 (20.82)	0.94 (0.03)
	6	607 (2.65)	80.97 (0.25)	13.23 (0.25)	0.39 (0.02)	12.83 (0.15)	2315 (17.35)	623 (8.08)	1.13 (0.02)
	6.5	605 (1.15)	76.53 (1.14)	12.37 (0.12)	0.44 (0.01)	13.13 (0.29)	2424 (36.68)	630 (10.02)	1.08 (0.02)
	7	602 (2.52)	69.67 (1.53)	11.87 (0.15)	0.34 (0.03)	12.01 (0.20)	2136 (48.23)	593 (6.66)	0.94 (0.04)
	7.5	609 (2.65)	79.01 (2)	13.4 (0.53)	0.26 (0.02)	11.17 (0.12)	1972 (57.62)	514 (4.04)	0.80 (0.03)
	8	201	29.33	5.17	0.04	3.03	503	70	0.23
Mat moisture changes of bottom-top Layer / *promjena sadržaja vode u vanjskim slojevima*	12	602 (3)	81.47 (1.10)	13.03 (0.06)	0.35 (0.02)	11.27 (0.45)	2117 (2.52)	593 (3.51)	0.85 (0.03)
	13	608 (5.51)	80 (0.20)	12.80 (0.10)	0.38 (0.02)	12.17 (0.25)	2219 (6.66)	612 (2.52)	1.01 (0.04)
	14	605 (4.73)	76.60 (0.53)	12.43 (0.06)	0.41 (0.01)	12.70 (0.53)	2398 (41.62)	633 (5.29)	1.12 (0.03)
	15	605 (3)	73.27 (0.64)	12.10 (0.10)	0.38 (0.01)	12.83 (0.15)	2337 (7.64)	618 (1.53)	1.13 (0.02)
	16	600 (2.52)	78 (0.80)	12..73 (0.25)	0.35 (0.01)	12.93 (0.15)	2161 (4.58)	592 (2.65)	1.03 (0.02)
	17	402	55 (47.83)	9.50	0.17 (0.15)	6.87 (6.18)	986	277	0.55 (0.48)

The values in parentheses indicate the standard deviation. / *Vrijednosti u zagradama standardne su devijacije.*

moisture contents. As the mat moisture contents of core layer increased from 5.5 % to 7 %, the water absorption decreased and then increased again to 7.5 – 8 % moisture content level. The moisture content of the glued particle board sample should never exceed 10 – 13 % for core layer and 15 – 18 % for bottom-top layer, so that the moisture contents of core layer would not exceed the level of 13 % (Hus, 1979). Moreover, since the moisture cannot be sufficiently vaporized, this prevents the hardening of resin at core layer, the bonding between the particles in this section decreases and then the water absorption increases (Nemli *et al.*, 2007).

The effects of mat moisture content changes on the thickness swelling (2h) characteristics, as seen in Figure 2, show similarities with those on water absorption. Thus, by examining the effects of mat moisture content changes on the water absorption and thickness swelling, the optimal production conditions were determined to be 7 % for core layer moisture and 15 % for bottom-top layer moistures. It was reported that, when the mean mat moisture content increased from 13 % to 17 %, the thickness swelling was negatively affected (Nemli *et al.*, 2007). The effects of mat moisture changes in particleboard production on IB are presented in Figure 3.

Figure 3 indicated that, together with the increase of core layers mat moisture from 5.5 % to 6.5 %, it was determined that the IB strength of particleboard increased and started to decrease after 7 % moisture con-

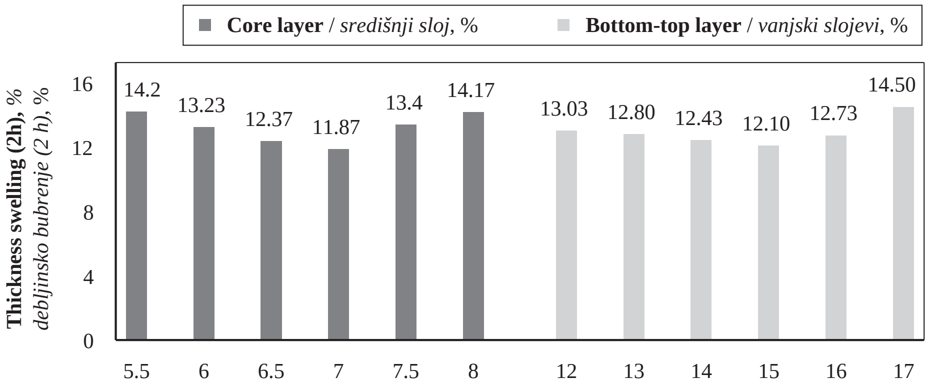

Figure 2 The effects of mat layers moisture content changes on thickness swelling (2h) characteristics
Slika 2. Utjecaj promjene sadržaja vode u slojevima ploče na debljinsko bubrenje (2h)

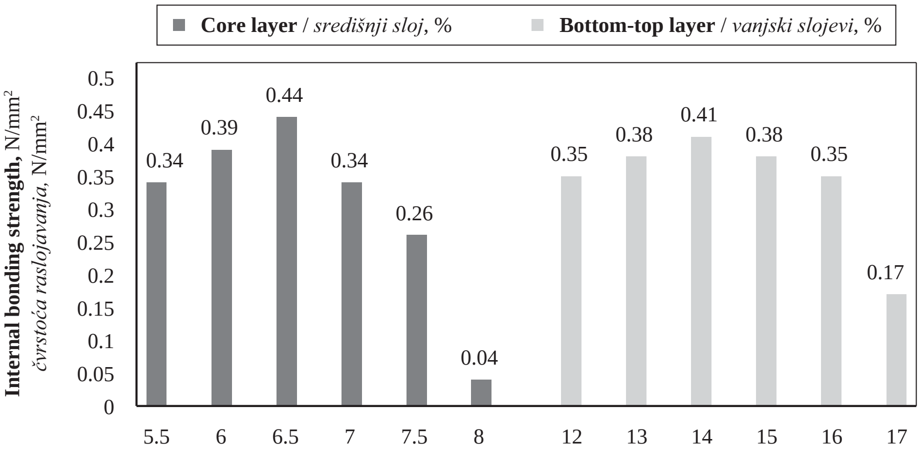

Figure 3 The effects of mat layers moisture changes on internal bonding strength
Slika 3. Utjecaj promjene sadržaja vode u slojevima ploče na čvrstoću raslojavanja

tent. Given the effect of mat moisture content change of bottom-top layer, the highest level of IB strength was observed to be 0.41 N/mm^2 at 14 % mat moisture content. According to TS-EN 312-1 (2012), P2-class 18 mm particleboards should have IB strength ≥ 0.35 N/mm^2. From this aspect, the highest level of IB strength was obtained at 6.5 % mat moisture for core layer and 14 % mat moisture for bottom-top layer. High level of moisture content at surface layers and low moisture content at core layer ensure soundness of surfaces and the increase in bending strength (BS) and MOE values, as well as the decrease in IB strength (Maloney, 1977). Moreover, with the increase of surface layers moisture from 12 % to 20 % and core layer moisture from 8 % to 10 %, the IB strength increased by 10 % (Bardak, 2010; Kollmann *et al*., 1975). The effects of mat moisture changes in particleboard production on BS are presented in Figure 4.

With the increase of mat moisture content from 5.5 % to 6.5 % in core layer, as seen in Figure 4 the BS of particleboard increased, while the BS decreased at 7 % and 8 % moisture contents. Besides that, with the increase of mat moisture contents from 12 % to 16 %, the BS was seen to increase, while it decreased at 17 %. The increase of surface layers moisture to a certain content causes the increase in surface density, hydrogen bonds, and formation of sounder surface structure. However, the decreasing MOE strength at moisture contents equal to and higher than 17 % can be explained with the non-removability of vapor from internal segments, as well as the absence of complete condensation. Nemli *et al*. (2007) reported that the BS values obtained at mean mat moisture of 17 % was lower than the value obtained at 9 % and 13 % mat moisture contents in particleboards. This was explained with the damage of resin bonds on the surface layers under the effects of vapor bubbles and hot pressure (Lynam, 1969; Johnson, 1956). In a study carried out by Hus (1979), it was reported that the total moisture of mat higher than 15 – 16 % before the pressing procedure increased the surface density, decreased the strength values, and caused the burst of board. The effects of mat moisture changes in particleboard production on modulus of MOE are presented in Figure 5. When the mat moisture content of top and bottom layer was between 18 % and 20 %, the maximum strength was achieved and the moisture exhibited the plasticizing effect (Bardak, 2010).

As seen in Figure 5, the MOE increased with the increase in mat moisture content of bottom-top layer from 12 % to 14 %, whereas it decreased together with the moisture content exceeding 15 %. Nemli *et al*. (2007) emphasized that the increase of mean mat moisture content of particleboards from 9 % to 13 % posi-

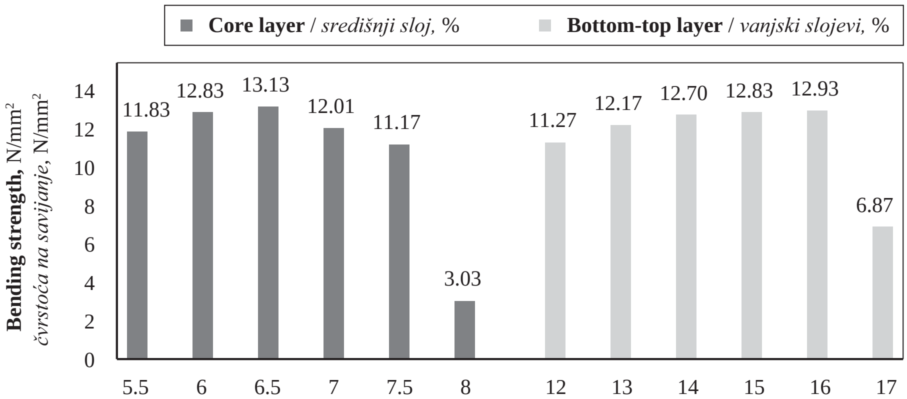

Figure 4 The effects of mat layers moisture changes on bending strength
Slika 4. Utjecaj promjene sadržaja vode u slojevima ploče na čvrstoću na savijanje

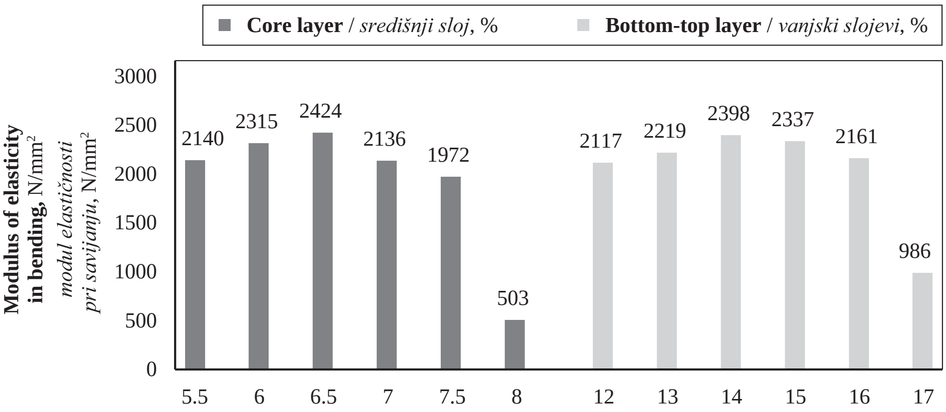

Figure 5 The effects of mat layers moisture changes on modulus of elasticity in bending
Slika 5. Utjecaj promjene sadržaja vode u slojevima ploče na modul elastičnosti pri savijanju

tively affected the MOE. According to TS-EN 312-1 (2012), the modulus of elasticity (MOE) of P2 class 18 mm particleboards should be ≥ 1600 N/mm^2. Similarly, with the increase of core layer moisture from 5.5 % to 6.5 %, MOE of particleboards increased and then decreased at 7.0 % and 8.0 % moisture contents. When the moisture content exceeded 8.0 %, some of the particleboards were observed to be not formed. The effects of mat moisture changes on the screw withdrawal are presented in Figure 6.

In case of high moisture in surface layers and low moisture in core layer, the surface layers are compressed more than core layer, and thus the BS and MOE levels increase in comparison to the uniform moisture samples, whereas the IB decreases. For this reason, the mean mat moisture content should be maintained within the acceptable limits in order to prevent the burst of boards after the pressing process (Maloney, 1977).

Under the production conditions of 8 % and 17 % core and bottom-top layer moisture contents, respectively, it was determined that the screw withdrawal characteristics do not meet the standard set in TS-EN 312-1 (2012) – the screw withdrawal of P2 class 18mm particleboards should be ≥ 450 N/mm^2 – but they meet the standards at other moisture contents. The highest

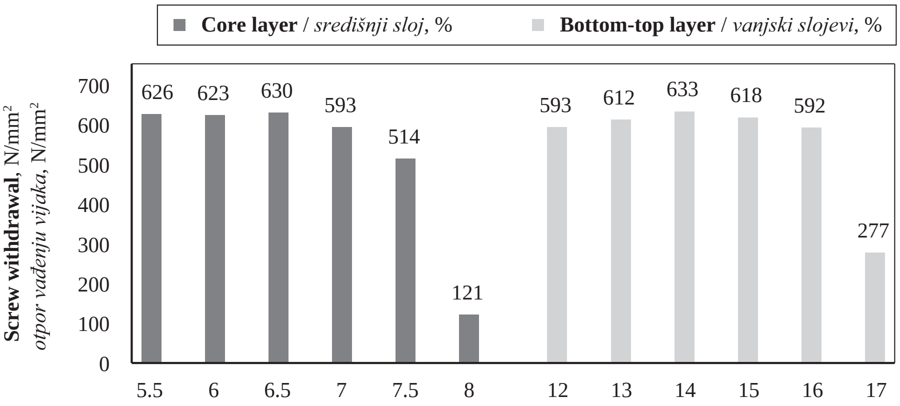

Figure 6 The effects of mat layers moisture changes on screw withdrawal
Slika 6. Utjecaj promjene sadržaja vode u slojevima ploče na otpor vađenju vijaka

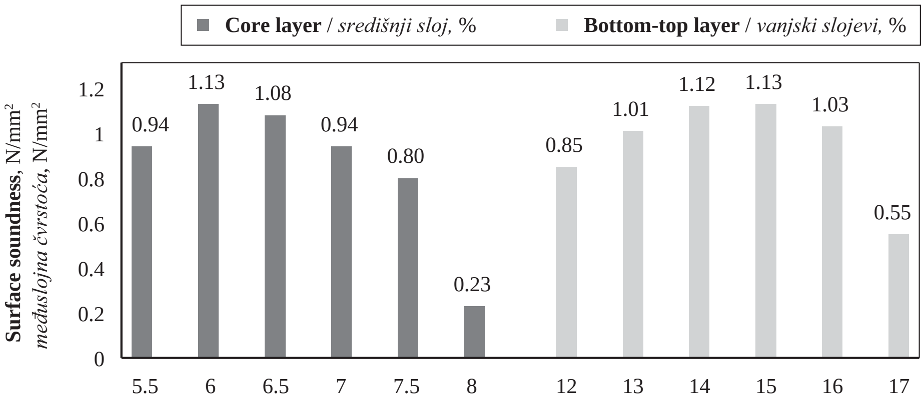

Figure 7 The effects of mat layers moisture changes on the surface soundness
Slika 7. Utjecaj promjene sadržaja vode u slojevima ploče na međuslojnu čvrstoću

level of screw withdrawal was observed at 6.5 % core layer moisture and 14 % bottom-top layer moisture as 630 N/mm^2 and 633 N/mm^2, respectively. It was reported that the mat moisture content change and the press closure speed have no statistically significant effect on the screw withdrawal (Wong *et al*., 1998). The effects of mat moisture changes on the surface soundness values are presented in Figure 7.

Under the production conditions of 8 % and 17 % core and bottom-top layer moisture contents, respectively, it was determined that the surface soundness level did not meet the TS-EN 312-1 (2012) quality control standards (≥ 0.8 N/mm^2 for P2 class 18 mm particleboard), but they meet the standards at other moisture contents. The highest level of surface soundness value was observed to be 1.13 N/mm^2 at 6 % core layer moisture and 15 % bottom-top layer moisture.

4 CONCLUSIONS
4. ZAKLJUČAK

Today, the particleboards of desired quality properties can be produced by means of technology and additives used in wood-based board production. In this study, carried out in order to contribute to the production of particleboard under the production principle “low-cost and high-quality”, the appropriate mat moisture contents were determined and the particleboard characteristics were expressed. Accordingly;

It was determined that the change of mat moisture content does not affect the density of boards.

It was reported that the production of particleboard is not possible in case of glued core layer moisture of 8 % and above and glued bottom-top layers moisture content of 17 % and above.

The water absorption and thickness swelling values of experimental boards reach at optimum moisture contents between 6 – 7 % in core layer. However, if the core layer moisture content exceeds 7 %, the IB, water absorption, and thickness swelling were observed to be negatively affected.

The optimum water absorption and thickness swelling values were observed at 12 – 16 % bottom-top layer moisture contents, while negative effects were observed on the IB strength and thickness swelling at contents higher than 16 %.

The highest level of BS was found to be 13.13 N/mm^2 under the circumstances of 6.5 % core layer moisture and it was found to be 12.93 N/mm^2 at 16 % bottom-top layer moisture.

Optimum MOE was found to be around 2300-2400 N/mm^2 under the condition of 6 – 6.5 % core layer moisture and 14 – 15 % bottom-top layer moisture.

The acceptable level of IB strength was determined to be 0.42 – 0.44 N/mm^2 at 6.5 % core layer moisture and 14 % bottom-top layer moisture. It was determined that the results obtained at 6 – 6.5 % core layer moisture and 12 – 16 % bottom-top layer moisture meet the quality standards of TS-EN 312-1 (2012).

The optimum level of screw withdrawal strength was found to be 620 N/mm^2 at 6 – 7 % core layer moisture contents. The interval between 12 % and 16 % top and bottom layer moisture contents were identified as a suitable range for screw withdrawal.

The 12 – 15 % top and bottom layer and 6 – 6.5 % core layer moisture contents were obtained as suitable range for surface soundness.

It was determined that the production of particleboard was not possible at ≥ 8 % core layer moisture and ≥ 17 % bottom-top layer moisture contents under the production conditions in this study. According to these findings, the ideal production conditions for particleboard quality were found to be 6 – 7 % core layer moisture content and 13 – 16 % bottom-top layer, when other production parameters were kept constant. Besides that, in case of ≥ 8 % core layer moisture and ≥ 17 % bottom-top layer moisture contents, it was determined that the board would burst and that quality standards could not be met during the pressing process of particleboard production.

5 REFERENCES
5. LITERATURA

1. Akbulut, T., 1998: The Effect of Formaldehyde/Urea Mole Ratio and Mat Moısture Content on Some Propertıes of Partıcleboards. Revıew of the Faculty of Forestry, Unıversıty of Istanbul, 48(2): 23-38.
2. Bardak, S., 2010: Bazı Faktörlerin Yongalevhanın Teknolojik Özellikleri Üzerine Etkileri (The Effects of Some Factors on the Technological Properties of Particleboard.). III. Ulusal Karadeniz Ormancılık Kongresi (III. National Black Sea Forestry Congress), vol. V: 1887-1898.
3. Chow, P.; Zhao, L., 1992: Medium-density fiberboard made from phenolic resin and wood residues of mixed species. Forest Products Journal, 42 (10): 65-67.
4. Güler, C.; Sancar, S., 2016: The Principle of a Particle Board Plant and The Effect of Pressing Techniques on Board Quality. Düzce University Journal of Forestry, 12 (1): 1-10.
5. Hague, J.; Robson, D.; Riepen, M., 1999: MDF process variables – An overview of their relative importance. In: Proc. of the 33th Inter. Particleboard/Composite Material Symp. T. M. Maloney (ed.). Washington State Univ., Pullman, WA.
6. Hata, T., 1993: Heat Flow in Particle Mat and Properties of Particleboard Under Steam Injection Pressing. Bull. For. and For. Prod. Res. Inst., No. 80. Japan. https://doi.org/10.11501/3070413.
7. Huş, S., 1979. Teknolojik Faktörlerin Yongalevhanın Özellikleri Üzerine Etkisi (The Effect of Technological Factors on the Properties of Particleboard). Review of the Faculty Forestry University of İstanbul, Series B, 29 (2): 1-9.
8. Istek A.; Sıradag, H., 2013: The Effect of Density on Particleboard Properties. International Caucasian Forestry Symposium, 932-938. (Edition No. 251261).
9. Istek, A.; Aydemir, D.; Aksu, S., 2010: The effect of décor paper and resin type on the physical, mechanical, and surface quality properties of particleboards coated with impregnated décor papers. BioResources, 5 (2): 1074-1083.
10. Johnson, E. C., 1956: Wood particleboard handbook. The industrial experimental program of the engineering. Raleigh (NC): North Coralina State College.

11. Kollmann, F.; Kuenzı, E. W.; Stam, A. S., 1975: Principles of Wood Science and Technology. Springer Verlag, Berlin, Heidelberg, New York.
12. Lynam, F. C. 1969: Factors influencing the properties of wood chipboard. In: Mitlin L. (ed.). Particleboard manufacture and applications. UK: Press media Books Ltd.
13. Maloney, T. M., 1977: Modern Particleboard and Dry-Process Fiberboard Manufacturing. Miller Freeman Publications, San Francisco-California.
14. Nemli, G.; Aydın, I.; Zekoviç, E., 2007: Evaluation of some of the properties of particleboard as function of manufacturing parameters. Materials and design, 28 (4): 1169-1176. https://doi.org/10.1016/j.matdes.2006.01.015.
15. Park, B. D.; Riedl, B.; Hsu, E. W.; Shields, J., 1999: Hot-pressing process optimization by response surface methodology. Forest Products Journal, 49 (5): 62-68.
16. RoffaeL, E., 1982: Formalclehyclahgabe von Spanplatten und anderen Werkstoffen. DRW Verlag, Stuttgart.
17. Sanabria, S. J.; Hilbers, U.; Neuenschwander, J.; Niemz, P.; Sennhauser, U.; Thömen, H.; Wenker, J. L., 2013: Modeling and prediction of density distribution and microstructure in particleboards from acoustic properties by correlation of non-contact high-resolution pulsed air-coupled ultrasound and X-ray images. Ultrasonics, 53 (1): 157-170. https://doi.org/10.1016/j.ultras.2012.05.004.
18. Sedano-Mendoza, M.; Navarrete, P.; Pizzi, A., 2010: Effect of layers' relative moisture content on the IB strength of pine tannin bonded particleboard. European Journal of Wood and Wood Products, 68 (3): 355-357. https://doi.org/10.1007/s00107-010-0452-8.
19. Wong, E. D.; Zhang, M.; Wang, Q.; Kawai, S., 1998: Effects of mat moisture content and press closing speed on the formation of density profile and properties of particleboard. Journal of Wood Science, 44 (4): 287-295. https://doi.org/10.1007/BF00581309.
20. ***TS EN 310, 1999 Wood – Based panels – Determination of modulus of elasticity in bending and of bending strength.
21. ***TS EN 311, 2005: Wood-based panels – Surface soundness – Test method.
22. ***TS EN 312, 2012: Particleboards – Specification.
23. ***TS EN 317, 1999: Particleboards and fibreboards – Determination of swelling in thickness after immersion in water.
24. ***TS EN 319, 1999: Particleboards and fibreboards – Determination of tensile strength perpendicular to the plane of the board.
25. ***TS EN 320, 2011: Particleboards and fibreboards – Determination of resistance to axial withdrawal of screws.
26. ***TS EN 323, 1999: Wood – Based panels – Determination of density.
27. ***TS EN 326-1, 1999: Wood – Based panels – Sampling, cutting and inspection, Part 1: Sampling test pieces and expression of test results.

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Polyglycerol- and Sucrose-based Green Polyurethane Adhesives for Veneering

Zelena poliuretanska ljepila za furniranje na bazi poliglicerola i saharoze

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ABSTRACT • *Veneering of particleboard with ABS foil and natural oak veneer was performed using polyglycerol- and sucrose-based polyurethane adhesives. Bonding strength between veneer and underlying board was determined according to EN 312 standard. Developed adhesive formulations exhibited bonding strengths between coating material and underlying board exceeding the surface soundness of particleboard (cohesive failure between 50 % and 100 %). Higher adhesion was found for natural oak veneers. Reactivity of the studied adhesives was comparable to those for commercial adhesives used in furniture industry. It has been demonstrated that bio-based polyols can be considered environmentally benign and efficient components of polyurethane adhesives for furniture industry.*

Keywords: *polyglycerol, polyol, polyurethane, sucrose, veneering*

SAŽETAK • *Furniranje ploča od usitnjenog drva ABS folijama i hrastovim furnirom provedeno je uz primjenu poliuretanskih ljepila na bazi poliglicerola i saharoze. Čvrstoća lijepljenja furnira na ploču određena je prema normi EN 312. Razvijenim formulacijama ljepila postignute su veće čvrstoće lijepljenja između prevlake i ploče nego što je međuslojna čvrstoća ploče od usitnjenog drva (kohezijski lom između 50 i 100 %). Veća adhezija zabilježena je na hrastovim furnirima. Reaktivnost ispitivanih ljepila bila je usporediva s komercijalnim ljepilima koja se upotrebljavaju u industriji namještaja. Utvrđeno je da se polioli na prirodnoj bazi mogu smatrati ekološki prihvatljivim komponentama poliuretanskih ljepila za industriju namještaja.*

Ključne riječi: *poligl icerol, poliol, poliuretan, saharoza, furniranje*

1 INTRODUCTION
1. UVOD

Nowadays, the principles of green chemistry and concept of sustainable development impose research and industrial implementation of the materials derived from renewable feedstock. Bioplastics or bio-based polymers seem to be the solutions of tomorrow, so that novel materials employing renewable resources are considered to be alternatives for oil-derived raw materials (Mamiński and Toczyłowska-Mamińska, 2017).

Technology of today and modern industrial operations are expected to comply with the principles of green chemistry, so that the impact on environment has been reduced. Increasing demand on greener products results in the development of renewable feedstock-based materials, including adhesives, wherever technically feasible.

These days intense development of furniture industry is observed. In Poland only market value reached 9.5 bln euro in 2016 and is expected to reach 11.1 bln euro in 2020 (KMPG, 2017). Furniture is mostly made of veneered wood-based panels like par-

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ticleboard and fiberboard. Thus, due to high volume of the materials used in veneering, they have substantial impact on the environment. One of the approaches to increase environmental friendiness of furniture production is asymmetrical veneering that was described for the first time long time ago by Hayward (1949). When properly implemented, it results in the reduction of production costs and reduced demand for wood of valuable species. It was demonstrated in the literature that mechanical and physico-chemical properties of the substrates subjected to adhesive bonding strongly affected the tendency of the 'veneer-adhesive-board' system to deformations (Oleńska *et al.*, 2014; Král *et al.*, 2013). It has been confirmed that the type of the adhesive has an effect on product durability and stability of its shape. As previously shown, polyurethanes combine excellent adhesive properties with elasticity providing reduced deflection in veneered materials (Mamiński *et al*., 2011; Oleńska *et al*., 2014). Therefore, a research on novel types of environmentally friendly adhesives is fully justified.

Glycerol is an environmental-friendly resource that can be readily transformed into a number of chemicals including polymers. One of the pathways is conversion of glycerol into polyglycerols (Rokicki *et al.*, 2005). Hyperbranched polyglycerols have been shown to be effective components of polyurethane (PUR) adhesives for wood bonding (Mamiński *et al.,* 2011; Mamiński *et al.*, 2012).

Sucrose is another cheap, easily available and renewable resource that can be conveniently converted into a variety of semi-products for industrial applications – including sucrose-based polyols for PUR (Ionescu and Petrović, 2010).

The present study deals with the use of sucrose-based and polyglycerol-based polyols in polyurethane adhesives to replace petroleum-derived ones. Typical areas of use of the sucrose-based polyols are insulating foams, elastomers and thermoplastic polyurethanes. Neither former nor latter have ever been used solely as polyol components in PUR adhesives for veneering. Thus, the aim of the present study is to maximize the content of polyols derived from renewable resources in the adhesives dedicated to furniture industry. Therefore, the investigated polyols were not used in mixtures with other types of polyhydroxyl compounds. The PUR adhesives were examined as binders in particleboard veneering for furniture manufacturing. The practical applicability of the sucrose- and polyglycerol-based polyols in polyurethane formulation has been demonstrated and, thus, they may be considered significant green resources in the future.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Two types of coating materials were employed in experiments: 0.6 mm thick oak veneer and 0.4 mm thick decorative ABS veneer.

Three green polyols were used in the study: a hyperbranched polyglycerol (A) and two commercially available propoxylated sucrose polyols C (yellow liquid, viscosity 7050 mPa·s at 20 °C, hydroxyl number 425 mg KOH/g, hydroxyl functionality 5) and J (transparent liquid, viscosity 6360 mPa·s at 25 °C, 422 mg KOH/g, hydroxyl functionality 4.5) both manufactured by Oltchim (Romania).

Polyglycerol A was synthesized according to the procedure described by Rokicki et al. (2005) from glycerol carbonate (4-hydroxymethyl-1,3-dioxolane-2-on) and 1,1,1-tris(hydroxymethyl)-propane (10/1, mol/mol). The product was a brown liquid of viscosity of 9100 mPa·s at 20 °C, hydroxyl number 735 mg KOH/g and hydroxyl functionality 13. Polymeric methylenediphenyldiisocyanate (PMDI, NCO content 36 %) manufactured by (Huntsman Co., USA) was used as obtained.

2.1 Adhesive preparation
2.1. Priprema ljepila

The amount of PMDI in PUR was calculated using the formula (1) (Monument Chemical, 2014), in which polyol amount and hydroxyl number are taken into account. NCO index is a molar NCO/OH ratio. When the number of NCO groups equals the number of OH groups, NCO index is 1.0. If more than one polyol is used in a formulation, the sum of weights multiplied by hydroxyl numbers are placed in the numerator in Eq. 1.

$$m_{\mathrm{iso}} = \left(\frac{\sum m_{\mathrm{polyol}} \times L_{\mathrm{OH}}}{56100} \right) \cdot \frac{4202}{c_{\mathrm{iso}}} \tag{1}$$

Where:

m_{iso} – stoichiometric amount of isocyanate for NCO index 1.0 (g),
m_{polyol} – amount of polyol (g),
L_{OH} – polyol hydroxyl number (mg KOH/g),
c_{iso} – NCO content in PMDI (%wt).

Target NCO index was 1.0. Weighted amounts of the polyol and isocyanate components were mixed in a plastic cup for 5 seconds using a high-speed mixer. Tin octanoate $Sn(Oct)_2$ was used as catalyst (0.05 %wt).

2.2 Veneering
2.2. Furniranje

The adhesive was applied on the substrate (300 mm × 300 mm × 16 mm particleboard) in the quantity of 200 g/m^2, and then veneer was placed onto the adhesive and pressed (60 °C, 1.0 MPa, 4 minutes). Specimens were conditioned at (20±2) °C and (65±5) % relative humidity for 7 days before testing.

2.2 Pull-off test
2.2. *Pull-off* ispitivanje

The strength of bonding between the coating material and the underlying board was determined from the pull-off test performed according to the European standard EN 311 24 hours after bonding steel pad with hot-melt adhesive onto the surface. The Eq. (2) was used to calculate the bondline strength (*R*).

$$R = \frac{F_{\max}}{S} \tag{2}$$

Where:

F_{max} – maximum force (N),
S – surface area (mm^2).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 PUR reactivity
3.1. Reaktivnost poliuretanskog ljepila

The polyurethane chemistry is mainly based on the reaction of an isocyanate group (NCO) with compounds with active hydrogen atoms, i.e. hydroxy and amine groups, and water. The relative reactivity of the isocyanate group (NCO) toward hydroxyls varies substantially. According to Lay and Cranley (1994) under conditions without a catalyst, the relative reaction rates for primary hydroxyl groups is about 100, while that for secondary hydroxyl groups is about 30. However, the use of appropriately selected catalysts can radically change these values, as well as the order of reactivity (Britain and Gemeinhardt, 1960). It is commonly agreed that chemical structure and hydroxyl functionality of the polyol also have a strong effect on such adhesive properties like gelling time and mechanical properties of bondline. On the other hand, strength of a polymer is determined by the stiffness, hardness and density of crosslinking (Suo, 1990). That is why the chemical structure of a polyol is an important parameter that affects polyurethane gelling time and its mechanical properties.

The basic properties of PURs used in the study are shown in Table 1. The polyols C and J may seem much alike and close in characteristics; however, slightly different OH functionality (5 vs 4.5, respectively, for C and J) was expected to yield different behavior. It is reported in the literature that physical and mechanical properties of polyurethane materials are largely associated with cross-linking density (Dong *et al.*, 2011; Maji and Bhowmick, 2009). The results indicate that reactivity of the PURs is adequate for industrial processing and the adhesives systems are suitable for veneering. What is more important, the gelling time will be markedly shortened under true industrial process, where applied temperature is much above ambient and usually ranging between 60 °C and 150 °C depending on the adhesive. The gelling tests performed at 80 °C revealed that the catalyzed adhesive I gelled in just 45 seconds. Thus, it is clear that short, industrially practical pressing times can be obtained after proper tuning of PUR formulations. Data in Table 1 indicate the effect of hydroxyl functionality on the gelling time of the formulations. The adhesive containing 13-functional polyglycerol A exhibited higher reactivity at 20 °C when compared to 5- and 4.5-functional sucrose-based polyols C and J. The phenomenon confirms the influence of hydroxyl groups abundancy on curing rate and network formation in PUR (Sonnenschein and Wendt, 2005).

3.2 Veneering and pull-off test
3.2. Furniranje i *pull-off* ispitivanje

In order to shorten pressing time, initial veneering was performed at 87 °C; however, due to too high temperature and plasticizing of the ABS, foil bubble forming occurred (Figure 1) which is an apparent and unacceptable defect in veneering. The phenomenon did not occur for natural oak veneers. Lowering the temperature to 60 °C improved the veneering quality, so that flat, smooth and non-defective surface was produced.

Table 1 Formulations and gelling times of the investigated PURs
Tablica 1. Formulacije i vrijeme želiranja istraživanih poliuretanskih ljepila

Adhesive *Ljepilo*	**Polyol** *Poliol*	**Isocyanate** *Izocijanat*	**NCO index** *NCO indeks*	**Gelling time at 20 °C, min** / *Vrijeme želiranja pri 20* °C, min	
				Catalyzed / *Kataliziran*	**Non-catalyzed** / *Nekataliziran*
I	A	PMDI	1.0	8.5	50
II	C	PMDI	1.0	10	> 60
III	J	PMDI	1.0	10	> 60

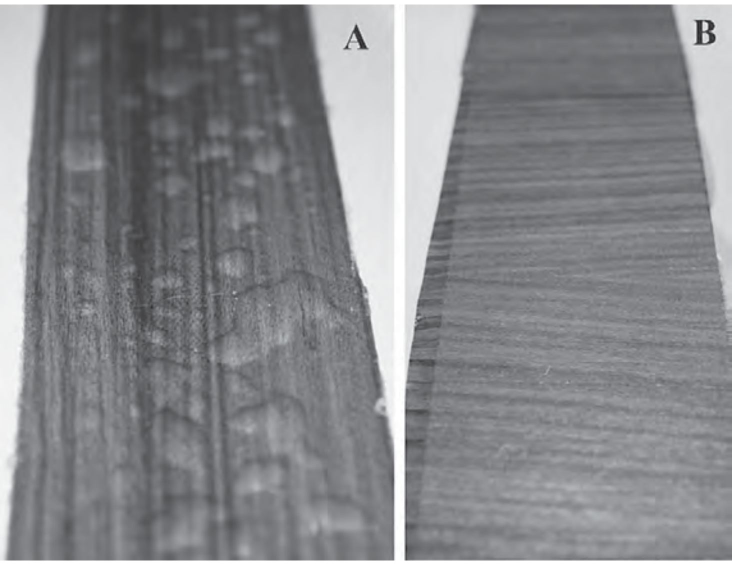

Figure 1 A – bubble forming under ABS foil (pressing at 87 °C) and B – avoided bubbling (pressing at 60 °C)
Slika 1. A – stvaranje mjehura ispod ABS folije (prešanje pri 87 °C), B – folija bez mjehuranja (prešanje pri 60 °C)

Table 2 Results of bonding strength determined according EN 311
Tablica 2. Rezultati čvrstoće lijepljenja određene prema EN 311

Adhesive *Ljepilo*	**Veneer** *Furnir*	**R**	**Cohesive failure in particleboard** *Kohezijski lom u ploči od usitnjenog drva*
		MPa	%
I	ABS	0.21±0.08	0
	Oak / *hrast*	0.23 ±0.05	0
II	ABS	0.51±0.12	50
	Oak / *hrast*	0.31±0.10	0
III	ABS	0.41±0.11	80
	Oak / *hrast*	0.44±0.10	100

Subsequently, specimens for pull-off tests were veneered at 60 °C (Figure 2). The results of determination of bonding strength in veneer-particleboard system are shown in Table 2. It can be seen that the adhesive I yielded the lowest bondline strengths and neither for ABS nor for oak veneer cohesive failure occurred. Thus, it is apparent that polyglycerol-polyol provided poor mechanical performance, which can be associated with high cross-link density in polymer due to hydroxyl functionality as high as 13. It has been reported in the literature that too high cross-linking results in lowered mechanical performance of PUR (Dong *et al*., 2011; Maji and Bhowmick, 2009).

On the other hand, adhesives II and III, both based on sucrose-polyols, rendered higher strengths. The observed *R* values ranged between 0.31 MPa and 0.51 MPa, while cohesive failure rates varied from 50 % to 100 % (Figure 3). Such low surface soundness of particleboard was surprising as the minimum requirement for commercial particleboard defined in EN 312 is 0.8 MPa. However, apparently the adhesives II and III are comparable in terms of veneer bonding quality, and adhesion to ABS and oak veneers is probably similar.

Hence, it is clear that, contrary to initial expectations, hydroxyl functionality of C and J polyols (5 and 4.5, respectively) had no effect on mechanical performance of bondlines.

The findings discussed above indicate that glycerol- and sucrose-based polyols can be considered perspective components of PUR adhesives; however, there is still a need for proper formulation of adhesives. When properly formulated, polyurethanes based on PMDI and green polyols, derived from renewable glycerol and sucrose, can be potentially used as binders in veneering at industrial scale

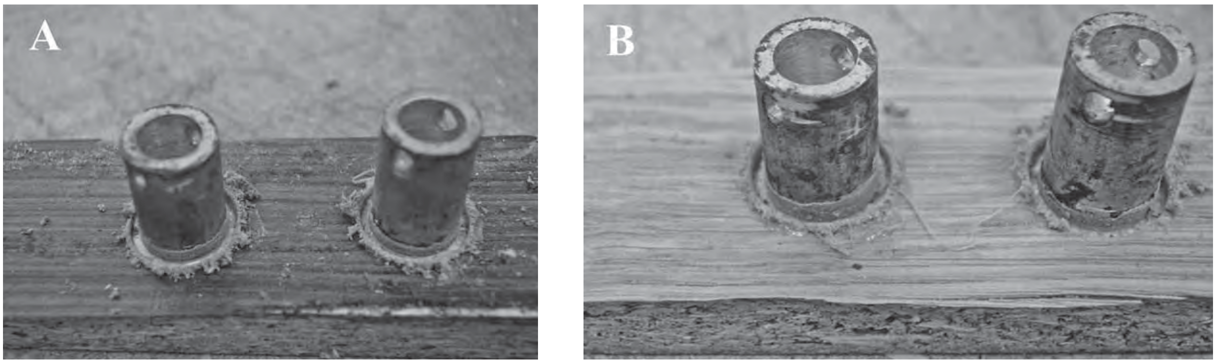

Figure 2 Specimens prepared for pull-off test: A – ABS veneer, B – oak veneer
Slika 2. Uzorci pripremljeni za *pull-off* ispitivanje: A – ABS, B – hrastov furnir

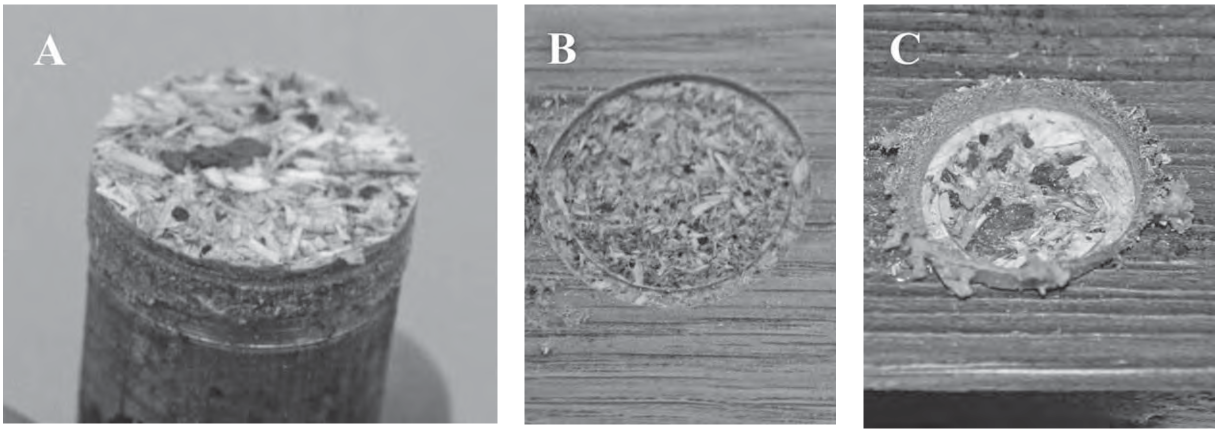

Figure 3 Pull-off tests: cohesive failure in particleboard: A – steel pad, B – oak veneer, C – ABS veneer
Slika 3. *Pull-off* ispitivanje: kohezijski lom u ploči od usitnjenog drva: A – čelični čepić, B – hrastov furnir, C – ABS

4 CONCLUSIONS
4. ZAKLJUČAK

It was demonstrated that the proposed PUR formulations exhibited practically useful reactivity as well as satisfactory strengths of bonding between coating material and underlying board. Therefore, it can be concluded that polyglycerol- and sucrose-based biopolyols are environmentally-benign, efficient and prospective components of polyurethane adhesives that may substitute petroleum-based polyols in furniture industry.

Further research should be focused on optimization of veneering conditions (temperature, pressure, time), so as to minimize the occurrence of defects (e.g. bubbles).

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5 REFERENCES
5. LITERATURA

1. Britain, J. W.; Gemeinhardt, P. G., 1960: Catalysis of the isocyanate-hydroxyl reaction. Journal of Applied Polymer Science, 4: 207-211. http://dx.doi.org/10.1002/app.1960.070041112.
2. Dong, L.; Liu, B.; Xu, L.; Budziński, K. L.; Shou C., 2011: Synthesis of hyperbranched polyester-amides and their application as crosslinkers for polyurethane curing systems. Journal of Applied Polymer Science, 121: 957-963. http://dx.doi.org/10.1002/app.33678.
3. Hayward, C., 1949: Practical veneering. Bell & Hyman, London.
4. Ionescu, M.; Petrović, Z. S., 2010: High Functionality Polyether Polyols Based on Polyglycerol. Journal of Cellular Plastics, 46: 223-237. http://dx.doi.org/10.1177/0021955X09355887.
5. Lay, D. G.; Cranley, P., 1994: Polyurethane adhesives. Pizzi, A. and Mittal, K. L. (eds.). Handbook of adhesive technology. Marcel Dekker, New York.
6. Král, P.; Hrázský, J.; Hrapková, L.; Hamšík, P., 2013: Shape Stability of Particleboards Covered with Decorative Veneers. Drvna industrija, 64: 211-220. http://dx.doi.org/10.5552/drind.2013.1234.
7. Maji, K. P.; Bhowmick, A. K., 2009: Influence of number of functional groups of hyperbranched polyol on cure kinetics and physical properties of polyurethanes. Journal of Polymer Science, Part A: Polymer Chemistry, 47: 731-745. http://dx.doi.org/10.1002/pola.23185.
8. Mamiński, M.; Parzuchowski, P.; Trojanowska, A.; Dziewulski, Sz., 2011: Fast-curing polyurethane adhesives derived from environmentally friendly hyperbranched polyglycerols – the effect of macromonomer structure. Biomass and Bioenergy, 35: 4461-4468. http://dx.doi.org/10.1016/j.biombioe.2011.09.012.
9. Mamiński, M. Ł.; Szymański, R.; Parzuchowski, P.; Antczak, A.; Szymona, K., 2012: Hyperbranched polyglycerols with bisphenol A core as glycerol-derived components of polyurethane wood adhesives. BioResources, 7: 1440-1451. http://dx.doi.org/10.15376/biores.7.2.1440-1451.
10. Mamiński, M. Ł.; Toczyłowska-Mamińska, R., 2017: Bio-derived adhesives and matrix polymers for composites. Thakur, V. K.; Thakur, M. K.; Kessler, M. R. (eds.). Handbook of composites from renewable materials, Vol. 1: Structure and Chemistry Wiley-Scrivener, pp. 151-188. http://dx.doi.org/10.1002/9781119441632.ch7.
11. Oleńska, S.; Tarcicki, P.; Mamiński, M.; Beer P., 2014: Effectiveness of asymmetrical veneering with hardwood species of varying shrinkage and porosity. Drvna industrija, 65: 139-142. http://dx.doi.org/10.5552/drind.2014.1315.
12. Rokicki, G.; Rakoczy, P.; Parzuchowski, P.; Sobiecki, M., 2005: Hyperbranched aliphatic polyethers obtained from environmentally benign monomer: glycerol carbonate. Green Chemistry, 7: 529-539. http://dx.doi.org/10.1039/b501597a.
13. Sonnenschein, M. F.; Wendt, B. L., 2005: Efficacy of polymeric MDI/Polyol mixtures for binding wood boards. Wood Science and Technology, 39: 27-36. http://dx.doi.org/10.1007/s00226-004-0266-0.
14. Suo, Z., 1990: Failure of brittle adhesive joint. Applied Mechanics Reviews, 43: 276-279. http://dx.doi.org/10.1115/1.3120827.
15. ***EN 311: 2002 Wood-based panels – Surface soundness – Test metod.
16. ***EN 312: 2004 Particleboards – Specifications.
17. ***Monument Chemical Kentucky LCC, Terms and formulas used in urethane polymer preparations, July 2014 http://www.pmahome.org/files/5314/1460/1437/Urethane_terms_NEW.pdf. (Accessed June 20, 2018).
18. ***KMPG, Rynek meblarski w Polsce – raport (in Polish), June 2017. https://assets.kpmg.com/content/dam/kpmg/pl/pdf/2017/06/pl-Raport-KPMG-Rynek-meblarski-w-Polsce-2017.pdf. (Accessed June 21, 2018).

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Znanje je naš kapital
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Physico-Mechanical Properties of Thermally Modified *Eucalyptus Nitens* Wood for Decking Applications

Fizička i mehanička svojstva toplinski modificiranog drva *Eucalyptus nitens* za vanjske podne obloge

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ABSTRACT • *Eucalyptus nitens is a fast growing plantation species that has a good acclimation in Spain and Chile. At the moment it is mainly used for pulp and paper production, but there is a growing market for solid wood products made from this species. Thermal modification offers a good alternative to produce high quality material to manufacture products with high added value. This study used unmodified and thermally modified E. nitens wood from Spanish and Chilean plantations to elaborate external decking and examine if it complies with the necessary properties to be a competitive product. A process similar to ThermoWood® was applied at the following temperatures: 185 °C, 200 °C and 215 °C. For each modification and for an unmodified specimen mass loss, volumetric swelling, anti-swelling efficiency (ASE) and equilibrium moisture content (EMC) were determined. Brinell hardness, dynamic hardness, screw and nail withdrawal resistance, and abrasion resistance according to the Shaker method and the Taber Abraser method were also determined. According to this study, thermally modified E. nitens from both countries showed high potential to be used as decking material, particularly when modified at 200 °C.*

Keywords: *Eucalypt, anti-swelling efficiency (ASE), hardness, abrasion resistance, timber*

SAŽETAK • *Eukaliptus nitens brzo je rastuća plantažna vrsta koja se dobro prilagodila klimi u Španjolskoj i Čileu. Trenutačno se uglavnom iskorištava za proizvodnju celuloze i papira, ali sve je veće tržište proizvoda izrađenih od masivnog drva te vrste. Toplinskom modifikacijom dobiva sa dobra alternativa za proizvodnju visokokvalitetnih proizvoda s visokom dodanom vrijednošću. U ovom je istraživanju kao materijal za vanjske podne obloge upotrijebljeno nemodificirano i toplinski modificirano drvo E. nitens sa španjolskih i čileanskih plantaža te je ispitana njegova sukladnost sa svojstvima potrebnima za postizanje konkurentnosti. Primijenjen je postupak sličan procesu ThermoWood®, i to pri temperaturama 185, 200 i 215 °C. Za svaki modificirani i nemodificirani uzorak određen je gubitak mase, volumno bubrenje, učinak smanjenja bubrenja (ASE) i ravnotežni sadržaj vode (EMC). Određene su i tvrdoća prema Brinellu, dinamička tvrdoća, otpornost na izvlačenje vijaka i čavala te otpornost na*

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habanje prema metodama Shaker i Taber abraser. Na temelju ovog istraživanja može se zaključiti da su toplinski modificirani uzorci drva E. nitens iz obje zemlje pokazali visok potencijal za uporabu u obliku vanjskih podnih obloga, posebice ako su modificirani pri 200 °C.

Ključne riječi: *eukalipt, učinak smanjenja bubrenja (ASE), tvrdoća, otpornost na habanje, drvo*

1 INTRODUCTION
1. UVOD

In the last 30 years there has been a steady growth of Eucalyptus nitens plantations in south of Chile and in the region of Galicia in Spain, as it is a species with great adaptability to frost and colder climate conditions. In Chile, there are about 250,000 ha planted as of 2014 (INFOR, 2015), while in Spain no official data are available. Only the current review for the Forestry Plan of Galicia (Xunta de Galicia, 2018), which analyzed the Spanish Forestry Inventory, and the Spanish Forestry Map suggested for *E. nitens* in this region forests of approximately 40,000 ha, and proposed an increase of 30.000 ha during the next 20 years. However, this number should be higher, as *E. nitens* plantations have been replacing *E. globulus* plantations due to its higher resistance against pathogens and cold.

Currently, *E. nitens* plantation wood is mostly used for pulp and paper or biofuels, but there is an interest to widen the use of this fast growing tree species. Solid wood made out of plantation *E. nitens* is being sold at the moment in Chile, but it cannot compete with other fast growing species, as the volume of plantations of radiata pine in Chile (INFOR, 2015) allows the species to maintain a competitive low price. As for Spain, there is still no market for dry *E. nitens* solid wood, but similar species (*E. globulus*). Thermal modification offers a good alternative to produce high quality material from this species that could be used for decking, claddings, windows, doors, flooring, garden products and even saunas or bathrooms (Militz and Altgen, 2014). Most thermal modification processes apply temperatures between 160 °C and 240 °C and limit the oxygen content during the process (Hill, 2006; Esteves and Pereira, 2009; Militz and Altgen, 2014). *E. nitens* (durability class 4, Australian Standard 5604 2005) and other eucalypt species, such as *E. globulus, E. grandis, E. regnans and E. pellita* (durability in ground contact class 3 – 4, Australian Standard 5604 2005), have been used as material for thermal modification (Esteves *et al*., 2007a; Esteves *et al*., 2007b; González-Prieto and Touza Vázquez, 2009; Calonego *et al*., 2012; Wang *et al*., 2014; de Cademartori *et al*., 2015; Wentzel *et al*. 2019). In most cases research has been focused on the variation of color, the changes of the mechanical and physical properties and variations of the chemical composition.

In Eucalypt species, durability increases after thermal modification, as it has been shown in the resistance against the brown rot fungus *Gloeophyllum trabeum* for modified *E. globulus* from durability class 3 (DC 3, moderately durable) to DC 1 (very durable) (González-Prieto and Touza Vázquez, 2009). Changes in mechanical properties of thermally modified Eucalypt species, such as a slight increase of *MOE* and a decrease in *MOR* (Table 1), were not a detriment of the potential for using this species for outdoor materials (Esteves *et al*., 2007a; Calonego *et al*., 2012;de Cademartori *et al*., 2015; Knapic *et al*., 2018; Wentzel *et al*., 2019), as the *MOE* and *MOR* were still higher than those of commonly used WPC boards (Dias and Alvarez, 2017), a material commonly used for decking production (Zeller, 2018).

Currently, tropical woods such as Bangkirai (*Shorea laevis*), IPE-Lapacho (*Tabulea* spp.) or European-grown timbers such as Douglas fir (*Pseudotsuga menziesii*) and Larch (*Larix* spp.), and preservative treated pine are the most commonly used materials for decking. In addition to these traditional decking materials in Europe, wood polymer composite (WPC) decking is gaining market share throughout Europe (Zeller, 2018) not at least due to their good capabilities to suppress the moisture uptake and resulting moisture movements, but also due to the thermal conductivity of polymers. Thermal modification improves natural durability and dimensional stability, and decreases the equilibrium moisture content (*EMC*) of wood (Stamm and Hansen, 1937; Hill, 2006; Esteves and Pereira, 2009). Živković *et al*. (2008) used thermally modified ash (*Fraxinus* spp.) and beech (*Fagus sylvatica*) as flooring elements. When compared to unmodified wood, it showed a lower *EMC* in room conditions and an improvement in dimensional stability.

Thermal modification also leads to an embrittlement of wood coming along with reduced abrasion resistance and the risk of splintering on the wood surface (Kubojima *et al*., 2000; Phuong *et al*., 2007). Surface hardness and resistance to abrasion are critical properties in less and non-load-bearing applications. In the case of decking, surface hardness turns into a decisive property for its use (Brischke *et al*., 2005). Welzbacher *et al*. (2009) showed that thermally treated beech and larch heartwood (*Larix decidua*) presented less abrasion and crack formation in relation to the unmodified wood, but showed long term discoloration by weathering. It is also important to consider how to connect the wood when installing the material. For outside use of thermally modified wood, it is recommended to use stainless screws and embedding screw heads (Aytin *et al*., 2015).

In this study the abrasion resistance, hardness (Brinell and dynamic), screw withdrawal resistance (*SWR*), maximum swelling, anti-swelling efficiency (*ASE*) and equilibrium moisture content (*EMC*) of thermally modified Eucalypt were determined since they are critical characteristics of outdoor exposed decking.

Table 1 Highest and lowest *MOE* and *MOR* from various thermally treated Eucalypts under different process conditions and their respective control values of unmodified specimens
Tablica 1. Najveći i najmanji modul elastičnosti i modul loma različitih toplinski obrađenih eukalipta pri različitim uvjetima obrade i vrijednosti njihovih nemodificiranih uzoraka

Species *Vrsta*	**Thermal modification** *Toplinska modifikacija*	**Temperature, °C** *Temperatura, °C*		***MOE* Unmodified specimen, MPa** *MOE nemodificiranih uzoraka*, MPa	***MOR* Unmodified specimen, MPa** *MOR nemodificiranih uzoraka*, MPa	***MOE*,** MPa		***MOR*,** MPa		**Reference** *Literatura*
		min	max			min	max	min	max	
E. nitens	Laboratory scale reactor (atmospheric pressure) *laboratorijski reaktor (atmosferski tlak)*	160	230	18449	119	14604	22224	88	134	Wentzel *et al.*, 2019
E. nitens	Laboratory scale reactor (high pressure) *laboratorijski reaktor (visoki tlak)*	150	170	18449	119	14464	16131	85	117	*Wentzel et al.*, 2019
E. grandis	Modified autoclave (air atmosphere) *modificirani autoklav (zračna atmosfera)*	180	240	12097	89	10623	12091	69	41	de Cademartori *et al.*, 2015
E. saligna	Modified autoclave (air atmosphere) *modificirani autoklav (zračna atmosfera)*	180	240	12869	90	12568	12805	75	47	de Cademartori *et al.*, 2015
E. grandis	Modified laboratory oven / *modificirani laboratorijski sušionik*	140	220	12800	69	12100	12400	65	33	Calonego *et al.*, 2012
E. globulus	Modified laboratory oven / *modificirani laboratorijski sušionik*	170	200	14197	-	10647	14339	-	-	Esteves *et al.*, 2007a
E. globulus	Modified laboratory oven / *modificirani laboratorijski sušionik*	-	210	13909	111	-	13379	-	102	Knapic *et al.*, 2018

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Material
2.1. Materijal

The Chilean *E. nitens* wood came from 19 year old plantations from the Región del Bío-Bío in Chile, while the wood from Spain came from 16 year old plantations from the north of the province of Lugo in Galicia. The wood specimens were taken randomly from piles of industrially dried wood from general production lines from sawmills in Chile and Spain, which is why the humidity was different at the same laboratory conditions before modification and there was a difference in their respective thickness. Flat sawn slats of 20 mm × 60 mm × 6 50 mm and 30 mm × 50 mm × 650 mm (radial × tangential × longitudinal) size, for the Chilean and Spanish origin, respectively, were prepared from kiln-dried wood free of large knots. Before the modification process, the slats from Chile had an average moisture content of 13 %, whereas the ones from Spain had an average of 15 %. Twelve slats (six for each country of origin) per modification process were used.

2.2 Thermal modification
2.2. Toplinska modifikacija

Thermal modification was performed in a laboratory-scale treatment reactor. The modification followed the ThermoWood® process (Mayes and Oksanen, 2002) and contained the following steps: The temperature in the vessel was first raised at 12 °C/h to 100 °C and then at 2 °C/h to 130 °C to allow a high-temperature drying of the slats to nearly 0 % MC, before increasing the temperature again at 12 °C/h until reaching the peak temperatures (185, 200 and 215 °C). The peak temperature was hold for 3 h. Afterwards, the temperature was decreased at 20 °C/h until reaching 65 °C, at which the vessel was opened and the specimens were removed.

2.3 Determination of mass loss (*ML*)
2.3. Određivanje gubitka mase (*ML*)

To determine the mass loss (*ML*) for each modified slat caused by the thermal modification, an adaptation of the procedure reported by Metsä-Kortelainen *et al*. (2006) was applied. The mass and the corresponding wood moisture content (*MC*) were recorded for each slat before and immediately after the process.

2.4 Determination of oven-dry density
2.4. Određivanje gustoće apsolutno suhog drva

The oven-dry density was determined according to ISO 13061-2 (2014) using five 8.5 mm × 8.5 mm × 35 mm (rad. × tang. × long.) specimens per modification, which were oven dried at (103±2) °C until constant mass. They were then weighed to the closest 0.01 g and their dimensions were measured to the nearest 0.01 mm.

2.5 Determination of equilibrium moisture content (*EMC*), volumetric swelling (S_{max}) and anti-swelling efficiency (*ASE*)
2.5. Određivanje ravnotežnog sadržaja vode (*EMC*), volumnog bubrenja (S_{max}) i učinka smanjenja bubrenja (*ASE*)

To measure *EMC*, S_{max} and *ASE*, 30 specimens per process run with dimensions of 10 mm × 10 mm × 10 mm (rad. × tang. × long.) were prepared from the modified wood and from unmodified references. The mass and the dimensions of the specimens were measured after each of the following steps: Conditioning at 20 °C/65 % RH until constant weight; oven drying at 103 °C until constant mass; water saturating (specimens were water-impregnated for 30 min at 13 kPa and water soaked for 14 days).

The *EMC* (in %) at 20 °C and 65 % RH was determined for each sample using Eq. 1:

$$EMC = 100 \cdot \left(m_{\mathrm{A}} - m_{\mathrm{B}}\right) / m_{\mathrm{B}}, \tag{1}$$

where m_A and m_B is the mass (in g) at the end of step A and B, respectively.

S_{max} (in %) was measured based on the sample volume at the end of step B and C for each cycle using Eq. 2:

$$S_{\max} = 100 \cdot \left[\left(V_{\mathrm{C}} - V_{\mathrm{B}}\right) / V_{\mathrm{B}}\right], \tag{2}$$

where V_B and V_c are the sample volumes at the end of step B and C, respectively.

ASE (in %) was measured using the S_{max} before and after modification using Eq. 3:

$$ASE = Su_{\max} - Sm_{\max} / Su_{\max} \cdot 100 \tag{3}$$

where Su_{max} is the maximum swelling of the unmodified sample and Sm_{max} is the maximum swelling of the modified sample, respectively.

2.6 Brinell hardness tests
2.6. Tvrdoća prema Brinellu

The Brinell hardness (static hardness) was measured according to DIN EN 1534 (2011) with a universal testing machine (Zwick Roell Z010, Zwick, Ulm, Germany). Ten specimens per modification and country of origin were used. A maximum force of 500 N using a steel ball with a diameter of 10 mm was applied for 25 seconds on specimens of 15 mm × 50 mm × 50 mm (rad. × tang. × long.) for the Chilean wood, and 25 mm × 50 mm × 50 mm (rad.× tang.× long.) for the Spanish wood. The specimens were conditioned at 20 °C/ 65 % RH during seven days until constant weight. The diameter of the residual impression was automatically determined by the testing machine. The Brinell hardness was then calculated according to Eg. 4:

$$BH = 2 \cdot F / \pi \cdot D \left[D - \sqrt{\left(D^2 - d^2\right)}\right], \tag{4}$$

where *BH* is the Brinell hardness (N/mm^2), *F* is the maximum force used (N), *D* is the diameter of the steel ball (mm) and *d* is the diameter of the imprint on the sample (mm).

2.7 Dynamic hardness tests
2.7. Dinamička čvrstoća

The dynamic hardness was determined according to Meyer *et al*. (2011) using specimens of the same quantity and dimensions as for the Brinell hardness tests. An indentation was generated in the surface of the specimen using a steel weight of 500 g that was dropped down on a steel ball from 300 mm of height. Four measurements were conducted on five replicates per material. The dynamic hardness was calculated according to Eq. 5:

$$DH = m \cdot \sqrt{\left(2 \cdot g \cdot h\right)} / r^2 \cdot \pi \tag{5}$$

where *DH* is the dynamic hardness (N/mm^2), *m* is the mass of the dropping weight (kg), *h* is the dropping height (m), *r* is the radius of the imprint on the sample (mm) and *g* is the gravity acceleration (m/s^2).

2.8 Resistance to abrasion: Shaker test
2.8. Otpornost na habanje: metoda *Shaker*

The resistance against abrasion was determined using the Shaker method described by Brischke *et al*. (2005). Five oven-dry specimens of 8.5 mm × 8.5 mm × 35 mm (rad. × tang. × long.) were placed in polyethylene flasks (V = 500 mL) together with 400 g stainless steel balls of 6 mm in diameter and shaken in an overhead shaker at 28 revolutions per minute during 72 h. 25 specimens per material were tested. The distances between the opposite corners at oven-dry state were measured of each specimen, before and after the abrasion process. The loss in dimension (%) was determined according to Eq. 6:

$$\Delta ab = \left[\left(d_{\mathrm{a}1} + d_{\mathrm{a}2}/2\right) - \left(d_{\mathrm{b}1} + d_{\mathrm{b}2}/2\right) / \left(d_{\mathrm{b}1} + d_{\mathrm{b}2}/2\right)\right] \cdot 100 \tag{6}$$

where Δab is the abrasion (%), d_{b1} is the diagonal 1 before abrasion (mm), d_{b2} is the diagonal 2 before abrasion (mm), d_{a1} is the diagonal 1 after abrasion (mm) and d_{a2} is the diagonal 2 after abrasion (mm). The average of the 5 samples per flax bottle was determined for each modification.

2.9 Resistance to abrasion: Taber Abraser test
2.9. Otpornost na habanje: metoda *Taber abraser*

The resistance against abrasion was determined according to the Taber Abraser method (EN 438-2, 2005). The following modifications of the Taber Abraser test were made in order to allow testing of solid wood: Specimens (n=4) of 100 mm × 100 mm × 7 mm of a finished decking were prepared and conditioned in 20 °C/65 % RH. The tree rings of all specimens had an orientation of 45° to their cutting edges. After weighing and measuring the thickness at four points over the ridges of the decking, the specimens (n=5) were clamped into the Taber Abraser and were abraded with sanding paper S-42 with approx. 72 min^{-1} for 1000 revolutions. Each wheel had a load of 500 g. Afterwards the decrease in thickness at each of the four abrasion points was determined. The percentage loss in thickness (Δt) was determined as a measure of abrasion according to the following Eq. 7 for each specimen and an average was calculated:

$$\Delta t = \left(t_{\mathrm{b}} - t_{\mathrm{a}} / t_{\mathrm{b}}\right) \cdot 100 \qquad (7)$$

where t_{b} is the thickness (mm) before the Taber Abrasion test and t_{a} is the thickness (mm) after the test.

2.10 Screw withdrawal resistance tests
2.10. Ispitivanje otpornosti na izvlačenje vijaka

Screw withdrawal resistance (*SWR*) tests were performed according to EN 320 (2011), but modified as follows: The same quantity and size of specimens used for the Brinell hardness test were used. Screws with nominal dimensions of 4.2 mm × 38 mm were used to penetrate the tangential face until (15±0.5) mm. Afterwards the screws were attached to a bracket to be pulled out at a constant speed of (10±1) mm min^{-1}. The screw withdrawal resistance corresponds to the maximum force determined to 10 N and was measured according to equation 8:

$$SWR = N_{\max} / t \qquad (8)$$

where *SWR* is the screw withdrawal resistance, $N_{\max}$ the maximum force (N) and *t* the thickness of the specimen (mm).

2.11 Statistical evaluation
2.11. Statistička analiza

Statistical analysis was performed using the Pearson Correlation Coefficient Test to show the correlations between the mass loss and density with the properties of the modified wood, and an ANOVA test to see if there was a significant difference between the unmodified and the modified wood properties. All statistics were performed using the Statistica Software package Version 13.1 (StatSoft Inc., Tulsa, USA).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Changes in mass, oven dry density, *EMC*, swelling and *ASE* by thermal modification
3.1. Promjene mase, gustoće apsolutno suhog drva, *EMC*-a, bubrenja i *ASE*-a zbog toplinske modifikacije

ML increased with rising treatment temperature (Table 2), which is in line with increasing *ML* obtained in tests with other Eucalypt species at similar process conditions, such as *E. saligna* (from 12.77 % at 180 °C and 19.12 % at 220 °C) in a modified autoclave modification (de Cademartori *et al*., 2015) and *E. globulus* (8.7 % at 190 °C and 12.1 % at 200 °C) in a modified laboratory oven modification (Esteves *et al*., 2007a). The higher *ML* of those modifications could be related to the different species and equipment used to do the modifications. Specimens from Chile and Spain showed similar *ML* at each modification temperature. On the other hand, oven-dry density (Table 1) decreased with increasing modification temperature, which also occurred in vacuum-thermally modified *E. pellita* wood (Wang *et al.*, 2014) and *E. grandis* (Calonego *et al*., 2012). The oven-dry density of the Spanish wood specimens was lower than that of the Chilean ones.

The *EMC* of the modified wood was reduced in both the Chilean and Spanish specimens (Figure 1a) after all the thermal modifications, and so was $S_{\max}$ (Figure 1b). Eucalypt modified under similar conditions, such as *E. grandis* in both *EMC* (5.9 % at 200 °C and 4.6 % at 220 °C) and $S_{\max}$ (9.94 % at 200 °C and 6.6 % at 220 °C) (Calonego *et al*., 2012) and *EMC* (3.1 % at 190 °C and 2.8 % at 210 °C) in *E. globulus* (Esteves *et al*., 2007b), showed similar results. Compared with other tropical wood species used for decking (Choong and Achmadi, 2007), the *EMC* of *E. nitens* was lower after treatment at 215 °C and similar at 185 °C and 200 °C. *ASE* of *E. nitens* was lower after modification at 185 °C (26.14 % and 23.11 % for Chile and Spain, respectively) (Figure 1c) compared to the modifications at higher temperatures. This improvement of the

Table 2 Mean mass loss (ML) determined for each process run and oven-dry density for each modification and unmodified reference (standard deviation in parentheses) for both Chilean and Spanish specimens

Tablica 2. Srednja vrijednost gubitka mase (ML) određena za svaki proces i gustoća apsolutno suhog drva određena za svaki modificirani i nemodificirani referentni uzorak (standardne devijacije u zagradama) za čileanske i španjolske vrste drva eukalipta

Country of origin *Zemlja podrijetla*	**Temperature, °C** *Temperatura*, °C	***ML***, %	**OD Density, kg/m³** *Gustoća apsolutno suhog drva*, kg/m³
Chile / Čile	Reference	-	617 ± (16)
	185	2.4 ± (0.4)	603 ± (39)
	200	6.1 ± (1.0)	592 ± (23)
	215	12.3 ± (0.5)	553 ± (29)
Spain / Španjolska	Reference	-	574 ± (26)
	185	2.6 ± (0.9)	555 ± (35)
	200	5.7 ± (1.3)	529 ± (18)
	215	12.0 ± (0.9)	517 ± (35)

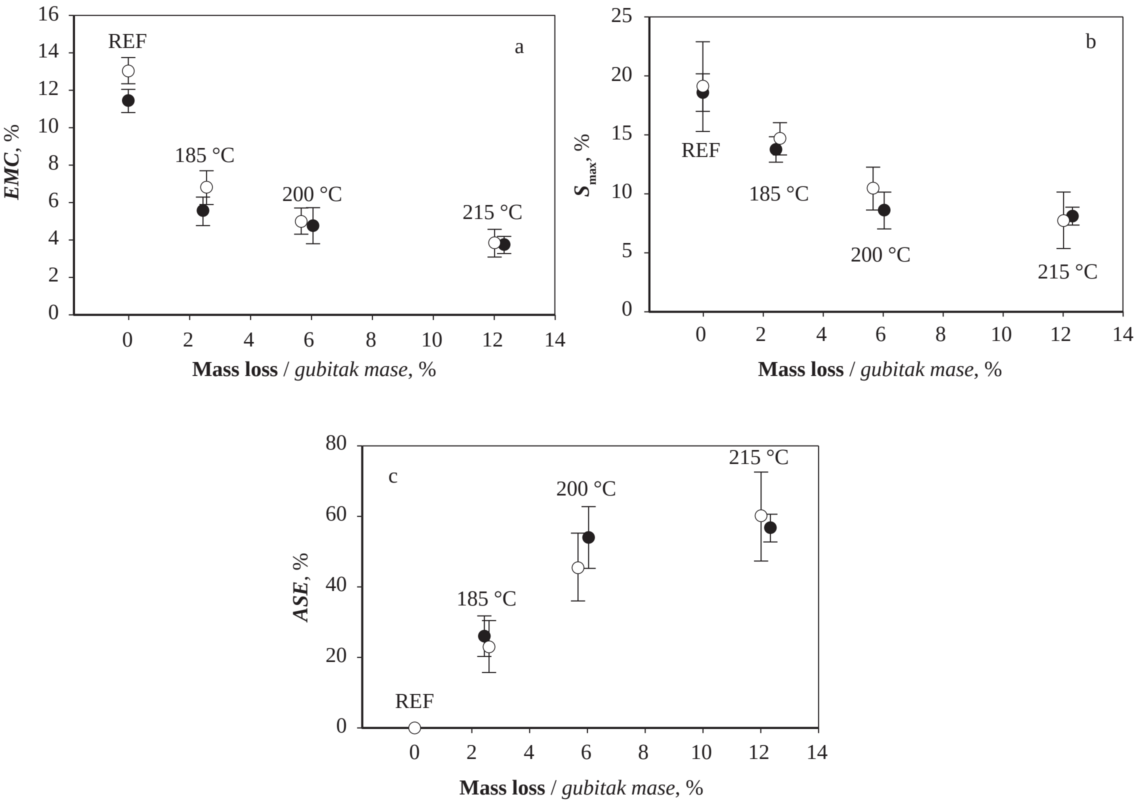

Figure 1 *EMC* at 20 °C and 65 % RH (a), S_{max} (b) and *ASE* (c) of *E. nitens* depending on the mass loss by thermal modification. Black circles: Chilean specimens. White circles: Spanish specimens. Standard deviations are indicated by error bars
Slika 1. *EMC* pri 20 °C i 65 % RH (a), S_{max} (b) i *ASE* (c) drva *E. nitens* u ovisnosti o gubitku mase zbog toplinske modifikacije (crni krugovi – čileanski uzorci; bijeli krugovi – španjolski uzorci); standardne devijacije prikazane su kao stupci pogreške

dimensional stability in thermally modified wood was also shown for *F. sylvatica* and *Fraxinus* spp. (Živković *et al.*, 2008). As for other eucalypt species, the *ASE* of thermally modified *E. globulus* reported by Esteves *et al*. (2007b) was higher (73 – 90 % at 190 to 210°C).

3.2 Changes in hardness, abrasion and screw withdrawal by thermal modification
3.2. Promjene tvrdoće te otpornosti na habanje i izvlačenje vijaka zbog toplinske modifikacije

Static hardness (Brinell) of the Chilean material was higher than that of the Spanish material. A Pearson correlation test showed that only the decrease in density was statistically significantly correlated with the dynamic and static hardness in the Chilean specimens (Table 3), while the Spanish specimens showed an increase in hardness unrelated to their densities after thermal modification at 200 °C (Figure 2). There was a slight decrease until 200 °C, and then a clear difference between unmodified specimens and those modified at 215 °C, while the Spanish material showed a noticeable decrease after all modifications (Figure 2a). Dynamic hardness decreased with increasing treatment temperature in the Chilean specimens, while at 185 °C and 200 °C similar results were obtained for the Spanish specimens (Figure 2b). The static and dynamic hardness at all temperatures was lower compared to both WPC (70 N/mm^2) and tro-

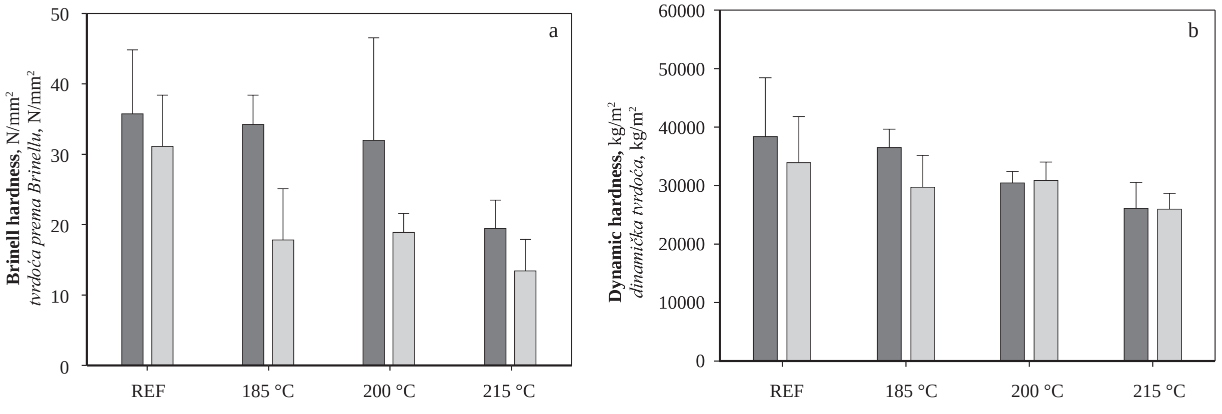

Figure 2 Brinell (a) and dynamic (b) hardness of *E. nitens* after each thermal modification process. Black column: Chilean specimens. Grey column: Spanish specimens
Slika 2. Tvrdoća prema Brinellu (a) i dinamička tvrdoća (b) drva *E. nitens* nakon svake toplinske modifikacije (crni stupci – čileanski uzorci; sivi stupci – španjolski uzorci)

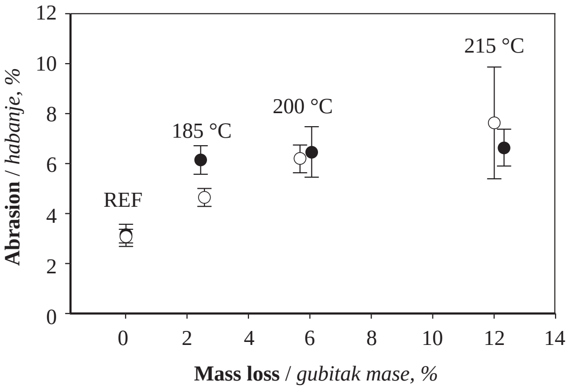

Figure 3 Abrasion of *E. nitens* after shaker tests depending on the mass loss by thermal modification. Black circles: Chilean specimens. White circles: Spanish specimens. Standard deviations are indicated by error bars
Slika 3. Otpornost na habanje drva *E. nitens* određena metodom *Shaker* u ovisnosti o gubitku mase zbog toplinske modifikacije (crni krugovi – čileanski uzorci; bijeli krugovi – španjolski uzorci); standardne devijacije prikazane su kao stupci pogreške

pical species, such as Bongossi (*Lophira alata*) and Balau (*Shorea* spp) (both 83 N/mm^2), but similar to Douglas fir (35 N/mm^2) and Beech (39 N/mm^2) (Brischke *et al*., 2014) at 200 °C for the Chilean specimens. The Brinell hardness was similar to thermally treated European beech and European ash (35 N/mm^2) treated between 180 and 200 °C in standard thermal modification under atmospheric conditions (Standfest and Zimmer, 2008), while the dynamic hardness was lower than that of European beech modified at 180 °C and with similar mass loss (Meyer *et al*., 2011).

The abrasion resistance of *E. nitens* decreased with increasing treatment intensity in all the specimens (Figure 3). Traces of abrasion on unmodified and thermally modified *E. nitens* at 215 °C after the shaker test can be seen in Figures 4 and 5 for Chilean and Spanish specimens, respectively. The thermally modified specimen (Figure 4c, d and Figure 5c, d) had more severely rounded edges and a slight loss of material due to splintering. The reduced abrasion resistance is likely due to an increased brittleness of the material (Kubojima *et al*., 2000; Phuong *et al*., 2007), and the lower density of the material after thermal modification (Esteves and Pereira, 2009). Previous reports indicated that the decrease in abrasion resistance is correlated with the decrease in wood density (Brischke *et al*., 2014). This also occurred in both our Spanish and Chilean specimens, shown to be statistically significant in Table 3. Wentzel *et al*. (2019) showed that there was a decrease in the degree of polymerization of the cellulose in thermally modified *E. nitens* wood, which means that there was a change in the cellulose crystallinity. Estevez and Pereira (2009) suggest that changes in the cellulose crystallinity influence the mechanical

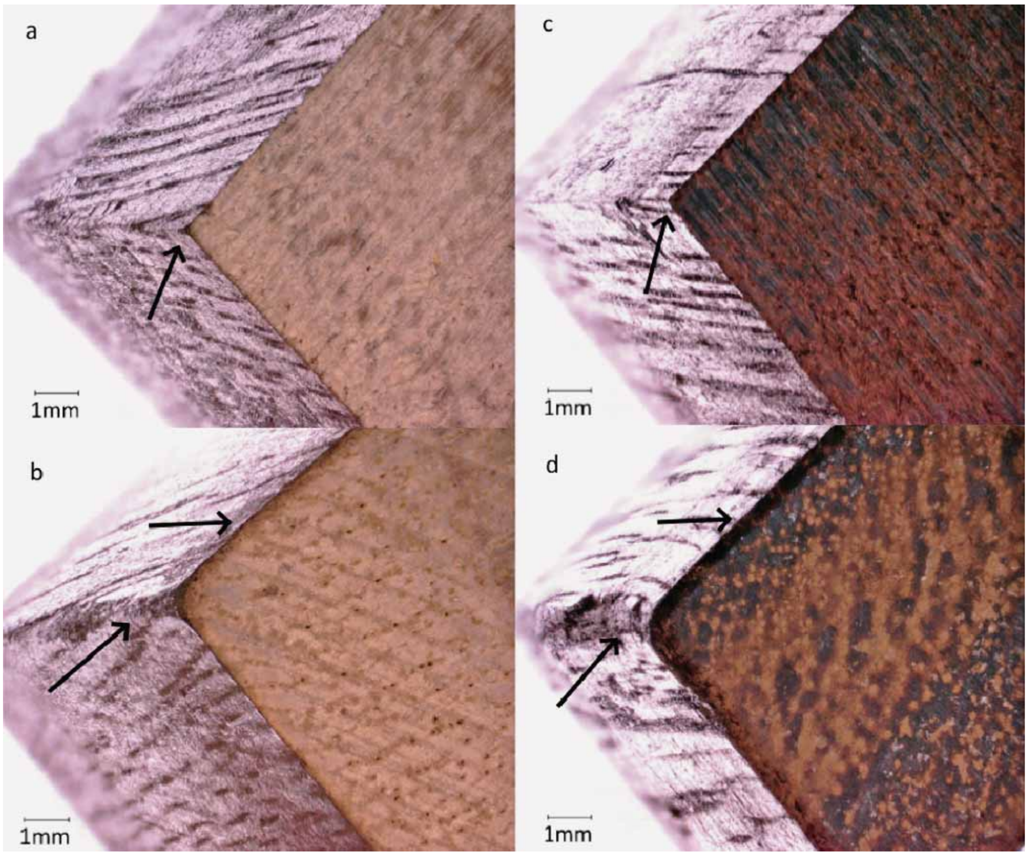

Figure 4 Cross section of *E. nitens*, unmodified and thermally modified at 215 °C of the Chilean specimens before (a and c) and after (b and d) the shaker abraser test. Arrows show the differences of wear between unmodified and modified specimens
Slika 4. Poprečni presjek čileanskih nemodificiranih i na 215 °C modificiranih uzoraka drva *E. nitens* prije (a i c) i nakon (b i d) ispitivanja otpornosti na habanje metodom *Shaker*; strelice pokazuju razlike u habanju između nemodificiranih i toplinski modificiranih uzoraka drva

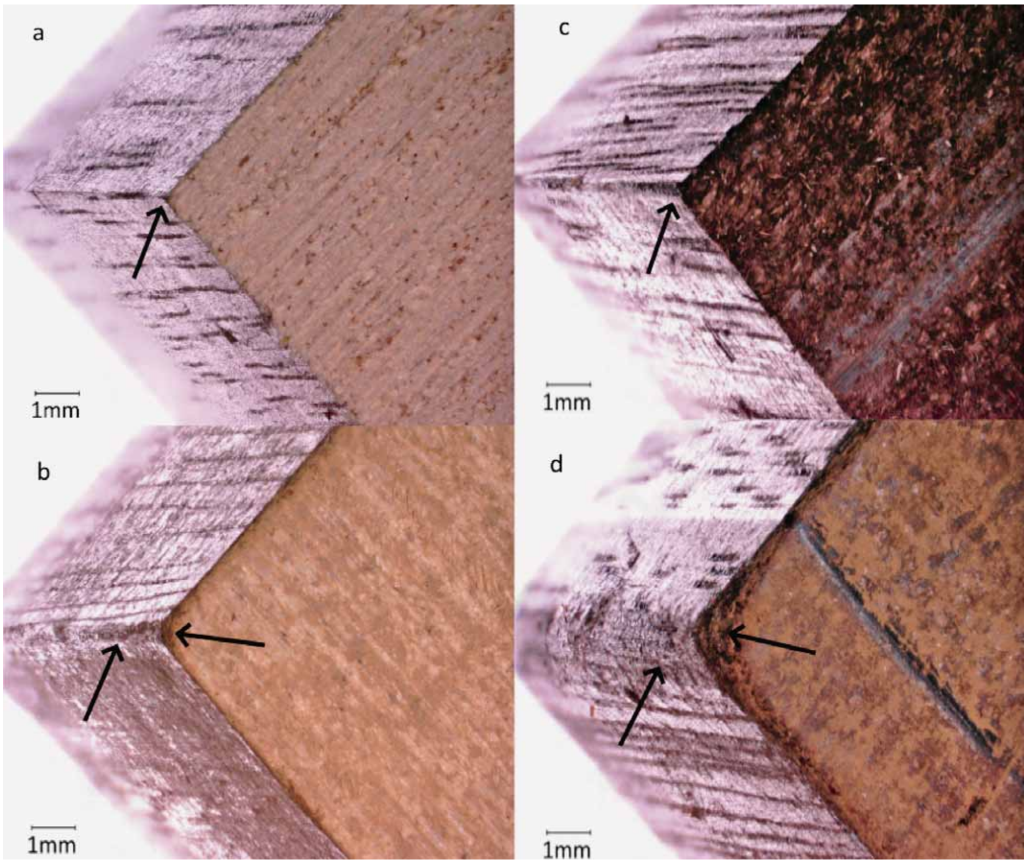

Figure 5 Cross section of *E. nitens*, unmodified and thermally modified at 215 °C of the Spanish specimens before (a and c) and after (b and d) the shaker abraser test. Arrows show the differences of wear between unmodified and modified specimens
Slika 5. Poprečni presjek španjolskih nemodificiranih i na 215 °C modificiranih uzoraka drva *E. nitens* prije (a i c) i nakon (b i d) ispitivanja otpornosti na habanje metodom *Shaker*; strelice pokazuju razlike u habanju između nemodificiranih i toplinski modificiranih uzoraka drva

properties of thermally modified wood, which could also be an explanation of the reduction of abrasion resistance. Compared to other flooring materials, the unmodified *E. nitens* showed similar abrasion resistance as wood-polymer composites (WPC) and tropical species such as Balau (2.9 and 3 %), while *E. nitens* modified at 200 °C and 215 °C presented similar resistance to abrasion as Douglas fir and Norway spruce (*Picea abies*), and namely 6.2 % (Brischke *et al*., 2014)

The abrasion expressed as Δt increased with increasing modification temperature in the Spanish specimens, while the Chilean specimens showed only small differences between modifications (Figure 6). The measurements were performed on finished decking (Figure 7), where the difference in Δt can be seen between the modified specimens at 215 °C (Chile in Figure 7c and Spain in Figure 7d), more material being lost in the Spanish specimens.

The screw withdrawal resistance (*SWR*) decreased with increasing treatment temperature, but did not differ between Spanish and Chilean *E. nitens* (Figure 8). Similar effects of thermal modification on

Table 3 Pearson correlation coefficients for mass loss and density in relation to *EMC*, *ASE*, shaker test, Taber Abraser test, Brinell hardness, dynamic hardness and SWR. Significant correlations (p< 0.05) were marked with an asterisk (*)
Tablica 3. Pearsonov koeficijent korelacije za gubitak mase i gustoću u ovisnosti o *EMC*-u, *ASE*-u, metodi *Shaker*, metodi *Taber abraser*, tvrdoći prema Brinellu, dinamičkoj tvrdoći i *SWR*-u. Značajne korelacije označene su zvjezdicom (*).

Proporties *Svojstva*	**Pearson correlation coefficient** *Pearsonov koeficijent korelacije*			
	Chile / *Čile*		**Spain** / *Španjolska*	
	Mass loss *Gubitak mase*	**Density** *Gustoća*	**Mass loss** *Gubitak mase*	**Density** *Gustoća*
EMC	-0.996*	0.991*	-0.952*	0.994*
ASE	0.797*	-0.913*	0.955*	-0.993*
Shaker Test / *Metoda Shaker*	0.950*	-0.996*	0.977*	-0.979*
Taber Abraser Test / *Metoda Taber abraser*	0.999*	-0.962*	0.943*	-0.996*
Brinell Hardness / *Tvrdoća prema Brinellu*	-0.973*	0.896*	-0.873*	0.597
Dynamic Hardness / *Dinamička tvrdoća*	-0.966*	0.999*	-0.856*	0.570
SWR	-0.985*	0.998*	-0.805*	0.492

Table 4 Average values of *EMC*, abrasion tests, hardness tests and screw withdrawal test of unmodified and modifies specimens. Significant differences with unmodified average values are marked by letter a. No significant differences are marked by letter b
Tablica 4. Srednja vrijednost *EMC*-a, otpornosti na habanje, tvrdoće i otpornosti na izvlačenje vijaka nemodificiranih i modificiranih uzoraka. Značajne razlike u odnosu prema srednjim vrijednostima nemodificiranih uzoraka označene su slovom a, dok su slučajevi bez značajne razlike označeni slovom b.

Chile / *Čile*	***EMC*,** %	**Shaker test** *Metoda Shaker*, %	**Taber Abraser test** / *Metoda Taber abraser*, %	**Brinell hardness** *Tvrdoća prema Brinellu*, N/mm²	**Dynamic hardness** *Dinamička tvrdoća* kg/m·s	***SWR***, N/mm
Unmodified *nemodificirani*	**11.48**^{a}	**5.79**^{a}	**3.21**^{a}	**35.82**^{a}	**38341**^{a}	**48.68**^{a}
C185	5.55	7.41	6.15	34.24	36481	40.46
C200	4.75	7.91	6.46	32.08	30395	31.62
C215	3.76	8.96	6.64	19.51	26224	23.34
Spain *Španjolska*	***EMC*,** %	**Shaker test** *Metoda Shaker*, %	**Taber Abraser test** / *Metoda Taber abraser*, %	**Brinell hardness** *Tvrdoća prema Brinellu*, N/mm²	**Dynamic hardness** *Dinamička tvrdoća* kg/m·s	***SWR***, N/mm
Unmodified *nemodificirani*	**13.06**^{a}	**3.41**^{a}	**3.06**^{a}	**31.19**^{a}	**33836**^{b}	**47.36**^{a}
S185	6.81	4.93	4.67	17.88	29728	34.12
S200	5.00	8.41	6.20	18.91	30835	37.48
S215	3.81	10.51	7.63	13.52	25891	26.60

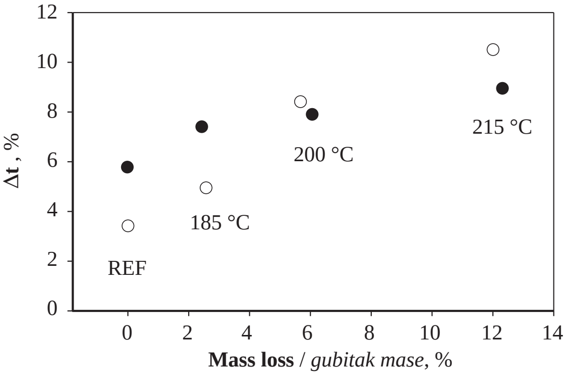

Figure 6 Abrasion of *E. nitens* after Taber Abraser tests depending on the mass loss by thermal modification. Black circles: Chilean specimens. White circles: Spanish specimens
Slika 6. Otpotnost na habanje drva *E. nitens* određena metodom *Taber abraser* u ovisnosti o gubitku mase zbog toplinske modifikacije (crni krugovi – čileanski uzorci; bijeli krugovi – španjolski uzorci)

SWR were previously reported for birch (Poncsák *et al*., 2006) and wild cherry (Aytin *et al.*, 2015).

3.3 Statistical analysis
3.3. Statistička analiza

The correlations presented in Table 3 show that mass loss was positively correlated with *ASE* and negatively with the resistance to abrasion in the shaker and abraser test, *EMC*, SWR and dynamic and Brinell hardness. Most correlations were significant. Only density was not correlated with SWR and dynamic and Brinell hardness in the modified wood from Spain, due to a slight increase of the properties in the modification at 200 °C.

As for the ANOVA test, all properties presented significant differences between the unmodified and modified specimens, with the exception of the dynamic hardness of the modified samples from Spain, as can be seen in Table 4.

Figure 7 Finished decking specimens after the Taber Abraser test. *E. nitens* wood, unmodified and thermally modified at 215°C of the Chilean and Spanish specimens before (a and b) and after (c and d) the Taber Abraser test
Slika 7. Uzorci vanjskih podnih obloga nakon ispitivanja otpornosti na habanje metodom *Taber abraser*; nemodificirani i na 215 °C modificirani uzorci drva *E. nitens* iz Čilea i Španjolske prije (a i c) i nakon (b i d) ispitivanja otpornosti na habanje metodom *Taber abraser*

The results indicate that the characteristics of thermally treated *E. nitens* from our study, especially the modification at 200 °C for both countries, were similar to other species commonly used for decking, such as Douglas fir (Brischke *et al*., 2014), and other thermally modified species, like *Larix decidua* (Welzbacher *et al*., 2009), *F. sylvatica* and *Fraxinus* spp. (Živković *et al*., 2008), which means that the modified *E. nitens* wood could be a probable alternative for decking.

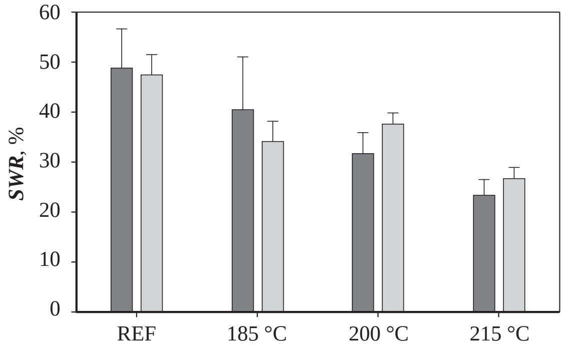

Figure 8 Screw withdrawal resistance of *E. nitens* depending on the mass loss by thermal modification. Black column: Chilean specimens. Grey column: Spanish specimens
Slika 8. Otpornost na izvlačenje vijaka drva *E. nitens* u ovisnosti o gubitku mase zbog toplinske modifikacije (crni stupci – čileanski uzorci; sivi stupci – španjolski uzorci)

4 CONCLUSIONS
4. ZAKLJUČAK

Thermally modified *E. nitens*, from both Chile and Spain, showed very similar characteristics compared to each other. The properties obtained modifying at 200 °C were similar to other species commonly used for decking, showing high abrasion resistance and similar dynamic and static properties. This shows the potential of use of *E. nitens* as decking material, particularly modified at 200 °C. To further develop the potential of this species as decking material, additional weathering and durability tests should be performed to determine the long-term use of this material.

5 REFERENCES
5. LITERATURA

1. Aytin, A.; Korkut, S.; As, N.; Ünsal, Ö.; Gündüz, G., 2015: Effect of heat treatment of wild cherry wood on abrasion resistance and withdrawal capacity of screws. Drvna industrija, 66 (4): 297-303. https://doi.org/10.5552/drind.2015.1440.
2. Brischke, C.; Iseler, N.; Meyer, L.; Sawyer, G., 2014: Testing the mechanical resistance of timber used for construction in the marine environment. International Wood Products Journal, 5: 39-49. https://dx.doi.org/10.1179/2042645313Y.0000000050.
3. Brischke, C.; Koch, S.; Rapp, A. O.; Welzbacher, C. R., 2005: Surface properties of thermally treated wood-wear abrasion and hardness. In: Proceedings of 2nd European Conference on Wood Modification, Hill, C. A. S.; Militz, H. (eds.). Göttingen, Germany, 6-7 October.
4. Calonego, F. W.; Severo, E. T. D.; Ballarin, A. W., 2012: Physical and mechanical properties of thermally modified wood from *E. grandis*. European Journal of Wood and Wood Products, 70: 453-460. https://dx.doi.org/10.1007/s00107-011-0568-5.
5. Choong, E. T.; Achmadi, S. S., 2007: Effect of extractives on moisture sorption and shrinkage in tropical woods. Wood and Fiber Science, 23: 185-196.
6. de Cademartori, P. H. G.; Missio, A. L.; Mattos, B. D.; Gatto, D. A., 2015: Effect of thermal treatments on technological properties of wood from two Eucalyptus species. Anais da Academia Brasileira de Ciências, 87: 471-481. https://dx.doi.org/10.1590/0001-3765201520130121.
7. Dias, Z. D.; Alvarez, C. E., 2017: Mechanical properties: wood lumber versus plastic lumber and thermoplastic composites. Ambiente Construído, 17 (2): 201-219. http://dx.doi.org/10.1590/s1678-86212017000200153.
8. Esteves, B.; Domingos, I.; Pereira, H., 2007a: Improvement of technological quality of eucalypt wood by heat treatment in air at 170-200 °C. Forest Products Journal, 57: 47-52.
9. Esteves, B.; Marques, A. V.; Domingos, I.; Pereira, H., 2007b: Influence of steam heating on the properties of pine (*Pinus pinaster*) and eucalypt (*Eucalyptus globulus*) wood. Wood Science and Technology, 41: 193-207. https://dx.doi.org/10.1007/s00226-006-0099-0.
10. Esteves, B.; Pereira, H., 2009: Wood modification by heat treatment: a review. BioResources, 4: 370-404.
11. González-Prieto, O.; Touza Vázquez, M. C., 2009: Properties of thermally modified wood of *Eucalyptus globulus* from Spanish plantations. Document IRG/WP 09-40469. International Research Group of Wood Protection, Stockholm.
12. Hill, C. A. S., 2006: Wood Modification: Chemical, Thermal and Other Processes. John Wiley & Sons, Ltd., West Sussex, England.
13. Knapic, S.; Santos, J.; Santos, J.; Pereira, H., 2018: Natural durability assessment of thermo-modifi ed young wood of eucalyptus. Maderas Ciencia y tecnología, 20: 489-498 https://dx.doi.org/10.4067/S0718-221X2018005031801.
14. Kubojima, Y.; Okano, T.; Ohta, M., 2000: Bending strength and toughness of heat-treated wood. Journal of Wood Science, 46: 8-15. https://dx.doi.org/10.1007/bf00779547.
15. Mayes, D.; Oksanen, O., 2002: ThermoWood Handbook. Finnish Thermowood Association, Helsinki, Finland.
16. Metsä-Kortelainen, S.; Antikainen, T.; Viitaniemi, P., 2006: The water absorption of sapwood and heartwood of Scots pine and Norway spruce heat-treated at 170°C, 190°C, 210°C and 230°C. Holz Als Roh-und Werkstoff, 64: 192-197. https://dx.doi.org/10.1007/s00107-005-0063-y.
17. Meyer, L.; Brischke, C.; Welzbacher, C. R., 2011: Dynamic and static hardness of wood: method development and comparative studies. International Wood Products Journal, 2: 5-11. https://dx.doi.org/10.1179/2042645311Y.0000000005.
18. Militz, H.; Altgen, M., 2014: Processes and properties of thermally modified wood manufactured in Europe. In: Deterioration and protection of sustainable biomaterials, Schultz, T. P; Goodell, B.; Nicholas, D. D. (eds). ACS Symposium Series 1158. Oxford University Press, pp. 269-285.
19. Phuong, L. X.; Shida, S.; Saito, Y., 2007: Effects of heat treatment on brittleness of *Styrax tonkinensis* wood. Journal of Wood Science, 53: 181-186. https://dx.doi.org/10.1007/s10086-006-0841-0.
20. Poncsák, S.; Kocaefe, D.; Bouazara, M.; Pichette, A., 2006: Effect of high temperature treatment on the mechanical properties of birch (*Betula papyrifera*). Wood Science and Technology, 40: 647-663. https://dx.doi.org/10.1007/s00226-006-0082-9.
21. Stamm, A. J.; Hansen, L. A., 1937: Minimizing wood shrinkage and swelling effect of heating in various gases. Industrial and Engineering Chemistry, 29: 831-833. https://dx.doi.org/10.1021/ie50331a021.
22. Standfest, G.; Zimmer, B., 2008: The surface hardness of thermally treated woods. In: Poster presentation at 62nd International Convention of the Forest Products Society, St. Louis, USA, 22-24 June 2008.

23. Wang, X. H.; Fei, B. H.; Liu, J. L., 2014: Effect of vacuum heat treatment temperature on physical and mechanical properties of *Eucalyptus pellita* wood. Wood and Fiber Science, 46: 368-375.
24. Welzbacher, C. R.; Brischke, C.; Rapp, A. O.; Koch, S.; Hofer, S., 2009: Performance of modified timber (TMT) in outdoor application – durability, abrasion and optical appearance. Drvna industrija, 60 (2): 75-82.
25. Wentzel M., Fleckenstein M., Hofmann T., Militz H. (2019) Relation of chemical and mechanical properties of *Eucalyptus nitens* wood thermally modified in open and closed systems. Wood Material Science and Engineering 14 (3): 165-173. https://doi.org/10.1080/17480272.2018.1450783. https://doi.org/10.1080/17480272.2018.1450783.
26. Zeller, F., 2018: Decking – Facade – Garden Timber: Product types and market share. In: Proceedings of the 10th European TMT – Workshop, Dresden, Germany, 3-4 Mai 2018.
27. Živković, V.; Prša, P.; Turkulin, H.; Sinković, T.; Jirouš-Rajković, V., 2008: Dimensional stability of heat treated wood floorings. Drvna industrija, 59 (2): 69-73.
28. ***AS 5604: 2005 Australian Standard: Timber – Natural durability ratings
29. ***DIN EN 320: 2011 Particleboards and fibreboards – Determination of resistance to axial withdrawal of screws. European Committee for Standardization, Brussels.
30. ***DIN EN 438: 2005 High-pressure decorative laminates (HPL) – Sheets based on thermosetting resins (usually called laminates), Part 2: Determination of properties. European Committee for Standardization, Brussels.
31. ***DIN EN 1534: 2011 Wood flooring – Determination of resistance to indentation – Test method. European Committee for Standardization, Brussels.
32. ***INFOR: 2015 Statistical bulletin N°154 – Chilean statistical yearbook of forestry 2016. Instituto Forestal de Chile, Santiago de Chile.
33. ***ISO 13061-2: 2014 Physical and mechanical properties of wood – Test methods for small clear wood specimens, Part 2: Determination of density for physical and mechanical tests. International Organization for Standardization, Geneva.
34. ***2018: Xunta de Galicia 1ª Revisión del Plan Forestal de Galicia Santiago de Compostela, Spain.

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Application of Artificial Neural Network to Predict the Effect of Paraffin Addition on Water Absorption and Thickness Swelling of MDF

Primjena umjetne neuronske mreže za predviđanje utjecaja dodatka parafina na upojnost vode i debljinsko bubrenje MDF-a

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ABSTRACT • *In this study, water absorption and thickness swelling values of medium density fiberboard (MDF) were modelled by artificial neural networks (ANN). MDF panels were produced with different rates of paraffin (0.0-control, 0.5, 1 and 1.5 %) at different press temperatures (170 and 190 °C). After conditioning of MDF, water absorption (WA) and thickness swelling (TS) of samples were carried out at specific intervals within 24 hours. Then, the data obtained from these experiment were modelled using ANN. Paraffin addition rate, press temperature and immersion time in water were used as the input parameters, while WA and TS values of MDF were used as the output parameters. After training of ANN, it was found that correlation coefficients (R) were close to 1 for training, validation, test and all data set. Mean absolute percentage error (MAPE) and mean square error (MSE) were determined as 2.94 % and 0.57, respectively, for all data sets. As a result of this study, the use of proposed ANN model may be recommended to predict the water absorption and thickness swelling of panels instead of complex and time-consuming studies such as empirical formulas.*

Keywords: *artificial neural network, water absorption, thickness swelling, medium density fiberboard, paraffin*

SAŽETAK • *U istraživanju je modelirana upojnost vode i debljinsko bubrenje ploče vlaknatice srednje gustoće (MDF ploče) uz pomoć umjetnih neuronskih mreža (ANN-a). MDF ploče proizvedene su uz dodatak različitih količina parafina (0,0 – kontrola, 0,5; 1 i 1,5 %) pri različitim temperaturama prešanja (170 i 190 °C). Nakon kondicioniranja MDF ploče, mjerena je upojnost vode (WA) i debljinsko bubrenje (TS) uzoraka u određenim intervalima unutar 24 sata. Zatim su ti podatci modelirani uz pomoć ANN-a. Kao ulazni parametri poslužili su količina parafina, temperatura prešanja i trajanje namakanja uzoraka u vodi, dok su WA i TS vrijednosti MDF ploče korištene kao izlazni parametri. Nakon provedbe ANN-a utvrđeno je da su koeficijenti korelacije (R) za provedbu, validaciju, ispitivanje i sve skupove podataka blizu 1. Srednja apsolutna pogreška (MAPE) i srednja*

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kvadratna pogreška (MSE) za sve su skupove podataka iznosile 2,94 % i 0,57. Kao rezultat ovog istraživanja može se preporučiti uporaba predloženog ANN modela za predviđanje upojnosti vode i debljinskog bubrenja ploča umjesto složenih i dugotrajnih studija poput empirijskih formula.

Ključne riječi: *umjetna neuronska mreža, upojnost vode, debljinsko bubrenje, ploča vlaknatica srednje gustoće, parafin*

1 INTRODUCTION
1. UVOD

Fiberboard is a wood-based panel that consists of wood lignocellulosic fibers, produced using synthetic resins or other bonding systems/materials under different temperature and pressure conditions. It is commonly used in buildings and constructions as panel, insulating and covering materials. Fiberboard is frequently preferred for many furniture applications instead of particleboard, plywood and solid wood (Ye *et al.*, 2007). Mechanical and physical properties of medium density fiberboard (MDF) change mainly depending on raw material properties (wood species, resin and additives) and production parameters (Ayrilmis, 2008).

It is known that fiberboard is a hygroscopic material like wood and other wood-based panels (Ayrilmis, 2007). When wood-based panels are exposed to moisture, some changes in dimensions and in their structure occur (Suzuki and Miyamoto, 1998). Therefore, this situation could be important for end use of the materials.

Some additives, which are known as water repellents, such as paraffin-wax, are used to improve the dimensional stability of fiberboards (Nazerian *et al.*, 2014). In a previous study, the effects of some experimental parameters, including paraffin rates at 0, 1 and 2 %, press temperature at 170-180 °C, and press time for 4 and 5 minutes, on the mechanical and physical characteristics of MDF samples were investigated. It has been reported that, while the paraffin addition had no significant effect on the mechanical properties of MDF, the rate of water absorption decreased as the paraffin ratio increased. The researchers also concluded that the increasing press temperature showed the same effect for WA and TS values with increasing paraffin rate (Akrami *et al.*, 2011). It was reported in another study (Winandy and Krzysik, 2007) that press temperature affected the dimensional properties of panels.

Recently, besides the classical methods and researches for determining the technological properties of materials, the use of artificial intelligence techniques has increased. Artificial neural network (ANN) is one of these artificial intelligence techniques. ANN is a logical software developed by imitating the working mechanism of the human brain, to perform basic functions such as brain learning the new information, recalling the learned information (Silva *et al.*, 2017). ANN also provides estimates of intermediate values that cannot be performed in experiments and is frequently used in scientific work areas such as engineering (Khorasani and Yazdi, 2017; Gurgen *et al.*, 2018), health sciences (Beauchet *et al.*, 2018), etc. Recently, ANN has received considerable attention in the field of wood products industry. Akyüz *et al.* (2017) modeled formaldehyde emission based on process parameters in particleboard manufacturing process with ANN. Tiryaki *et al.* (2014) proposed an ANN model to predict surface roughness of wood in machining process. Fu *et al.* (2017) predicted elastic strain of white birch disks during drying using ANN. In addition, ANN was used to detect the structural damage in medium density fiberboard (Long and Rice, 2008), to predict bending strength and modulus of elasticity of structural plywood board (Fernández *et al.*, 2012), to model the moisture absorption and thickness swelling of oriented strand board (Özşahin, 2012).

It is known that the values of water absorption and thickness swelling of materials show different trends depending on many different production parameters. Generally, *WA* and *TS* values of wood-based materials tend to increase unless some water repellant chemicals and treatments are used. In addition, it is possible to estimate the *WA* and *TS* values of panel samples at specific immersion times using an ANN model. There is limited study about modeling the effect of paraffin addition and hot press temperature on *WA* and *TS* of MDF in the literature. The objective of the present study is to develop an ANN model to predict the changes in the *WA* and *TS* values of MDF depending on some parameters such as different paraffin rates and press temperatures.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Medium density fiberboard production
2.1. Proizvodnja ploča vlaknatica srednje gustoće

In this study, commercial beech-pine fibers were used as raw material to produce fiberboard. The fibers were dried in a laboratory oven until they reached 2 % moisture content. Urea-formaldehyde (UF) was taken as adhesive at 13 % ratio. Paraffin emulsion (solid content 37 %) were added to UF at the ratio of 0.5, 1, 1.5 % by weight, and 1 % ammonium chloride was used as hard-

Table 1 Panel types and experimental parameters
Tablica 1. Vrste ploča i parametri istraživanja

Panel code *Oznaka ploče*	**Press temperature, °C** *Temperatura prešanja*, °C	**Paraffin addition rate, %** *Udio parafina*, %
A0	170	0
A1	170	0.5
A2	170	1.0
A3	170	1.5
B0	190	0
B1	190	0.5
B2	190	1.0
B3	190	1.5

ener. Later, adhesive was sprayed onto fibers and mats were manually formed. These mats were pressed at 170, 190 °C for 7 min in a hot press. The panel density was set to 750 kg/m^3. Panels were produced with thickness of 10 mm. Before the experiments, the produced panels were conditioned in an acclimatized room at 20 °C and 65 % relative humidity. The panel types and experimental parameters are presented in Table 1.

2.2 Water absorption and thickness swelling
2.2. Upojnost vode i debljinsko bubrenje

The water absorption (*WA*) and thickness swelling (*TS*) of MDF samples within 24 h immersion in water were determined according to EN 317 (1993). The measurements of samples were carried out at 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 14, 16, 18, 20, 22 and 24 hours.

Ten samples, 50 mm × 50 mm, were cut from panels and used for *WA* and *TS* measurements. At the beginning of tests, weight and thickness of all samples were measured. Then, MDF samples were immersed in water at 20 ˚C. At the end of each immersion time, the final thickness and weights of the samples were determined. The water absorption and thickness swelling of the MDF samples were calculated according to Eq. 1 and 2.

$$WA = (W_2 - W_1) / W_1 \cdot 100 \qquad (1)$$

WA – water absorption (%)
W_1 – weight before immersion (g)
W_2 – weight after immersion (g)

$$TS = (T_2 - T_1) / T_1 \cdot 100 \qquad (2)$$

TS – thickness swelling (%)
T_1 – thickness before immersion (mm)
T_2 – thickness after immersion (mm)

All the experimental studies were carried out in the laboratory of the forest industrial engineering, Karadeniz Technical University. The precision scale (Radwag, AS 220.R2) was used to measure the weight of panel samples with high resolution of 0.0001 g. Electronic digital caliper (Mitutuyo, 913-102) was used to measure the thickness of the same samples with resolution of 0.01 mm.

2.3 Artificial neural network (ANN)
2.3. Umjetna neuronska mreža

ANN is one of the branches of artificial intelligence that can be applied in different disciplines. ANN consists of artificial neurons tied together with various weights and is usually organized in layers. It has a structure in which complex relationships can be learned between dependent and independent variables introduced to the network. There is no need for learning about the neural network system. ANN is only trained with the data. Therefore, it looks like a "black box" (Haykin, 1994; Sivamani *et al.*, 2018). The fundamental structure of an artificial neural network is illustrated in Figure 1.

As shown in Figure 1, it consists of five main components: inputs, weights, summation function, activation function, and output.

The inputs provide the information to the neuron and they are independent variables of the problem. Weights are the coefficients that determine the influence of inputs on the network. The summation function calculates the net input value for a neuron. Generally, it can be expressed as in Eq. 3.

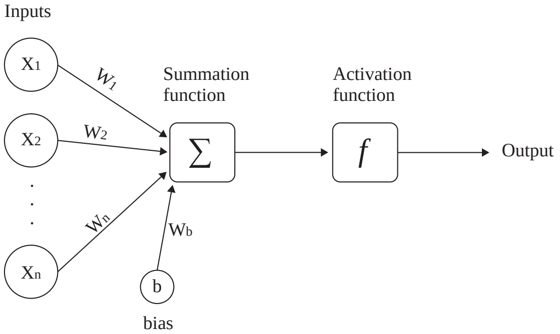

Figure 1 The fundamental structure of an artificial neural network
Slika 1. Temeljna struktura umjetne neuronske mreže

$$Net = \sum_{i=1}^{n} X_i \cdot W_i \qquad (3)$$

where, *X* is input, *W* is weight and *n* is the number of samples.

The activation function processes the net input value and then produces the output. Linear function, sigmoid function and hyperbolic tangent function are commonly used as activation function.

The outputs are determined by the activation function and they are dependent variables of the problem. The weight values are initially chosen randomly to start the network training. These values are updated according to the learning rule in each iteration to obtain the desired output. Weights are completely random and have no meaning before training, but they become meaningful information after training. When ANN's performance reaches a satisfactory level, the training ends at this epoch and the network uses these weights to make decisions (Erdemir and Ayata, 2017). In general, the flow chart in Figure 2 can be followed when modeling any problem with ANN.

3 MODELING OF PRESENT STUDY WITH ANN
3. MODELIRANJE SADAŠNJE STUDIJE ANN-om

3.1 Selection of input and output parameters
3.1. Odabir ulaznih i izlaznih parametara

In order to model the problem correctly, it must be fully understood, and the variables must be selected correctly. It is easy to define the input and output parameters originating from the nature of some problems. However, preliminary research in the literature is needed to determine the input and output of some problems. In this work, paraffin content, press temperature and immersion time in water were used as the input variables, while WA and TS were used as the output variables. Figure 3 illustrates the architecture of ANN model.

3.2 Choice of network structure
3.2. Izbor mrežne strukture

There are many alternatives for the activation function, as described in the above section. The log-

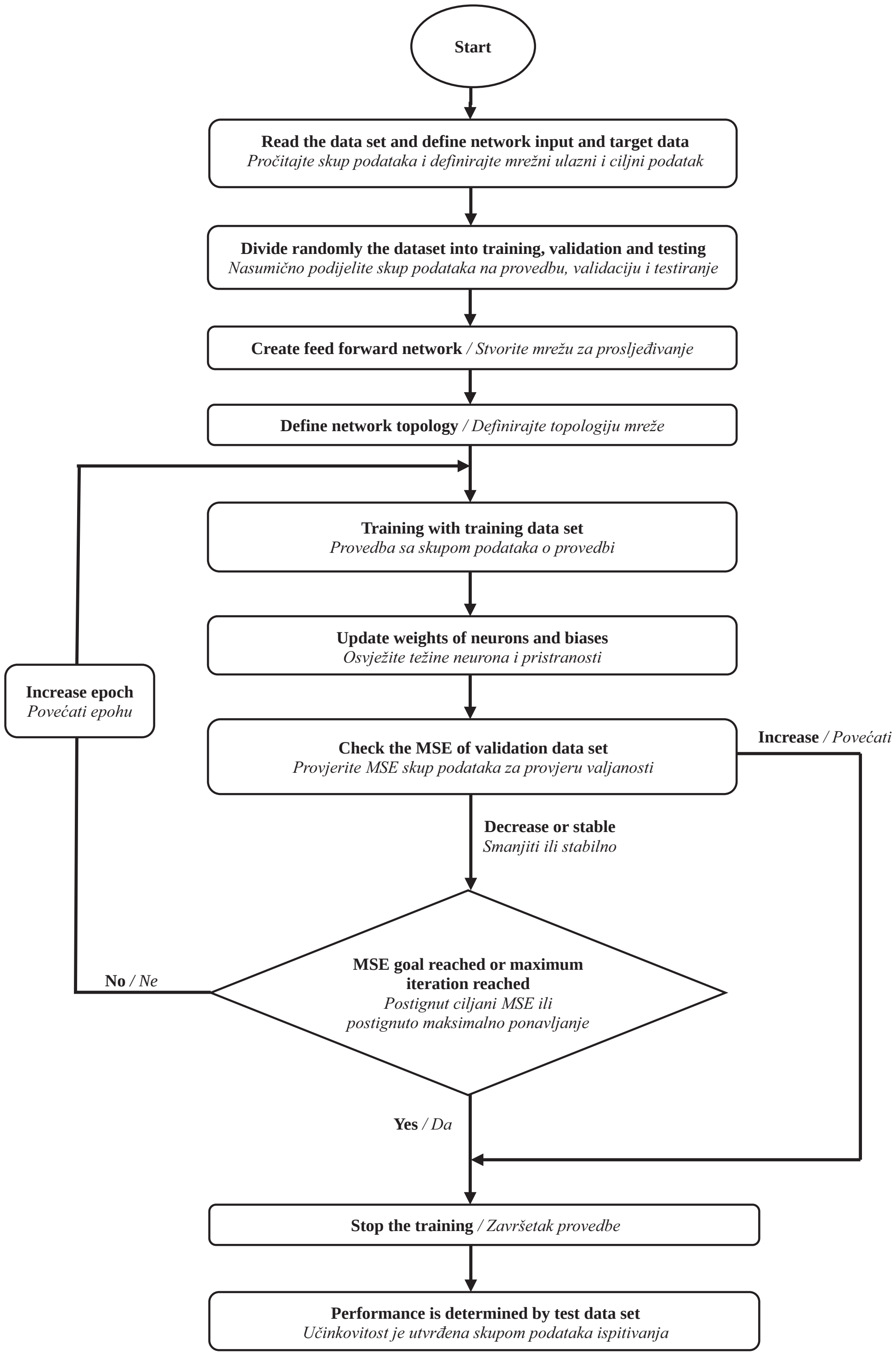

Figure 2 Flow chart of ANN modeling stages
Slika 2. Dijagram toka modeliranja uz pomoć ANN-a

sigmoid (logsig) function was chosen in the hidden layer, while the purelin function was applied in output layer as the activation functions. These functions are given in Eq. 3 and 4.

$$\mathrm{logsig}(x) = \frac{1}{1+\mathrm{e}^{-x}} \tag{3}$$

$$\mathrm{purelin}\ (x) = x \tag{4}$$

Performance function of the model was set to mean squared error (*MSE*) since it has advantageous features such as convexity, symmetry and differentiability. *MSE* was determined using Equation 5.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(e_i - p_i)^2 \tag{5}$$

where is the experimental result, p is the prediction result, and n is the number of samples.

3.3 Choice of learning rule
3.3. Izbor pravila učenja

Choosing an appropriate learning rule for optimizing network weights is crucial to the success of the network. The error between the actual value and predicted value of the network is minimized by a gradient descent approach, often known as back propagation

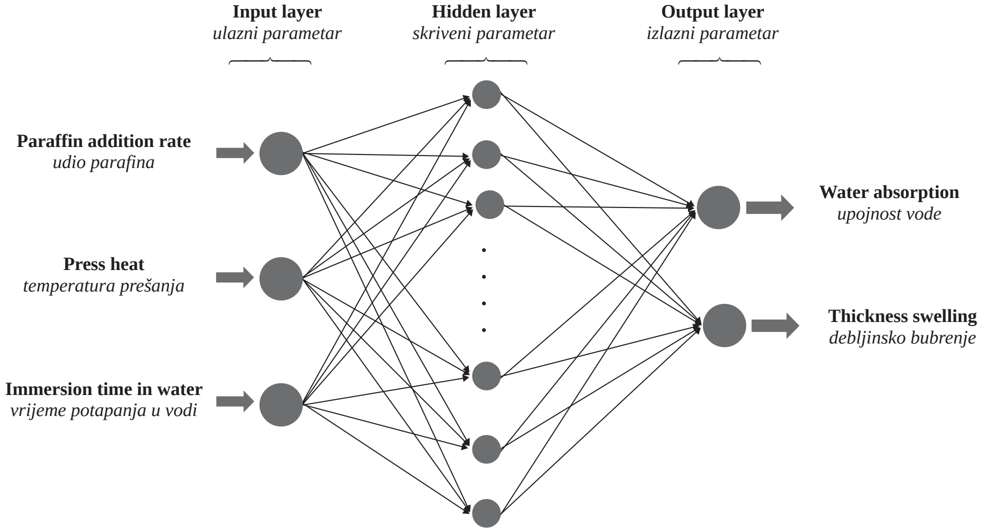

Figure 3 The architecture of ANN model
Slika 3. Arhitektura ANN modela

learning. The use of back propagation neural network in combination with various variants provides many benefits such as fast convergence.

In this study, both Levenberg-Marquardt (LM) and Scaled Conjugate Gradient (SCG) optimization algorithm were used. The performance of these two algorithms was compared and the most appropriate performance was chosen.

3.4 Arrangement of data set
3.4. Uređenje skupa podataka

Three input and two output parameters were used to model this work. A total of 128 values were obtained after the experimental study. In ANN modeling, 70 % (90 values) of all experimental data obtained for model training, 15 % (19 values) for validation and 15 % (19 values) for testing of network performance were utilized.

3.5 Stopping criteria for ANN training
3.5. Zaustavljanje kriterija za ANN provedbu

Three stopping criteria were determined for the current study. If the MSE value of validation data set continues to increase for a given epoch, the network training process is terminated. Maximum validation failure, which is the first stopping criteria, was set to 100. So, the MSE value was checked for 100 epochs and if the MSE did not decrease, then the training was stopped. The other stopping criterion was the target MSE value of the training data set. The performance target of the model that stopped the training stage was considered to be 10^{-6}. Finally, the maximum number of epochs was determined as the last stopping criterion. The maximum number of epochs was selected as 500 epochs.

3.6 Statistical evaluation of ANN models
3.6. Statistička evaluacija ANN modela

MSE and mean absolute percentage error (*MAPE*) values were used to assess prediction performance of the proposed ANN models. *MSE* and *MAPE* were determined using Eq. 5 and 6.

$$MAPE = \frac{1}{n}\sum\left|\frac{e_i - p_i}{p_i}\right|\cdot 100 \qquad (6)$$

where is the experimental result, is the prediction result, and is the number of samples.

In this study, 30 different ANN structures were obtained by using two different training algorithms and 15 different (5 – 20) hidden neuron numbers. The applied models were compared with each other and the final optimum model was proposed. Table 2 summarizes the ANN model topology.

Table 2 Model topology
Tablica 2. Model topologije

Parameters / *Parametri*	**Value** / *Vrijednost*
Training algorithm / *algoritam provedbe*	Levenberg–Marquardt (trainlm), Scaled Conjugate Gradient (trainscg)
Performance function / *izvedbena funkcija*	Mean square error (mse)
Hidden layer activation function / *funkcija aktiviranja skrivenog parametra*	Logistic sigmoid (logsig)
Output layer activation function / *funkcija aktiviranja izlaznog parametra*	Linear transfer function (purelin)
Number of hidden layers / *broj skrivenih parametara*	1
Input layer nodes / *čvorovi ulaznog parametra*	3
Hidden layer nodes / *čvorovi skrivenog parametra*	5:20
Output layer nodes / *čvorovi izlaznog parametra*	2
Maximum validation error epochs / *epohe najveće pogreške u validaciji*	100

4 RESULTS AND DISCUSSION
4. REZULTATI I DISKUSIJA

4.1 Experimental studies
4.1. Eksperimentalne studije

In this study, MDFs were produced using two different press temperatures and four different rates of paraffin. WA and TS values of the produced panel samples were measured for 16 different times within 24 hours. The maximum and minimum values determined among these periods are given in Table 3. In all experiments, the WA and TS values were calculated in the samples measured after 1 hour and 24 hours, respectively, and the minimum and maximum values are shown in Table 3.

As seen in Table 3, the *WA* and *TS* values decreased as the paraffin additive rate increased. Some researchers have investigated the effect of the chemical composition of paraffin and the emulsifier type on the hydrophobic properties of MDF. They have reported that high paraffin content (>0.25 %) had a significant effect on the swelling behavior of MDF and that 0.1 % to 1.0 % (relative to dry fibers) of paraffin rate did not have a negative impact on the physical and mechanical properties of panels (Roffael *et al.*, 2005). Likewise, the *WA* and *TS* values of the panels produced at 190 °C were found to be lower than those of the same contents produced at 170 °C. It has been reported in previous studies that the press temperature and duration affected the water soaking properties of MDF (Li *et al.*, 2009; Kargarfard *et al.*, 2009).

4.1 Modeling with ANN
4.2. Modeliranje ANN-om

In this study, the results of *WA* and *TS* of 8 different MDFs were modeled at certain intervals within 24 hours. For this purpose, measurements were carried out at 1, 2, 3, 4, 5, 6, 7, 8, 10, 12, 14, 16, 18, 20, 22 and 24 hours. To select the optimum model, 15 different (5-20) hidden neuron numbers and two different training algorithms were applied: LM and SCG. In general, various error values were calculated to determine the accuracy of an ANN model. The smaller value of these errors means that the proposed model is more reliable. *MAPE* and *MSE* were used as the performance criterion of the model in this study. The network with the lowest *MAPE* and *MSE* value from the applied models was obtained in the LM algorithm and at 16 hidden neurons. When the performance values of applied networks were examined, it was concluded that the LM algorithm predicts the *WA* and *TS* rates with minimum *MAPE* and *MSE*, and lower than SCG algorithm. So, the optimal ANN architecture was found as model architecture, which has three neurons in input layer, sixteen neurons in hidden layer and two neurons in output layer (3-16-2). *MAPE* and *MSE* results of *WA* and *TS* of the optimal network among the applied networks are given in Table 4 and 5.

As shown in Table 4, *MAPE* values for *WA* were found to be 1.15 %, 6.44 % and 6.63 % for training, validation and testing data set, respectively. In addition, *MAPE* was determined as 2.75 % for all data set. *MAPE* values for the training, validation, test and all data of the proposed ANN model were found to be 2.53 %, 4.2 %, 4.88 % and 3.13 %, respectively. When two outputs were evaluated together, *MAPE* values were found to be 1.84 % for training, 5.33 % for validation and 5.75 % for test data. As a result, error value including all data was found to be 2.94 %. This result shows that the proposed model produces forecast results with high reliability.

It can be seen that *MSE* values were calculated as 0.27, 2.44, 2.84 and 0.97 for training, validation, test and all data, respectively, for *WA* rates (Table 5). *MSE* values for *TS* were determined as 0.14, 0.20, 0.26 and 0.17 for training, validation, test and all data, respectively. When two outputs were evaluated together,

Table 3 The maximum and minimum values of measurements
Tablica 3. Najveće i najmanje vrijednosti mjerenja

Press temperature, °C *Temperatura prešanja,* °C	**Panel code** *Oznaka ploče*	**Water absorption, %** *Upojnost vode*, %		**Thickness swelling, %** *Debljinsko bubrenje*, %	
		Max.	Min.	Max.	Min.
170	A3	54.94	9.11	21.67	3.98
	A2	83.64	15.35	24.07	4.53
	A1	85.32	15.65	28.20	4.59
	A0	99.62	15.68	29.17	5.04
190	B3	40.05	6.65	15.20	2.20
	B2	49.73	7.18	16.31	2.65
	B1	54.55	11.50	18.11	3.62
	B0	59.54	12.01	19.34	3.88

Table 4 *MAPE* results of *WA* and *TS* of optimum network
Tablica 4. *MAPE* rezultati *WA* i *TS* optimalne mreže

	Train data, % *Podatci za provedbu*, %	**Validation data, %** *Podatci za validaciju*, %	**Test data, %** *Podatci za testiranje*, %	**All data, %** *Svi podatci*, %
Water absorption / *Upojnost vode*	1.15	6.44	6.63	2.75
Thickness swelling / *Debljinsko bubrenje*	2.53	4.21	4.88	3.13
Mean value / *Srednja vrijednost*	1.84	5.33	5.75	2.94

Table 5 *MSE* results of *WA* and *TS* of optimum network
Tablica 5. *MSE* rezultati *WA* i *TS* optimalne mreže

	Train data *Podatci za provedbu*	**Validation data** *Podatci za validaciju*	**Test data** *Podatci za testiranje*	**All data** *Svi podatci*
Water absorption / *Upojnost vode*	0.27	2.44	2.84	0.97
Thickness swelling / *Debljinsko bubrenje*	0.14	0.20	0.26	0.17
Mean value / *Srednja vrijednost*	0.21	1.32	1.55	0.57

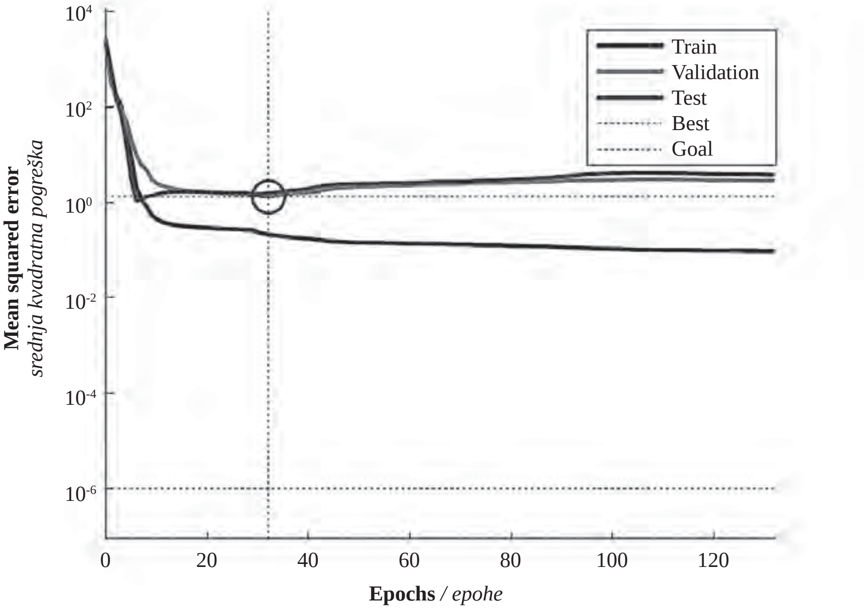

Figure 4 Performance graphic of the training stage
Slika 4. Grafika provedbene faze

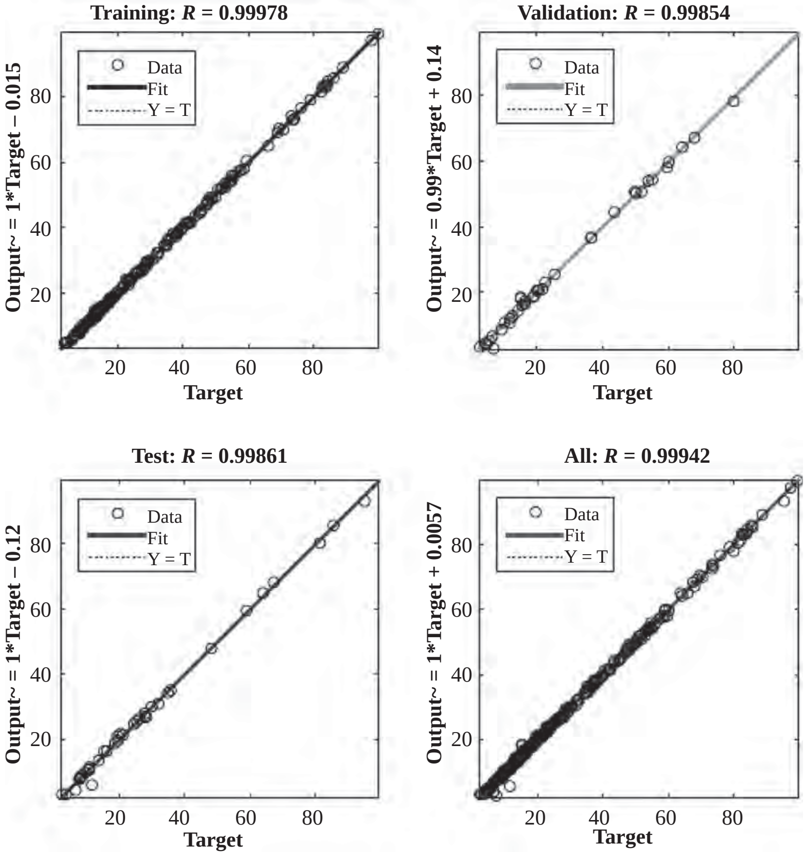

Figure 5 Regression graphics of the optimal network for training, validation, test and all data
Slika 5. Regresijske grafike optimalne mreže za provedbu, validaciju, testiranje i za sve podatke

MSE values were found to be 0.21 for training, 1.32 for validation and 1.55 for test data. As a result, error value including all data was found to be 0.57. Similar to *MAPE* values, *MSE* values were also seen to be very low, and this supports the statement that the model prediction reliability is quite high.

As shown in Figure 4, the *MSE* of the validation data tended to increase after the 32nd epoch, and this trend continued throughout the 100 epoch, which is the validation of results. This means that the network has begun to memorize instead of learning. Therefore, network training was stopped on the 32nd epoch, when optimal networking was achieved.

Figure 5 depicts the regression graphics of the network with the best performance recommended in this study. The correlation coefficients (*R*) were calculated as 0.99978, 0.99854, 0.99861 for training, validation and testing data sets, respectively. When all the data are considered together, *R* is found to be 0.99942. It means that the prediction results are in correlation with experimental results, hence *R* value is close to one.

5 CONCLUSIONS
5. ZAKLJUČAK

This study consists of two stages: experimental study and development of an ANN model. A total of 128 data obtained from experimental study were used to set an ANN model. The number of different hidden neurons (5-20) and two different training algorithms (LM and SCG) were used to achieve the optimal network with the best performance. As a result, the optimal network was obtained in 16 hidden neurons and the LM algorithm. Results showed that the experimental and predicted values were well correlated with each other. The important finding of the present study can be summarized as follows:

While the values of *WA* and *TS* decreased with the increment of paraffin rate and press temperature, same values increased with an increase in water immersion time.

The maximum value of *WA* was determined as 99.62 %, which was obtained from A0 panel at 24th hours. The minimum value of *WA* was determined as 6.66 %, which was obtained from B3 panel at 1st hours.

The maximum value of *TS* was calculated as 29.17 %, which was obtained from A0 panel at 24th hours. The minimum value of *TS* was calculated as 2.20 %, which was obtained from B3 panel at 1st hours.

MAPE values of proposed ANN model were in the range of 1.15-6.44 %. In addition, *MAPE* including all data was found to be 2.94 %.

MSE values of proposed ANN model were in the range of 0.15–2.85. In addition, *MSE* including all data was found to be 0.58.

The correlation coefficient values for the training, validation, test and all data of the proposed ANN model were found to be 0.99978, 0.99854, 0.99861 and 0.99942, respectively.

Applicability of ANN has been proved to predict water absorption and thickness swelling of MDFs.

6 REFERENCES
6. LITERATURA

1. Akrami, A.; Doosthoseini, K.; Faezipour, M.; Jahan Latabari, A., 2011: The effect of paraffin addition and pressing conditions on some properties of medium density fiberboard (MDF) with emphasis on surface roughness. Journal of Forest and Wood Products, 64: 343-353.
2. Akyüz, İ.; Özşahin, Ş.; Tiryaki, S.; Aydın, A., 2017: An application of artificial neural networks for modeling formaldehyde emission based on process parameters in particleboard manufacturing process. Clean Technol. Environ., 19 (5): 1449-1458. https://doi.org/10.1007/s10098-017-1342-0.
3. Ayrilmis, N., 2007. Effect of panel density on dimensional stability of medium and high density fiberboards. Journal of Materials Science, 42 (20): 8551-8557. https://doi.org/10.1007/s10853-007-1782-8.
4. Ayrilmis, N., 2008. Effect of compression wood on dimensional stability of medium density fiberboard. Silva Fennica, 42 (2): 285-293.
5. Beauchet, O.; Noublanche, F.; Simon, R., 2018: Falls risk prediction for older inpatients in acute care medical wards: Is there an interest to combine an early nurse assessment and the artificial neural network analysis? The Journal of Nutrition Health and Aging, 22 (1): 131-137. https://doi.org/10.1007/s12603-017-0950-z.
6. Da Silva, I. N.; Hernane Spatti, D.; Andrade Flauzino, R.; Liboni, L. H. B.; dos Reis Alves, S. F., 2017: Artificial Neural Networks, Springer. https://doi.org/10.1007/978-3-319-43162-8.
7. Erdemir, D.; Ayata, T., 2017: Prediction of temperature decreasing on a green roof by using artificial neural network. Applied Thermal Engineering, 112: 1317-1325. https://doi.org/0.1016/j.applthermaleng.2016.10.145.
8. Fernández, F. G.; de Palacios, P.; Esteban, L. G., Garcia-Iruela, I.; Rodrigo, B. G.; Menasalvas, E., 2012: Prediction of MOR and MOE of structural plywood board using an artificial neural network and comparison with a multivariate regression model. Composites Part B: Engineering, 43 (8): 3528-3533. https://doi.org/10.1016/j.compositesb.2011.11.054.
9. Fu, Z.; Avramidis, S.; Zhao, J.; Cai, Y., 2017: Artificial neural network modeling for predicting elastic strain of white birch disks during drying. European Journal of Wood and Wood Products, 75 (6): 949-955. https://doi.org/949-955;10.1007/s00107-017-1183-x.
10. Gurgen, S.; Altin, I.; Ozkok, M., 2018: Prediction of main particulars of a chemical tanker at preliminary ship design using artificial neural network. Ships and Offshore Structures, 13 (5): 459-465. https://doi.org/10.1080/17445302.2018.1425337.
11. Haykin, S., 1994: Neural Network: A Comprehensive Foundation. New York, Macmillan College.
12. Kargarfard, A.; Nourbakhsh, A.; Hajihassani, R., 2009: The effect of press temperature and press time on medium density fiberboard (MDF) properties produced from *Eucalyptus intertexta* fibers. Iranian Journal of Wood and Paper Science Research., 24 (1): 26-35.
13. Khorasani, A.; Yazdi, M. R. S., 2017: Development of a dynamic surface roughness monitoring system based on artificial neural networks (ANN) in milling operation. The International Journal of Advanced Manufacturing Technology, 93 (1-4): 141-151. https://doi.org/10.1007/s00170-015-7922-4.
14. Li, X.; Li, Y.; Zhong, Z.; Wang, D.; Ratto, J. A.; Sheng, K.; Sun, X. S., 2009: Mechanical and water soaking

properties of medium density fiberboard with wood fiber and soybean protein adhesive. Bioresource Technology, 100 (14): 3556-3562. https://doi.org/10.1016/j.biortech.2009.02.048.
15. Long, W.; Rice, R. W., 2008: Detection of structural damage in medium density fiberboard panels using neural network method. Journal of Composite Materials, 42 (11): 1133-1145. https://doi.org/10.1177/0021998308090455.
16. Nazerian, M.; Dalirzadeh, A.; Farrokhpayam, S. R., 2014: Use of almond shell powder in modification of the physical and mechanical properties of medium density fiberboard. BioResources, 10 (1): 169-181.
17. Özşahin, Ş., 2012: The use of an artificial neural network for modeling the moisture absorption and thickness swelling of oriented strand board. BioResources. 7 (1): 1053-1067.
18. Roffael, E., Schneider, T., Dix, B., Buchholz, T., 2005: On paraffin sizing of medium density fiberboards (MDF). Part 1: Influence of the chemical composition of paraffin and type of emulsifier on the hydrophobic properties of MDF. Holz als Roh- und Werkstoff, 63 (3): 192-203. https://doi.org/10.1007/s00107-004-0556-0.
19. Sivamani, S.; Selvakumar, S.; Rajendran, K.; Muthusamy, S., 2018: Artificial neural network – genetic algorithm-based optimization of biodiesel production from *Simarouba glauca*. Biofuels, 1-9. https://doi.org/10.1080/17597269.2018.1432267.
20. Suzuki, S.; Miyamoto, K; 1998: Effect of manufacturing parameters on the linear expansion and density profile of particleboard. J. Wood Sci., 44 (6): 444-450.
21. Tiryaki, S.; Malkoçoğlu, A.; Özşahin, Ş., 2014: Using artificial neural networks for modeling surface roughness of wood in machining process. Construction and Building Materials, 66: 329-335. https://doi.org/10.1016/j.conbuildmat.2014.05.098.
22. Winandy, J. E.; Krzysik, A. M., 2007: Thermal degradation of wood fibers during hot-pressing of MDF composites: Part I. Relative effects and benefits of thermal exposure. Wood and Fiber Science, 39 (3): 450-461.
23. Ye, X. P.; Julson, J.; Kuo, M.; Womac, A.; Myres, D., 2007: Properties of medium density fiberboards made from renewable biomass. Bioresource Technology, 98 (5): 1077-1084. https://doi.org/10.1016/j.biortech.2006.04.022.
24. ***EN-317: 1993 European Committee for Standardization, Particleboards and fibreboards, determination of swelling in thickness after immersion in water, Brussels.

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Estimating Modulus of Elasticity (MOE) of Particleboards Using Artificial Neural Networks to Reduce Quality Measurements and Costs

Procjena modula elastičnosti (MOE) iverica uz pomoć umjetnih neuronskih mreža radi smanjenja opsega i troškova kontrole kvalitete

Original scientific paper • Izvorni znanstveni rad
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ABSTRACT • *There are a large number of costs that enterprises need to bear in order to produce the same product at the same quality for a more affordable price. For this reason, enterprises have to minimize their expenses through a couple of measures in order to offer the same product for a lower price by minimizing these costs. Today, quality control and measurements constitute one of the major cost items of enterprises. In this study, the modulus of elasticity values of particleboards were estimated by using Artificial Neural Networks (ANN) and other mechanical properties of particleboards in order to reduce the measurement costs in particleboard enterprises. In addition to that, the future values of modulus of elasticity were also estimated using the same variables with the purpose of monitoring the state of the process. For this purpose, data regarding the mechanical properties of the boards were randomly collected from the enterprise for three months. The sample size (n) was: 6 and the number of samples (m): 65 and a total of 65 average measurement values were obtained for each mechanical property. As a result of the implementation, the low Mean Absolute Percentage Error (MAPE), Mean Absolute Deviation (MAD) and Mean Squared Error (MSE) performance measures of the model clearly showed that some quality characteristics could easily be estimated by the enterprises without having to make any measurements by ANN.*

Keywords: *estimate, modulus of elasticity, particleboard, ANN*

SAŽETAK • *Tvrtke u proizvodnji imaju velik broj troškova, a cilj im je proizvesti kvalitetne proizvode po što pristupačnijoj cijeni. Stoga nizom mjera nastoje smanjiti proizvodne troškove, ali ponuditi jednako kvalitetan proizvod po nižoj cijeni. Danas su kontrola i provjera kvalitete jedna od glavnih stavki troškova poduzeća. U ovom su istraživanju procijenjene vrijednosti modula elastičnosti i drugih mehaničkih svojstava iverice primjenom umjetnih neuronskih mreža (ANN) kako bi se smanjili troškovi kontrole kvalitete. Osim toga, uz pomoću istih varijabli procijenjene su buduće vrijednosti modula elastičnosti radi praćenja stanja procesa. S tim ciljem poduzeće je tri mjeseca nasumično prikupljalo podatke o mehaničkim svojstvima ploča. Istraživanje je provedeno na uzorku*

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od šest ploča i za svako mehaničko svojstvo dobiveno je ukupno 65 prosječnih mjernih vrijednosti. Kao rezultat implementacije modela, mjerenja su jasno pokazala da tvrtke mogu lako procijeniti neka obilježja kvalitete iverice uz pomoć niske srednje apsolutne pogreške (MAPE), srednjega apsolutnog odstupanja (MAD) i srednje kvadratne pogreške (MSE), bez bilo kakvih mjerenja.

Ključne riječi: *procjena, modul elastičnosti, iverica, ANN*

1 INTRODUCTION
1. UVOD

In order for the enterprises to operate successfully and efficiently in an increasingly competitive environment and to sustain their existence, their products and services need to outperform their competitors in terms of both price and quality. Enterprises that seek to attract more customers by producing quality products on the one hand, are looking for some ways to reduce the costs of quality on the other hand (Kurt, 2018).

Quality cost management in enterprises is seen as one of the most important aspects of the development of a quality management system (Martinez and Selles, 2015; Glogovac and Flipovic, 2018). The aim of the quality management system is not only to improve quality and fulfil customer requirements, but also to find a way to do it with the lowest costs (Holota *et al*., 2016).

In quality improvement efforts, knowing the future status of the process and achieving successful results with fewer measurements are crucial in reducing operational costs. Today, there are many statistical methods used for prediction purposes. Artificial Neural Networks (ANN), which is inspired by the working principles of the human brain and which is the result of the transfer of the learning process to computer systems, has become a widely used method for estimation purposes in many fields from finance and marketing sector to various engineering sectors (Kurt *et al*., 2017).

In the literature, ANN method has been widely applied for prediction purposes. For instance, Balestrino *et al*. (1994); Chen (1994); Aiken *et al*. (1995); Haas *et al*. (1995); Kiartzis *et al*. (1995); Chiang *et al*. (1996); Gately (1996); Kariniotakis *et al*. (1996); Kolehmainen *et al*. (2001); Ho *et al*. (2002); Pijanowski *et al*. (2002); Niska *et al*. (2004); Elminir *et al*. (2005); Pindoriya *et al*. (2008); Asilkan and Irmak (2009); Hadavandi *et al*. (2010); Sahin *et al*. (2013); Tiryaki and Hamzacebi (2014); Yildirim *et al*. (2014); Madhoushi and Daneshvar (2016); Mia and Dhar (2016); Fu *et al*. (2017); Yucesan *et al*. (2017); Ozsahin and Murat (2018); Qiu *et al*. (2018) studied ANN method in a wide variety of fields including production, marketing, finance, stock exchange, agriculture, forestry, food, energy, automotive and aviation industry.

Effective use of ANN for solving non-linear problems and giving reliable results has made the use of this method even more common. ANN is able to reveal unknown and unpredictable relationships and provide their more effective and optimum use. Therefore, ANN has an important place in the quality improvement and development stages.

Nowadays, many types of wood-based panels with different properties, such as particleboards and medium density fiberboards, are produced industrially (Istek *et al*. 2017). The quality control measures carried out in the production processes of these products are of great importance in terms of quality and customer satisfaction of the final product, and these processes require a certain cost and time. The purpose of this study is to reduce the costs of the measurements, which constitute one of the major expense items of the enterprises, and to estimate the future status of the process. In this context, some data were collected about the mechanical properties of the particleboards for three months and efforts were made to estimate the modulus of elasticity of the boards without making any measurements. ANN was used for the estimation, as it has been commonly and successfully used in recent times.

1.1 Artificial neural network
1.1. Umjetna neuronska mreža

An ANN is a soft computing technique for output prediction, classification, data fitting, and model recognizing during complex systems (Taghavifa *et al*., 2013). ANN are constructed from simple operational elements in a serial form. These elements have been inspired by biological neural elements (Mafakheri *et al*., 2012)

A typical ANN configuration consists of an input layer, hidden layers and an output layer (Cho *et al*., 2014). Hidden layer(s) and output layer can consist of one or more neurons, while the input layer feeds the neurons in the hidden layer(s) with input values. Each neuron in the hidden layer(s) is interconnected with all the neurons in the output layer. The number of neurons in each layer depends on the user and the scale of the problem (Tumac, 2016)

The function of the network is described as follows:

$$Y_j = f\,(\textstyle\sum_i w_{ij} x_{ij}) \tag{1}$$

where Y_j is the output of node *j*, *f* is the transfer function, w_{ij} is the connection weight between node *j* and node *i* in the lower layer, x_{ij} is the input signal from the node *i* in the lower layer node *j*.

One of the most important features distinguishing ANN from other methods is the fact that it is capable of learning. The learning process is defined as the calculation of the connection weights to provide the best result with the given data. ANN keeps the information it collects during learning as connection weights between nerve cells (Kurt *et al*., 2017).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Data
2.1. Podatci

The samples were taken from the enterprise, which operates in three shifts per day, for three months in accordance with the sampling plan determined by the enterprise. The boards, from which the samples were taken, were 18 mm in thickness, 630 kg/m^3 in density and 2100 mm × 2800 mm in size, and they were produced for internal furniture applications (including furniture) under dry conditions. The sizes and parts of the samples used for the tests were determined in accordance with the TS EN 310 (1993), TS EN 311(2005), TS EN 319 (1999) and TS EN 320 (2011).

For the estimation of the modulus of elasticity averages of the boards, the internal bond strength, surface soundness, screw withdrawal strength and post-sanding thickness were used. In the study, MATLAB software was utilized for developing the ANN models and for training and estimating the data. 70 % of the total of 65 samples with the sample size (n) of 6 for each mechanical property was allocated for training, 15 % for validation and 15 % for testing.

2.2 Network architectures
2.2. Struktura mreže

Multilayer Perceptron (MLP) was used as the most appropriate ANN model for the estimation. The MLP, which is commonly used in the literature, consists of an input layer taking the data from outside, an output layer giving the network output to outside and at least one hidden layer between the two of them (Hamzacebi, 2008; Akcan and Kartal, 2011). The MLPs are networks trained as feed-forward and supervised with full connection between layers (Haykin, 1998; Beale *et al*., 2010).

The studies conducted showed that the single hidden layer gave successful results at any desired degree of accuracy in nonlinear complex structured function approximations. There is no fixed rule for determining the number of neurons in the hidden layer. In general, keeping the number of hidden neurons low may lead to a learning problem in the network, while keeping the number of hidden neurons high may cause the network to memorize instead of learning. Therefore, 1 to 10 tests were made in order to determine the number of hidden neurons in the models and the best result was found to be 8.

Since the output neuron is directly connected to the studied problem, it is taken equal to the number of dependent variables to be estimated in estimation problems. Sigmoid activation function, which is mostly used in ANN, was preferred as the activation function.

The structure of the ANN model developed for the modulus of elasticity is shown in Figure 1. The values of post-sanding thickness, internal bond strength, screw withdrawal strength and surface soundness of the boards were used as input variables. The output variable, i.e. the modulus of elasticity, was the variable to be estimated.

After the number of neurons in the layers were determined for the ANN model, dependent and independent variables were normalized to be used in the system. In the normalization process, a linear transformation formula in the range of 0 to 10, namely Min-Max normalization, which is commonly used in the literature, was used as shown by Eq. 2.

$$x_n = \frac{x_0 - x_{min}}{x_{max} - x_{min}} \qquad (2)$$

After the normalization process, the data was transferred to the program, and training of the network, one of the most important steps, was commenced. At this stage, the data was presented to the network and the network was ensured to be trained.

In order for the model to be installed to give the optimum result, 81 different variations between the values of 0.1 – 0.9 were tried for each model by keeping the number of epochs at 1000, and efforts were made to determine the most appropriate momentum and learning coefficient values. After the training of the network was completed, test and validation processes were carried out and the estimation process started.

Since the future values of the dependent variables used in the input layer are necessary in the estimation stage, first of all, these values were estimated by ARIMA (Box-Jenkins) method and re-normalized and future quality values were estimated.

2.3 Performance evaluation
2.3. Ocjena učinka

Mean Squared Error (*MSE*), Mean Absolute Deviation (*MAD*) and Mean Absolute Percentage Error (*MAPE*) were used as performance criteria in the study,

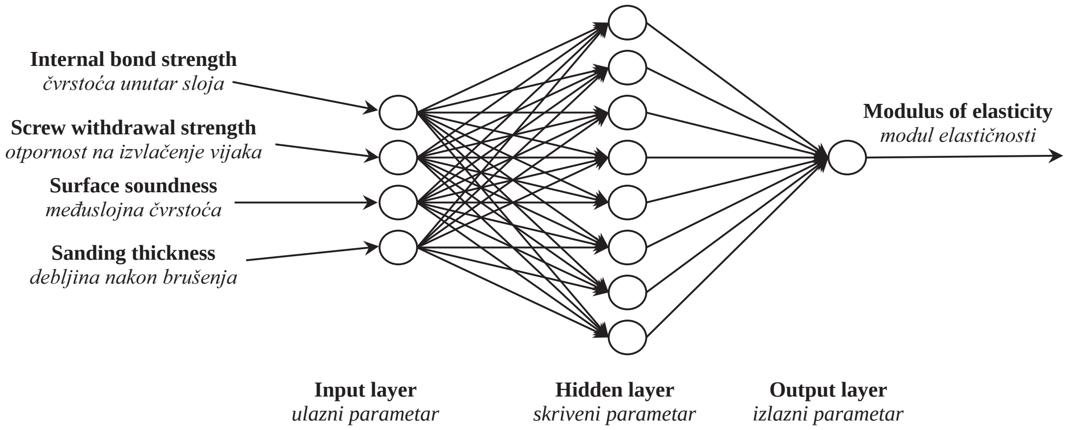

Figure 1 Structure of the ANN model for elasticity module
Slika 1. Struktura ANN-a za modul elastičnosti

as shown by Eq. 3. Since these are criteria frequently used in the literature and each measure has its own limitations, more than one performance criteria can be used to solve any problem (Gentry *et al*., 1995).

$$MSE = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n} \qquad MAD = \frac{\sum_{i=1}^{n}\left|y_i - \hat{y}_i\right|}{n}$$

$$MAPE = \frac{\sum_{i=1}^{n}\frac{\left|y_i - \hat{y}_i\right|}{y_i}}{n}\cdot 100 \qquad (3)$$

where, y_i is the actual observation values, $\hat{y}_i$ the estimated values, and *n* is the number of forecasts.

3 RESULTS AND DISCUSSION
3 REZULTATI I RASPRAVA

3.1 Data analysis, model selection and forecast
3.1. Analiza podataka, odabir modela i prognoza

Before starting the training of the modulus of elasticity, firstly, the learning and momentum coefficients were tested with different variations and the results were compared. 81 different test results, the MSE values of 5 momentum and learning coefficients giving the best performance are given in Table 1. The most appropriate learning coefficient for the modulus of elasticity was determined as 0.6 and momentum coefficient as 0.8, respectively.

After the most appropriate parameters for the model were determined, the training of network stage started. The graph showing the change of error values, training status and regression values regarding the training, validation and test sets in each iteration of the modulus of elasticity values as a result of network training is included in Figure 2. The graph shows that over 85 % of the training, validation and test regression values were successful. The best *MSE* value was obtained as 0.0023615 at the 44th iteration.

In order to see the training success and estimation ability of the model, the network was tested with test data, which it had never seen before, and successful results were obtained. Table 2 shows the comparison of the estimation values of the test set estimated by the model and the actual values and the error performance criteria *MSE*, *MAD* and *MAPE*. *MAD* value for modulus of elasticity was found to be 70.89, the *MAPE* value was found to be 3.022 and the *MSE* value was found to be 6969.58. The results show that network training is successful and able to make effective estimations.

After the successful completion of the training, the estimation process started. Figure 3 shows a graphical representation of the actual modulus of elasticity averages and the estimated modulus of elasticity averages used for the test. As it can be seen from the figure, the estimation accuracy of the present average is quite good and some test values are estimated very closely to the actual values. In addition, the graph also shows the change in the future 25 averages of the modulus of elasticity values. The model estimated that there would be a periodic decrease in the estimated values of the modulus of elasticity.

The literature shows that the results of ANN are more successful than other statistical methods. In their study, Gungor *et al*. (2004), Yucesoy (2011) and Ersen

Table 1 The most appropriate learning and momentum coefficients for the modulus of elasticity ANN model
Tablica 1. Najprikladniji koeficijenti učenja i momenta za modul elastičnosti ANN modela

Trial Number *Broj ponavljanja*	**Learning rate** *Koeficijent učenja*	**Momentum rate** *Koeficijent momenta*	***MSE***
19	0.3	0.1	0.00321
28	0.4	0.1	0.00424
29	0.4	0.2	0.00367
44	0.5	0.8	0.00298
53	0.6	0.8	0.00286

Table 2 Actual and estimated values of modulus of elasticity and their error performances (for test data) (N/mm^2)
Tablica 2. Stvarne i procijenjene vrijednosti modula elastičnosti i njihove pogreške (za podatke ispitivanja) (N/mm^2)

Sample *Uzorak*	**Actual values** *Stvarna vrijednost*	**Projected values** *Procijenjena vrijednost*	***MAD***	***MAPE***	***MSE***
56	2411.83	2496.9161	85.08274	3.527721	7239.073
57	2337.66	2407.9113	70.24465	3.004904	4934.311
58	2508.16	2458.7836	49.38302	1.968889	2438.683
59	2262.30	2298.7184	36.38505	1.608298	1323.872
60	2542.50	2504.2217	38.27826	1.505536	1465.225
61	2253.50	2435.5461	182.0461	8.078371	33140.780
62	2387.00	2499.2648	112.2648	4.703176	12603.390
63	2387.00	2439.8620	52.86204	2.214581	2794.395
64	2232,83	2287.4963	54.66296	2.448143	2988.039
65	2398.16	2370.4538	27.71284	1.155584	768.0014
Average / *prosječna vrijednost*			70.8922	3.02152	6969.58

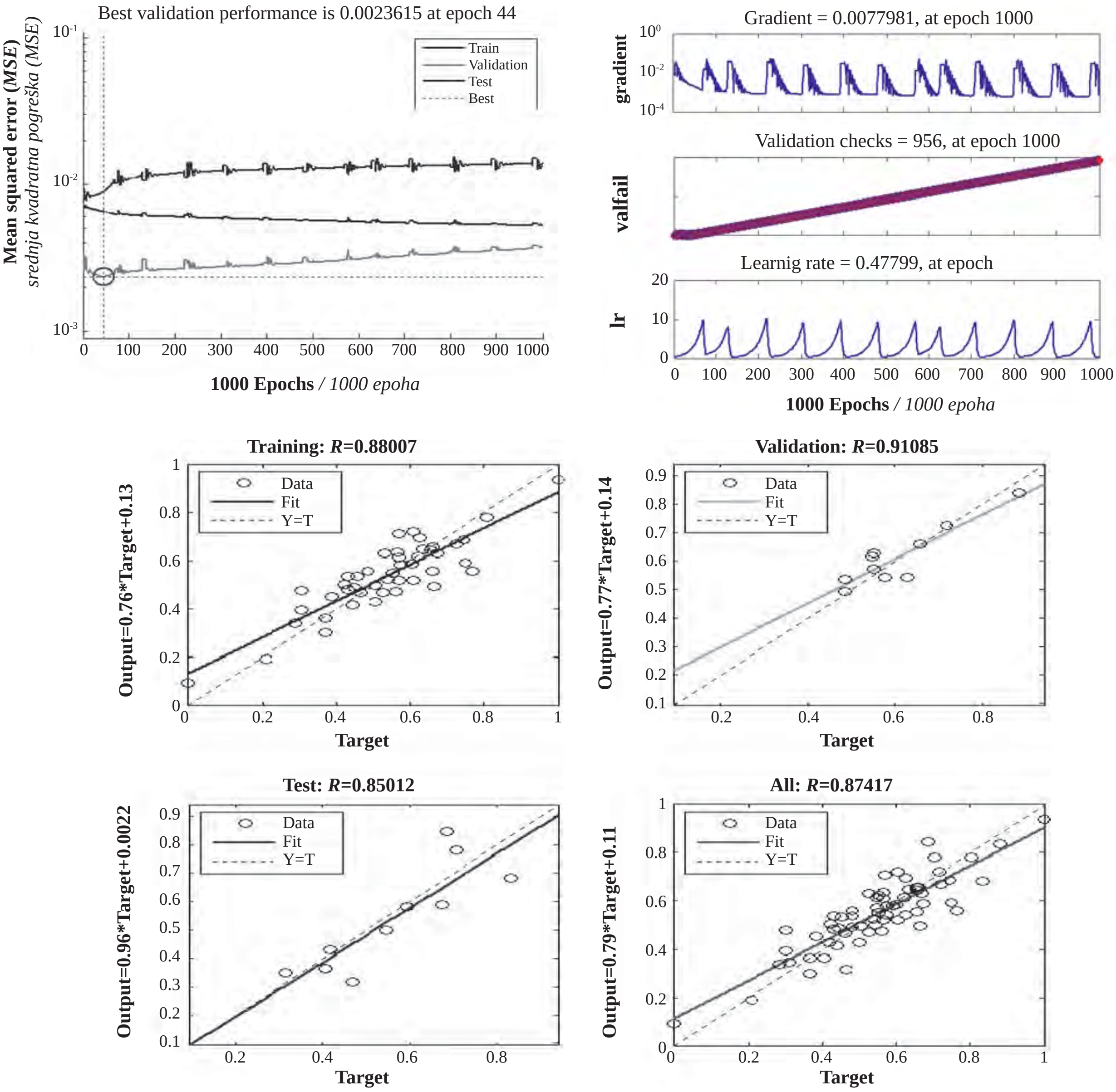

Figure 2 Performance results for the modulus of elasticity ANN model
Slika 2. Rezultati ANN modela za modul elastičnosti

(2016) compared the ANN with different estimation methods such as Moving Averages, Exponential Smoothing, Simple-Multiple Regression, Box Jenkins, and they found that ANN method gives better estimation results than other methods. Also, using ANN, Cook and Shannon (1992) have accurately and successfully predicted the parameters of the composite panel production process (about 70 %).

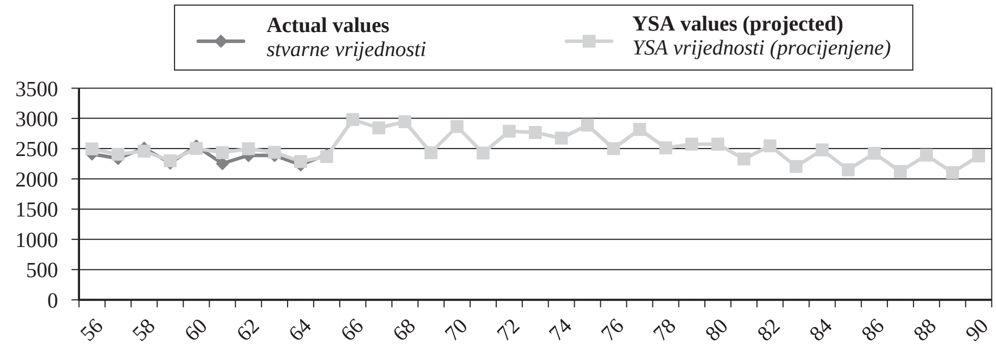

Figure 3 Modulus of elasticity ANN estimation graph (N/mm^2)
Slika 3. Procijenjeni ANN graf modula elastičnosti (N/mm^2)

4 CONCLUSIONS
4. ZAKLJUČAK

The most appropriate learning coefficient in the ANN model developed to estimate the modulus of elasticity was determined as 0.6 and momentum coefficient as 0.8. It is seen that the regression values of the model in training, testing and validation stages are above 85 %. When the values estimated by the model and the performance results of the actual modulus of elasticity were examined, the *MSE* value was found to be 6969.58, the *MAPE* value was found to be 3.022 % and the *MAD* value was found to be 70.89. It is seen that the performance values obtained are very successful, sufficient and usable for the enterprise. Likewise, in the literature, the models with *MAPE* values below 10 % are classified as "very good" (Lewis, 1982; Witt and Witt, 1992). Moreover, as it can be seen in Figure 3, the actual and estimated values for the modulus of elasticity are very close to each other. Also, in the estimation of future values of modulus of elasticity, it was determined that the method used in estimating the input variables (ARIMA) was effective and that the results varied according to the performance of the method used.

In general, the use of other mechanical properties as input variables in order to estimate the values of the modulus of elasticity and the fact that it gave successful outcomes showed that some quality values in the enterprises can also be estimated without making any measurements. This is extremely important in terms of reducing the measurement costs of the enterprise. Besides, the possibility of forecasting the future state of these values with ANN shall also enable the enterprise to take precautions against possible problems in advance.

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5 REFERENCES
5. LITERATURA

1. Aiken, M.; Krosp, J.; Vanjani, M.; Govindarajulu, C.; Sexton, R., 1995: A Neural network for predicting total industrial production. Journal of End User Computing, 7: 19-23.
2. Akcan, A.; Kartal, C., 2011: The forecasting of stock prices in ISE insurance index with artificial neural networks. The Journal of Accounting and Finance, 51: 27-40.
3. Asilkan, O.; Irmak, S., 2009: Forecasting the future prices of the Second-hand automobiles using artificial neural networks. Suleyman Demirel University, The Journal of Faculty of Economics and Administrative Sciences, 14: 375-391.
4. Balestrino, A.; Bini Verona, F.; Santanche, M., 1994: Time series analysis by neural networks: Environmental temperature forecasting. Automazione e Strumentazione, 42: 81-87.
5. Beale, M. H.; Hagan, M. T.; Demuth, H. B., 2010: Neural network toolbox 7 User's guide. The MathWorks Inc., Natick, MA.
6. Chen, C. H., 1994: Neural networks for financial market prediction. In: Proceedings of the IEEE International Conference on Neural Networks, 2: 1199-1202. https://doi.org/10.1109/ICNN.1994.374354.
7. Chiang, W. C.; Urban, T. L.; Baldridge, G. W., 1996: A neural network approach to mutual fund net asset value forecasting. Omega, 24: 205-215. https://doi.org/10.1016/0305-0483(95)00059-3.
8. Cho, S.; Lim, B.; Jung, J.; Kim, S.; Chae, H.; Park, J.; Park, S.; Park, J. K., 2014: Factors affecting algal blooms in a man-made lake and prediction using an artificial neural network. Measurement, 53: 224-233. https://doi.org/10.1016/j.measurement.2014.03.044.
9. Cook, D. F.; Shannon, R. E., 1992: A predictive neural network modeling system for manufacturing process parameters. International Journal of Production Research, 30 (7): 1537-1550. https://doi.org/10.1080/00207549208948106.
10. Elminir, H. K.; Areed, F. F.; Elsayed, T. S., 2005: Estimation of solar radiation components incident on Helwan site using neural networks. Solar Energy, 79: 270-279. https://doi.org/10.1016/j.solener.2004.11.006.
11. Ersen, N., 2016: The Estimation and Comparison in Turkey's Export and Import Values of Wood and Wood Products with Using Artificial Neural Networks and Box-Jenkins Methods. Ph.D. Thesis, Karadeniz Technical University, Graduate School of Natural and Applied Sciences, Forest Industrial Engineering, 207 pp.
12. Fu, Z.; Avramidis, S.; Zhao, J.; Cai, Y., 2017: Artificial neural network modeling for predicting elastic strain of white birch disks during drying. European Journal of Wood and Wood Products, 75 (6): 949-955. https://doi.org/10.1007/s00107-017-1183-x.
13. Gately, E., 1996: Neural networks for financial forecasting. John Wiley, New York.
14. Gentry, T. W.; Wiliamowski, B. M.; Weatherford, L. R., 1995: A comparison of traditional forecasting techniques and neural networks. Intelligent Engineering Systems Through Artificial Neural Networks, 5: 765-770.
15. Glogovac, M.; Filipovic, J., 2018: Quality costs in practice and an analysis of the factors affecting quality cost management. Total Quality Management and Business Excellence, 29 (13-14): 1521-1544. https://doi.org/10.1080/14783363.2016.1273105.
16. Gungor, I.; Kayacan, C.; Korkmaz, M., 2004: Artificial Neural Networks Use in the Forecasting of Industrial Wood Demand and Comparison with Different Estimation Methods. National Operations Research and Industrial Engineering (ORIE) Congress, Cukurova University, Adana.
17. Haas, D. J.; Milano, J.; Flitter, L., 1995: Prediction of helicopter component loads using neural networks. Journal of the American Helicopter Society, 40: 72-82. https://doi.org/10.4050/JAHS.40.72.
18. Hadavandi, E.; Shavandi, H.; Ghanbari, A., 2010: Integration of genetic fuzzy systems and artificial neural networks for stock price forecasting. Knowledge-Based Systems, 23: 800-808. https://doi.org/10.1016/j.knosys.2010.05.004.
19. Hamzacebi, C., 2008: Improving artificial neural networks: Performance in seasonal time series forecasting. Information Sciences, 178: 4550-4559. https://doi.org/10.1016/j.ins.2008.07.024.
20. Haykin, S., 1998: Neural Networks: A comprehensive foundation, 2 ed. Prentice Hall PTR Upper Saddle River, NJ, USA.
21. Ho, S. L.; Xie, M.; Goh, T. N., 2002: A comperative study of neural network and box-jenkins ARIMA model-

ing in time series prediction. Computers and Industrıal Engineering, 42: 371- 375. https://doi.org/10.1016/S0360-8352(02)00036-0.
22. Holota, T.; Hrubec, J.; Kotus, M.; Holienčinová, M.; Čapošová, E., 2016: The management of quality costs analysis model. Serbian journal of management, 11 (1): 119-127. https://doi.org/10.5937/sjm11-9347.
23. Istek, A.; Ozlusoylu, I.; Kizilkaya, A., 2017: Turkish wood based panel sector analysis. Journal of Bartin Faculty of Forestry, 19 (1): 132-138. https://doi.org/10.24011/barofd.297231.
24. Kariniotakis, G. N.; Stavrakakis, G. S.; Nogaret, E. F., 1996: Wind power forecasting using advanced artificial neural network models. IEEE Transactions on Energy conversion, 11: 762-767. https://doi.org/10.1109/60.556376.
25. Kiartzis, S. J.; Bakirtzis, A. G.; Petridis, V., 1995: Short-term load forecasting using neural networks. Electric Power Systems Research, 33: 1-6. https://doi.org/10.1016/0378-7796(95)00920-D.
26. Kolehmainen, M.; Martikainen, H.; Ruuskanen, J., 2001: Neural networks and periodic components used in air quality forecasting. Atmospheric Environment 35: 815-825. https://doi.org/10.1016/S1352-2310(00)00385-X.
27. Kurt, R., 2018: Integrated Use of Artificial Neural Networks and Shewhart, CUSUM and EWMA Control Charts in Statistical Process Control: A Case Study in Forest Industry Enterprise. Ph.D. Thesis, Bartin University, Graduate School of Natural and Applied Sciences, Forest Industrial Engineering, 206 pp.
28. Kurt, R.; Karayilmazlar, S.; Cabuk, Y., 2017: Forecasting by using artificial neural networks: Turkey's Paper-paperboard industry case. Journal of Bartin Faculty of Forestry 19: 99-106. https://doi.org/10.24011/barofd.334773.
29. Lewis, C. D., 1982: Industrial and business forecasting methods. Butterworths Publishing, London.
30. Madhoushi, M.; Daneshvar, S., 2016: Predicting the static modulus of elasticity in eastern cottonwood (Populus deltoides) using stress wave non-destructive testing in standing trees. European Journal of Wood and Wood Products, 74 (6): 885-892. https://doi.org/10.1007/s00107-016-1043-0.
31. Mafakheri, E.; Tahmasebi, P.; Ghanbari, D., 2012: Application of artificial neural networks for prediction of coercivity of highly ordered cobalt nanowires synthesized by pulse electrodeposition. Measurement 45: 1387-1395. https://doi.org/10.1016/j.measurement.2012.03.027.
32. Martinez, J. M. B.; Selles, M. E. S., 2015: A fuzzy quality cost estimation method. Fuzzy Sets and Systems, 266: 157-170. https://doi.org/10.1016/j.fss.2014.12.014.
33. Mia, M.; Dhar, N. R., 2016: Prediction of surface roughness in hard turning under high pressure coolant using artificial neural network. Measurement, 92: 464-474. https://doi.org/10.1016/j.measurement.2016.06.048.
34. Niska, H.; Hiltunen, T.; Karppinen, A.; Ruuskanen, J.; Kolehmainen, M., 2004: Evolving the neural network model for forecasting air pollution time series. Engineering Applications of Artificial Intelligence, 17: 159-167. https://doi.org/10.1016/j.engappai.2004.02.002.
35. Ozsahin, S.; Murat, M., 2018: Prediction of equilibrium moisture content and specific gravity of heat treated wood by artificial neural networks. European Journal of Wood and Wood Products, 76: 563-572. https://doi.org/10.1007/s00107-017-1219-2.
36. Pijanowski, B. C.; Brown, D. G.; Shellito, B. A.; Manik, G. A., 2002: Using neural networks and GIS to forecast land use changes: A land transformation model. Computers, Environment and Urban Systems, 26: 553-575. https://doi.org/10.1016/S0198-9715(01)00015-1.
37. Pindoriya, N. M.; Singh, S. N.; Singh, S. K., 2008: An adaptive wavelet neural network-based energy, price forecasting in electricity markets. IEEE Transactıons On Power Systems, 23: 1423-1432. https://doi.org/10.1109/TPWRS.2008.922251.
38. Qiu, S.; Chen, B.; Wang, R.; Zhu, Z.; Wang, Y.; Qiu, X., 2018: Atmospheric dispersion prediction and source estimation of hazardous gas using artificial neural network, particle swarm optimization and expectation maximization. Atmospheric Environment, 178: 158-163. https://doi.org/10.1016/j.atmosenv.2018.01.056.
39. Sahin, M.; Buyuktumturk, F.; Oguz, Y., 2013: Light quality control with artificial neural networks. Afyon Kocatepe University Journal of Science and Engineering, 13: 1-10. https://doi.org/10.5578/fmbd.6222.
40. Taghavifa, H.; Mardani, A.; Taghavifar, L., 2013: A hybridized artificial neural network and imperialist competitive algorithm optimization approach for prediction of soil compaction in soil bin facility. Measurement, 46: 2288-2299. https://doi.org/10.1016/j.measurement.2013.04.077.
41. Tiryaki, S.; Hamzacebi, C., 2014: Predicting modulus of rupture (MOR) and modulus of elasticity (MOE) of heat treated woods by artificial neural networks. Measurement, 49: 266-274. https://doi.org/10.1016/j.measurement.2013.12.004.
42. Tumac, D., 2016: Artificial neural network application to predict the sawability performance of large diameter circular saws. Measurement, 80: 12-20. https://doi.org/10.1016/j.measurement.2015.11.025.
43. Yildirim, I.; Ozsahin, S.; Okan, O. T., 2014: Prediction of non-wood forest products trade using artificial neural networks. Journal of Agricultural Science and Technology, 16: 1493-1504.
44. Yucesan, M.; Gul, M.; Erkan, E., 2017: Application of artificial neural networks using Bayesian training rule in sales forecasting for furniture industry. Drvna industrija, 68 (3): 219-228. https://doi.org/10.5552/drind.2017.1706.
45. Yucesoy, M., 2011: Sales Forecasting with Artificial Neural Networks in Tissue Paper Sector. Master Thesis, Istanbul Technical University, Graduate School of Natural and Applied Sciences, Industrial Engineering, 115 pp.
46. Witt, S. F.; Witt, C. A., 1992: Modeling and forecasting demand in tourism. Academic Press, Londra.
47. ***TS EN 310: 1993 Wood-Based panels-Determination of modulus of elasticity in bending and of bending strength. Ankara.
48. ***TS EN 311: 2005 Wood-based panels-Surface soundness-Test. Ankara.
49. ***TS EN 319: 1999 Particleboards and fibreboards-Determination of tensile strength perpendicular to the plane of the board. Ankara.
50. ***TS EN 320: 2011 Fibreboards; determination of resistance to axial withdrawal of screws. Ankara.

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HRVATSKA KOMORA
INŽENJERA ŠUMARSTVA
I DRVNE TEHNOLOGIJE

HRVATSKA KOMORA INŽENJERA ŠUMARSTVA I DRVNE TEHNOLOGIJE

Osnovana je na temelju Zakona o Hrvatskoj komori inženjera šumarstva i drvne tehnologije.

Komora je samostalna i neovisna strukovna organizacija koja obavlja povjerene joj javne ovlasti, čuva ugled, čast i prava svojih članova, skrbi da ovlašteni inženjeri obavljaju svoje poslove savjesno i u skladu sa zakonom, promiče, zastupa i usklađuje njihove interese pred državnim i drugim tijelima u zemlji i inozemstvu.

Članovi komore:

inženjeri šumarstva i drvne tehnologije koji obavljaju stručne poslove iz područja šumarstva, lovstva i drvne tehnologije.

Stručni poslovi:

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The Effect of Thermo-Mechanical Treatment of Moso Bamboo (*Phyllostachys Pubescens*) on Its Sorption and Physicomechanical Properties

Utjecaj termo-mehaničke obrade moso-bambusa (*Phyllostachys pubescens*) na njegovu sorpciju i fizičko-mehanička svojstva

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ABSTRACT • *The aim of this study was to examine some properties of heat-treated (200 °C) and densified (treated) bamboo. Density (ρ), equilibrium moisture content (EMC), sorption hysteresis (H), swelling (S), and Brinell hardness (HB) were examined and compared with untreated bamboo (Phyllostachys sp.) and common oak (Quercus robur L.). The density of heat-treated bamboo (ρ = 1170 kg/m^3) was higher than that of untreated bamboo (ρ = 850 kg/m^3) and oak wood (ρ = 670 kg/m^3). The sorption isotherms were parameterized with the Guggenheim-Anderson-deBoer (GAB) model. Treated bamboo showed lower EMC than untreated bamboo and oak wood in the entire hygroscopic range. The swelling anisotropy index of treated bamboo was the lowest (1.09). The mean HB of treated bamboo (HB=132 MPa) was significantly higher than that of oak and untreated bamboo.*

Keywords: *dynamic vapor sorption, equilibrium moisture content, sorption properties, Brinell hardness, GAB model, sorption hysteresis*

SAŽETAK • *Cilj ovog rada bio je istražiti neka svojstva toplinski obrađenoga (200 °C) i ugušćenog (obrađenog) bambusa. Ispitivana je gustoća bambusovih uzoraka (ρ), ravnotežni sadržaj vode u njima (EMC), histereza sorpcije (H), bubrenje (S) i tvrdoća prema Brinellu (HB), a dobivene su vrijednosti uspoređene s neobrađenim uzorcima*

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bambusa (Phyllostachys sp.) i drvom hrasta lužnjaka (Quercus robur L.). Pokazalo se da je gustoća toplinski obrađenog bambusa (ρ = 1170 kg/m^3) veća od gustoće neobrađenih uzoraka bambusa (ρ = 850 kg/m^3) i uzoraka hrastovine (ρ = 670 kg/m^3). Izoterme sorpcije parametrirane su modelom Guggenheim-Anderson-deBoer (GAB). Obrađeni su uzorci bambusa imali niži ravnotežni sadržaj vode od neobrađenih, kao i od uzoraka hrastovine, i to u cijelom rasponu higroskopnosti. Indeks bubrenja obrađenog bambusa bio je najniži (1,09). Srednja vrijednost tvrdoće prema Brinellu obrađenog bambusa (HB = 132 MPa) bila je značajno veća od tvrdoće prema Brinellu hrastovine i neobrađenog bambusa.

***Ključne riječi:** dinamička sorpcija pare, ravnotežni sadržaj vode, sorpcijska svojstva, tvrdoća prema Brinellu, GAB model, histereza sorpcije*

1 INTRODUCTION
1. UVOD

The suitability of a given type of wood for flooring is determined by high stability of dimensions, limited hygroscopicity, high density and hardness (Tsoumis, 1991). Among exotic species, those most often mentioned as suitable for flooring include: African mahogany (*Khaya ivorensis* A. Chev.), iroko (*Milicia excels* Welw.), merbau (*Intsia bijuga* Kuntze.*)*, sucupira (*Diplotropis purpura* Sprague), jatoba (*Hymenea courbaril* Linn.). Wood of these species shows very good mechanical properties and high resistance to adverse effects of outside factors (e.g. biotic ones). Among European wood species often used as flooring material, oak (*Quercus robur* L.) is often mentioned, for both indoor and outdoor use. Oak wood shows a rather low fibre saturation point, close to 24 %, good mechanical properties and intermediate shrinkage values (Wagenführ, 2007). Increasing deficit of oak wood on the European market has prompted the interest in wood of different species and in modifications of wood of fast growing species. The latter group includes bamboo, as it is one of the fastest growing plants in the world and shows the ability to generate wooden stems. The great diversity of bamboo applications, evaluated as 5000 types, comprises the production of flooring materials (Lee *et al*., 2012) and construction boards (Sumardi and Suzuki, 2014). Among 1500 bamboo species (Khalil *et al*., 2012), moso bamboo (*Phyllostachys pubescens*) seems to be particularly attractive as it shows good physical and mechanical properties (Amada *et al*., 1997; Shao *et al*., 2010) and can be successfully grown in Europe because it tolerates low temperatures. Bamboo is hygroscopic, similarly as other lignocellulose materials, which affects the stability of its dimensions and its mechanical parameters. In order to reduce the effect of hygroscopicity on the above properties, bamboo is subjected to thermal treatment, which also changes its physical properties, e.g. may lead to a 50 % increase in dimensional stability, and mechanical properties (Bekhta and Niemz, 2003; Esteves and Pereira, 2008). Densification is one of the first procedures used for the improvement of wood properties (Kollmann *et al*., 1975). Densification of fast-growing species, which leads to material of high density and good mechanical properties, is of particular importance (Morsing, 2000). Bamboo subjected to a combination of heat treatment and densification becomes an attractive flooring material. The aim of the study is to determine the physical and mechanical properties of bamboo and oak wood and compare these properties with those of bamboo subjected to thermal treatment and densification.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

The material studied was moso bamboo (untreated). It was not possible to obtain reference material of the same species, so the material of the genus *Phyllostachys* was used. Its properties were compared to those of moso bamboo (*Phyllostachys pubescens*) subjected to densification (up to the density of over 1000 kg/m^3) and patented heat-treatment process at 200 °C according to the MOSO technology. In Europe, bamboo is classified as an exotic species. The properties of untreated and treated bamboo were compared with those of the control material, which was heartwood of oak trees (*Quercus robur* L.).

2.2 Methods
2.2. Metode

2.2.1 Chemical analysis
2.2.1. Kemijska analiza

The samples were ground in a laboratory mill Fritsch type Pulverisette 15 (Fritsch GmbH, Germany). For chemical analyses, the 0.5-1.0 mm wood sawdust fraction was used. Substances soluble in organic solvent (96 % ethanol), in cold and hot water, in alkali (1 % NaOH), ash, cellulose, pentosans and lignin were analysed. The substances soluble in organic solvent, water and alkali were analysed according to TAPPI T 204 cm-07 (2007), TAPPI T 207 cm-08 (2008) and TAPPI T 212 om-18 (2018) standards, respectively. Ash content was determined based on TAPPI T 211 om-07 standard (2007). The content of cellulose was determined using the Kürschner–Hoffer method. The content of pentosans was determined according to the procedure recommended by the Technical Association of Pulp and Paper Industry (TAPPI) T 223 cm-01 standard (2001). The content of acid-insoluble lignin was estimated based on TAPPI T 222 om-06 standard (2006), using 72 % sulphuric acid to hydrolyse and solubilise carbohydrates. All analyses were repeated three times for each examined sample batch.

2.2.2 Determination of wood density
2.2.2. Određivanje gustoće drva

Physical properties and wood hardness were determined on wood samples 20 (R) mm × 20 (T) mm × 30 (L) mm. For the untreated bamboo sample, the radial dimension (R) was the thickness of the stem wall, while for the treated bamboo the radial dimension was the thickness of the terrace board. The sample densities were determined according to the method recommended by ISO 13061-2:2014. The mass of each sample was measured on an analytical balance (Sartorius GmbH, Germany) (±0.001 g accuracy). The dimensions were measured with digital calliper to the accuracy of ±0.01 mm.

2.2.3 Sorption experiments
2.2.3. Istraživanje sorpcije

Sorption experiments were made using a dynamic vapour sorption (DVS) apparatus (DVS Advantage 2 from Surface Measurement Systems, London, UK). The *EMC* values were recorded for 10 levels of air humidity (*RH*) in the range from 0 to 95 % in the adsorption/desorption modes at 20 °C. The appropriate air *RH* levels were achieved by mixing dry and saturated air streams. The samples were stored in a desiccator over P_2O_5 for two weeks leading to an *EMC* close to 0. The average mass of each sample was ca. (7±0.5) mg.

The pre-dried samples were always equilibrated in a DVS apparatus in dry nitrogen. Then, the air *RH* was stepwise increased. It was assumed that the hygroscopic equilibrium was obtained at a given air *RH* value when the mass change was less than 0.001 %/min for at least 60 min. The procedure was repeated for each *RH* step for the adsorption/desorption modes and the *EMC* values were calculated.

2.2.4 Sorption isotherm modelling
2.2.4. Modeliranje izoterme sorpcije

The adsorption/desorption isotherms were calculated according to the Guggenheim, Anderson, and De Boer (GAB) equation (Basu *et al*., 2006):

$$EMC = M_\mathrm{m} \frac{100 \cdot K \cdot C \cdot RH}{\left(100 - K \cdot RH\right) \cdot \left(100 - K \cdot RH + C \cdot K \cdot RH\right)} \quad (1)$$

where *EMC* (%) – equilibrium moisture content, *RH* (%) – air relative humidity, M_m (%) – monolayer capacity, *C* – equilibrium constant related to the monolayer sorption (also known as the Guggenheim constant), *K* – equilibrium constant related to the multilayer sorption. The GAB model is an extension of the Brunauer-Emmett-Teller (BET) model. In contrast to the BET equation, it postulates an enthalpy decrease of polymolecular water. The mathematical analysis of the GAB model shows that it can be simplified to the BET equation when $K = 1$ (e.g. Furmaniak *et al*., 2007).

The estimators of the sorption hysteresis, i.e. the maximum difference of *EMC* for desorption and adsorption (ΔEMC), the hysteresis loop (*H*) and its relative change (δH), proposed by Majka *et al*. (2016) were used.

2.2.5 Wood swelling
2.2.5. Bubrenje drva

Swelling (*S*) was measured for twin samples of the size 20 mm × 20 mm × 30 mm in radial (R), tangential (T) and longitudinal (L) anatomical direction, respectively. The dimensions of the samples were measured by a digital calliper to the accuracy of 0.01 mm. Mass of the samples was determined to the accuracy of 0.001 g. All samples were placed in desiccators above an oversaturated salt solution ensuring the air *RH* equal to 25 (CH_3COOK), 45 ($K_2CO_3 \times 2H_2O$), 85 (KCl) and 98 % (K_2So_4) at the temperature of 25 °C. The samples were conditioned in such environment until the stabilisation of their mass or until the moment when in three consecutive weightings, made after an interval of 12 hours, the weight difference was not greater than 0.01 g. The swelling (*S*) was measured after the sample reached the hygroscopic equilibrium, the tangential (T) and radial (R) anatomical directions according to the following equation:

$$S = \frac{l - l_0}{l_0} \cdot 100 \quad (2)$$

where *l* (mm) – dimension of a sample, i.e. for the equilibrium moisture content, l_0 (mm) – dimension of a sample in oven-dry state (initial dimension).

2.2.6 Brinell hardness
2.2.6. Tvrdoća prema Brinellu

The wood hardness in transversal direction was measured by the Brinell method, according to PN-EN 1534 norm. The measurements were made using a steel ball of 10 mm diameter and a maximum load of 1 kN. It took 15 seconds to reach the maximum load; the load was maintained for 30 seconds, then within 15 seconds the load gradually decreased to zero. Brinell hardness was calculated as follows:

$$H_B = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})} \quad (3)$$

where *HB* is the Brinell hardness (MPa), *F* is the nominal force (N), *D* is the diameter of the steel ball (10 mm), and *d* is the mean diameter of the residual indentation (mm).

2.2.7 Statistical analysis
2.2.7. Statistička analiza

The experimental data were analysed using the Dell^{TM}Statistica^{TM}13.1 software with the analysis of variance (ANOVA). Significant differences between mean values of the parameters describing the properties of oak, and untreated and treated bamboo samples were determined using Tukey's HSD test. The comparison tests were performed at a 0.05 significance level. Identical superscripts e.g. a, b, c denote no significant difference between mean values of the investigated properties.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Chemical analysis
3.1. Kemijska analiza

Table 1 presents the results of chemical composition determined for the samples of untreated and treated bamboo and oak wood. The untreated bamboo contained lower amounts of substances soluble in ethanol (resins, waxes and fats) and soluble in water (monosac-

Table 1 Chemical composition of bamboo and oak wood (%)
Tablica 1. Kemijski sastav bambusa i hrastovine (%)

Material *Materijal*		**Substances soluble in** *Komponente topljive u…*				**Ash** *Pepeo*	**Carbohydrates** *Ugljikohidrati*		**Lignin** *Lignin*	**C/L ratio** *Omjer C/L*
		Ethanol *Etanolu*	**Cold water** *Hladnoj vodi*	**Hot water** *Vrućoj vodi*	**1 % NaOH**		**Cellulose** *Celuloza*	**Pentosanes** *Pentozani*		
Bamboo *bambus*	Untreated *neobrađen*	2.8 ^{a} ±0.1	1.8 ^{a} ±0.1	3.1 ^{a} ±0.1	24.1 ^{b} ±0.2	5.3 ^{c} ±0.10	57.0 ^{b} ±1.5	22.7 ^{b} ±1.1	32.8 ^{b} ±0.1	1.74
	Treated *obrađen*	6.7 ^{c} ±0.7	5.4 ^{c} ±0.1	7.8 ^{c} ±0.6	26.4 ^{c} ±1.0	2.7 ^{b} ±0.01	52.3 ^{b} ±3.9	12.5 ^{a} ±0.5	50.7 ^{c} ±0.5	1.03
Oak wood *hrastovina*		4.7 ^{b} ±0.1	3.5 ^{b} ±0.1	5.7 ^{b} ±0.1	20.4 ^{a} ±0.6	0.3 ^{a} ±0.04	46.1 ^{a} ±0.3	27.0 ^{c} ±1.0	24.0 ^{a} ±0.6	1.90

Mean values (n = 3) ± standard deviations / *srednje vrijednosti (n = 3) ± standardne devijacije*

charides, tannins, dyes and starch) than oak wood and treated bamboo. Statistically significant differences in chemical composition between the untreated and treated bamboo illustrate the impact of heat treatment. The content of substances soluble in 1 % NaOH (hemicelluloses and products of lignin and cellulose degradation, phenolic compounds) in the untreated and treated bamboo is higher than in oak wood, which agrees with literature data for the species (Tamolang *et al*., 1980). The content of substances soluble in 1 % NaOH higher in treated than in untreated bamboo can be related to the degradation of pentosanes upon bamboo treatment. In general, treated bamboo contains more non-structural components than untreated bamboo, which is probably the result of their thermal decomposition. Untreated and treated bamboo show higher contents of cellulose and lignin than oak heartwood which, however, contains more pentosanes. The differences in the content of cellulose between untreated and treated bamboo are not statistically significant, which means that this component is resistant to heat treatment. However, the differences in the contents of pentosanes and lignin between untreated and treated bamboo are statistically significant. The heat treatment caused degradation of about 45 % pentosanes sensitive to elevated temperatures (Fengel and Wegener, 1989). The increase in the content of lignin as a result of heat treatment is probably related to the decrease in the content of pentosanes. Moreover, the heat-treated bamboo is characterized by a low C/L index (1.03), which means that the contents of cellulose and lignin in this sample are very close. A low C/L value and high content of non-structural substances imply that the physicomechanical properties of heat-treated bamboo are probably much different from those of untreated bamboo and oak.

3.2 Wood density
3.2. Gustoća drva

The results of density measurements for the samples studied are given in Table 2.

The results revealed statistically significant differences between the mean values of all samples. The smallest variation in density was found for oak wood. The density of untreated bamboo was by 27 % higher than that of oak. The average density of bamboo can vary from 550 to 1010 kg/m^3 depending on the site of sample cutting (Razak *et al*., 2007). The heat treatment and densification of bamboo resulted in the density increase by 38 % with respect to that of untreated bamboo.

Table 2 Densities of wood samples studied (kg/m^3)
Tablica 2. Gustoća istraživanih uzoraka drva (kg/m^3)

Material / *Materijal*		**Mean ± SD**	**Min**	**Max**
Bamboo *bambus*	Untreated *neobrađen*	852 ^{b} ±54	781	940
	Treated *obrađen*	1171 ^{c} ±62	1076	1260
Oak wood / *hrastovina*		672 ^{a} ±7	656	683

Mean values (n = 10) ± standard deviations / *srednje vrijednosti (n = 10) ± standardne devijacije*

3.3 Adsorption and desorption
3.3. Adsorpcija i desorpcija

The obtained sorption isotherms are presented in Figure 1. Each plot consists of two sets of isotherm loops, i.e. oak wood and untreated or treated bamboo. The isotherms were constructed by fitting the GAB model to each set of experimental data, the measured *EMC* values are also depicted in the plots.

A comparison of the sorption isotherms, shown in Figure 1a, reveals small differences in the equilibrium moisture content between oak and untreated bamboo. For the *RH* greater than 40 %, the equilibrium moisture content of untreated bamboo was lower than that of oak in both sorption phases. The treated bamboo showed much reduced *EMC* in the entire range of relative air humidity studied and much smaller area of the hysteresis loop than that of oak wood, Figure 1b. The decrease in *EMC* is interpreted as a consequence of about 10.2 % reduced contribution of pentosanes in treated bamboo relative to that in the untreated sample (see Table 1). It is a well-known result of thermal decomposition of hemicelluloses, i.e. the most hygroscopic component of wood cell walls. The lowest *EMC* for treated bamboo is also a result of high content of extractives as shown in Table 1. The influence of extractives on the sorption phenomenon has been previously reported by Simón *et al*. (2015), and it has been

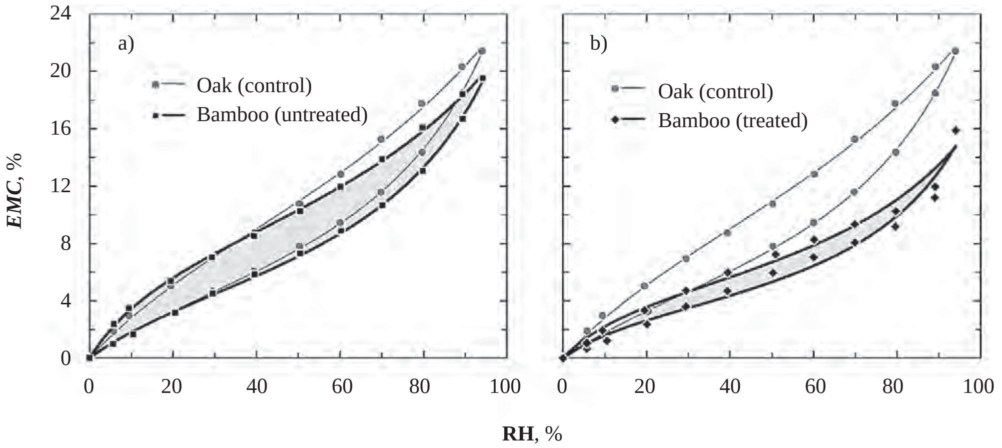

Figure 1 Sorption isotherms of bamboo at temperature of 25 °C compared to those of oak wood. Sorption isotherms estimated with the GAB model, dots represent experimental data, grey area is the sorption hysteresis loop
Slika 1. Izoterme sorpcije bambusa pri temperaturi 25 °C u usporedbi s hrastovinom; izoterme sorpcije procijenjene su GAB modelom; točke predočuju eksperimentalne podatke, a siva je zona histereza sorpcije

pointed out that high concentration of extractives causes a decrease in *EMC*. Spalt (1958) has observed that wood with a high content of extractives reveals low *EMC*, especially when air *RH* is above 50 %.

The GAB sorption model was separately fitted to the data obtained for bamboo and oak wood whose adsorption and desorption isotherms were determined. The Statistica™ 13.1 software, with the implemented Levenberg-Marquardt iterative algorithm, was applied to estimate the coefficients of the models of the sorption isotherms. The results of fitting are presented in Table 3.

The values of M_m coefficient of the GAB model of untreated bamboo were slightly lower than those of oak wood, while for thermally treated and densified bamboo this parameter was much lower. This can be explained by the fact that the treatment reduced the accessibility of the primary sorption sites in the treated bamboo.

The values of *C* coefficient were higher than 2 for all estimated isotherms, which is the necessary condition for classifying the isotherms as type II. An additional condition for recognizing sorption isotherms as type II was proposed by Lewicki (1997). The conjunction of the relations 5.57 £ *C* < ∞ and 0.24 < *K* £ 1 was not satisfied (Table 3). Therefore, not all isotherms could be classified as (fully sigmoidal) type II. This coefficient represents the total heat of sorption of the monolayer water and its values have to be positive (Maskan and Göğüş, 1997). The *C* values were significantly higher than *K,* which indicates much higher heat of sorption of the monolayer as compared to the multilayer (de Oliveira *et al*., 2017). It was found that the thermal modification and densification of bamboo caused an increase in *C* coefficient for adsorption, which can be interpreted as a result of stronger binding of the water monolayer to the primary sorption sites. In the process of desorption, the *C* coefficient value was higher for untreated bamboo than for oak wood, which means that the removal of the water monolayer from the material structure required more heat. Almost identical values of *C* coefficient in the assumed model of sorption for the untreated and treated bamboo indicate that thermal treatment and densification of bamboo do not lead to an increase in the heat needed for the removal of water from the material structure.

The *K* coefficient is related to the water multilayer. The coefficient was significantly lower than 1 for all the studied sorption isotherms (Table 3), which complies with its physical meaning (Timmermann, 2003). A decrease in the *K* coefficient was interpreted by Timmermann *et al*. (2001) as corresponding to the less structured state of the water multilayer. The highest values of *K* were recorded for treated bamboo, which implied that in this wood sample the water multilayer was characterized by a higher degree of ordering than in untreated bamboo and oak wood.

The obtained descriptors of sorption hysteresis are presented in Figure 2 and Table 4. The most remarkable alteration of the hysteresis was found for thermal modified and densified bamboo. The hysteresis loop (*H*) was significantly reduced, i.e. it was as small

Table 3 Estimated coefficients of the sorption GAB model for bamboo and oak wood
Tablica 3. Procijenjeni koeficijenti sorpcijskoga GAB modela za bambus i hrastovinu

Material / *Materijal*		**Sorption phase** *Faza sorpcije*	M_m **(%)**	***K***	***C***	R^2	***SE***
Bamboo *bambus*	Untreated *neobrađen*	Adsorption	5.86	0.7646	4.8451	0.9994	0.0018
		Desorption	9.10	0.6131	8.4089	0.9993	0.0019
	Treated *obrađen*	Adsorption	3.90	0.7969	6.9023	0.9800	0.0074
		Desorption	5.28	0.7044	8.4476	0.9829	0.0069
Oak wood / *hrastovina*		Adsorption	6.54	0.7663	4.0795	0.9998	0.0010
		Desorption	12.11	0.5653	4.6743	0.9991	0.0024

Table 4 Sorption hysteresis loop (*H*), hysteresis relative change (δ*H*), maximum difference in equilibrium moisture content for desorption and adsorption (Δ*EMC*) and corresponding air relative humidity (*RH*) indices for bamboo and oak wood
Tablica 4. Histereza sorpcije (*H*), relativna promjena histereze (δ*H*), najveća razlika ravnotežnog sadržaja vode za desorpciju i adsorpciju (Δ*EMC*) i odgovarajuća relativna vlažnost zraka (*RH*) za bambus i hrastovinu

Material / *Materijal*		**Hysteresis descriptors** / *Deskriptori histereze*			
		***H* (arb. units)**	**δ*H*, %**	**Δ*EMC*, %**	***RH*, %**
Bamboo *bambus*	Untreated / *neobrađen*	233.7	+2.2	3.26	57
	Treated / *obrađen*	97.9	-57.2	1.42	61
Oak wood / *hrastovina*		228.6	–	3.54	63

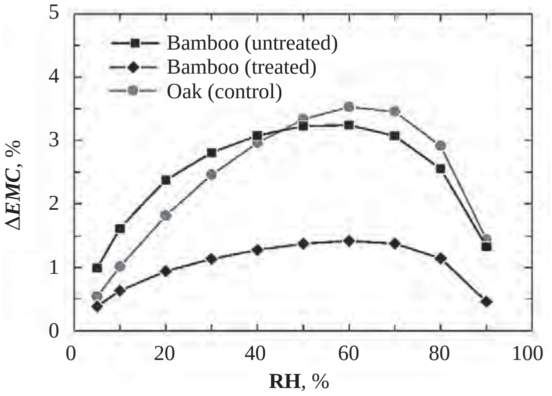

Figure 2 Sorption hysteresis of untreated and treated bamboo and oak wood
Slika 2. Histereza sorpcije neobrađenih i obrađenih uzoraka bambusa i hrastovine

as 97.9 and it corresponded to the plot in Figure 2. The applied treatment of bamboo resulted in a significant reduction of the sorption hysteresis loop to the level of ca. 57 % as compared with that of the untreated material (Table 4). The reduction in the area of the hysteresis loop indicates a decrease in the free energy of the sorption process and a consequent improvement in dimensional stability (Esteban *et al*. 2008). The untreated bamboo revealed only slightly lower sorption hysteresis than oak wood i.e. 233.7. This tendency was also supported by other estimators presented in Table 4 and the course of Δ*EMC* for desorption and adsorption as a function of air *RH* (Figure 2). Moreover, for the untreated bamboo, the maximum difference in *EMC* between the desorption and adsorption phases was by ca. 2.5 times smaller than for oak wood.

3.4 Swelling
3.4. Bubrenje

Figure 3 illustrates the swelling of the sample studied in the tangential and radial directions. According to Wagenführ (2007), oak wood is characterised by intermediate values of shrinkage, while for untreated bamboo the corresponding values are low. The oak wood swelling reached about 4 and 7 % in the radial and tangential anatomical directions, respectively, while the corresponding values for untreated bamboo were about 5 and 6 %, respectively. As follows from the comparison of swelling recorded for treated and untreated bamboo, Figure 3, the thermo-mechanical modification of bamboo also led to a reduction of its moisture deformation. Thermo–mechanically treated bamboo showed much smaller degree of swelling in the whole range of hygroscopicity than untreated bamboo and oak wood. The wood swelling of treated bamboo was about 3 % in both radial and tangential directions. This result means that it is reasonable to expect that the thermo-mechanical treatment of bamboo will improve the dimensional stability of products made of this wood. The reduced swelling of thermally treated bamboo relative to that of untreated wood is a result of decreased hygroscopicity of the former.

Thermo-mechanical treatment of moso bamboo also resulted in a decrease in the swelling anisotropy index. Its lowest value of 1.09 was obtained for treated bamboo, while the value obtained for oak wood was much higher, 1.58.

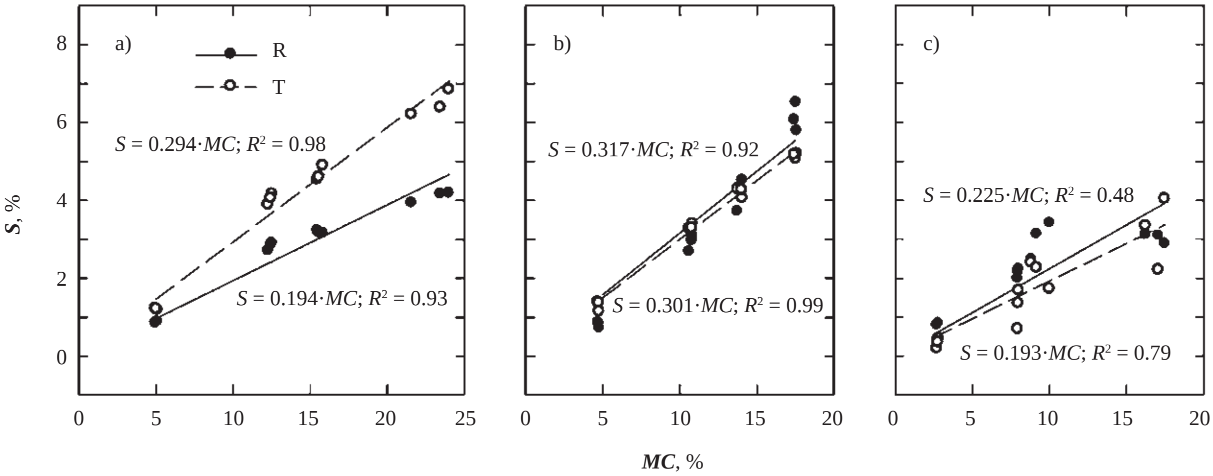

Figure 3 Comparison of swelling of (a) oak wood, (b) untreated bamboo and (c) treated bamboo in radial (R) and tangential (T) anatomical direction
Slika 3. Usporedba bubrenja (a) hrastovine, (b) neobrađenog bambusa i (c) obrađenog bambusa u radijalnome (R) i tangentnom (T) smjeru

3.5 Brinell hardness
3.5. Tvrdoća prema Brinellu

Table 5 presents the results of *HB* determination for all samples studied. Oak wood is considered to be of high hardness, and the mean value of hardness for oak wood in the transversal plane was $HB_{\perp}$=56 MPa. The differences between the mean HB values determined for oak wood and untreated bamboo are statistically insignificant. The hardness of both treated and untreated bamboo was higher than that of oak wood; however the hardness of treated bamboo was about 3 times higher. The process of densification resulted in a significant increase in *HB*. Thanks to the applied modification (thermal treatment and densification), moso bamboo has become an excellent material for high quality flooring. Its *HB* was higher than that of merbau ($HB_{\perp}$=89 MPa), courbaril ($HB_{\perp}$=56 MPa) or ipe ($HB_{\perp}$=49 MPa) (Wagenführ, 2007).

Table 5 Bamboo and oak wood (*HB*) in radial R and tangential T anatomical directions
Tablica 5. Tvrdoća prema Brinellu (*HB*) bambusa i hrastovine u radijalnome (R) i tangentnom (T) smjeru

Material *Materijal*		***HB*, MPa**		
		R	**T**	⊥
Bamboo *bambus*	Untreated *neobrađen*	62.7 ^{a} ±5.5	54.7 ^{b} ±6.6	58.7
	Treated *obrađen*	149.9 ^{b} ±11.0	114.7 ^{a} ±9.5	132.3
Oak wood *hrastovina*		52.8 ^{a} ±8.2	59.9 ^{b} ±6.7	56.4

4 CONCLUSIONS
4. ZAKLJUČAK

According to the results presented and discussed above, untreated bamboo can satisfactorily replace oak wood for flooring production as the properties of these two types of wood are similar. The applied modification of moso bamboo, comprising heat treatment and densification, has been proved to considerably improve the properties of this wood qualifying it as the flooring material. The thermomechanical treatment of bamboo resulted in increasing its density from about 800 to over 1150 kg/m^3, in increasing the degree of the water multilayer and in increasing the amount of heat needed for the removal of water from moso bamboo structure. It also brought about a significant decrease in hygroscopicity, decrease in the hysteresis of sorption and restricted the water access to primary sorption sites in modified moso bamboo, which enhanced its dimensional stability. Another beneficial effect of the treatment applied is almost double reduction of swelling in the direction perpendicular to the fibres. Also, the Brinell hardness of modified bamboo was almost twice greater than that of untreated bamboo and oak wood. In view of the above, it can be concluded that treated bamboo is a highly suitable material for the applications in which it is exposed to the adverse effects of external factors and elements.

5 REFERENCES
5. LITERATURA

1. Amada, S.; Ichikawa, Y.; Munekata, T.; Nagase, Y.; Shimizu, H., 1997: Fiber texture and mechanical graded structure of bamboo. Composites Part B: Engineering, 28B: 1-20. https://doi.org/10.1016/S1359-8368(96)00020-0.
2. Basu, S.; Shivhare, U. S.; Mujumdar, A. S., 2006: Models for sorption isotherms for food: A review. Drying Technology, 24: 917-930. https://doi.org/10.1080/07373930600775979.
3. Bekhta, P.; Niemz, P., 2003: Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood. Holzforschung, 57: 539-546. https://doi.org/10.1515/HF.2003.080.
4. Esteban, L. G.; de Palacios, P.; Fernandez, F. G.; Guindeo, A.; Conde, M.; Baonza, V., 2008: Sorption and thermodynamic properties of juvenile *Pinus sylvestris* L. wood after 103 years of submersion. Holzforschung, 62: 745-751. https://doi.org/10.1515/HF.2008.106.
5. Esteves, B.; Pereira, H., 2008: Quality assessment of heat-treated wood by NIR spectroscopy. Holz als Roh- und Werkstoff, 66: 323-332. https://doi.org/10.1007/s00107-008-0262-4.
6. Fengel, D.; Wegener, G., 1989: Wood-Chemistry, Ultrastructure, Reactions, 2nd ed. Walter de Gruyter, Berlin. https://doi.org/10.1002/pol.1985.130231112.
7. Furmaniak, S.; Terzyk, A. P.; Gauden, P. A., 2007: The general mechanism of water sorption on foodstuffs – Importance of the multi temperature fitting of data and the hierarchy of models. Journal of Food Engineering, 82: 528-535. https://doi.org/10.1016/j.jfoodeng.2007.03.012.
8. Khalil, H. P. S. A.; Bhat, I. U. H.; Jawaid, M.; Zaidon, A.; Hermawan, D.; Hadi, Y. S.; 2012: Bamboo fibre reinforced biocomposites: A review. Materials & Design, 42: 353-368. https://doi.org/10.1016/j.matdes.2012.06.015.
9. Kollmann, F. P.; Kuenzi E. W.; Stamm A. J., 1975: Principles of Wood Science and Technology, Vol. II: Wood Based Materials. Springer-Verlag, New York, Heidelberg, Berlin: 139-149. https://doi.org/ 10.1007/978-3-642-87931-9.
10. Kürschner, K.; Hoffer, A., 1929: Ein neues verfahren zur bestimmung der cellulose in holzern und. Zellstoffen Tech Chem Pap Zellst. 26: 125-129.
11. Lee, C. H.; Chung, M. J.; Lin, C. H.; Yang, T. H., 2012: Effects of layered structure on the physical and mechanical properties of laminated moso bamboo (*Phyllosachys edulis*) flooring. Construction and Building Materials, 28: 31-35. https://doi.org/10.1016/j.conbuildmat.2011.08.038.
12. Lewicki, P. P., 1997: The applicability of the GAB model to food water sorption isotherms. International Journal of Food Science & Technology, 32: 553-557. https://doi.org/10.1111/j.1365-2621.1997.tb02131.x.
13. Majka, J.; Czajkowski Ł.; Olek, W., 2016: Effects of cyclic changes in relative humidity on the sorption hysteresis of thermally modified spruce wood. BioResources, 11: 5265-5275. https://doi.org/10.15376/biores.11.2.5265-5275.
14. Maskan, M.; Göğüş, F., 1997: The fitting of various models to water sorption isotherms of pistachio nut paste. Journal of Food Engineering, 33(3-4): 227-237. https://doi.org/10.1016/S0260-8774(97)00061-7.
15. Morsing, N., 2000: Densification of wood – The influence of hygrothermal treatment on compression of beech perpendicular to the grain. Department of structural engi-

neering and materials technical university of Denmark, Series R, 79: 138 pp.

16. de Oliveira, G. H. H.; Corrêa, P. C.; de Oliveira, A. P. L. R.; Devilla, I. A., 2017: Application of GAB model for water desorption isotherms and thermodynamic analysis of sugar beet seeds. Journal of Food Process Engineering, 40: e12278. https://doi.org/10.1111/jfpe.12278.
17. Razak, W.; Janshah, M.; Hashim, W. S. S. B., 2007: Morphological and anatomical characteristics ofmanaged natural bamboo stands *Gigantochloa scortechinii*. Journal of Bamboo and Rattan, 6 (2).
18. Shao, Z. P.; Fang, C. H.; Huang, S. X.; Tian, G. L., 2010: Tensile properties of Moso bamboo (*Phyllostachys pubescens*) and its components with respect to its fiber-reinforced composite structure. Wood Science and Technology, 44 (4): 655-666. https://doi.org/10.1007/s00226-009-0290-1.
19. Simón, C.; Esteban, L. G.; Palacios, P.; Fernández, F. G., 2015: Thermodynamic analysis of water vapour sorption behaviour of juvenile and mature wood *Abies alba* Mill. Journal of Material Science, 50: 7282-7292. https://doi.org/10.1007/s10853-015-9283-7.
20. Spalt, H. A., 1958: The fundamentals of water vapor sorption by wood. Forest Products Journal, 8 (10): 288-295.
21. Sumardi, I.; Suzuki, S., 2014: Dimensional stability and mechanical properties of strandboard made from bamboo. BioResources, 9 (1): 1159-1167. https://doi.org/10.15376/biores.9.1.1159-1167.
22. Tamolang, F. N.; Lopez, A. R.; Semara, J. A.; Casin, R. F., Espiloy, Z. B., 1980: Properties and utilization of Philippine erect bamboos. Forpride digest, Laguna, v. 99, n. 34, p. 31-41, 1980.
23. Timmermann, E. O.; Chirife, J.; Iglesias, H. A., 2001: Water sorption isotherms of foods and foodstuffs: BET or GAB parameters. Journal of Food Engineering, 48 (1): 19-31. https://doi.org/10.1016/S0260-8774(00)00139-4.
24. Timmermann, E. O., 2003: Multilayer sorption parameters: BET or GAB values. Colloid. Surface A, 220 (1-3): 235-260. https://doi.org/10.1016/S0927-7757(03)00059-1.
25. Tsoumis, G., 1991: Science and technology of wood: structure, properties, utilization. New York: Chapman & Hall, 1991, 494 p. https://doi.org/10.1163/22941932-90001279.
26. Wagenführ, R., 2007: Holzatlas. Fachbuchverlage, Lipsk. https://doi.org/10.1163/22941932-90001585.
27. *** PN-EN 1534: 2011 Wood flooring – determination of resistance to indentation – test method.
28. *** ISO 13061-2: 2014 Physical and mechanical properties of wood – Test methods for small clear wood specimens, part 2: Determination of density for physical and mechanical tests.
29. *** TAPPI, 1996-7 Standards, Technical Association of Pulp and Paper Industry, 15 Technology Parkway South, Norcross, GA 30092, USA, T204, T207, T211 and T222.

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Influence of Natural Surface Ageing on Bonding Quality of Thermally Modified Oak and Beech Wood

Utjecaj prirodnog starenja površine na kvalitetu lijepljenja toplinski modificiranog drva hrasta i bukve

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ABSTRACT • *This paper presents the influence of natural surface ageing in indoor conditions on bonding quality of thermally modified wood used in structural laminated products. Two unmodified and thermally modified wood species were used for the experiment: oak and beech. Samples were planed and glued with MUF adhesive 2 hours, 1, 2, 6, 10, and 18 days after planing. Properties of laminated beech and oak beams, namely shear strength, delamination and contact angle, were measured in order to detect 1) suitability of wood species for lamination process and 2) influence of extended storage time after planing on properties of laminated wood. Generally, both native and thermally modified beech exhibited better results of shear strength and delamination and had lower contact angles compared to oak and thermally modified oak. Results of the delamination test (total delamination) indicate time dependence of surface ageing. Both unmodified and thermally modified beech may be successfully laminated at least up to 2 days after planing, whereas neither oak nor thermally modified oak are suitable for lamination process due to excessive delamination. Results of delamination may be related to contact angle measurements. Shear strength of glue lines did not show any influence on natural surface ageing. However, whereas beech and thermally modified beech samples exhibited almost the same values of the shear strength regardless of the duration of surface ageing, there is an obvious difference in shear strength of oak and thermally modified oak samples.*

Keywords: *bonding, delamination, modified wood, shear strength, surface ageing*

SAŽETAK • *U radu je prikazan utjecaj prirodnog starenja površine zbog stajanja u interijeru na kvalitetu lijepljenja toplinski modificiranog drva. U pokusu su korištene dvije nemodificirane i toplinski modificirane vrste drva: hrast i bukva. Uzorci su blanjani i lijepljeni MUF ljepilom 2 sata, 1, 2, 6, 10 i 18 dana nakon blanjanja. Mjerena su svojstva lameliranih bukovih i hrastovih gredica, njihova čvrstoća na smik, delaminacija i kontaktni kut kako bi se ustanovila (1) prikladnost vrste drva i postupka modifikacije za proces lameliranja te (2) utjecaj produljenog vremena skladištenja nakon blanjanja na svojstva lameliranog drva. Općenito, i prirodna i toplinski modificirana bukovina pokazale su bolje rezultate smične čvrstoće i manju sklonost delaminaciji, kao i niže kontaktne kutove nego hrastovina i toplinski modificirana hrastovina. Rezultati ispitivanja delaminacije (potpune delaminacije) upućuju na ovisnost površinskog starenja o vremenu. I nemodificirana i toplinski modificirana bukov-*

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ina mogu se uspješno lamelirati najmanje dva dana nakon blanjanja, dok ni hrastovina ni toplinski modificirana hrastovina zbog sklonosti prekomjernoj delaminaciji nisu prikladne za lameliranje. Rezultati delaminacije mogu biti povezani s mjerenjima kontaktnog kuta. Čvrstoća lijepljenja na smik nije uvjetovana prirodnim starenjem površine. Međutim, dok su nemodificirani i toplinski modificirani uzorci bukve imali gotovo jednake vrijednosti čvrstoće lijepljenja na smik bez obzira na trajanje površinskog starenja, bila je očita razlika u smičnoj čvrstoći hrastovih nemodificiranih i toplinski modificiranih uzoraka.

Ključne riječi: *lijepljenje, delaminacija, modificirano drvo, smična čvrstoća, starenje površine*

1 INTRODUCTION
1. UVOD

It is well known that bonding quality of wood depends not only on the type and quality of the adhesive and parameters of the technological process, but also on the condition of the wood material and especially of its surface. For optimal results, adhesive should be applied to wood surface within 24 hours after the surface is prepared (by planing or sanding), as this ensures the removal of extractives and other physical and chemical contaminants from the surface (Vick, 1999). Surface wettability is linearly reduced during 4 – 6 days, which may negatively affect the bonding strength (Nussbaum, 1999). A lot of attention was given to establishing the influence of specimen size (especially lamella width and thickness), the alignment of the annual rigs in the lamellas, closed assembly time and pressure on bond durability (Aicher and Reinhardt, 2007; Schmidt *et al*., 2010). Adhesive penetration into wood was reviewed in detail by Kamke and Lee (2007), who identified several important factors; these are fluid properties of the resin, anatomical characteristics and permeability of wood, and processing conditions. Penetration of adhesive is particularly important because it needs to be sufficient to encapsulate damaged cells near the bonded interface, but not excessive in order to eliminate waste of resin and low mechanical properties if bondline remained starved.

Thermally modified wood has many applications both indoors and outdoors, mainly for decorative purposes and non-load bearing structures. The degradation of mechanical properties during treatment at high temperatures requires additional tests before the material can be used for load bearing purposes (Borrega and Kärenlampi, 2008). However, thanks to its good biological resistance and aesthetic attributes (Hill, 2006), it is an attractive building material.

Thermal modification process also reduces the surface wettability and increases surface brittleness, which then negatively affects bond performance of wood (Chu *et al*., 2016; Šernek *et al*., 2008; Kariž and Šernek, 2012; Uzun *et al*., 2016). However, shear strength and delamination tests performed on native and thermally modified Norway spruce and poplar glued with PUR and MUF adhesives were found to meet the requirements for glued laminated timber (Šernek *et al*., 2008). Additionally, surface structure of hardwoods (ring-porous oak wood and diffuse to semi-ring-porous beech) might additionally affect the bonding quality. Experiments performed on ash wood laminated with different structural adhesives showed that shear strength of bonded ash is comparable with that of solid ash, but resistance to delamination could not be met by any of the adhesives (Knorz *et al*., 2014). Widmann *et al*. (2012) investigated the influence of thermal treatment at 180-190 °C on structural beech wood. The treatment resulted in a significant reduction of most strength properties – the strength properties perpendicular to grain suffered a lot, brittle behaviour of the specimens and big variations in strength were detected as the main disadvantages of thermal treatment, whereas compression strength parallel to grain and stiffness properties were unchanged. Based on these results, a general use of thermally modified beech as structural timber was not recommended, except for structural facade elements or for columns. Testing of glulam beams made of thermally modified beech timber (Widmann *et al*., 2014) showed sufficient quality of manually produced finger-joints, poor 4-point bending strength, but high stiffness, high degree of delamination and good shear properties with over 80 % wood failure.

Hardwoods (especially oak) are challenging for both thermal modification and gluing. Some companies put modified and mechanically prepared material on stock, which may then affect negatively the bonding properties. Therefore, the aim of our paper was to investigate the influence of natural surface ageing of both native and thermally modified oak and beech wood in indoor conditions on bonding quality in structural applications.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

Two wood species were used for the experiment: oak (*Quercus robur* L.) (O, OT) and beech (*Fagus sylvatica*) (B, BT). The material for testing was flat sawn and commercially thermally modified by a local manufacturer at 210 °C in water vapor atmosphere. Unmodified and thermally modified samples of 1000 mm × 100 mm × 20 mm (L × T × R) were planed and glued with MUF adhesive 2 hours, 1, 2, 6, 10, and 18 days after planing. Each beam consisted of 5 lamellae. The adhesive was applied in industrial conditions using rollers. Application rate of the adhesive was 180 g/m^2 per side (360 g/m^2 in total), pressure 1.5 MPa, pressing time 16 hours. Pressing was performed at normal ambient conditions. After curing of the adhesive, beams were cut into 5 test pieces of 75 mm × 100 mm × 100 mm (L × T × R) for delamination tests and 10 test bars of 40 mm × 40 mm × 100 mm (L × T × R) for shear strength tests

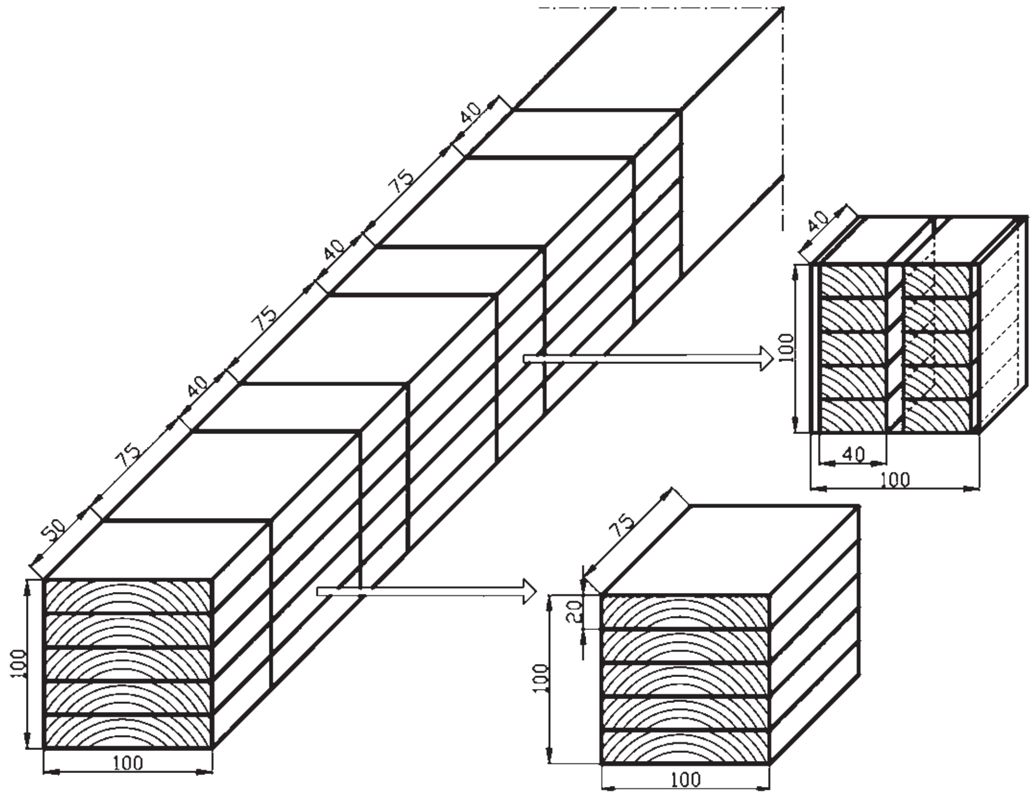

Figure 1 Cutting scheme of experimental beams for delamination and shear tests
Slika 1. Shema izrezivanja ispitnih uzoraka za potrebe ispitivanja čvrstoće na smik i delaminacije

(scheme shown in Figure 1). An additional set of samples was used for contact angle measurements.

Contact angle of distilled water was measured using a sessile drop method with an optical goniometer. Drops of 2 μL were observed using a digital camera installed on the opposite side of the light source. Droplets were applied at 10 different places on tangential surfaces on each specimen, and images for contact angle were taken 3 seconds after detachment of the drop.

The samples for the delamination test were fully impregnated with water within a single cycle process that consisted of 30 min vacuum of 85 kPa that was followed by 2 hours pressure of 600 kPa. After this intensive impregnation step, the samples were placed into the drying duct at 70 °C and 10 % RH to reach 110 % of the original mass. Delamination is expressed as percentage of the total bondline length. Details of this method are given in EN 14080:2013 Annex C, method B.

Shear test of glue lines was performed using a compression-loading shear tool on universal testing machine with continuous shearing speed. Shear strength was then calculated for each individual bondline based on the ratio of maximum load at failure and shear areas according to EN 14080:2013.

All the measurements were taken after conditioning the samples in standard laboratory conditions (20±2) °C and (65±5) % RH.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Contact angle continuously increased with surface ageing over the period of 10 days (Figure 2). At all the stages of ageing, the contact angle was lowest in the case of unmodified beech (B: 24 – 41°), oak (O: 50 – 65°), thermally modified beech (BT: 50 – 65°) and highest in the case of thermally modified oak (OT: 64 – 76°). This is in accordance with the results of Žlahtič and Humar (2016), who have also reported higher contact angles on oak compared to beech wood. Increase of the contact angles on beech wood samples subjected to thermal modification was reported earlier by several researchers (Gérardin *et al.*, 2007; Miklečić and Jirouš-Rajković, 2016; Pétrissans *et al.*, 2003; Žlahtič and Humar, 2016). However, due to differences in methodology of contact angle measurement, it is hard to compare individual values (Petrič and Oven, 2015).

Results of total delamination clearly show the influence of both wood species and thermal treatment as well as the time dependence of surface ageing (Figure 3). There is relatively small delamination during the first 2 days of natural surface ageing in the case of unmodified and modified beech and unmodified oak. However, if lamination is performed later than 2 days after planing, the delamination exceeds the maximum value set by EN 14080. At the same time, delamination of thermally modified oak is too excessive regardless of the duration of surface ageing, indicating that this species is not suitable for laminations under conditions presented in this experiment.

Both unmodified and thermally modified beech may, therefore, be successfully laminated for at least up to 2 days after planing, whereas neither oak nor thermally modified oak are suitable for the lamination process under conditions presented here. According to EN 14080:2013, when the glue line integrity is tested

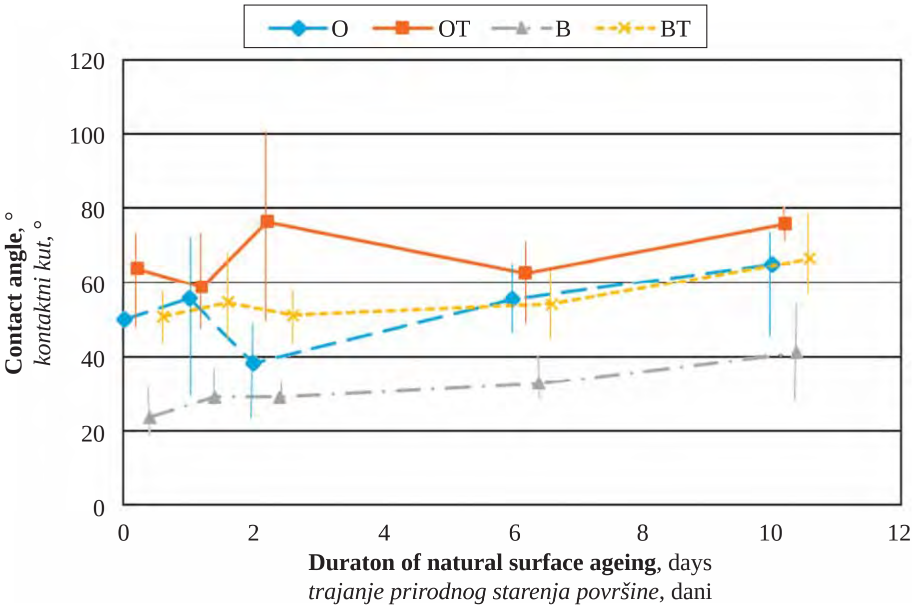

Figure 2 Influence of duration of natural surface ageing on contact angle measurements
Slika 2. Utjecaj vremena prirodnog starenja površine na vrijednosti kontaktnog kuta

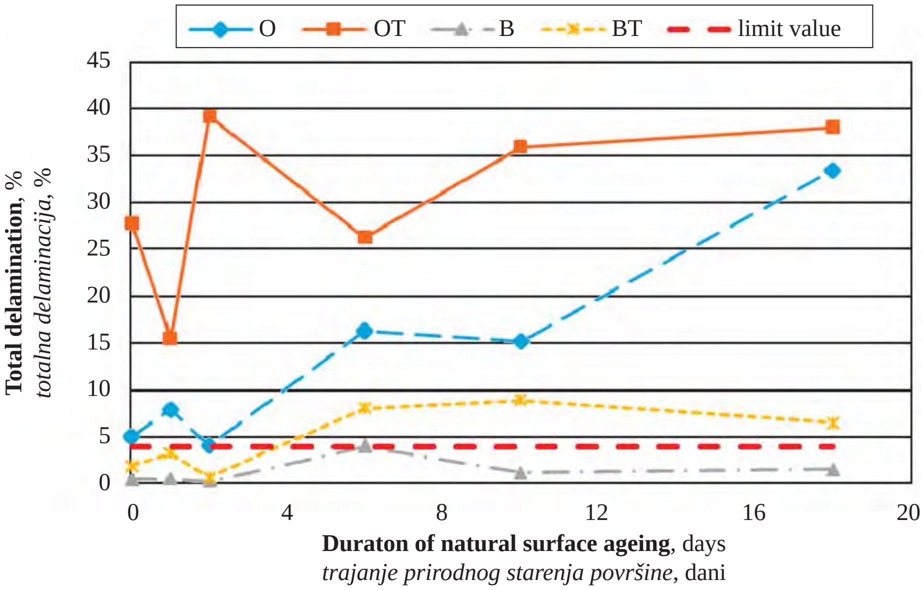

Figure 3 Influence of duration of natural surface ageing on total delamination
Slika 3. Utjecaj vremena prirodnog starenja površine na potpunu delaminaciju

by delamination test (method B), the total delamination after one cycle should not exceed 4 %.

Results of delamination may be related to contact angle measurements, which indicated that freshly prepared surface is easier to wet compared to naturally aged surface, but also that contact angle is lowest on beech (20°, 2 hours after planing) and highest on thermally modified oak surface (~76°, 10 days after planing).

Shear strength of glue lines in dry conditions did not depend on surface ageing, and the results for each set of samples for a specific species are in very narrow range (Figure 4). Shear strength is lowest in the case of thermally modified oak (~11 N/mm^2) and unmodified oak (~15.5 N/mm^2), whereas the shear strength values are very similar in case of unmodified and thermally modified beech (~20 N/mm^2). The shear test showed > 95 % wood failure for all tested species and variables.

Šernek *et al*. (2008) recorded about 10 % decrease of shear strength of glue lines and no delamination on heat treated Norway spruce with MUF adhesive. On the other hand, Knorz *et al*. (2014) tested structural bonding of ash wood with different adhesives including MUF. Ash is also a ring porous species and with similar density as oak wood, which makes the results comparable with those in this experiment. The results showed high wood failure and bond strength close to that of solid ash. However, resistance to delamination could not meet the requirements of the standard by any of the adhesives. Both, delamination and shear strengths correspond well with those obtained on oak in our experiment.

Here presented results clearly show the following:

1. Thermal modification process influenced the reduction of shear strength of glue lines of oak wood by ~

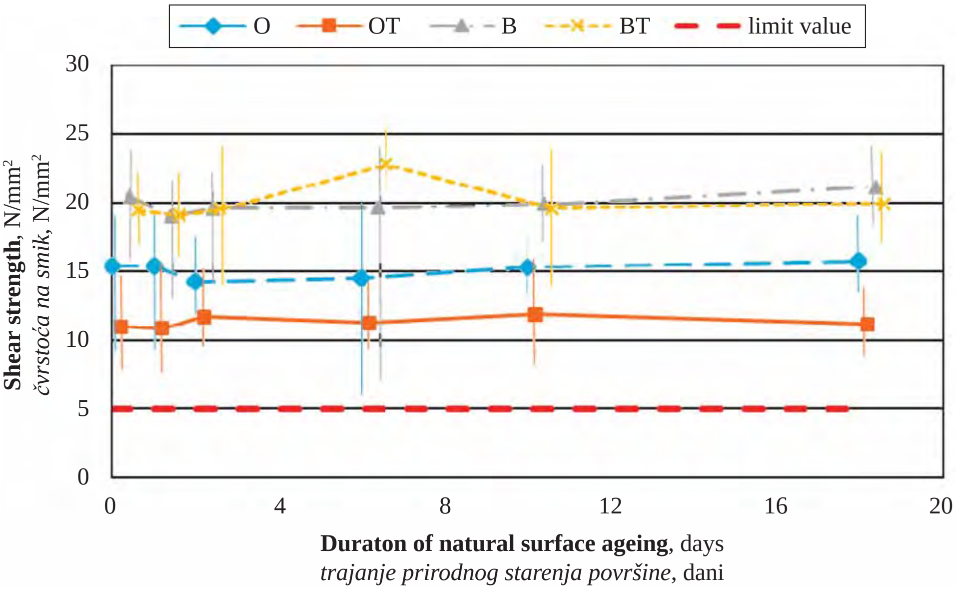

Figure 4 Influence of duration of natural surface ageing on shear strength
Slika 4. Utjecaj vremena prirodnog starenja površine na čvrstoću na smik

30 %, but subsequent natural surface ageing had no effect on shear strength of glue lines.

2. There was no influence of either modification process or natural surface ageing on shear strength of glue lines of beech wood.
3. Based on shear test of glue lines, both unmodified and thermally modified beech and oak may be used in laminations for timber structures because they meet the requirements for minimum values as defined by EN 14080, according to which shear strength of each glue line is at least 6 N/mm^2 provided that minimum wood failure is at least 90 %.

No relation between shear strength and delamination could be seen. The same behaviour was reported earlier for unmodified beech and ash wood (Schmidt *et al*., 2010; Knorz *et al*., 2014).

4 CONCLUSIONS
4. ZAKLJUČAK

Generally, both unmodified and thermally modified beech exhibited better results compared to oak and thermally modified oak.

Results of the delamination test (total delamination) indicate a time dependence of surface ageing. Both native and thermally modified beech may be successfully laminated at least up to 2 days after planing, whereas neither oak nor thermally modified oak are suitable for lamination process under the above conditions.

Shear strength of glue lines did not show any influence of natural surface ageing. Average shear strength of glue lines (in dry conditions) indicates that both native and thermally modified beech and oak may be successfully laminated regardless of the duration of natural surface ageing. However, whereas beech and thermally modified beech samples exhibited almost the same values regardless of the duration of surface ageing (~20 N/mm^2), there is an obvious difference in shear strength of oak (~15 N/mm^2) and thermally modified oak samples (~11 N/mm^2).

Results of delamination may be related to contact angle measurements, which indicated that freshly prepared surface is easier to wet compared to naturally aged surface, but also that contact angle is lowest on beech (20°, 2 hours after planing) and highest on thermally modified oak surface (~64°, 2 hours after planing).

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5 REFERENCES
5. LITERATURA

1. Aicher, S.; Reinhardt, H. W., 2007: Delaminierungseigenschaften und Scherfestigkeiten von verklebten rotkernigen Buchenholzlamellen. Holz als Roh- und Werkstoff, 65: 125-136. https://doi.org/10.1007/s00107-006-0135-7.
2. Borrega, M; Kärenlampi, P. P., 2008: Mechanical behavior of heat-treated spruce (Picea abies) wood at constant moisture content and ambient humidity. Holz als Roh- und Werkstoff, 66: 63-69. https://doi.org/10.1007/s00107-007-0207-3.
3. Chu, D.; Xue, L.; Zhang, Y.; Kang, L.; Mu, J., 2016: Surface characteristics of poplar wood with high-temperature heat treatment: Wettability and surface brittleness. BioResources, 11 (3): 6948-6967. https://doi.org/10.15376/biores.11.3.6948-6967.
4. Gérardin, P.; Petrič, M.; Petrissans, M.; Lambert, J.; Ehrhrardt, J. J., 2007: Evolution of wood surface free energy after heat treatment. Polymer Degradation and Stability, 92: 653-657. https://doi.org/10.1016/j.polymdegradstab.2007.01.016.

5. Hill, C., 2006: Wood modification – chemical, thermal and other processes. John Wiley & Sons, Ltd.
6. Kamke, A. F.; Lee, J. N., 2007: Adhesive penetration in wood – a review. Wood and Fiber Science, 39: 205-220.
7. Kariž, M.; Šernek, M., 2012: Bonding of heat-treated spruce with PVAc, PU and MUF adhesives. In: Proceedings of the Sixth European Conference on Wood Modification. Jones, D.; Militz, H.; Petrič, M.; Pohleven, F.; Humar, M.; Pavlič, M. (eds.), Ljubljana, Slovenia, pp. 247-250.
8. Knorz, M.; Schmidt, M.; Torno, S.; van de Kuilen, J.-W., 2014: Structural bonding of ash (*Fraxinus excelsior* L.): resistance to delamination and performance in shearing tests. European Journal of Wood and Wood Products, 72: 297-309. https://doi.org/10.1007/s00107-014-0778-8.
9. Miklečić, J.; Jirouš-Rajković, V., 2016: Influence of thermal modification on surface properties and chemical composition of beech wood (*Fagus sylvatica* L). Drvna industrija, 67 (1): 65-71. https://doi.org/10.5552/drind.2016.1520.
10. Nussbaum, R. M., 1999: Natural surface inactivation of Scots pine and Norway spruce evaluated by contact angle measurements. Holz als Roh- und Werkstoff, 57 (6): 419-424. https://doi.org/10.1007/s001070050067.
11. Petrič, M.; Oven, P., 2015: Determination of wettability of wood and its significance in wood science and technology: A critical review. Reviews of Adhesion and Adhesives 3(2): 121-187. https://doi.org/10.7569/RAA.2015.097304.
12. Pétrissans, M.; Gérardin, P.; El Bakali, I.; Serraj, M., 2003: Wettability of heat-treated wood. Holzforschung, 57: 301-307. https://doi.org/10.1515/HF.2003.045.
13. Schmidt, M.; Glos, P.; Wegener, P., 2010: Verklebung von Buchenholz für tragende Holzbauteile. European Journal of Wood and Wood Products, 68: 43-57. https://doi.org/10.1007/s00107-009-0382-5.
14. Šernek, M.; Boonstra, M.; Pizzi, A.; Despres, A.; Gerardin, P., 2008: Bonding performance of heat treated wood with structural adhesives. Holz als Roh- und Werkstoff, 66: 173-180. https://doi.org/10.1007/s00107-007-0218-0.
15. Uzun, O.; Perçin, O.; Altinok, M.; Kureli, I., 2016: Bonding strength of some adhesives in heat-treated hornbeam (*Carpinus betulus* L.) wood used for interior and exterior decoration. BioResources, 11 (3): 7686-7696. https://doi.org/10.15376/biores.11.3.7686-7696.
16. Vick, C. B., 1999: Adhesive bonding of wood materials. In: Wood Handbook: Wood as an Engineering Material. Forest Products Laboratory, pp. 9-1 – 9-24.
17. Widmann R.; Beikircher W.; Cabo J. L. F.; Steiger R., 2014: Bending strength and stiffness of glulam beams made of thermally modified beech timber. In: Aicher S.; Reinhardt H. W.; Garrecht, H. (eds,): Materials and Joints in Timber Structures. RILEM Bookseries, vol 9. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7811-5_52.
18. Widmann, R.; Fernandez-Cabo, J. L.; Steiger, R., 2012: Mechanical properties of thermally modified beech timber for structural purposes. European Journal of Wood and Wood Products, 70: 775-784. https://doi.org/10.1007/s00107-012-0615-x.
19. Žlahtič, M.; Humar, M., 2016: Influence of artificial and natural weathering on the hydrophobicity and surface properties of wood. BioResources, 11 (2): 4964-4989. https://doi.org/10.15376/biores.11.2.4964-4989.
20. ***EN 14080:2013 Timber structures – Glued laminated timber and glued solid timber – Requirements. Comité Européen de Normalisation CEN, Brussels, Belgium.

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Accelerated Weathering and Decay Resistance of Heat-Treated Wood Reinforced Polypropylene Composites

Ubrzano izlaganje polipropilenskih kompozita ojačanih pregrijanim drvom vremenskim utjecajima i otpornost na propadanje

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ABSTRACT • *The aim of this study was to determine the accelerated weathering and decay resistance of the heat-treated wood reinforced polypropylene composites (HT-WPC). Polypropylene (PP) was used as a matrix and the heat-treated wood treated at 180 °C and 220 °C as reinforcement filler. The effect of three filler type, such as 40, 60 and 100 mesh, on the outdoor performance of composites was also investigated. The composites were prepared with twin screw extruder, and the test samples were obtained with compression molding. Lightness index (L*), color changes (ΔE*) and physical changes on the surface of the composites after the accelerated weathering, and decay resistance of the composites were investigated. According to the results, the effects of heat-treated wood on color changes were found to be more than its filler size, and while the filler loadings were increased from 5 % to 20 %, it was determined to increase the color changes of the composites. In scanning electron microscopy (SEM) images, crack formation and deterioration on the surface of the composites were determined. In FTIR spectra, no difference was determined between the composites, and all peaks were similar to each one. The addition of heat-treated wood improved the antifungal efficiency of the composite, and the mass losses decreased with the increasing of heat treatment temperature. As a result, adding heat-treated wood to PP was found to improve the outdoor performance of the HT-WPCs.*

Keywords: *wood polymer composites, heat-treated wood, polypropylene (PP), outdoor performance, thermoplastics*

SAŽETAK • *Cilj ovog rada bio je utvrditi otpornost na propadanje polipropilenskih kompozita ojačanih pregrijanim drvom (HT-WPC) pri ubrzanom izlaganju vremenskim utjecajima. Polipropilen (PP) upotrijebljen je kao matrica, a drvo pregrijano na 180 i 220 °C kao armaturno punilo. Ispitivan je i učinak triju vrsta punila (mreža 40, 60 i 100) na svojstva kompozita u eksterijeru. Kompoziti su pripremljeni dvostrukim vijčanim ekstruderom,*

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a ispitni su uzorci dobiveni kompresijskim lijevanjem. Ispitivana je svjetlina (L), promjena boje (ΔE*) i fizičke promjene na površini kompozita nakon ubrzanog izlaganja vremenskim utjecajima, kao i otpornost na propadanje kompozita. Prema dobivenim rezultatima, utvrđeno je da su učinci pregrijavanja drva na promjenu boje veći od učinka veličine punila. Nadalje, zamijećeno je povećanje promjene boje kompozita s povećanjem udjela punila od 5 na 20 %. Na snimkama dobivenim elektronskim mikroskopom (SEM) uočeno je stvaranje pukotina i propadanje površine kompozita. Međutim, na FTIR spektru nije ustanovljena razlika između kompozita i svi su vrhovi bili slični. Dodavanjem pregrijanog drva poboljšala se otpornost kompozita na gljive te se smanjio gubitak mase s povećanjem temperature pregrijavanja. Utvrđeno je da se dodavanjem pregrijanog drva u polipropilen (PP) poboljšavaju svojstva kompozita HT-WPC-a u eksterijeru.*

Ključne riječi: *drvno-plastični kompoziti, pregrijano drvo, polipropilen (PP), svojstva u eksterijeru, termoplasti*

1 INTRODUCTION
1. UVOD

Wood polymer composites (WPCs) have been of interest due to major advantages such as cost, durability, high mechanical properties, etc. WPC has two main constituents: wood and polyolefins. The addition of wood can provide an increase in the mechanical properties of the WPC as compared with neat polymer (Kallakas *et al.*, 2015). However, wood is a biological material, which is degraded by biological degradation factors such as fungi, insect, bacteria, etc. It also has a hygroscopic structure, and it can absorb a lot of water in a wet medium or desorb by evaporating the water outside the cell in a dry medium. The behavior turns the wood into, dimensionally, an unstable structure. Therefore, in many outdoor applications, the durability and dimensional stability of wood is an important issue for the WPC performance. Biological durability of wood is known as a significant drawback of polymer composites reinforced with wood in outdoor conditions (Luo *et al.*, 2012). Pilarski and Matuana (2005) observed that the composites absorbed more moisture in outdoor uses, and some deterioration of the interfacial adhesion between the wood flour and the polymer matrix was seen. Naumann *et al.* (2012) reported the formation of micro- and macrocracks in the surface of the wood polymer composite due to outdoor use. The results showed that the cracks cause the enhancement of moisture sorption and microbial attacks due to the weathering under UV radiation, water spray. Many studies in the literature have reported that the deteriorations occurred on the surface of the composites due to higher moisture content after the natural and artificial weathering (Kallakas *et al.*, 2015; Stark and Gardner, 2008; Butylina and Karki, 2014; Yilgor *et al.*, 2014; Lopez-Naranjo *et al.*, 2016). To eliminate these drawbacks, many studies related to the heat treatment in terms of different properties, such as the physical and mechanical properties of wood materials, were conducted (Aytekin *et al*.; 2009, Gunduz *et al*., 2009; Kaygin *et al*., 2009; Kaygin *et al*., 2014). The heat treatment also improves the water sorption and fungal resistance of wood (Gunduz *et al.*, 2009; Gunduz *et al.*, 2010; Žlahtič-Zupanc *et al*., 2018). When wood is thermally modified at a temperature of 180 °C and above, its thermal properties can also be improved because some components of wood are decomposed or at least have gone through various changes in its structure after the heat-treatment (Segerholm *et al.*, 2012; Kaboorani, 2009; Pelaez-Samaniego *et al.*, 2013; Karakus *et al.*, 2017).

The objective of this paper was to investigate the accelerated weathering performance and decay resistance of the heat-treated wood reinforced polypropylene composites in various filler sizes and loadings and to determine the feasibility of heat-treated wood in polymer composites for outdoor applications as an alternative to untreated wood.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials
2.1. Materijali

Polypropylene matrix used in the study was obtained by Petkim Inc. (Turkey, Izmir). It has a density of 0.90 g/cm^3, melt flow index of 24 g/min and melting temperature (T_m) of 180 °C. Beech (*Fagus orientalis* L.) wood used as filler was kindly supplied by the local timber mill. (Bartin, Turkey). The heat-treated wood was prepared at 180 °C (HT1) and 220 °C (HT2) for 4 hours in a heating cabin with ±1 °C sensitivity. Both the heat-treated and untreated wood were ground to small diameters of 40, 60 and 100 mesh to determine the effects of filler size and amount on the outdoor performance of the composites.

2.2 Preparation of composites
2.2. Priprema kompozita

Polypropylene was separately mixed with both the untreated (UT) and heat-treated wood (HT). The compounding was provided with a twin-screw extruder (Gulnar Extruder, Turkey) at a temperature of 180 °C and rotor speed of 65 min^{-1}. The polymer–wood blends were granulated after water bath, they were dried at (105±2) °C for 24 h, and all blends were compression molded at the processing temperature of 180 °C and the injection pressure of 25 kg/cm^2. The formulations of the composites are shown in Table 1.

2.3 Characterization of composites
2.3. Karakterizacija kompozita

2.3.1 Accelerated weathering performance (QUV)
2.3.1. Ubrzano izlaganje vremenskim utjecajima (QUV)

The accelerated weathering tests were performed by cycles of UV-light irradiation during 500 hours in a QUV test cycle chamber according to ASTM G154.

Table 1 Formulations of composites
Tablica 1. Formulacije kompozita

Samples *Uzorci*	**Filler type** *Vrsta punila*	**Filler size, mesh** *Veličina punila*, mesh	**Filler loadings, %** *Udio punila*, %	**Polymer, %** *Polimer*, %
PP				100
UT40_5	Untreated (UT)	40	5	95
HT1-40_5	Treated at 180°C (HT1)			
HT2-40_5	Treated at 220°C (HT2)			
UT40_20	Untreated (UT)	40	20	80
HT1-40_20	Treated at 180°C (HT1)			
HT2-40_20	Treated at 220°C (HT2)			
UT60_5	Untreated (UT)	60	5	95
HT1-60_5	Treated at 180°C (HT1)			
HT2-60_5	Treated at 220°C (HT2)			
UT60_20	Untreated (UT)	60	20	80
HT1-60_20	Treated at 180°C (HT1)			
HT2-60_20	Treated at 220°C (HT2)			
UT100_5	Untreated (UT)	100	5	95
HT1-100_5	Treated at 180°C (HT1)			
HT2-100_5	Treated at 220°C (HT2)			
UT100_20	Untreated (UT)	100	20	80
HT1-100_20	Treated at 180°C (HT1)			
HT2-100_20	Treated at 220°C (HT2)			

The average irradiance level was 0.85 W/m^2 at 340 nm and the temperature in the chamber was approximately 50 °C. Three replicates of each composite were used. After the QUV test, color changes were determined and surface characterization with SEM of all the composites was conducted.

2.3.2 Color measurement
2.3.2. Mjerenje boje

Color changes were determined with a Konica Minolta spectrophotometer (Osaka, Japan) by measuring the *L*, a and b values on the specimens. For each specimen, four-color measurement was made and the color analysis was carried out according to ISO 7724-2 standard. The changes in color coordinates (ΔL^*, Δa^* and Δb^*) were determined with the difference between the initial and final values. The total color changes (ΔE^*) were calculated according to the following equations:

$$(\Delta E^*) = [(\Delta a^*)^2 + (\Delta b^*)^2 + (\Delta L^*)2]\ ½ \qquad (1)$$

2.3.3 Determination of antifungal efficiency
2.3.3. Određivanje otpornosti na gljive

Decay test was carried out on the composites during 12 weeks in a climate chamber with a temperature of 23 °C and relative humidity of 70 % according to the principles of EN 113. Test specimens were prepared in dimensions of 30 mm × 12 mm × 2 mm. White rot fungi were used in the test because hardwood was used for the production of WPCs. The decay test for white rot, *T. versicolor* (*L.: Fr.*) *Pilat* was based on the specimens on 48 % malt extract agar in Petri dishes. At the end of the exposure time, the mycelia layers on the surfaces of the composites were removed and weighed. The mass loss was determined based on the dry mass before and after the decay test. Six replicates were used for each composite in the decay test.

2.3.4 Scanning Electron Microscopy (SEM)
2.3.4. Skenirajuća elektronska mikroskopija (SEM)

The morphological analysis of the composites was conducted with environmental scanning electron microscopy (ESEM) (Tescan MAIA3 XMU-SEM), with an accelerating voltage of 5 kV. For enhanced conductivity, the surface of all samples was sputter-coated with a blend of gold-palladium using a Denton sputter coater.

2.3.5 Fourier Transfer Infrared Spectroscopy (FTIR)
2.3.5. Fourierova transformacijska infracrvena spektroskopija (FTIR)

The FTIR-ATR analysis was carried out with a Shimadzu IRAAffinity-1 spectrometer equipped with a single reflection ATR pike MIRacle sampling accessory. Four accumulated spectra with a resolution of 4 cm-1 were obtained for wavenumbers from 800 cm^{-1} to 4000 cm^{-1} with 32 scans for each sample.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

3.1 Accelerated weathering performance
3.1. Ubrzano izlaganje vremenskim utjecajima

The color and physical changes on the surface of the composites after the accelerated weathering were examined. Figure 1 and Figure 2 show the color changes (ΔE^*) as a percentage of all the composites.

As shown in Figure 1 and 2, it was determined that the filler size of wood had no important effect on the color changes after QUV exposure. The maximum color changes were found for the composites with wood treated at 220 °C in all mesh sizes. It can be said that the status caused due to the heat-treated wood tends to grease rapidly in the weathering environment

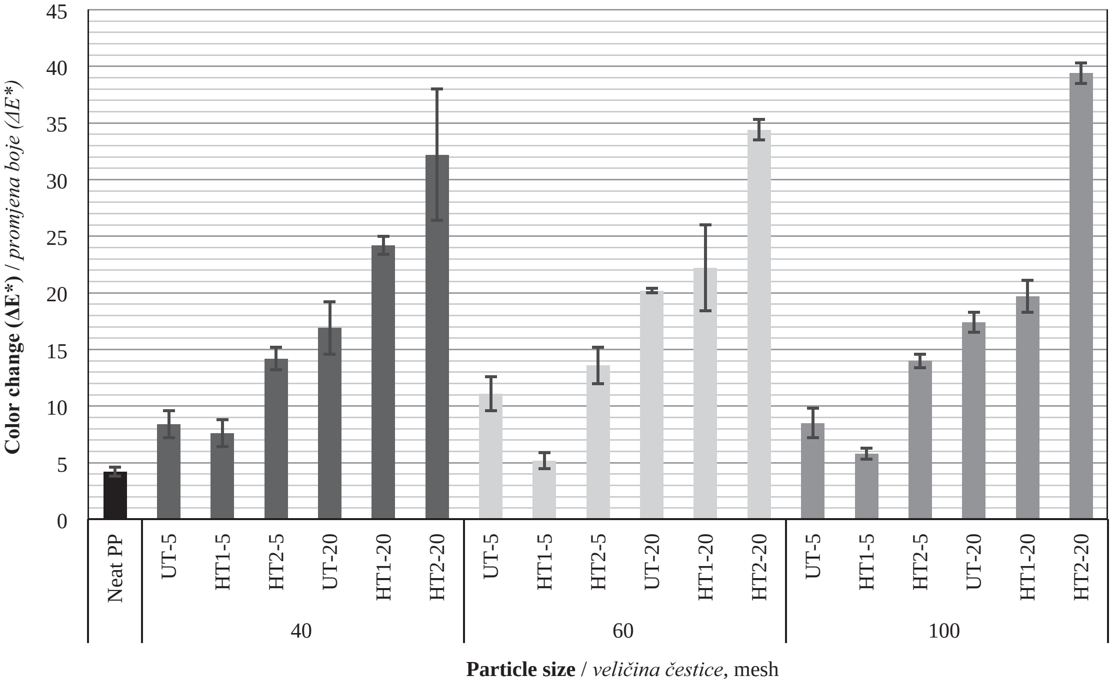

Figure 1 Color changes (Δ*E**) of all composites
Slika 1. Promjena boje (Δ*E**) svih kompozita

(Baysal *et al*., 2014). The color changes in the composites with 20 % wood filler were found to be higher than the composites with 5 % wood filler. Hence, it can be said that the higher the addition of wood, the higher are the color changes. In a study, it was determined that the addition of the heat-treated wood to polymer composite had negative effects on the color change, and heat-treatment was found to be ineffective in improving UV resistance of wood (Xing *et al*., 2015). After QUV test, whitening on the surface of the polypropylene composites with heat-treated wood was observed, and when heat-treatment temperature was raised from 180 °C to 220 °C, the whitening on the surface of polymer composites was found to increase. As shown by SEM images in Figure 3, various small cracks and deep slits were also observed on the surfaces of the composites with both untreated and heat-treated wood as given in Figure 3c and d, and the pieces of wood in the plastic matrix were observed to come to the surface of the composites (Figure 3a and b). Similar results were obtained after the accelerated or natural weathering in other studies (Turku and Karki, 2016; Selden *et al*., 2004; Lee *et al*., 2012).

Table 2 shows the decay resistance of the composites with untreated and heat-treated wood. The weight losses of the composites with both heat-treated and untreated wood were determined to be higher than those of the neat polypropylene. The heat-treated wood

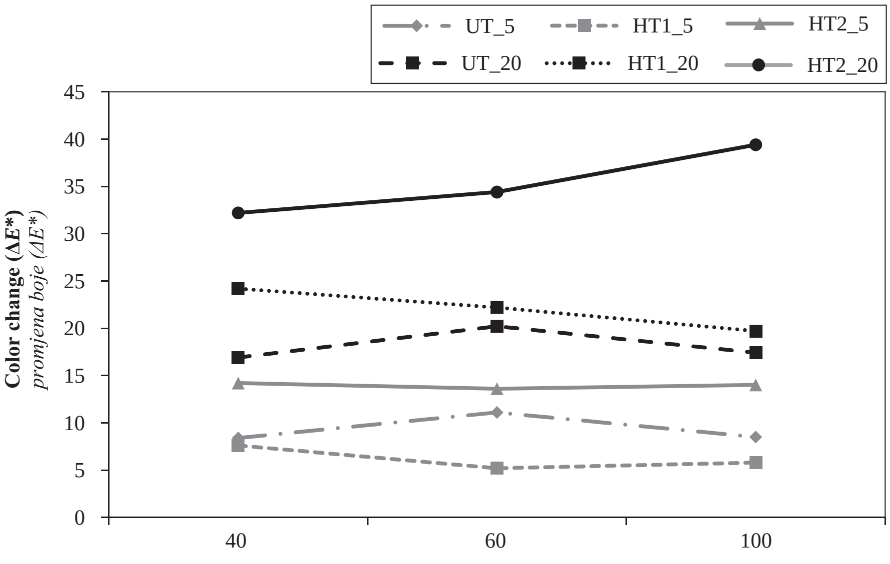

Figure 2 Color changes of composites according to filler size
Slika 2. Promjena boje kompozita s obzirom na veličinu punila

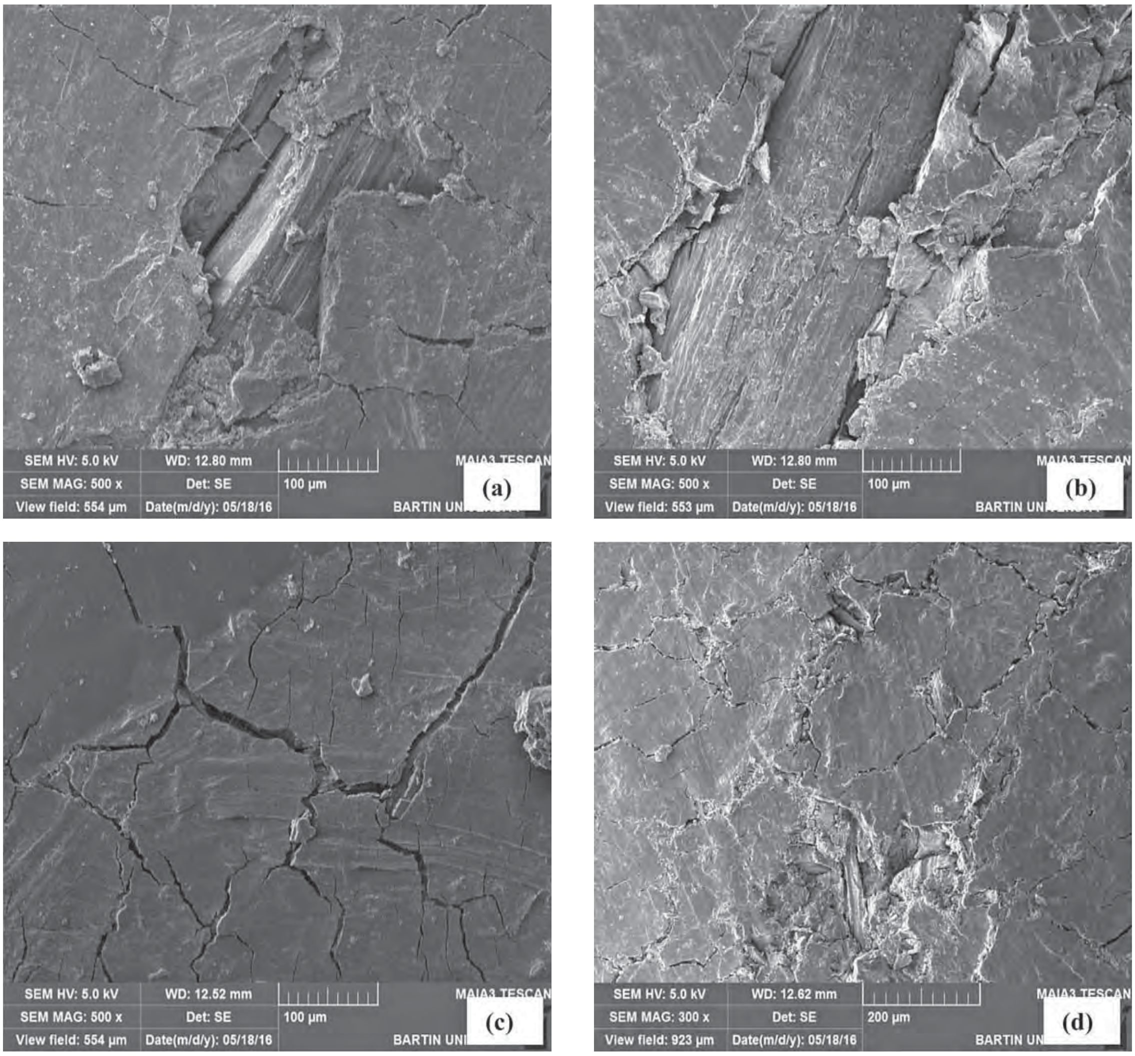

Figure 3 Physical changes on the surface of composites: (a, b) small pieces of wood, (c, d) surface deterioration and cracks
Slika 3. Fizičke promjene na površini kompozita: (a, b) mali komadići drva, (c, d) propadanje površine i pukotine

Table 2 Mass loss of neat polypropylene and composites exposed to decay test
Tablica 2. Gubitak mase čistog polipropilena i kompozita izloženih testu propadanja

Samples *Uzorci*	**Filler loading, %** *Udio punila, %*	**Mesh size** *Veličina*	**Mass loss, %** *Gubitak mase, %*
Neat PP			0.2 (±0.02)
UT	5	40	0.9 (±0.10)
HT1			0.9 (±0.14)
HT2			0.8 (±0.12)
UT		60	1.4 (±0.14)
HT1			1.0 (±0.12)
HT2			0.9 (±0.13)
UT		100	1.0 (±0.14)
HT1			0.9 (±0.15)
HT2			0.9 (±0.14)
UT	20	40	1.2 (±0.15)
HT1			1.1 (±0.12)
HT2			0.8 (±0.11)
UT		60	1.6 (±0.16)
HT1			1.5 (±0.15)
HT2			1.1 (±0.12)
UT		100	1.2 (±0.14)
HT1			1.2 (±0.14)
HT2			1.1 (±0.16)

was found to improve the decay resistance of the composites. However, decay resistance of all the composite was determined to be lower than that of the neat polypropylene. According to Table 2, the decay resistance of the composites with heat-treated wood was higher as compared with the composites with untreated wood. The results showed that the decay resistance of the composites decreased when the filler size decreased from 40 to 60, while the decay resistance of the composites generally increased with 100 mesh wood filler. As a result, it can be said that both heat treatment of wood and filler loading and size have an effect on the decay resistance of the composites.

The weight loss was determined to range from 0.9 % to 1.6 %, and the maximum and minimum mass losses were found for the composites with 60 mesh untreated wood for 20 % loadings, and with 40 mesh heat-treated wood for 20 % loadings.

3.2 FTIR Analysis
3.2. FTIR analiza

The FTIR analysis was conducted to determine the chemical structure of neat PP, composites with untreated wood, wood heat-treated at 180 °C and 220 °C. The FTIR-ATR main peaks of neat PP, PP composites

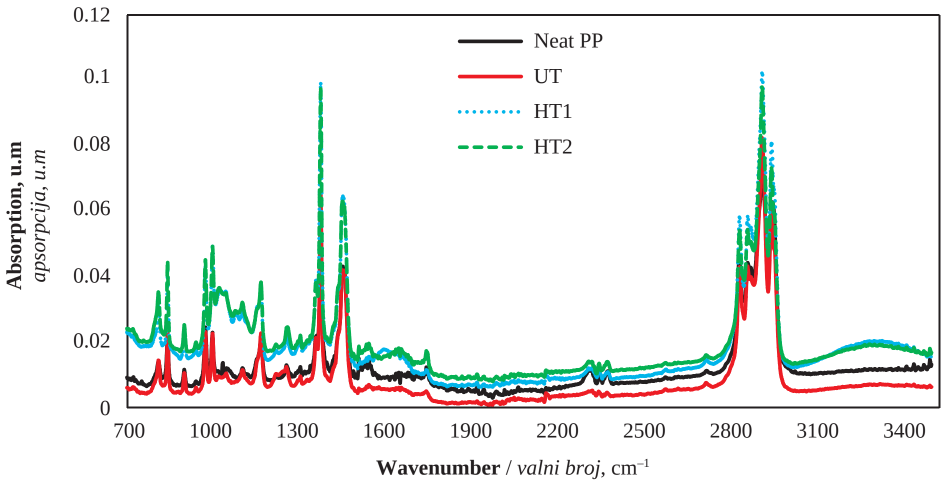

Figure 4 Spectra of neat polypropylene and composites with untreated and heat-treated wood
Slika 4. Spektri čistog polipropilena i kompozita s nepregrijanim i pregrijanim drvom

Table 3 Spectra of neat polypropylene, and composites with untreated and heat-treated wood (Li *et al*., 2015; Ha *et al*., 2016)
Tablica 3. Spektri čistog polipropilena i kompozita s nepregrijanim i pregrijanim drvom (Li *et al*., 2015.; Ha *et al*., 2016.)

Wavenumber, cm^{-1} *Valni broj*, cm^{-1}	**Functional groups** *Funkcionalne skupine*
3300	Hydroxyl groups of cellulose (-OH)
2950, 2839	C-H stretch vibration of PP
1601	C=C stretch vibration of hemicellulose
1457	–CH$_2$ bending vibration of PP
1376	–CH$_3$ bending vibration of PP
1167	Symmetric –CH$_3$ deformation vibration
1043	C-O-C and C-O groups of cellulose and lignin
998, 973	–CH$_3$ wagging vibration of PP

with untreated wood, wood heat-treated at 180 °C and 220 °C are given in Figure 4.

According to Figure 4, the main spectra of neat polypropylene were ranged from 973 cm^{-1} to 2950 cm^{-1}. 1457 cm^{-1} and 1376 cm^{-1} peaks show –CH$_2$ and –CH$_3$ bending vibration of polypropylene (Sagativo *et al*., 2017). 1167 cm^{-1}, 998 cm^{-1}, and 973 cm^{-1} peaks belong to –CH$_3$ deformation vibration and –CH$_3$ wagging vibration, respectively. 3300 cm^{-1} peak means –OH groups of cellulose and lignin in the composites with untreated wood (UT) and heat-treated wood (HT1 and HT2). 1601 cm^{-1} and 1043 cm^{-1} peaks show C=C stretch of hemicellulose and C–O–C and C–O stretch of carbohydrates in cellulose chains (Li *et al*., 2015; Ha *et al*., 2016) (Table 3). As a result, the structural properties of all the composites were observed to be similar.

4 CONCLUSIONS
4. ZAKLJUČAK

In the study, the accelerated weathering performance and decay resistance of the heat-treated wood reinforced polypropylene composites were investigated. SEM images of the specimens showed the deterioration and some cracks on the surface of the composites. According to the color change results, the effect of heat treatment on the color changes was higher than that of filler size, and while the filler loadings increased from 5 % to 20 %, it was determined to increase the color changes of the composites. FTIR spectra showed that the composites had similar chemical structure. The decay test showed that the mass loss decreased with the increase of temperature in the heat-treatment of wood. The heat-treatment of wood showed to improve the antifungal efficiency of the composites. Finally, it can be said that heat-treated wood has more potential for related applications than the composite with untreated wood. However, the heat-treated wood tends to gray out rapidly in the weathering environment, which could be a drawback for common outdoor use.

5 REFERENCES
5. LITERATURA

1. Aytekin, A.; Gündüz, G.; Kaygin, B.; Korkut, S.; Onat, S. M., 2009. Drying schedules calculation of Camiyani Black Pine (*Pinus nigra* Arn. subsp. pallasiana var. pallasiana) by computer programming. African Journal of Biotechnology, 8 (8): 1703-1712.
2. Baysal, E.; Degirmentepe, S.; Simsek, H., 2014: Some surface properties of thermally modified scots pine after artificial weathering. Maderas. Ciencia y tecnología, 16 (3): 355-364. https://doi.org/10.4067/S0718-221X2014005000028.
3. Butylina, S.; Kärki, T., 2014: Effect of Weathering on the Properties of Wood-polypropylene Composites Containing Minerals. Polymers & Polymer Composites, 22 (9): 763. https://doi.org/10.1177/096739111402200902.
4. Gunduz, G.; Aydemir, D.; Karakas, G., 2009: The effects of thermal treatment on the mechanical properties of wild Pear (*Pyrus elaeagnifolia* Pall.) wood and changes in physical properties. Materials and Design, 30 (10): 4391-4395. https://doi.org/10.1016/j.matdes.2009.04.005.
5. Gunduz, G.; Aydemır, D.; Kaygın, B.; Aytekin, A., 2009: The effect of treatment time on dimensionally stability, moisture content and mechanical properties of heat treat-

ed Anatolian chestnut (*Castanea sativa* Mill.) wood. Wood Research, 54 (2): 117-126.

6. Gunduz, G.; Aydemir, D.; Korkut, S., 2010: The effect of heat treatment on some mechanical properties and color changes of Uludag fir wood. Drying Technology, 28 (2): 249-255. https://doi.org/10.1080/07373930903530162.
7. Ha, H. A.-T.; Son, L.-T.; Viet, N. T.-B., 2016: Oil Sorbents Based on Methacrylic Acid – Grafted Polypropylene Fibers: Synthesis and Characterization. Journal of Chemical Engineering and Process Technology. 7 (2): 1-7. https://doi.org/10.4172/2157-7048.1000290.
8. Kaboorani, A., 2009: Thermal properties of composites made of heat-treated wood and polypropylene. Journal of Composite Materials, 43 (22): 2599-2607. https://doi.org/10.1177/0021998309345291.
9. Kallakas, H.; Poltimae, T.; Suld, T. M.; Kers, J.; Krumme, A., 2015: The influence of accelerated weathering on the mechanical and physical properties of wood-plastic composites. In: Proceedings of the Estonian Academy of Sciences, 64: 94-105. https://doi.org/10.3176/proc.2015.1S.05.
10. Karakus, K.; Aydemir, D.; Oztel, A.; Gunduz, G.; Mengeloglu, F., 2017: Nanoboron nitride filled heat-treated wood polymer nanocomposites: Comparison of three different multicriteria decision making models to predict optimum properties of the nanocomposites. Journal of Composite Materials, 51 (30): 4205-4218. https://doi.org/10.1177/0021998317699984.
11. Kaygin, B.; Gunduz, G.; Aydemir, D., 2009: The effect of mass loss on mechanic properties of heat-treated paulownia wood. Wood Research, 54 (2): 101-108.
12. Kaygin, B.; Koc, K. H.; Hiziroglu, S., 2014: Surface quality and hardness of eastern red cedar as function of steaming. Journal of Wood Science, 60 (4): 243-248. https://doi.org/10.1007/s10086-014-1399-x.
13. Lee, C. H.; Hung, K. C.; Chen, Y. L., 2012: Effects of polymeric matrix on accelerated UV weathering properties of wood-plastic composites. Holzforschung, 66: 981-987. https://doi.org/10.1515/hf-2011-0198.
14. Li, G.; Lao, W.; Qin, T., 2015: Rapid determination of biomass and polypropylene in three types of wood plastic composites (WPCs) using FTIR spectroscopy and partial least squares regression (PLSR). Holzforschung, 69 (4): 399-404. https://doi.org/10.1515/hf-2014-0157.
15. Lopez-Naranjo, E. J.; Alzate-Gaviria, L. M.; Hernández-Zárate, G.; Reyes-Trujeque, J.; Cruz-Estrada, R. H., 2016: Termite resistance of wood-plastic composites treated with zinc borate and borax. Journal of Thermoplastic Composite Materials, 29 (2): 281-293. https://doi.org/10.1177/0892705714563343.
16. Luo, S. P.; Cao, J. Z.; Wang, X., 2012: Properties of PEG/thermally modified wood flour/polypropylene (PP) composites. Forestry Studies in China, 14 (4): 307-314. https://doi.org/ 10.1007/s11632-012-0405-x.
17. Naumann, A.; Stephan, I.; Noll, M., 2012: Material resistance of weathered wood-plastic composites against fungal decay. International Biodeterioration and Biodegradation, 75: 28-35. https://doi.org/10.1016/j.ibiod.2012.08.004.
18. Pelaez-Samaniego, M., R.; Yadama, V.; Lowell, E.; Espinoza-Herrera, R., 2013: A review of wood thermal pretreatments to improve wood composite properties. Wood Science and Technology, 47 (6): 1285-1319. https://doi.org/10.1007/s00226-013-0574-3.
19. Pilarski, J. M.; Matuana, L. M., 2005: Durability of wood flour-plastic composites exposed to accelerated freeze–thaw cycling, part I: Rigid PVC matrix. Journal of Vinyl and Additive Technology, 11: 1-8. http://doi.org/10.1002/vnl.20029.
20. Sagitova, E. A.; Donfack, P.; Nikolaeva, G. Y.; Prokhorov, K. A.; Pashinin, P. P.; Nedorezova, P. M.; Materny, A., 2017: New insights into the structure of polypropylene polymorphs and propylene copolymers probed by low-frequency Raman spectroscopy. Journal of Physics: Conference Series (vol. 826, no. 1, p. 012006). IOP Publishing.
21. Segerholm, B. K.; Ibach, R., E.; Westin, M., 2012: Moisture sorption, biological durability, and mechanical performance of WPC containing modified wood and polylactates. BioResources, 7(4): 4575-4585.
22. Selden, R.; Nystrom, B.; Langstrom, R., 2004: UV aging of poly (propylene) / wood-fiber composites. Polymer Composite, 25: 543-553. https://doi.org/10.1002/pc.20048.
23. Stark, N. M.; Gardner, D. J., 2008: Outdoor durability of wood-polymer composites. Woodhead Publishing, Philadelphia.
24. Turku, I.; Karki, T., 2016: Accelerated weathering of wood-polypropylene composite containing carbon fillers. Journal of Composite Materials, 50 (10): 1387-1393. https://doi.org/10.1177/0021998315591842.
25. Xing, D.; Wang, S.; Li, J., 2015: Effect of artificial weathering on the properties of industrial scale thermally modified wood. BioResources, 10 (4): 8238-8252.
26. Yilgor, N.; Köse, C.; Terzi, E.; Figen, A. K.; Ibach, R.; Kartal, S. N.; Pişkin, S., 2014: Degradation behavior and accelerated weathering of composite boards produced from waste Tetra Pak® packaging materials. BioResources, 9 (3): 4784-4807.
27. Žlahtič-Zupanc, M.; Lesar, B.; Humar, M., 2018: Changes in moisture performance of wood after weathering. Construction and Building Materials, 193: 529-538. https://doi.org/10.1016/j.conbuildmat.2018.10.196.

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LABORATORY FOR HYDROTHERMAL PROCESSING OF WOOD AND WOODEN MATERIALS

Testing of hydrothermal processes of wood and wooden materials

Thermography measurement in hydrothermal processes

Standard and nonstandard determination of moisture content in wood

Determination of climate and microclimate conditions in air drying and storage of wood, organization of lumber storage

Project and development of conventional and unconventional drying systems

Steaming chamber projects

Establishing and modification of kiln drying schedules

Consulting in selection of kiln drying technology

Introduction of drying quality standards

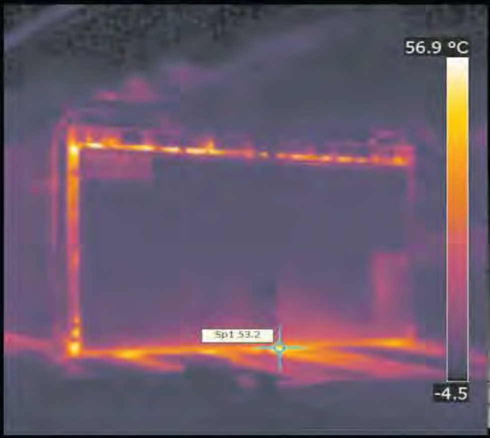
Determination of wood bending parameters

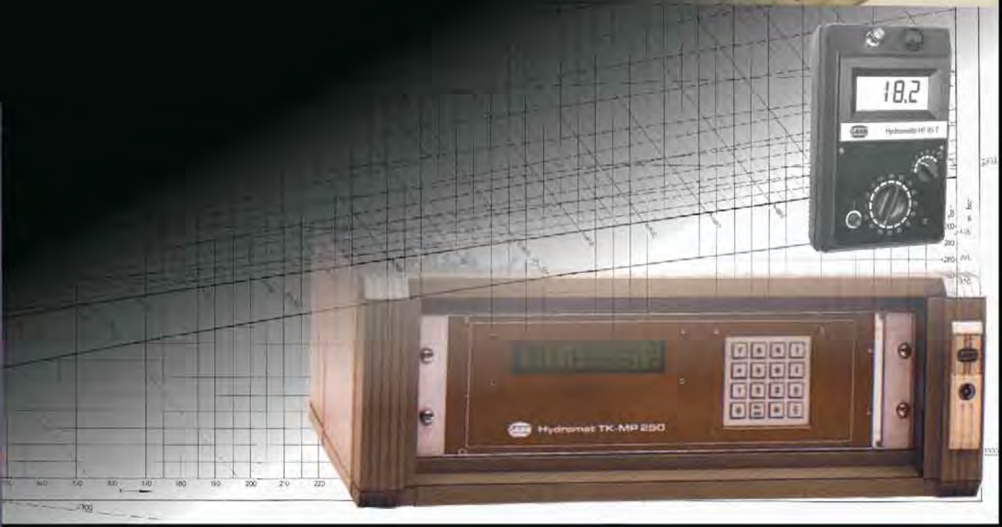
Detection and reducing of hydrothermal processes wood defects

Reducing of kiln drying time

Drying costs calculation

Kiln dryer capacity calculation





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A Comparative Evaluation of Operational Efficiency of Wood Industry Using Data Envelopment Analysis and Malmquist Productivity Index: the Cases of Slovenia and Croatia

Usporedna procjena operativne učinkovitosti drvne industrije Slovenije i Hrvatske primjenom analize omeđivanja podataka i Malmquistova indeksa produktivnosti

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ABSTRACT • *The wood industry, as a traditional sector, represents a very important part of the economy in terms of ensuring a sustainable development of society and transition to a low-carbon society in both countries studied, Slovenia and Croatia. For its further development, it is crucial to know the current position of the industry. The best way to achieve this is an analysis of financial data and international comparative evaluation of its operational efficiency. The aim of the research is to compare the relative efficiency of the wood industry using Data Envelopment Analysis (DEA) and the Malmquist Productivity Index (MI), focusing on the Slovenian and Croatian wood industry sectors (C16 and C31) for a recent five-year period (from 2013-2017). With this purpose, the combined measure DEA/MI was applied. The analysis includes only the highest rated companies with more than five employees, divided into 12 clusters regarding the company size. As a result, it was established that clusters CRO-C31-micro, CRO-C16-micro and SI-C16-larger have the highest operational efficiency, due to the effects of different financial indicators, especially activity and liquidity ratios. In general, within the grouped clusters regarding country and subsector, groups SI-C16 and CRO-C31 achieve the highest values for the average of weighted score of efficiency, while CRO-C16 achieves the lowest values.*

Keywords: *financial analysis, financial ratio, wood industry, Slovenia, Croatia, DEA, Malmquist Index*

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SAŽETAK • *Drvna industrija Sloveniji i Hrvatskoj tradicionalan je gospodarski sektor tih zemalja i vrlo važan dio gospodarstva u smislu osiguranja održivog razvoja društva i prijelaza na društvo s niskim udjelom ugljika. Za daljnji razvoj drvnoga sektora bitno je poznavati trenutačni položaj industrije, a najbolji način za to je analiza financijskih podataka i internacionalna usporedna procjena industrijske operativne učinkovitosti. Cilj istraživanja bio je usporediti relativnu učinkovitost drvne industrije uz pomoć analize omeđivanja podataka (DEA) i Malmquistova indeksa produktivnosti (MI), s naglaskom na slovenski i hrvatski drvnoindustrijski sektor (C16 I C 31) tijekom posljednjih pet godina (2013. – 2017.). Za tu je svrhu primijenjena kombinirana mjera DEA/MI. Analizom su obuhvaćene samo najbolje ocijenjene tvrtke s više od pet zaposlenih, koje su s obzirom na njihovu veličinu podijeljene na 12 klastera. Utvrđeno je da klasteri CRO-C31-mikro, CRO-C16-mikro i SI-C16-veliki zbog utjecaja različitih financijskih pokazatelja, posebice omjera aktivnosti i likvidnosti, imaju najveću operativnu učinkovitost. Općenito, unutar klastera grupiranih prema zemlji i podsektoru istraživanja, skupine SI-C16 i CRO-C31 pokazale su najviše vrijednosti za prosjek ponderirane ocjene učinkovitosti, a CRO-C16 imao je najniže vrijednosti.*

Ključne riječi: *financijska analiza, financijski omjer, drvna industrija, Slovenija, Hrvatska, DEA, Malmquistov indeks*

1 INTRODUCTION
1. UVOD

The wood industry, as a traditional sector, represents a very important part of the economy in terms of ensuring a sustainable development of society, enabling a circular economy and transition to a low-carbon society (Klarić *et al*., 2016; Perić *et al*., 2015; Perić *et al*., 2019; Šooš *et al*., 2017). The management of natural resources must be effective and sustainable, and on the other hand, it must provide growth and development for the economy, in order to make it even more successful. Financial analysis is often used in order to see the current condition of individual companies, sectors and countries, and this is an important tool for assessing the financial position and success of a company and/or sector, in terms of calculating fiscal indicators, while measuring current fiscal conditions and performance, and predicting trends (Friedlob and Schleifer, 2003; Helfert, 2001; Palepu *et al*., 2003; Vance, 2003).

However, knowing the fiscal position of a country is rather limited in terms of understanding the broader situation and trends, and it is also not enough to provide data and financial analysis for just one sector (Kropivšek and Grošelj, 2019; Potkány and Giertl, 2014), as only a comparative analysis using data from companies in different sectors and different countries can provide comprehensive information. There is little information with regard to international comparative financial analysis of the wood sector in the literature, and there is no such analysis for Slovenia and Croatia. The wood-industry sector in Slovenia and Croatia has already been analysed financially (Kropivšek *et al*., 2017, 2011; Kropivšek and Jošt, 2013; Pirc Barčić *et al*., 2015; Tratnik *et al*., 2001), but such analysis has been done separately for each country. In addition, an international comparative evaluation of the operational efficiency of the wood-industry sector has never been done. This comparison would be very interesting, as Slovenia has a long tradition in the wood sector with a relatively stable economic situation, while Croatia has experienced significant economic growth in recent years (CBS, 2019).

So, the aim of the current research is to use Data Envelopment Analysis (DEA) and the Malmquist Productivity Index (MI) to compare the relative efficiency of the Slovenian and Croatian wood industry sectors (C16 (manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials; in short: wood processing) and C31 (manufacture of furniture)) (Braunsberger *et al*., 2010) for a recent five-year period (from 2013-2017). With this purpose, the combined measure DEA/MI was applied. DEA/MI enables us to measure the productivity of decision-making units (DMUs), which is a combination of relative efficiency and the change in productivity between two time periods, and to rank the DMUs regarding their productivity. The analysis includes only the highest rated companies (with a grade A financial rating with regard to credit appraisal in 2017) and with more than five employees.

The DEA approach and MI are widely used for evaluating the efficiency and productivity changes of sectors in addition to the use of financial indicators (Bui *et al*., 2016; Fenyves *et al*., 2015; Fernández *et al*., 2018; Halkos and Tzeremes, 2012a, 2012b; Johnes *et al*., 2009; Li and Wu, 2016; Liu and Wang, 2008; Örkcü *et al*., 2016; Sueyoshi and Goto, 2013). The DEA method has also been applied several times in the wood industry. For example, Salehirad and Sowlati (2006) prepared a review of productivity and efficiency assessments of the wood industry in Canada. An analysis of productive efficiency has also been carried out for Spain's wood-based industry (Diaz-Balteiro *et al*., 2006), the Iranian wood panels industry (Hemmasi *et al*., 2011), Canadian wood-product manufacturing subsectors (Sowlati and Vahid, 2006) and Slovenian wood industry (Kropivšek and Grošelj, 2019). The MI has been used for evaluating the changes in productivity of manufacturing industries in Canada, with a focus on the wood manufacturing sector (Sowlati and Vahid, 2006) and on primary wood producers in British Columbia (Salehirad and Sowlati, 2007). The combined DEA/MI measure was also applied for evaluating police force efficiency (Hadad *et al*., 2015) and public forest services in Slovenia (Zadnik Stirn *et al*., 2015).

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Sample
2.1. Uzorak

In calculating the indicators, the financial data for the highest rated companies and sole proprietors (with the grade A in the financial rating for the credit appraisal in 2017) and with more than five employees in 2017 operating in sub-sectors C16 (wood processing) and C31 (manufacture of furniture) in Slovenia and Croatia were considered, according to the sub-sector level data in the classification of economic activities NACE (Nomenclature of Economic Activities) rev.2 classification (NACE, 2019). The research was based on searching and preparing data from official statistical databases (Ajpes JOLP, 2019; Analitika GZS, 2019; Bisnode, 2019) for the period from 2013 to 2017 (five years).

The sample size was based on the number of companies in both sectors as of 27th February 2019 (Bisnode, 2019). The data show (Table 1) that the numbers of active companies in two sub-sectors separately are more or less similar in both countries; this also applies to the size proportion of C16 and C 31 sub-sectors. However, only 13 % (in Slovenia) and 22 % of companies in Croatia have more than 5 employees; majority of companies in both countries are very small with less than 5 employees. On average 3.1 % and 4 % of all active companies were rated with the grade A credit appraisal and these companies were than evaluated. On the other hand, almost 25 % of companies in Slovenia and 18.7 % in Croatia with more than 5 employees were rated with the grade A credit appraisal.

In the next phase, these companies were grouped into clusters regarding the size of the company (according to: ZGD-1-UPB3, 2009). These clusters are: (1) micro, (2) small, (3) middle-sized and (4) large companies. Since a very small number of companies was established in the cluster of large companies (>250 employees) with the grade A credit appraisal for both countries and sectors (only one in Slovenia and two in Croatia), we decided to join that cluster and cluster of middle-sized companies into the cluster of larger companies (>50 employees). Consequently, three comparable clusters regarding the size were obtained (Table 2). The majority of companies (81 % in Croatia, and 91.6 % in Slovenia) belong to clusters of micro and small companies, while the clusters of larger companies is rather small, especially in Slovenia (8.4 %).

2.2 Data
2.2. Podatci

For further analysis, the method of financial ratio analysis was used, where the resulting ratio is an expression of a mathematical relationship between two quantities (Peterson-Drake and Fabozzi, 2010). Data sources for financial analysis are the firm's financial statements, in which a large amount of data is reduced to a few key parameters (Gitman, 2003). The data for this research were obtained from official statistical databases (Bisnode, 2019) for the period from 2013 to 2017 (5 years), where data of all companies were gath-

Table 1 Sample size and structure of companies in the year 2017 (Bisnode, 27. 2. 2019.)
Tablica 1. Veličina uzorka i struktura tvrtki u 2017. (Bisnode, preuzeto 27. veljače 2019.)

			Number of companies *Broj tvrtki*		**Share of grade A companies** *Postotni udio tvrtki s bonitetnom ocjenom A*	
Country *Država*	**Sector** *Sektor*	**All active companies** *Sve aktivne tvrtke*	**>5 employees** *>5 zaposlenih*	**Grade A, >5 employees** *Ocjena A, >5 zaposlenih*	**All companies** *Sve tvrtke*	**>5 employees** *>5 zaposlenih*
Slovenia *Slovenija*	C 16	2212	250	63	2.8 %	25.2 %
	C 31	1189	180	44	3.7 %	24.4 %
	Total	3401	430	107	3.1 %	24.9 %
Croatia *Hrvatska*	C 16	2099	473	90	4.3 %	19.0 %
	C 31	1170	234	42	3.6 %	17.9 %
	Total	3269	707	132	4.0 %	18.7 %

Table 2 Classification of cluster companies with the grade A credit appraisal by number of employees in 2017 (Bisnode, 27. 2. 2019)
Tablica 2. Klasifikacija klasterskih tvrtki s bonitetnom ocjenom A prema broju zaposlenih za 2017. (Bisnode, preuzeto 27. veljače 2019.)

		Clusters / *Klasteri*, n			**Clusters** / *Klasteri*, %		
	Cluster *Klaster*	**Micro: 5-9 employees** *Mikro: 5-9 zaposlenih*	**Small: 10-49 employees** *Mala: 10-49 zaposlenih*	**Large: >50 employees** *Velika: >50 zaposlenih*	**Micro: 5-9 employees** *Mikro: 5-9 zaposlenih*	**Small: 10-49 employees** *Mala: 10-49 zaposlenih*	**Large: >50 employees** *Velika: >50 zaposlenih*
Country *Država*	**Sector** *Sektor*						
Slovenia *Slovenija*	C 16	25	31	7	39.7 %	49.2 %	11.1 %
	C 31	22	20	2	50.0 %	45.5 %	4.5 %
	Total	47	51	9	43.9 %	47.7 %	8.4 %
Croatia *Hrvatska*	C 16	20	54	16	22.2 %	60.0 %	17.8 %
	C 31	14	18	9	34.1 %	43.9 %	22.0 %
	Total	34	72	25	26.0 %	55.0 %	19.0 %

Table 3 A list of analysed financial indicators
Tablica 3. Pregled analiziranih financijskih pokazatelja

Financial indicator / *Financijski pokazatelj*		**Classification /** *Klasifikacija*
CR	Current ratio / *koeficijent tekuće likvidnosti*	Liquidity ratio *omjer likvidnosti*
QR	Quick ratio / *koeficijent ubrzane likvidnosti*	
CashR	Cash ratio / *trenutačna likvidnost*	
ROE	Return on equity / *stopa povrata kapitala*	Profitability ratio *omjer profitabilnosti*
ROA	Return on assets / *stopa povrata imovine*	
ROS	Return on sales / *stopa povrata od prodaje*	
GVA	Gross value added per employee ratio / *omjer bruto dodane vrijednosti po zaposleniku*	Activity ratio *omjer aktivnosti*
ATR	Asset turnover ratio / *omjer prometa imovine*	
CAT	Current asset turnover ratio / *omjer obrtanja aktive*	
EBITDA	Earnings before interest, taxes, depreciation, and amortization *dobit prije kamata, poreza, deprecijacije i amortizacije*	Efficiency ratio *omjer učinkovitosti*
E	Total efficiency ratio / *omjer ukupne učinkovitosti*	
AU	Asset utilization ratio / *omjer iskorištenja imovine*	
D/E	Debt to equity ratio / *omjer duga i kapitala*	Leverage ratio *omjer financijske poluge*
TDA	Total debt to total assets ratio / *omjer ukupnog duga*	
TLTSF	Total liabilities to total sources of funds ratio / *omjer ukupnih obveza prema svim izvorima sredstava*	

ered and calculated in aggregate form within each cluster separately for both countries.

The right selection of financial ratios and/or indicators is of key importance for the financial analysis; it has to be adapted to the intended use. There are many different financial indicators, which are classified into different groups, taking into account the content of indicators (Delen *et al*., 2013; Gombola and Ketz, 1983; Pirc Barčić *et al*., 2015; Sayari and Simga-Mugan, 2017). Kropivšek and Grošelj (2019) divided financial indicators into five categories: (1) liquidity ratios (which provide information on a firm's ability to meet its short-term obligations), (2) profitability ratios (providing information on how well the company is managing its expenses), (3) activity ratios (with information on a firm's ability to manage its resources efficiently), (4) leverage ratios (including information on the degree of a firm's fixed financing obligations and its ability to meet them), and (5) efficiency ratios (indicating a firm's operating efficiency and explaining its business results in relation to various investments that have been made in the business process). This classification was also used within this research, where all 15 indicators from that study were analysed for further and detailed analysis (Table 3). Beside these indicators, Assets (A), Capital (C) and Number of Employees (NE) were also analysed.

2.3 DEA analysis and Malmquist Productivity Index
2.3. DEA analiza i Malmquistov indeks produktivnosti

DEA is a linear programming technique for evaluating the efficiency of decision-making units (DMUs) under multiple inputs and outputs. The technique creates a frontier set by efficient DMUs and compares it with inefficient DMUs to produce relative efficiency scores that are restricted to 1. It was first proposed by Charnes *et al*. (1978) as the CCR model, named after the authors Charnes, Cooper and Rhodes. Besides CCR with constant returns to scale, the BCC model, named after the authors Banker, Charnes and Cooper (Banker *et al*., 1984), with variable returns to scale, is one of the most popular models. Both models can be input oriented, aiming to minimize the level of inputs, while maintaining the current level of outputs, or output oriented, aiming to maximize the level of outputs, while maintaining the current level of inputs.

When using ratios, the DEA formulation with variable returns to scale (BCC model) should be used (Ablanedo-Rosas *et al*., 2010; Hollingsworth and Smith, 2003). To include negative data in the DEA models, the appropriate translation that assures positive values should be performed (Pastor and Ruiz, 2007). This was the case with the profitability ratios ROA, ROE and ROS in the current study. To include the data where greater values are undesirable in the DEA models, the data should be multiplied by factor (-1), followed by an appropriate translation to gain positive values (Seiford and Zhu, 2002). This was the case with the leverage ratios D/E, TDA and TLTSF. If a translation of the data is undertaken, it is important to ensure that the results of a model do not change from what they would be under the original data (Cook and Seiford, 2009). Considering BCC models, the BCC output oriented model is translation invariant in inputs, while the BCC input oriented model is translation invariant in outputs (Cooper *et al*., 2006). We selected the latter model to get ratios as outputs.

We considered N decision units (DMUs), n=1,…, N to be evaluated on the basis of r inputs and s outputs. The input-oriented DEA BCC model (in envelopment form) with variable returns to scale (VRS) is formulated by the following linear programs:

$$\begin{gathered}\min E_i - \varepsilon\left(\sum_{j=1}^{r} s_j^- + \sum_{k=1}^{s} s_k^+\right)\\ \text{subject to } \sum_{n=1}^{N}\lambda_n x_{jn} + s_j^- = E_i x_{ji},\ j = 1,\dots,r\\ \sum_{n=1}^{N}\lambda_n y_{kn} + s_k^+ = y_{ki},\ \mathrm{k} = 1,\dots,\mathrm{s}\\ \sum_{n=1}^{N}\lambda_n = 1\\ \lambda_n, s_j^-, s_k^+ \geq 0,\ n = 1,\dots,N,\ j = 1,\dots,r,\ \mathrm{k} = 1,\dots,\mathrm{s}\\ E_i \text{ unconstrained}\end{gathered} \tag{1}$$

where E_i is the relative efficiency of assessed DMU *i*, ε is a non-Archimedean infinitesimal value designed to enforce strict positivity on the variables, x_{jn} is the amount of input *j* used by DMU *n*, y_{kn} is the amount of output *k* produced by DMU *n*, s_j^- and s_j^+ are vectors of slack variables and λ_n are linear weights.

The Malmquist Productivity Index MI was developed by Färe *et al.* (1994) to measure the total productivity changes between time periods *t* (base period) and *t+1*

$$MI\left(x^t, \mathrm{y}^t, x^{t+1}, \mathrm{y}^{t+1}\right) = \left[\frac{D^t\left(x^{t+1}, \mathrm{y}^{t+1}\right)}{D^t\left(x^t, \mathrm{y}^t\right)} \times \frac{D^{t+1}\left(x^{t+1}, \mathrm{y}^{t+1}\right)}{D^{t+1}\left(x^t, \mathrm{y}^t\right)}\right]^{1/2} \tag{2}$$

where *y* represents the output vector that can be produced by the input vector *x*. $D^t(x^t, y^t)$ is defined as the output distance function. DMU's total productivity improves if *MI>1*, remains unchanged for *MI=1* and declines for *MI<1*.

The combined DEA/MI score is calculated to rank the DMUs (Hadad *et al*., 2015; Zadnik Stirn *et al*., 2015). First, we calculate the average efficiency $\overline{E}_i$ of DMU *i* as the arithmetic mean of the relative efficiencies of DMU *i* over *T* time periods

$$\overline{E}_i = \tfrac{1}{T}\sum_{t=1}^{T} E_{i,\mathrm{t}}, \tag{3}$$

where $E_{i,t}$ is a relative efficiency of DMU *i* in time period *t* derived by the VRS model. Then we calculate the average Malmquist productivity index $\overline{MI}_i$ of DMU *i* as the geometric mean of MI of DMU *i* over *T* time periods. As MI can be greater than 1, the average MI should be normalized:

$$\overline{MI}_i = \left(MI_{i,1,2} \times MI_{i,2,3} \times \dots \times MI_{i,\mathrm{T}-1,\mathrm{T}}\right)^{1/(\mathrm{T}-1)} \Big/ \max_{i=1,\dots,N}\left(MI_{i,1,2} \times MI_{i,2,3} \times \dots \times MI_{i,\mathrm{T}-1,\mathrm{T}}\right)^{1/(\mathrm{T}-1)}, \tag{4}$$

where $MI_{i,\,\mathrm{t}-1,\,\mathrm{t}}$ is a MI of DMU *i* over time periods *t* and *t+1* derived by model. The DEA/MI score for each model *j=1,…,M* is the weighted sum of the average efficiency and the normalized average of MI:

$$DEA/MI_i(j) = w_1\overline{E}_i + w_2\overline{MI}_i,\ i = 1,\dots,N, j = 1,\dots,M, \tag{5}$$

where w_1 and w_2 are the weights of importance of the DEA and MI parts, respectively, with $w_1 + w_2 = 1$. The final *DEA / MI*$_i$ score is the weighted sum of *DEA/MI*$_i$(*j*) scores over all the models *j=1,…,M*:

$$DEA/MI_i = \sum_{j=1}^{M} u_j DEA/MI_i(j), \tag{6}$$

where u_j, $j = 1,\dots, M$ are the weights of importance of the DEA/MI models, with $\sum_{j=1}^{M} u_j = 1$.

Different models have been created for detailed analysis of the efficiency of sub-sectors in both countries. Based on many studies (Bui *et al*., 2016; Fenyves *et al*., 2015; Halkos and Tzeremes, 2012a, 2012b; Li and Wu, 2016; Nikoomaram *et al*., 2010; Oberholzer and Westhuizen, 2004), where financial ratios have been used for DEA models, we formed our models using different ratios.

Five DEA models were considered with selected groups of ratios as outputs. Liquidity ratios were the outputs for Model 1, profitability ratios for Model 2, activity ratios for Model 3, efficiency ratios for Model 4 and leverage ratios for Model 5 (Table 3). Non-ratio data (Assets (A), Capital (C) and Number of Employees (NE)) were used as inputs for all models.

For all inputs and outputs of Models 1-5, the time series within the period from 2013 to 2017 were analysed using IBM SPSS Statistics V25. One-way ANOVA was used to test the differences in input and output values between two sub-sectors and between Slovenia and Croatia. The Kolmogorov–Smirnov test was performed to check the normality of the data and Levene's test was performed to check the differences between the variances of the groups. Post-hoc tests were used to detect the differences between pairs of compared groups, Bonferroni's procedure when the data variances were similar and Games-Howell procedure in case of doubt about the equality of data variances.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

3.1 Descriptive statistics and post-hoc tests

3.1. Deskriptivna statistika i post-hoc testovi

The descriptive statistics of inputs and outputs of Models 1-5 for the year 2017 are presented in Table 4. The sample for calculating descriptive statistics includes companies with the grade A financial rating for their credit appraisal and with more than five employees in 2017. It is shown that there were statistically significant differences between the values of variables A, C, NE and EBITDA among the observed companies, which was expected as the sample includes micro, small and larger companies. It is interesting, however, that the values of most other indicators are very different, although only companies with a credit appraisal rating A with at least five employees were taken into account. It can be established that, on average, all companies showed excellent solvency (liquidity) and profitability ratios, with a very low share of debts, which shows their excellence.

We tested the differences between the values of indicators for Slovenia (SI) and Croatia (CRO) and sectors C16 and C31. The differences between the four groups were statistically significant for the majority of the indicators. Although the comparison also shows that the average values of the indicators are quite simi-

Table 4 Descriptive statistics of inputs and outputs in Models 1-5 for the year 2017
Tablica 4. Deskriptivna statistika ulaza i izlaza u modelima 1. – 5. za 2017.

Model *Model*	**Group** *Skupina*	**Financial indicator** *Financijski pokazatelj*	**Mean** *Srednja vrijednost*	**Min** *Minimum*	**Max** *Maksimum*	**Std. Dev.** *Standardna devijacija*
Input for Model 1-5 *ulazi za modele 1. – 5.*	Assets / *imovina*	A	2,725,001 €	22,922 €	65,155,475 €	6,706,358 €
	Capital / *kapital*	C	1,837,445 €	17,667 €	57,413,853 €	5,331,940 €
	Number of employees *broj zaposlenih*	NE	36.2	5.0	458.0	64.7
Output for Model 1 *izlazi za model 1.*	Liquidity ratio *omjer likvidnosti*	CR	3.430	0.377	21.070	3.158
		QR	2.584	0.163	18.464	2.687
		CashR	1.493	0.000	16.877	2.302
Output for Model 2 *izlazi za model 2.*	Profitability ratio *omjer profitabilnosti*	ROA	13.3 %	0.0 %	83.3 %	12.2 %
		ROE	23.6 %	0.0 %	166.9 %	22.5 %
		ROS	8.7 %	0.0 %	46.8 %	7.2 %
Output for Model 3 *izlazi za model 3.*	Activity ratio *omjer aktivnosti*	GVA	34,157 €	5,957 €	451,464 €	32,817 €
		ATR	1.742	0.453	11.547	1.133
		CAT	3.433	0.603	24.945	2.587
Output for Model 4 *izlazi za model 4.*	Efficiency ratio *omjer učinkovitosti*	EBITDA	552,149 €	154 €	14,349,918 €	1,475,460 €
		E	1.132	1.003	2.291	0.133
		AU	1.738	0.454	9.474	1.063
Output for Model 5 *izlazi za model 5.*	Leverage ratio *omjer financijske poluge*	D/E	0.753	0.032	5.492	0.769
		TDA	0.118	0.000	0.593	0.134
		TLTSF	0.329	0.026	0.846	0.185

lar (Table 5), the objective of this paper is to focus on some more interesting results. Table 5 shows that the biggest differences can be observed in variables A (one-way ANOVA, F(3.16)=56.109, p<0.001) and C (one-way ANOVA, F(3.16)=26.294, p<0.001), where the values in SI-C16 are above average and SI-C31 below average, while those in CRO-C16 and CRO-C31 are average. Moreover, the variances of the groups differ for the variables A (Levene's test, F(3.16)=3.423, p=0.043) and C (Levene's test, F(3.16)=3.822,

Table 5 Average values of inputs and outputs in Models 1-5 for 2017, for groups of financial indicators by country and subsector
Tablica 5. Prosječne vrijednosti ulaza i izlaza u modelima 1. – 5. za skupine financijskih pokazatelja po državama i podsektorima u 2017.

Country / *Država*			**SI+CRO**	**SI**	**SI**	**CRO**	**CRO**
Model *Model*	**Group** *Skupina*	**Financial indicator** *Financijski pokazatelj*	**C16+C31**	**C16**	**C31**	**C16**	**C31**
Input for Model 1-5 *ulazi za modele 1. – 5.*	Assets / *imovina*	A	2,725,001 €	4,145,299 €	1,453,053 €	2,305,357 €	2,818,543 €
	Capital / *kapital*	C	1,837,445 €	3,086,710 €	902,264 €	1,419,960 €	1,827,696 €
	Number of employees *broj zaposlenih*	NE	36.2	32.2	22.8	41.2	46.0
Output for Model 1 *izlazi za model 1.*	Liquidity ratio *omjer likvidnosti*	CR	3.430	3.183	3.438	3.722	3.166
		QR	2.584	2.364	2.772	2.842	2.162
		CashR	1.493	1.273	1.592	1.772	1.120
Output for Model 2 *izlazi za model 2.*	Profitability ratio *omjer profitabilnosti*	ROA	13.3 %	8.3 %	8.4 %	16.1 %	20.1 %
		ROE	23.6 %	14.7 %	17.6 %	26.9 %	36.8 %
		ROS	8.7 %	6.1%	6.5%	10.3%	11.5%
Output for Model 3 *izlazi za model 3.*	Activity ratio *omjer aktivnosti*	GVA	34,157 €	47,024 €	35,617 €	28,826 €	24,390 €
		ATR	1.742	1.569	1.723	1.742	2.029
		CAT	3.433	3.433	3.344	3.404	3.596
Output for Model 4 *izlazi za model 4.*	Efficiency ratio *omjer učinkovitosti*	EBITDA	552,149 €	724,127 €	260,280 €	520,578 €	669,647 €
		E	1.132	1.093	1.109	1.154	1.170
		AU	1.738	1.576	1.673	1.747	2.036
Output for Model 5 *izlazi za model 5.*	Leverage ratio *omjer financijske poluge*	D/E	0.753	0.723	0.692	0.741	0.892
		TDA	0.118	0.124	0.099	0.116	0.132
		TLTSF	0.329	0.315	0.310	0.330	0.372

SI – Slovenia; CRO – Croatia; C16 – Wood processing; C31 – Furniture manufacturing / *SI – Slovenija; CRO – Hrvatska; C16 – prerada drva; C31 – proizvodnja namještaja* p=0.031). Further, the Games–Howell post hoc test revealed that the differences between all pairs of four groups, except the pair SI-C16 and CRO-C16 for variable A and for all pairs of four groups for variable C, are statistically significant. The differences between the four groups for variable NE is also statistically significant (one-way ANOVA, F(3.16)=105.669, p<0.001). The Bonferroni post hoc test revealed that the differences between pairs of all groups except pair SI-C16 and CRO-C31 are statistically significant. There are no statistically significant differences between the groups of the profitability ratios ROE (one-way ANOVA, F(3.16)=1.172, p=0.351) and ROA (one-way ANOVA, F(3.16)=2.578, p=0.090), and the only statistically significant difference for variable ROS is between SI-C16 and SI-C31 (one-way ANOVA, F(3.16)=4.182, p=0.023, Games-Howell post hoc test p=0.024). However, the average values of the profitability ratios differ quite a lot, as do their variances. The differences between the four groups for variable GVA are statistically significant (one-way ANOVA, F(3.16)=66.963, p<0.001) as well as for variable EBITDA (one-way ANOVA, F(3.16)=15.660, p<0.001). GVA shows much higher values in SI groups that CRO groups, with the highest value for the group SI-C16. Regarding the variable EBITDA, both CRO groups have average values, while SI-C31 achieves the highest and SI-C16 the lowest values.

3.2 Results of DEA and Malmquist Productivity Index
3.2. Rezultati DEA analize i Malmquistova indeksa produktivnosti

The DEA efficiency analysis using the models over the years did not give any specific trend based on which it could be concluded that the efficiency is increasing or decreasing over time. By comparing the efficiency of average values using the models (Figure 1), it can be concluded that for all of them the most effective clusters are SI-C16-larger, CRO-C16-micro and CRO-C31-micro, while the worst efficiency is

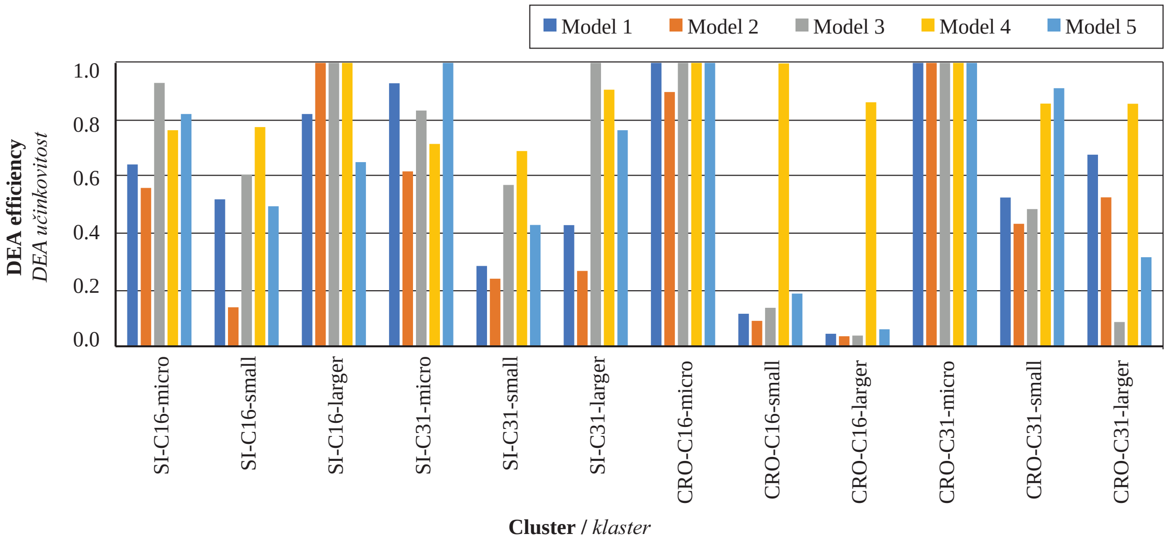

Figure 1 DEA efficiency analysis - average by years of Models 1-5
Slika 1. Analiza učinkovitosti DEA – prosjek po godinama za modele 1. – 5.

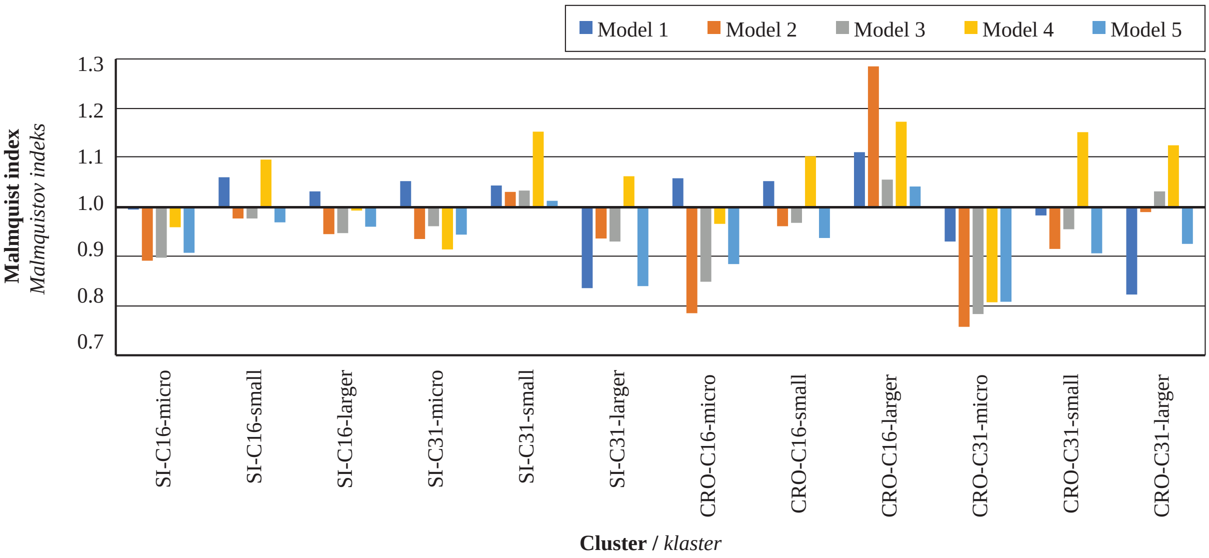

Figure 2 Malmquist Index - average by year of models 1-5
Slika 2. Malmquistov indeks – prosječne vrijednosti po godinama za modele 1. – 5.

Table 6 DEA/MI weighted score of all models and ranking of clusters
Tablica 6. DEA/MI ponderirana ocjena svih modela i rangiranje klastera

DMU	Weighted Score / *Ponderirana vrijednost*					Average of Models 1-5 *Posječne vrijednosti modela 1. – 5.*	
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**	**Weighted score** *Ponderirana vrijednost*	**Ranking** *Rangiranje*
CRO-C31-micro	0.967	0.910	0.893	0.900	0.957	0.925	1
CRO-C16-micro	0.984	0.802	0.924	0.941	0.949	0.920	2
SI-C16-larger	0.856	0.911	0.966	0.949	0.741	0.884	3
SI-C31-micro	0.935	0.654	0.858	0.736	0.969	0.830	4
SI-C16-micro	0.726	0.604	0.903	0.781	0.837	0.770	5
CRO-C31-small	0.668	0.584	0.599	0.904	0.934	0.738	6
SI-C31-larger	0.536	0.420	0.949	0.906	0.777	0.718	7
CRO-C31-larger	0.717	0.670	0.356	0.904	0.543	0.638	8
SI-C16-small	0.664	0.345	0.713	0.827	0.640	0.638	9
SI-C31-small	0.502	0.427	0.706	0.787	0.610	0.606	10
CRO-C16-small	0.393	0.309	0.385	0.979	0.424	0.498	11
CRO-C16-larger	0.363	0.358	0.331	0.907	0.374	0.467	12

DMU – decision-making units / *DMU – donošenje odluka u jedinicama*

found in CRO-C16- small and CRO-C16-larger, where, except for model 4 (efficiency ratios), the DEA values are very low. For model 4, the differences between the DMUs are the smallest and the average values are the highest.

The Malmquist productivity index (MI) average by year (Figure 2) shows the highest MI values on average for Model 4. This means that variables EBITDA, E and AU have improved over the years in all models. On the other hand, there is an interesting situation: the MI values are the lowest in CRO-C31-micro, a little higher, but still very low in CRO-C16-micro and SI-C16-larger, although these clusters reached the highest values of DEA efficiency index. This means that these classes have high efficiency and at the same time low total productivity in converting inputs into outputs in practically all models. The reason for this is that MI values are directly influenced by the actual values of inputs and outputs. The best in this regard are CRO-C16-larger and SI-C31-small, while the others have an average efficiency of about 1.

To determine the most efficient cluster, we used the ranking of clusters according to both indexes (Table 6). We calculated the DEA/MI score for each model as the weighted sum of average efficiency and the normalized average of MI (5). Based on the assumption that the contribution of the annual efficiency is greater than the contribution of efficiency improvement over time (Zadnik Stirn *et al*., 2015), we set the weights $w_1 = 0.667$ and $w_2 = 0.333$ in DEA/MI (5) calculation. For final ranking the DEA/MI results of the Models 1-5 were aggregated by eq. (6). We assumed that all five models are equally important and set the weights $u_1 = u_2 = u_3 = u_4 = u_5 = 0.2$.

It was established that the ranking of DMUs depends also on the subjective selection of weights of importance w_1 and w_2 in eq. (5). The sensitivity analysis showed that the final ranking of DMUs remains unchanged if w_1 remains on the interval [0.547, 0.669] and consequently w_2 on the interval [0.331, 0.453].

If we assume that the relative efficiency is slightly to moderately more important than efficiency im-

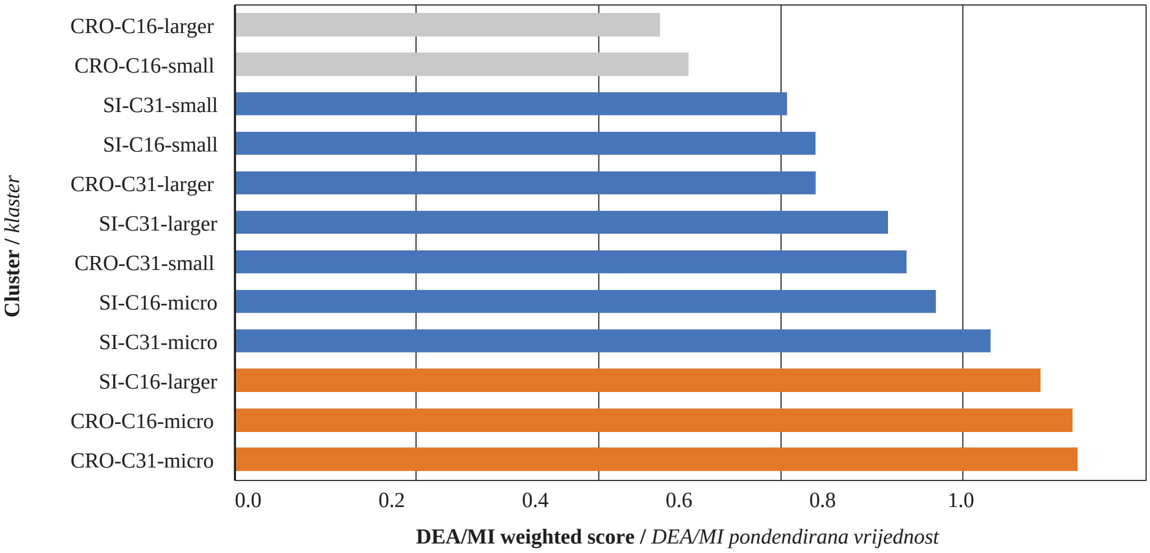

Figure 3 DEA/MI weighted score - average of models 1-5
Slika 3. DEA/MI ponderirana ocjena – prosjek modela 1. – 5.

provement over time, then this assumption is covered by the received interval. We can conclude that the DMUs' final ranking is robust.

Regarding the DEA/MI weighted score of all models, the most effective clusters are CRO-C31-micro, CRO-C16-micro and SI-C16-larger (Figure 3). On the other hand, CRO-C16-small and CRO-C16-larger have the worst results. It can also be concluded that the CRO-C31-micro cluster is quite balanced, with high values of the DEA/MI index in all models, but not the highest relative values in any model regarding the other clusters (Table 6). In the CRO-C16-micro and SI-C16-larger clusters, in contrast to the aforementioned CRO-C31-micro cluster, there are bigger differences between the values of the DEA/MI index among the models: CRO-C16-micro has the highest relative value in model 1, which demonstrates its effectiveness in liquidity ratios, but it is relatively low in profitability ratios, while the SI-C16-larger is the best in activity ratios, and much worse with leverage ratios. The final results are very similar to the DEA values that were highest in these clusters.

Clusters CRO-C31-micro and CRO-C16-micro are undoubtedly the most effective, both with DEA/MI weighted scores over 0.9, and cluster SI-C16-larger with an overall score just a bit below 0.9. A more detailed view of the average values of the variables/indicators in these clusters shows that the CRO-C31-micro cluster achieved exceptionally high values in all activity ratios and variable E, these values being the highest among all clusters. In CRO-C16-micro, very high values (above average) were recorded both in activity ratios and liquidity ratios and in variable E. For the cluster SI-C16-larger, a very high value can be observed in the GVA indicator, while the other values are slightly above average. For clusters CRO-C16-small and CRO-C16-larger, however, slightly under-average values were observed in all indicators and very low values for GVA and QR. Consequently, it can be concluded that the efficiency of a cluster is also strongly related to the average values of indicators: the higher these values, the more effective the cluster.

Clusters can also be grouped into four major groups (by country and subsector), as we did in calculating the average values of indicators in Chapter 3.1, where the differences are statistically significant for the majority of the indicators, except profitability ratios, where no statistically significant differences between the groups was established. We also established that the SI-C16 deviates in particular in values A, C, EBITDA and GVA, while the HR-C31 is the best in activity ratios (ROA, ROE and ROS) and NE. A similar distribution is obtained if the average of the DEA/MI weighted score of efficiency for these groups is calculated. The SI-C16 and CRO-C31 groups achieve above average overall efficiency and, however, the values are almost identical (SI-C16 with a value of 0.764 and CRO-C31 with a value of 0.767). Regarding this group, SI-C31 reached the value of 0.718, and CRO-C16 group achieved the worst average efficiency (0.628). It can be concluded that the performance of the group is also greatly influenced by the average values of individual indicators for the last year (i.e., 2017). Similar results were obtained for the wood industry in Slovenia (Kropivšek and Grošelj, 2019). Interestingly, CRO-C16 achieved a very poor performance, and this may be a consequence of various factors, such as the lower degree of technological development and less use of innovative solutions that generate higher added value in production, as well as the long-term stability of domestic production in the supply of wood raw material from state forests in Croatia and the stability of wood assortments prices (MPS, 2017).

4 CONCLUSIONS
4. ZAKLJUČAK

The wood industry, as a traditional sector, represents a very important part of the economy in terms of ensuring a sustainable development of society and transition to a low-carbon society in both studied countries, Slovenia and Croatia. In recent years, the wood industry in Slovenia has undergone a great deal of improvement: many new investments have been made, a lot has been invested in the promotion of wood, especially wooden construction, practically all financial indicators have improved, exports have increased and many macroeconomic and political measures for its improvement have been undertaken (Kropivšek *et al.*, 2017). Similarly, Croatia has also taken many steps to improve its wood industry (CWC, 2019). For instance, the Croatian government has recognized the wood-processing industry as one of its strategic priorities, and used financial instruments to support development of wood processing and furniture production in accordance with the principles and policies of a sustainable economy and rural development (MPS, 2017).

To ensure the development of the wood sector, it is crucial to know its current status, and one way to achieve this is through an international comparative evaluation of its operational efficiency, based on financial data and/or indicators. For the evaluation carried out in the present study, we used Data Envelopment Analysis (DEA), the Malmquist Productivity Index (MI) and DEA/MI weighted score, which has been rarely used before for the evaluation of operational efficiency of wood sector, especially not for the comparison between different countries. The research covered the most successful companies in the wood industry sectors (C16 and C31) in Slovenia and Croatia with the highest credit appraisal rating in 2017 and with more than five employees, divided into 12 clusters regarding the size of a company. We studied the effectiveness of the clusters for the period 2013-2017.

The descriptive statistics of the inputs and outputs of models 1-5 for the year 2017 show that all the observed companies are excellent, especially in terms of their solvency (liquidity) and profitability ratios, with a very low share of debt. Analysing the four groups (C16 and C31 sectors in both Slovenia and Croatia) the differences are statistically significant for the majority of the indicators, except for the profitability ratios, where no statistically significant differences between the groups were established.

Regarding the DEA/MI weighted score of all models (Models 1-5), the most effective clusters are CRO-C31-micro, CRO-C16-micro and SI-C16-larger, while CRO-C16-small and CRO-C16-larger have the worst results. Those clusters are most effective (with the highest DEA values), but have low total productivity (low MI values). The average values of the indicators in these groups are also above average, especially in activity ratios, liquidity ratios, indicator E and/or GVA. Consequently, it can be concluded that the efficiency of the cluster is also strongly correlated with the average values of the indicators. In general, within grouped clusters regarding country and subsector, groups SI-C16 and CRO-C31 achieve the highest average values for the weighted score of efficiency, while CRO-C16 has the lowest values.

Important potential limitations of this study are the sample size, where only 3.1% of the related firms in Slovenia and 4.0 % in Croatia were analysed, and a short period of observation. However, the results are still meaningful as they cover the best and largest companies (those with more than five employees and rated A in credit appraisal), and give a more comparable picture between the countries and industries with all input data from business reports. As an extension of this study, it may be of interest to observe all the companies in the related sectors to get a more complete picture. It would also be very interesting to expand the sample to more countries and use a longer observation period.

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5 REFERENCES
5. LITERATURA

1. Ablanedo-Rosas, J. H.; Gao, H.; Zheng, X.; Alidaee, B.; Wang, H., 2010: A study of the relative efficiency of Chinese ports: a financial ratio-based data envelopment analysis approach. Expert Systems, 27: 349-362. http://dx.doi.org/10.1111/j.1468-0394.2010.00552.x.
2. Banker, R. D.; Charnes, A.; Cooper, W. W., 1984: Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis. Management Science, 30: 1078-1092. http://dx.doi.org/10.1287/mnsc.30.9.1078.
3. Braunsberger, F.; Hlavaty, M.; Schlamberger, N.; Stevanovič, S., 2010: Standardna klasifikacija dejavnosti 2008. Ljubljana: Statistični urad Republike Slovenije.
4. Bui, Y. H.; Sarath, D.; Ahmed, A. D., 2016: Efficiency of Australian superannuation funds: a comparative assessment. Journal of Economic Studies, 43: 1022-1038. http://dx.doi.org/10.1108/JES-05-2015-0088.
5. Charnes, A.; Cooper, W. W.; Rhodes, E., 1978: Measuring the efficiency of decision making units. European Journal of Operational Research, 2: 429-444. http://dx.doi.org/10.1016/0377-2217(78)90138-8.
6. Cook, W. D.; Seiford, L. M., 2009: Data envelopment analysis (DEA) – Thirty years on. European Journal of Operational Research, 192: 1-17. http://dx.doi.org/10.1016/j.ejor.2008.01.032.
7. Cooper, W. W.; Seiford, L. M.; Tone, K., 2006: Introduction to Data Envelopment Analysis and Its Uses: With DEA-Solver Software and References. Springer US.
8. Delen, D.; Kuzey, C.; Uyar, A., 2013: Measuring firm performance using financial ratios: A decision tree approach. Expert Systems with Applications, 40: 3970-3983. http://dx.doi.org/10.1016/j.eswa.2013.01.012.
9. Diaz-Balteiro, L.; Casimiro Herruzo, A.; Martinez, M.; González-Pachón, J., 2006: An analysis of productive efficiency and innovation activity using DEA: An application to Spain's wood-based industry. Forest Policy and Economics, Innovation and entrepreneurship in the forest sector, 8: 762-773. http://dx.doi.org/10.1016/j.forpol.2005.06.004.
10. Färe, R.; Grosskopf, S.; Norris, M.; Zhang, Z., 1994: Productivity Growth, Technical Progress, and Efficiency Change in Industrialized Countries. The American Economic Review, 84: 66-83.
11. Fenyves, V.; Tarnóczi, T.; Zsidó, K., 2015: Financial Performance Evaluation of Agricultural Enterprises with DEA Method. Procedia Economics and Finance, Emerging Markets Queries in Finance and Business 2014, EMQFB 2014, 24-25 October 2014, Bucharest, Romania 32: 423-431. http://dx.doi.org/10.1016/S2212-5671(15)01413-6.
12. Fernández, D.; Pozo, C.; Folgado, R.; Jiménez, L.; Guillén-Gosálbez, G., 2018: Productivity and energy efficiency assessment of existing industrial gases facilities via data envelopment analysis and the Malmquist index. Applied Energy, 212: 1563-1577. http://dx.doi.org/10.1016/j.apenergy.2017.12.008.
13. Friedlob, G. T.; Schleifer, L. L. F., 2003: Essentials of Financial Analysis. John Wiley & Sons.
14. Gitman, L. J., 2003: Principles of Managerial Finance. Person.
15. Gombola, M. J.; Ketz, J. E., 1983: Financial Ratio Patterns in Retail and Manufacturing Organizations. Financial Management, 12: 45-56. http://dx.doi.org/10.2307/3665210.
16. Hadad, Y.; Keren, B.; Hanani, M. Z., 2015: Combining data envelopment analysis and Malmquist Index for evaluating police station efficiency and effectiveness. Police Practice and Research, 16: 5-21. http://dx.doi.org/10.1080/15614263.2013.845945.
17. Halkos, G. E.; Tzeremes, N. G., 2012a: Industry performance evaluation with the use of financial ratios: An application of bootstrapped DEA. Expert Systems with Applications, 39: 5872-5880. http://dx.doi.org/10.1016/j.eswa.2011.11.080.
18. Halkos, G. E.; Tzeremes, N. G., 2012b: Analyzing the Greek renewable energy sector: A Data Envelopment Analysis approach. Renewable & Sustainable Energy Reviews, 16: 2884-2893. http://dx.doi.org/10.1016/j.rser.2012.02.003.
19. Helfert, E. A., 2001: Financial Analysis Tools and Techniques: A Guide for Managers. McGraw-Hill Education.
20. Hemmasi, A.; Talaeipour, M.; Khademi-Eslam, H.; Farzipoor Sean, R.; Pourmousa S., H., 2011: Using DEA window analysis for performance evaluation of Iranian wood panels industry. African Journal of Agricultural Research, 6: 1802-1806. http://dx.doi.org/10.5897/AJAR10.733.

21. Hollingsworth, B.; Smith, P., 2003: Use of ratios in data envelopment analysis. Applied Economics Letters, 10: 733-735. http://dx.doi.org/10.1080/1350485032000133381.
22. Johnes, J.; Izzeldin, M.; Pappas, V., 2009: Efficiency in Islamic and conventional banks: A comparison based on financial ratios and data envelopment analysis. Lancaster: Economics Working Paper Series. The Economics Department, Lancaster University.
23. Klarić, K.; Greger, K.; Klarić, M.; Andrić, T.; Hitka, M.; Kropivšek, J., 2016: An Exploratory Assessment of FSC Chain of Custody Certification Benefits in Croatian Wood Industry. Drvna industrija, 67 (3): 241-248.
24. Kropivšek, J.; Grošelj, P., 2019: Long-term Financial Analysis of the Slovenian Wood Industry Using DEA. Drvna industrija, 70 (1): 61-70. http://dx.doi.org/10.5552/drvind.2019.1810.
25. Kropivšek, J.; Grošelj, P.; Likar, B.; Jošt, M., 2011: Economics of Slovenian wood-industry. Presented at the Development trends in economics and management in wood processing and furniture manufacturing. Kozina, Slovenia: WoodEMA, i.a, pp. 91-96.
26. Kropivšek, J.; Jošt, M., 2013: Financial analysis of Slovenian wood industry. In: Markets for wood and wooden products. Jelačić, D. (ed.), WoodEMA, i.a., Zagreb, Croatia, pp. 57-74.
27. Kropivšek, J.; Milavec, I.; Likar, B., 2017: Analiza poslovanja slovenske lesne panoge: Les/Wood, 66: 47-56. http://dx.doi.org/10.26614/les-wood.2017.v66n02a05.
28. Li, H.; Wu, L., 2016: Analysis of financial support efficiency for China's wind power industry. Energy Sources, part B: Economics, Planning, and Policy, 11: 1035-1041. http://dx.doi.org/10.1080/15567249.2016.1185480.
29. Liu, F.-H. F.; Wang, P., 2008: DEA Malmquist productivity measure: Taiwanese semiconductor companies. International Journal of Production Economics, Special Section on Recent Developments in the Design, Control, Planning and Scheduling of Productive Systems, 112: 367-379. http://dx.doi.org/10.1016/j.ijpe.2007.03.015.
30. Nikoomaram, H.; Mohammadi, M.; Mahmoodi, M. R., 2010: Efficiency Measurement of Enterprises Using the Financial Variables of Performance Assessment and Data Envelopment Analysis. Applied Mathematical Sciences, 4: 1843-1854.
31. Oberholzer, M.; Westhuizen, G. V. der, 2004: An empirical study on measuring efficiency and profitability of bank regions. Meditari: Research Journal of the School of Accounting Sciences, 12: 165-178.
32. Örkcü, H. H.; Balıkçı, C.; Dogan, M. I.; Genç, A., 2016: An evaluation of the operational efficiency of turkish airports using data envelopment analysis and the Malmquist productivity index: 2009 – 2014 case. Transport Policy, 48: 92-104. http://dx.doi.org/10.1016/j.tranpol.2016.02.008.
33. Palepu, K. G.; Healy, P. M.; Bernard, V. L., 2003: Business Analysis and Valuation Using Financial Statements: Text and Cases, 3rd ed. ed. Manson, Ohio: Thomson South-Western.
34. Pastor, J. T.; Ruiz, J. L., 2007: Variables With Negative Values In Dea. In: Zhu, J., Cook, W. D. (eds.), Modeling Data Irregularities and Structural Complexities in Data Envelopment Analysis. Boston, MA: Springer US, pp. 63-84. http://dx.doi.org/10.1007/978-0-387-71607-7_4.
35. Perić, I.; Grladinović, T.; Greger, K.; Jože, K., 2015: Sources of Competitiveness for Furniture Manufacturing Firms: A Review of Literature and Research Issues. In: Proceeding of the 26th International Conference on Wood Modification and Technology: Implementation of wood science in woodworking sector. Grbac, I. (ed.), Faculty of Forestry, University of Zagreb, Zagreb, Croatia, pp. 179-185.
36. Perić, I.; Grošelj, P.; Sujova, A.; Kalem, M.; Greger, K.; Kropivšek, J., 2019: Analysis of Implementation of Integrated Information Systems in Croatian Wood Processing Industry. Drvna industrija, 70 (2): 129-139. https://doi.org/10.5552/drvind.2019.1911.
37. Peterson-Drake, P.; Fabozzi, F. J., 2010: The Basics of Finance: An Introduction to Financial Markets, Business Finance, and Portfolio Management. John Wiley & Sons.
38. Pirc Barčić, A.; Liker, B.; Motik, D.; Moro, M., 2015: Financial Analysis of Croatian Furniture Industry. In: Proceeding of the 26th International Conference on Wood Modification and Technology: Implementation of wood science in woodworking sector. Grbac, I. (ed.), Faculty of Forestry, University of Zagreb, Zagreb, Croatia, pp. 187-191.
39. Potkány, M.; Giertl, G., 2014: Comparison of selected performance indicators of woodworking industry in the Czech Republic and Slovakia. Presented at the Position and role of the forest based sector in the green economy, Zvolen, Slovakia: WoodEMA, i.a, pp. 131-138.
40. Salehirad, N.; Sowlati, T., 2006: Productivity and efficiency assessment of the wood industry: A review with a focus on Canada. Forest Products Journal 56.
41. Salehirad, N.; Sowlati, T., 2007: Dynamic efficiency analysis of primary wood producers in British Columbia. Mathematical and Computer Modelling, 45: 1179-1188. http://dx.doi.org/10.1016/j.mcm.2006.10.003.
42. Sayari, N.; Simga-Mugan, C., 2017: Industry specific financial distress modeling. BRQ Business Research Quarterly, 20: 45-62. http://dx.doi.org/10.1016/j.brq.2016.03.003.
43. Seiford, L. M.; Zhu, J., 2002: Modeling undesirable factors in efficiency evaluation. European Journal of Operational Research, 142: 16-20. http://dx.doi.org/10.1016/S0377-2217(01)00293-4.
44. Šooš, T.; Lautar, K.; Urbančič, H.; Kobe Logonder, N.; Kmet Zupančič, R.; Fajić, L.; Čokl, A.; Gantar, J.; Lenarčič, M.; Culpa, N., 2017: Strategija razvoja Slovenije 2030. Ljubljana: Služba Vlade Republike Slovenije za razvoj in evropsko kohezijsko politiko.
45. Sowlati, T.; Vahid, S., 2006: Malmquist productivity index of the manufacturing sector in Canada from 1994 to 2002, with a focus on the wood manufacturing sector. Scandinavian journal of forest research, 21: 424-433. http://dx.doi.org/10.1080/02827580600917304.
46. Sueyoshi, T.; Goto, M., 2013: A use of DEA-DA to measure importance of R&D expenditure in Japanese information technology industry. Decision Support Systems, 54: 941-952. http://dx.doi.org/10.1016/j.dss.2012.09.017.
47. Tratnik, M.; Zager, M.; Zupanec, J., 2001: Key factors of (non)competitiveness of Slovene wood industry. In: Ways for improving woodworking industry for transitional economics: proceedings. Preddvor, Slovenia: International Symposium, pp. 107-114.
48. Vance, D. E., 2003: Financial Analysis and Decision Making: Tools and Techniques to Solve Financial Problems and Make Effective Business Decisions. New York: McGraw-Hill.
49. Zadnik Stirn, L.; Leban, V.; Grošelj, P.; Krč, J.; Pezdevšek Malovrh, Š., 2015: Public forest service in Slovenia over last decade – efficiency assessment. In: Proceedings of Extended Abstracts. Presented at the International IUFRO Symposium Cross-sectoral policy impacts on managerial economics and accounting in forestry, Sarajevo, pp. 25-30.

50. ***Ajpes JOLP, 2019: Public posting of annual reports [online]. https://www.ajpes.si/jolp (Accessed Mar. 1, 2019).
51. ***Analitika GZS, 2019: Analitika GZS [online]. https://analitika.gzs.si/ (Accessed Feb. 4, 2019).
52. ***Bisnode, 2019: Bonitete.Si – bonitetne informacije podjetij. https://bonitete.bisnode.si (Accessed Mar. 1, 2019).
53. ***CBS, 2019: Croatian Bureau of Statistics – Republic of Croatia. https://www.dzs.hr/default_e.htm (Accessed Apr. 8, 2019).
54. ***CWC, 2019: Croatian Wood Cluster. http://www.drvniklaster.hr/ (Accessed May. 6, 2019).
55. ***MPS, 2017: Odluka o donošenju Strategije razvoja prerade drva i proizvodnje namještaja Republike Hrvatske 2017. – 2020. s Akcijskim planom provedbe 2017. – 2020. https://narodne-novine.nn.hr/clanci/sluzbeni/2017_05_44_1001.html (Accessed Mar. 10, 2017).
56. ***NACE, 2019: Glossary:Statistical classification of economic activities in the European Community (NACE) – Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Statistical_classification_of_economic_activities_in_the_European_Community_(NACE) (Accessed Feb. 10, 2019).
57. ***ZGD-1-UPB3, 2009: Zakon o gospodarskih družbah. https://www.uradni-list.si/glasilo-uradni-list-rs/vsebina/2009-01-3036?sop=2009-01-3036 (Accessed Feb. 4, 2019).

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Influence of Air Humidity Variation on Strength of Rotary Welded Dowel Joints of Pinewood

Utjecaj promjene vlažnosti zraka na čvrstoću kružno zavarenih spojnih elemenata od borovine

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ABSTRACT • *A rotary welded joint is a combination of wood in which chemical and physical reactions occur due to friction. During the welding process, heat is generated which softens and melts the wood structure. In this way, interlocked wood fibres in the lignin melt are created within the joint. As the welded joint cools down, it becomes a tight weld. The paper describes the research based on studying the impact of individual factors on the welded joint. Outcome variables are the average ring width, the water content in the wood, and the influence of different humidity levels on the strength of rotary welds. Samples were subjected to the influence of different humidity levels achieved by air conditioning, magnesium chloride and sodium chloride. Absolutely dry samples exhibited the lowest embedded force values (the average embedded force value for heartwood amounted to 1901 N and for sapwood 1920.36 N), while the air conditioned samples (the average embedded force value amounted to 2649.06 N; for sapwood 2679.6 N and for heartwood 2619.6 N). The samples exposed to sodium chloride (the average embedded force value amounted to 2907.7 N; for sapwood 2766.07 N and for heartwood 3049.33 N) exhibited the highest embedded force values. This paper presents a descriptive statistical analysis of the strength of rotary welded dowels in the pine base. The aim of the study was to research the influence of different air humidity levels on the embedded force of Scots pine rotary welds. As the air relative humidity and temperature change during the daily application of the product (which affects the moisture content in the wood), the knowledge on the influence that humidity and water content in the wood exert on the welded joint strength turns out to be of great importance for its use.*

Keywords: *welding solid wood, Scots pine (Pinus sylvestris L.), dowels, strength of welded joints, weld factors, embedded force, the impact of humidity on wood, wood moisture content*

SAŽETAK • *Kružno zavareni spoj jest spoj drva u kojemu se zbivaju kemijsko-fizikalne reakcije pod utjecajem trenja. Tijekom procesa zavarivanja stvara se toplina, zbog koje struktura drva omekša i rastali se, pa se te drvna vlakanca u talini lignina međusobno isprepletu. Pri hlađenju zavarenog spoja nastaje čvrsto zavareni spoj. U radu je opisano istraživanje utjecaja pojedinih čimbenika na zavareni spoj, u sklopu kojega su promatrani sadržaj vode u drvu te utjecaj različite vlažnosti zraka na čvrstoću kružno zavarenih spojeva. Uzorci su izlagani zraku različite vlažnosti, što je postignuto njihovim kondicioniranjem te solima magnezijeva i natrijeva klorida. Apsolutno suhi*

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uzorci pokazali su najniže vrijednosti izvlačne sile (prosječna vrijednost te sile za srž iznosila je 1901 N, a za bjeljiku 1920,36 N), a zatim slijede klimatizirani uzorci (prosječna vrijednost izvlačne sile iznosila je 2649,06 N; za bjeljiku 2679,6 N, a za srž 2619,6 N). Uzorci izloženi natrijevu kloridu pokazali su najviše vrijednosti izvlačne sile (njezina prosječna vrijednost iznosila je 2907,7 N; za bjeljiku 2766,07 N, a za srž 3049,33 N). U radu je prikazana deskriptivna statistička analiza čvrstoće moždanika kružno zavarenih u borovinu. S obzirom na to da se pri svakodnevnoj uporabi proizvoda mijenja relativna vlažnost zraka i temperatura (što utječe na promjene sadržaja vode u drvu), poznavanje utjecaja vlažnosti zraka i sadržaja vode u drvu na čvrstoću zavarenog spoja vrlo je važno za njegovu primjenu.

Ključne riječi: *zavarivanje masivnog drva, borovina (Pinus sylvestris L.), moždanik, čvrstoća zavarenog spoja, čimbenici zavarivanja, izvlačna sila, utjecaj vlažnoga zraka na drvo, sadržaj vode u drvu*

1 INTRODUCTION
1. UVOD

Humankind is showing an increasing environmental awareness and social responsibility nowadays so that the demand for environmentally friendly products is increasing as well. The application of welded wood joints may play a major role in the production and use of wood products. Welded joints not only achieve approximately the same embedded force values as glued joints, but they are also ecologically friendly as only natural materials are used for welding. During their recycling or incineration, such joints do not release toxins and they behave as natural wood. (Stamm *et al*., 2005).

Wood welding is done by heat and pressure (rotation and vibration) generated between one or more elements. The advantage of this procedure is that no adhesive is needed and, as such, it is the most environmentally benign. During the welding process, the components (lignin and hemicelluloses) soften thermally, which leads to polymerization, while surface wood layers melt when in contact (due to friction between materials). As a result, the cell wall in the interfacial zone is destroyed and the density in the welding zone increases considerably. Mechanical friction (which produces high temperatures), pressure forces and chemical reactions at the cooling stage make cell walls burst. The joints produced in this way can be compared to other ways of bonding. Chemical changes resulting from welding have not been included in this research. Instead, already known facts from available literature have been used. Much recent research has been dedicated to wood to find new ways of application of this valuable and renewable raw material (Župčić, 2010).

During the rotation in wood welding, the dowel surface and volume decrease, while the welding hole increases. The wood density in the welding zone increases considerably because of the total destruction of cells. Wood welding is determined by the temperature, melting of certain amorphous polymeric substances and by mutual bonding of wood tissue in the wood structure. Certain studies showed that the welded joint could be much stronger than the glued joint (Župčić, 2010).

This paper presents the descriptive statistical analysis of the strength of a rotary welded dowel that was exposed to different humidity levels. The aim was to research the influence of different humidity levels on the strength of welded joints with regard to the fact that relative humidity and temperature change during the application of the product, which affects the water content in the wood. The knowledge of the influence that relative air humidity has on the welded joint strength turns out to be important for the future application in manufacture and for everyday use.

The research is based on studying the impact of individual factors on the welded joint. The factors that were observed include the water content in the wood and impact of different humidity levels on the strength of rotary welded joints. Eighty samples were used for the research. Three holes were drilled on each sample into which dowels were welded. After the selection of 80 samples, they were divided into two groups consisting of 40 samples from the sapwood zone, and 40 samples from the heartwood zone. The samples divided in this way were exposed to different air humidity levels. One group consisted of samples that were absolutely dry, the other group of air-conditioned samples and the remaining two of samples exposed to different of air humidity (obtained by magnesium chloride and sodium chloride).

Pizzi *et al*. (2006) researched the influence of water on the welded joint. A grooved beech dowel having 10 mm in diameter was welded to a beech base (30 mm × 30 mm × 30 mm) in an 8 mm hole. The welding depth was 20 mm, the rotation frequency 1515 revolution/min, and the weld time was 3 s. The control samples were glued using PVAc adhesive and conditioned over 24 h. The samples were immersed in cold water over a period of 24 hours. The research results show that the embedded force of the treated samples amounted to 88 % of the embedded force of the untreated samples.

Jones and Pizzi (2007) studied the influence of cold and boiling water on the strength of the welded joint of modified Sitka spruce wood. The results show a greater embedded force of the joints of thermally and chemically (alcohol based) modified wood during a 2-hour period of exposure to boiling water. The unmodified samples exhibited the greatest embedded force under normal conditions, whereas the chemically modified samples (modified by an acetylation agent) exhibited the greatest embedded force when exposed to cold water. It was demonstrated that the technique of modified wood welding is applicable, and that it improves the joint strength when exposing the welded joints to the influence of humidity and moisture. The research results show that the use of modified wood for welding can produce a joint that is more resistant to humidity. This opens up new opportunities for the application of the wood welding technique.

Leban *et al*. (2008) studied the impact of frequency on rotational welding. They used grooved beech dowels (*Fagus Sylvatica*) of 12 mm in diameter and 80 mm in length. The samples were made of spruce wood (*Picea Abies*) with a water content of 12 %. Receiver holes had a diameter of 9.5 mm to a depth of 15 mm, and of 8 mm to a depth of 46 mm. Embedded strength was examined on the samples that were welded at the frequencies of 1500, 4000, 6000 and 6500 min^{-1}. Welding time was between 2 and 4 s. The best results in embedded strength were obtained at a frequency of 1500 min^{-1}, whereas an increase in frequency resulted in lower strength. Higher welding frequencies produced a higher concentration of destroyed tissue i.e. a high increase in temperature was generated, so that melted material shifted further away from the bond line and thus created a gap.

Župčić *et al*. (2014) examined the impact of wood species such as beech, oak and spruce on the welded joint strength by examining the embedded strength (parallel and perpendicular to the fibres) and the impact of the ring width on the joint strength. Altogether 365 samples were made, out of which 359 were used for further research (bursting occurred in six samples). There were 16 different sample types with the dimensions of 200 mm × 30 mm × 30 mm with 30 sample pieces of each type. For each sample, grooved dowels were welded into drilled holes of 8 mm in diameter in the radial, radial-tangential and tangential direction. The sample type, where the hole was drilled in the same direction as the fibre orientation, had the dimensions of 30 mm × 30 mm × 64 mm, and when the sample was cut to be examined under the magnifying glass, its dimensions were of 30 mm × 30 mm × 30 mm. The average dowel was 10.04 mm in diameter and the weld penetration amounted to 20 mm. The rotation frequency was 1520 min^{-1} and the average tightness after the welding was 2.09 mm. A computer for measuring force and displacement was used for testing the embedded strength on the universal testing machine so that values were determined with a 5 N certainty. The testing was carried out with a 5 mm/min displacement. The results showed that there is a significant difference between the dowels welded parallel and perpendicular to the fibre orientation. The beech samples, with the dowels welded in the same direction as the fibre orientation, showed the best embedded strength values. The spruce samples, with the dowels welded in the same direction as the fibre orientation, showed the lowest embedded force values. In case of the dowels welded perpendicular in the radial, radial-tangential and tangential direction no statistically significant difference was recorded.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Solid wood selection

2.1. Izbor masivnog drva

Scots pine (*Pinus sylvestris* L.) was used for the research. The material was selected randomly from the stack of sawn dry timber. The only selection criterion was that the sawn timber be of regular structure, without any knots, cracks and damages. Scots pine belongs to conifers. Conifer tissue between wood rays consists exclusively or mostly of tracheids arranged in regular radial sequences. Such wood structure is suitable for evenly distributed stress along the joint and, therefore, for the preparation and processing of welding samples of good quality. Materials required for the testing were taken from the commercial stack so that possible changes during the testing could be linked to wood elements from the standard manufacture. Results obtained in this way could reveal joint properties that could be applied later under real conditions.

2.2 Preparation of samples for welding perpendicular to fibre orientation

2.2. Priprema uzoraka za zavarivanje okomito na smjer vlakanaca

2.2.1 Determination of initial moisture content in samples

2.2.1. Određivanje početnog sadržaja vode u uzorcima

The initial moisture content was determined by the gravitational method according to HRN ISO 13061-1:2015 by Eq. 1:

$$W=\frac{m_W-m_2}{m_2}\cdot 100 \tag{1}$$

where W is the moisture content in the wood after 7 days according to HRN ISO 13061-1:2015 (%), m_W is the initial probe mass (g) and m_2 is the probe mass after 7 days (g).

Wood density was determined on the same samples according to HRN ISO 13061-2:2015 by Eq. 2:

$$\rho=\frac{m}{V} \tag{2}$$

where ρ is wood density (g/cm^3), m = mass (g) and V = volume (cm^3).

2.2.2 Preparation of Scots pine specimens

2.2.2. Priprema uzoraka borovine

At the beginning of the samples preparation, specimens were taken to determine the initial moisture content and wood density (pinewood). Specimens were divided into two sample groups, 12 heartwood specimens and 12 sapwood specimens, which were used to determine the initial moisture content. Specimen dimensions and masses were measured to determine the specimen moisture content and density by the gravimetric method. The average moisture content in sapwood specimens amounted to 10.25 % (the minimum moisture content was 9.71 and maximum 12.37 %), while the average density amounted to 0.498 g/cm^3 (the minimum density was 0.488 g/cm^3 and maximum 0.511 g/cm^3). The average moisture content in heartwood samples amounted to 9.78 % (the minimum moisture content was 9.21 % and maximum 11.99 %), while the average density amounted to 0.560 g/cm^3 (the minimum density was 0.549 g/cm^3 and maximum 0.569 g/cm^3).

During their preparation all specimens were sawn, planed and cut down to their final dimensions, and receiver holes were drilled. Specimens with dimensions of 30 mm × 200 mm × 30 mm were used for the research. Sawn and planed laths with the dimen-

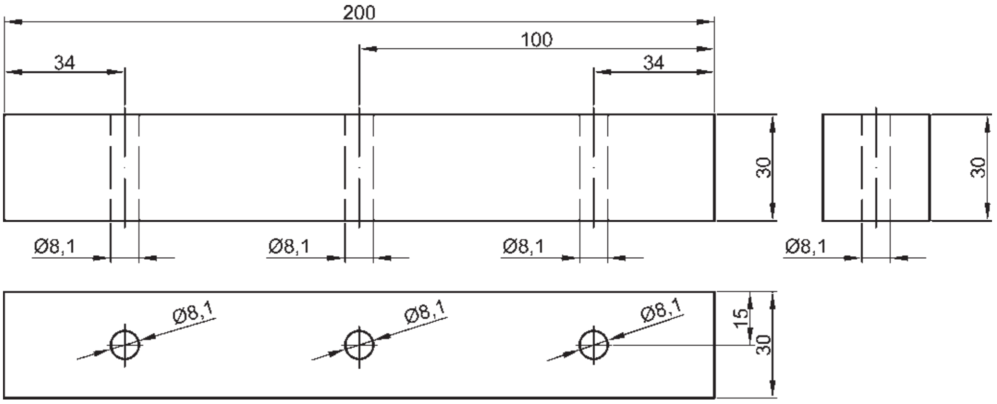

Figure 1 Testing sample for dowel welding
Slika 1. Ispitni uzorak pripremljen za zavarivanje moždanika

Figure 2 Specimens prepared for drying
Slika 2. Uzorci pripremljeni za sušenje

sions of cross section of 30 mm × 30 mm were cut to the length of 200 mm by transversal sawing. After transversal sawing of the sample laths, specimens were divided into 40 specimens from the sapwood zone and 40 specimens from the heartwood zone. All specimens were of radial-tangential texture.

Three receiver holes were drilled in each specimen. The distance between the hole and the sample ends was 34 mm, while the middle hole was made 100 mm from the sample end. The holes had a diameter of 8.1 mm and the welding direction was radial-tangential. Figure 1 shows the sample with drilled holes of 8.1 mm.

The sample holes were drilled by means of a tightly fixed drilling machine on the working desk at the rotation frequency of 1520 min^{-1} with the spiral steel drilling bit of 8.1 mm in diameter and HSS mark. The prepared samples were weighed on a digital weighing scale with the reading possibility of 0.0001 g and then dried in an oven at the temperature of (103±2) °C and 0 % moisture content (Figure 2).

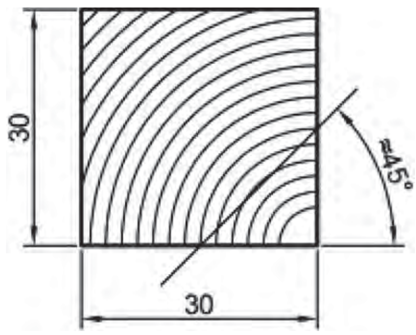

Figure 3 Manner of determining the ring width
Slika 3. Način određivanja širine goda

Besides the density and the average water content, the average ring width was determined as well by counting rings along the 30 mm width. The average ring width was measured by dividing the width of 30 mm (radial direction) by the number of rings on that width (Figure 3). The average ring width on heartwood samples amounted to 1.74 mm and on sapwood samples to 1.98 mm.

2.2.3 Dowel preparation
2.2.3. Priprema moždanika

Dowels were needed for the testing. They were obtained from smooth wooden sticks of 1000 mm in length and 10 mm in diameter and they were sawn to the length of 120 mm. Subsequently, their ends were bevelled by 1 mm at the angle of 45°.

Dowel bevelling was necessary for easier welding of the samples. After the processing, the dowels were weighed on the digital weighing scale with the reading possibility of 0.0001 g and put in the oven together with the samples at the temperature of (103 ± 2) °C. The average moisture content and density were obtained by the gravimetric method. The average moisture content of the dowels amounted to 9.57 % according to HRN ISO 13061-1:2015 and the dowel density to 0.662 g/cm³ according to HRN ISO 13061-2:2015.

2.3 Dowel rotary welding in prepared specimens
2.3. Kružno zavarivanje moždanika u pripremljene uzorke

After drying in the oven at (103±2) °C, the specimens and dowels were weighed on a digital scale. The weighed specimens and dowels were put into plastic boxes to keep their moisture content constant during their transport to the room for dowel welding. The dowel rotary welding in specimens was performed in a room with the temperature of 22 °C and the relative humidity of 58 %.

The sample welding was carried out by an adapted device with the possibility of dowel rotation. The welding was performed by rotating the dowel at the rotation frequency of 1520 min^{-1} during the welding. The time needed to weld the dowel into the specimen

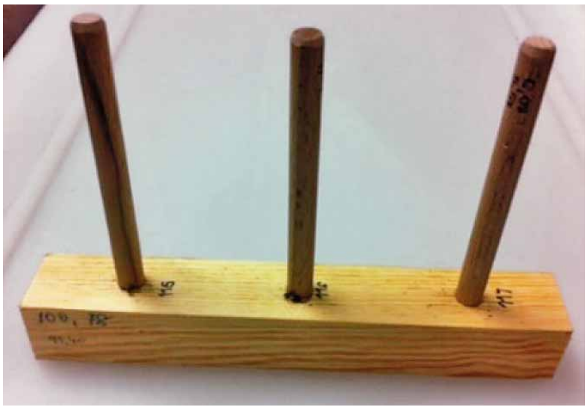

Figure 4 Testing specimens prepared for testing
Slika 4. Uzorci pripremljeni za ispitivanje

was 1.4 s, while the pressure on the dowel after the welding was applied for 3 to 5 seconds. The weld penetration amounted to 20 mm. The specimen, into which the dowels were welded, was immovable (static). Figure 4 shows the testing specimen prepared for embedded force testing.

After 80 samples had been welded, the probes were divided into four groups. Within each group there were 10 samples of sapwood and 10 samples of heartwood (three holes were drilled on each sample, each group with 60 welded dowels, 30 on heartwood samples and 30 on sapwood samples). One of the four sample groups (10 samples of sapwood and 10 samples of heartwood) was tested on the universal testing machine immediately.

The other sample group was conditioned under the laboratory conditions for a month at the temperature of (23±2) °C and the relative humidity of (50±5) %. After exposing the samples to climatic conditions for a month, the samples were transferred to the room equipped with the universal testing machine at the Department for Wood Science. Immediately after the testing, the water content was measured by the gravimetric method. The average water content after the exposure to climatic conditions amounted to 10.05 %.

The third sample group was exposed to magnesium chloride ($MgCl_2$) and the fourth to sodium chloride (NaCl). The magnesium and sodium chloride salts were dissolved in water until the mixture turned into mesh. After the mixture has been prepared, metal stands were put in plastic boxes in which samples were placed. The boxes with closed samples were left for four weeks (25 days). After removing the samples from the boxes, the water content was determined.

The average water content for the samples exposed to sodium chloride (NaCl) amounted to 13.05 % (the average water content for heartwood samples was 12.41 % and for sapwood samples 13.70 %). The average water content for the samples exposed to magnesium chloride ($MgCl_2$) amounted to 8.87 % (the average water content for heartwood samples was 8.71 % and for sapwood samples 9.03 %).

2.4 Embedded force testing
2.4. Ispitivanje izvlačne sile

The testing was carried out on the universal testing machine. Due to the specific nature of the testing, a new part for the universal testing machine was made for catching dowels to avoid their slipping out so that the testing could be carried out smoothly (Figure 5). The universal testing machine adapted in this way allows the centreline axis of the sample to be parallel with the centreline axis of the universal testing machine on which the force acts. The displacement on the universal testing machine during the testing was 5 mm/min.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Properties of the welded joint were determined by measuring the embedded force of the dowel from the sample. All research results were processed in *Microsoft Excel 13 and Statistica 12* programs and the embedded force results were compared accordingly after the testing (Table 1). Figure 6 shows the comparison of embedded forces for all sample groups. It may be concluded that there is no significant statistical difference ($p < 0.001$) between embedded force values of the conditioned samples (heartwood and sapwood), the

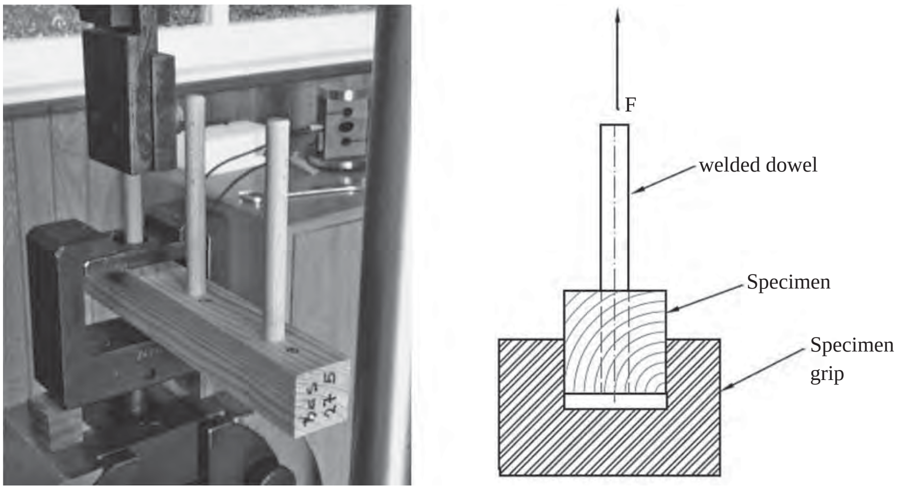

Figure 5 Manner of placing the testing specimen in the universal testing machine
Slika 5. Način postavljanja ispitnih uzoraka u univerzalni stroj za ispitivanje

Table 1 Descriptive statistics of embedded force for all groups of specimens
Tablica 1. Deskriptivna statistika izvlačne sile za sve skupine uzoraka

Sample code *Oznaka uzorka*	**MC in specimens, %** *Sadržaj vode u uzorcima,%*	**Number of speci-mens** *Broj uzoraka*	**Embedded force** / *Izvlačna sila*						
			Means, N *Srednja vrijed-nost, N*	**Standard deviation, N** *Standardna devijacija,* N	**Min, N**	**Max, N**	**Q25, N**	**Median, N**	**Q75, N**
1. Oven dry (heartwood) *1. osušeno (srž)*	0.0	30	1900.7	305.3	1335	2455	1622	1953,5	2185
2. Oven dry (sapwood) *2. osušeno (bjeljika)*	0.0	30	1920.3	394.8	1155	2840	1670	1832,5	2110
3. Magnesium Chloride (heartwood) *3. magnezijev klorid (srž)*	8.71	30	2901.1	300.0	2250	3510	2650	2935	3100
4. Magnesium Chloride (sapwood) *4. magnezijev klorid (bjeljika)*	9.03	24	2948.9	488.9	2130	4000	2620	2912,5	3237,5
5. Conditioned samples (heartwood) *5. kondicionirani uzorci (srž)*	10.05	30	2619.6	240.1	2270	3190	2420	2610	2810
6. Conditioned samples (sapwood) *6. kondicionirani uzorci (bjeljika)*	10.05	30	2679.6	588.4	1320	4080	2340	2625	3150
7. Sodium chloride (heartwood) *7. natrijev klorid (srž)*	12.41	30	3049.3	514.4	1950	4050	2675	3045	3440
8. Sodium chloride (sapwood) *8. natrijev klorid (bjeljika)*	13.70	28	2766.0	548.0	1785	4095	2295	2710	3147,5
All groups / *sve skupine*		232	2587.7	603.0	1155	4095	2207	2620	3000

samples exposed to magnesium chloride (heartwood and sapwood) and the samples exposed to sodium chloride (sapwood).

The statistical analysis showed no statistically significant difference between embedded forces for absolutely dry samples (heartwood and sapwood). Namely, absolutely dry samples exhibited the lowest embedded force values (the average embedded force value for heartwood amounted to 1901 N and for sapwood to 1920.36 N), while the air conditioned sam-

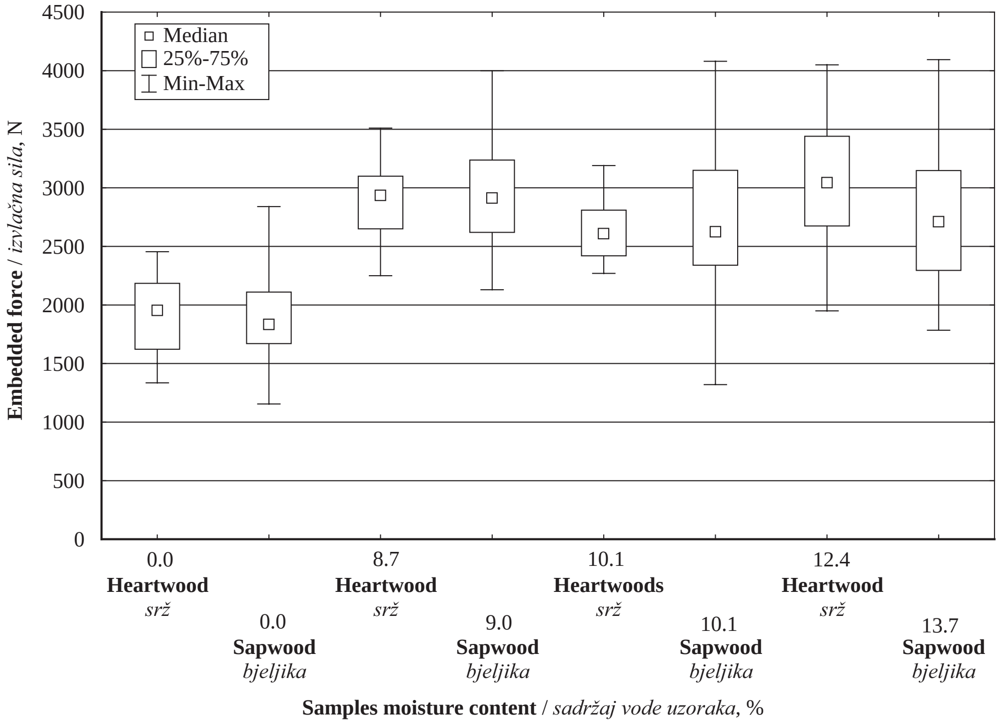

Figure 6 Comparison of embedded forces between groups of specimens conditioned to different MC
Slika 6. Usporedba izvlačne sila uzoraka kondicioniranih na različit sadržaj vode

ples (the average embedded force value amounted to 2649.06 N; for sapwood 2679.6 N and for heartwood 2619.6 N), and the samples exposed to sodium chloride (the average embedded force value amounted to 2907.7 N; for sapwood 2766.07 N and for heartwood 3049.33 N) exhibited the highest embedded force values.

A comparison between the results obtained by the statistical analysis of the embedded force values and the water content in the wood, and the statistical analysis of the embedded force values of the samples exposed to different levels of humidity, clearly shows that the embedded force increases as the humidity increases. An increase in air humidity resulted in an increased water content in the wood leading to wood swelling and changes in dimensions. This is why the embedded force values of the absolutely dry samples were much lower than those of other samples (the average embedded force for heartwood samples was 1900.73 N; the average embedded force for sapwood samples was 1920.36 N). The samples exposed to sodium chloride salts exhibited the highest embedded force values (the average of 3049.33 N). The samples with water content above 13.05 % exhibited the best embedded force values.

4 CONCLUSIONS
4. ZAKLJUČAK

Significant influence of moisture content on the embedded force or the strength of beech dowels welded in the Scots pine bases (specimens) was determined. There was a statistically significant increase in the embedded force between the oven dry specimens and specimens conditioned to average moisture content of 8.87 %. Embedded force slightly decreased for the samples conditioned to 10.05 % moisture content, and slightly increased for the samples conditioned to 13.05 % moisture content, but only for heartwood specimens, although these changes in embedded force were not statistically significant. Embedded forces for sapwood samples conditioned to 10.05 % and 13.7 % were almost the same.

Based on the obtained results, the moisture content of wood in the interval between 9 and 13 % does not have statistically significant effect on the embedded force and this moisture content of wood is optimal for dowel rotary welding. In the future research, the observed moisture content intervals should be expanded to determine at which water content embedded force decreases significantly.

Oven dry samples had the smallest embedded forces, due to increased brittleness of wood. Dowels welded in heartwood and sapwood did not show statistically significant difference in embedded force.

5 REFERENCES
5. LITERATURA

1. Bocquet, J. F.; Pizzi, A.; Resch, L., 2007: Full-scale industrial wood floor assembly and structures by welded-through dowels. Holz als Roh- und Werkstoff, 65: 149-155. https://doi.org/10.1007/s00107-006-0170-4.
2. Ganne-Chedeville, C.; Properzi, M.; Leban, J. M.; Pichelin, F., 2006: Parameters of wood welding: A study with infrared thermography. Holzforschung, 60: 434-438. https://doi.org/10.1515/HF.2006.068.
3. Gfeller, B.; Pizzi, A.; Zanetti, M.; Pichelin, F.; Lehmann, M.; Delmotte, L., 2004: Solid wood joints by in situ welding of structural wood constituents. Holzforschung, 58 (1): 45-53. https://doi.org/10.1515/HF.2004.007.
4. Gfeller, B.; Zanetti, M.; Properzi, M.; Pizzi, A.; Pichelin, F.; Lehmann, M.; Delmotte, L., 2003: Wood bonding by vibrational welding. Journal of Adhesion Science and Technology, 17 (11): 1573-1589. https://doi.org/10.1163/156856103769207419.
5. Kanazawa, F.; Pazzi, A.; Kanazawa, M.; Delmotte, L.; Pichelin, F., 2005: Parameters influencing wood-dowel welding by high-speed rotation. Journal of Adhesion Science and Technology, 19 (12): 1025-1038. https://doi.org/10.1163/156856105774382444.
6. Leban, J. M.; Mansouri, H. R.; Omrani, P.; Pizzi, A., 2008: Dependence of dowel welding on rotation rate. Holz als Roh- und Werkstoff, 66: 241-242. https://doi.org/10.1007/s00107-008-0228-6.
7. Omrani, P.; Mansouri, H. R.; Pizzi, A., 2009: Linear welding of grooved wood surfaces. European Journal of Wood and Wood Products, 67 (4): 479-481. https://doi.org/10.1007/s00107-009-0334-0.
8. Omrani, P.; Masson, E.; Pizzi, A.; Mansouri, H. R., 2008: Emission of gases and degradation volatiles from polymeric wood constituents in friction welding of wood dowels. Polymer Degradation and Stability, 93: 794-799. https://doi.org/10.1016/j.polymdegradstab.2008.01.017.
9. Pizzi. A.; Leban, J. M.; Kanazawa, F.; Properzi, M.; Pichelin, F., 2004: Wood dowel bonding by high – speed rotation welding. Journal of Adhesion Science and Technology, 18 (11): 1263-1278. https://doi.org/10.1163/1568561041588192.
10. Pizzi, A.; Properzi, M.; Leban, J. M.; Pichelin, F., 2003: Mechanically – induced wood welding. Maderas. Ciencia y technologia, 5 (2): 101-106. http://dx.doi.org/10.4067/S0718-221X2003000200001.
11. Pizzi, A.; Despres, A.; Mansouri, H. R.; Leban, J. M.; Rigolet, S., 2006: Wood joints by through-dowel rotation welding: microstructure, 13C-NHR and water resistante. Journal of Adhesion Science and Technology, 20 (5): 427-436. https://doi.org/10.1163/156856106777144327.
12. Jones, D.; Pizzi, A., 2007: Frictional welding of dowels into modified wood. In: Proceedings of the 5th COST E34, Bonding of Modified Wood., University of Ljubljana, Biotechnical Faculty, Bled-Slovenia, September 6th 2007, pp. 13-19.
13. Resch, L.; Despres, A.; Pizzi, A.; Bocquet, J. F.; Leban, J. M., 2006: Welding-through doweling of wood panels. Holz als Roh- und Werkstoff, 64: 423-425. https://doi.org/10.1007/s00107-005-0090-8.
14. Stamm, B.; Natterer, J.; Navi, P. 2005: Joining of wood layers by friction welding. J Adhesion Sci. Technol., 19 (13-14): 1129-1139. https://doi.org/10.1163/156856105774429046.
15. Župčić, I.; Mihulja, G.; Bogner, A.; Govorčin, S.; Grbac, I., 2009: Zavarivanje termički modificirane grabovine. Drvna industrija, 60 (3): 161-166. https://doi.org/10.5552/drind.2011.1034.
16. Župčić, I.; Mihulja, G.; Bogner, A.; Grbac, I., 2011: Vrijeme trajanja zavarivanja kao važan čimbenik zavarivanja bukovine. Drvna industrija, 62 (2): 115-121. https://doi.org/10.5552/drind.2011.1041.

17. Župčić, I., 2010: Čimbenici koji utječu na spajanje tokarenih bukovih elemenata tehnikom zavarivanja: Dissertation. University of Zagreb, Faculty of Forestry.
18. Župčić, I.; Vlaović, Z.; Domljan, D.; Grbac, I., 2014: Influence of Various wood species and cross-sections on strength of a dowel welding joint. Drvna industrija, 65 (2): 121-127. https://doi.org/10.5552/drind.2014.1324.
19. ***HRN ISO 13061-1:2015 Fizikalna i mehanička svojstva drva – Metode ispitivanja za manje uzorke masivnog drva, 1. dio: Određivanje sadržaja vode za provođenje ispitivanja fizikalnih i mehaničkih svojstava.
20. ***HRN ISO 13061-2:2015 Fizikalna i mehanička svojstva drva – Metode ispitivanja za manje uzorke masivnog drva, 2. dio: Određivanje gustoće za provođenje ispitivanja fizikalnih i mehaničkih svojstava.

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Vibracije križno lameliranih drvenih međukatnih panela

Vibrations of Cross-Laminated Timber Floors

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SAŽETAK • *U radu su ispitane vibracije peteroslojnih međukatnih križno lameliranih drvenih panela visine 14 cm izazvane ljudskim djelovanjem. Analizirana su tri međukatna panela identičnih visina, ali s različitim kombinacijama debljine lamela u križnim slojevima variranjem njihovih raspona. Navedeni su bitni kriteriji što ih pri projektiranju treba zadovoljiti međukatna konstrukcija da bi se osiguralo njezino prihvatljivo ponašanje u uvjetima dinamičkog opterećenja. Izračun efektivne krutosti na savijanje panela obavljen je Gamma metodom, K-metodom i Kreuzingerovom analogijom. Analitički je određena osnovna frekvencija vibriranja svakog panela, kao i maksimalni progib zbog jedinične statičke sile, a dobiveni su rezultati uspoređeni s vrijednostima dobivenim modalnom i statičkom analizom u programskom paketu Ansys. Svi su dobiveni podatci uspoređeni s važećim kriterijima i selektirani su paneli koji ispunjavaju kriterije sa stajališta graničnog stanja uporabivosti. Rezultati su pokazali da su analizirani međukatni paneli raspona do 4,5 m prihvatljivi sa stajališta adekvatnoga dinamičkog ponašanja pri ljudskom djelovanju. Rezultati su također pokazali da su kombinirani kriterij i kriterij maksimalnoga dopuštenog progiba zbog jedinične statičke sile znatno stroži od kriterija minimalne vrijednosti osnovne frekvencije vibriranja.*

Ključne riječi: *križno lamelirano drvo, međukatna konstrukcija, vibracije*

ABSTRACT • *This paper investigates the vibrations caused by human action of five-layer cross-laminated timber panels with a height of 14 cm. Analysis is made of three floor panels of identical height, but with different combinations of thicknesses of the laminas in cross-layers, varying their spans. The longitudinal layers of the panels have better physical and mechanical characteristics than transverse layers. The relevant criteria to be observed in floor construction at the designing stage are specified in order to ensure acceptable behavior regarding the dynamic load. Limit values are also given. As it is very difficult to determine the threshold of human acceptability, since vibrations that someone finds disturbing do not have to be disturbing for others, the relevant criteria used in the work has been chosen on the basis of the highest representation in the literature: Natural Frequency Limit, Unit Load Deflection Limit and the Combined Criterion. Calculation of the effective bending stiffness of the panel was performed using Gamma method, K-method and Kreuzinger analogy. The natural frequency of each panel was determined analytically, and so was the maximum deflection due to unit static force and the obtained results were compared with the values obtained by modal and static analysis in the Ansys software package. All the obtained data were compared with the valid criteria, and panels that meet the criteria in terms of the serviceability limit state were selected. The results showed that the analyzed floor panels of the span up to 4.5 m are acceptable in terms of adequate dynamic behavior related to human action according to all criteria. Also, the results showed that the Combined Criterion and the Unit Load Deflection Limit are significantly stricter due to the unit static force compared to the Natural Frequency Limit. If the minimum required natural frequency of the CLT panel were*

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accepted with a value of 8 Hz, which corresponds to the milder recommendations in the available literature, the spans could go up to 6 m.
On the basis of the obtained results, it can be concluded that in the design of floor structures, in addition to static stability, an adequate dynamic response to the initiative caused by everyday human activities must be provided. The results also show that the analyzed floor CLT panels can be very successfully applied in the floor constructions of residential and commercial buildings, provided that the required dynamic calculations are made.

Keywords: *cross-laminated timber, floor construction, vibrations*

1. UVOD
1 INTRODUCTION

Križno lamelirano drvo (CLT – cross-laminated timber) moderni je proizvod visoke tehnologije koji je znatno unaprijedio fizička svojstva punog drva (Wieruszewski i Mazela, 2017.; Jeleč *et al*., 2018.). Križno slaganje drva osigurava stabilnost, a paneli su dovoljno jaki da se rabe kao konstruktivni elementi, bez potrebe da se konstrukcije zbog statičkog opterećenja ojačavaju opekom ili betonom

Međutim, pri svakodnevnim ljudskim aktivnostima kao što su hodanje, skakanje, plesanje i trčanje ljudi mogu osjetiti nelagodu ako su amplitude vibracija međukatnih konstrukcija nekontrolirane. Neugodne vibracije međukatnih konstrukcija najčešće su posljedica njihove male osnovne frekvencije zbog uporabe lakih konstrukcijskih materijala i projektiranja konstrukcija velikih raspona.

Da bi vibracije međukatnih konstrukcija bile prihvatljive, njihova osnovna frekvencija mora biti veća od frekvencije dinamičke sile. Određivanje osnovne frekvencije vibracija međukatnih konstrukcija uglavnom se temelji na izračunu osnovne frekvencije jednostavnog modela s jednim stupnjem slobode (Wyatt, 1989.; Allen, 1990.; Murray *et al*., 2003.; Eurokod 5, 2009.).

Vibracije spregnutih međukatnih konstrukcija problem su graničnog stanja uporabivosti koji se odnosi na neudobnost tijekom uporabe te pri opterećenjima koja se redovito pojavljuju pri svakodnevnom korištenju konstrukcije.

2. GRANIČNO STANJE UPORABIVOSTI KONSTRUKCIJA
2 SERVICEABILITY LIMIT STATE OF CONSTRUCTIONS

Osjećaj nelagode pri vibriranju međukatne konstrukcije zbog ljudske aktivnosti individualan je i varira od osobe do osobe. Vrlo je teško odrediti prag ljudske prihvatljivosti vibracija jer one koje su za jednu osobu uznemirujuće ne moraju takve biti i za nekoga drugog. U standardima i literaturi mogu se pronaći različiti predloženi kriteriji koje međukatna konstrukcija pri projektiranju treba ispuniti da bi se osiguralo njezino prihvatljivo ponašanje pod dinamičkim opterećenjem, pri čemu se kao kriterij najčešće uzima kombinacija kriterija minimalne vrijednosti osnovne frekvencije vibriranja i kriterija maksimalnoga dopuštenog progiba zbog jedinične statičke sile (CLT Handbook, 2011.), a on glasi:

$$\frac{f}{d^{0.7}} \geq 13 \text{ ili } d \leq \frac{f^{1.43}}{39} \qquad (1)$$

gdje je f – osnovna frekvencija vibriranja u Hz; d – maksimalni statički progib zbog sile $F = 1$ kN, izražen u mm.

2.1. Kriterij minimalne vrijednosti osnovne frekvencije vibriranja
2.1 Natural Frequency Limit

Jedan od zahtjeva pri dokazivanju graničnog stanja uporabivosti međukatne konstrukcije jest i provjera osnovne frekvencije vibriranja kako bi se spriječile neželjene vibracije koje u korisnika izazivaju nelagodu i smanjuju osjećaj komfora. Hanes je (1970.) upozorio projektante da izbjegavaju međukatne konstrukcije čija je osnovna frekvencija niža od 3 Hz jer su one osjetljive na ljudski korak, tj. hodanje može lako uzrokovati rezonanciju. Osim toga, naglasio je da treba izbjegavati i frekvencije između 5 i 8 Hz jer je to osnovna frekvencija vibriranja naših unutarnjih organa. Taj je raspon frekvencija utvrđen različitim studijama i istraživanjima udobnosti putnika u automobilima i zrakoplovima. Ispitujući više od sto problematičnih međukatnih konstrukcija, Murray je (1991.) također ustanovio da je njihova frekvencija najčešće između 5 i 8 Hz. Stoga bi se trebali izbjegavati ovi rasponi osnovnih frekvencija međukatnih konstrukcija:

- frekvencije niže od 3 Hz, da bi se izbjegla rezonancija zbog ljudskih koraka
- frekvencije između 5 i 8 Hz, da bi se izbjegla neugoda i neudobnost korisnika.

U literaturi se mogu naći različite preporuke za projektiranje minimalnih osnovnih frekvencija međukatnih konstrukcija. Prema Hanesu (1970.), minimalna osnovna frekvencija međukatnih konstrukcija stambeno-poslovnih objekata mora biti 10 Hz. Norma Eurokod 5 (EN 1995-1-1) donosi upozorenje da u međukatnim konstrukcijama s osnovnom frekvencijom nižom od 8 Hz postoji realna opasnost od rezonancije, pa je potrebno provesti posebna ispitivanja. Dolan *et al.* (1999.) iznose mnogo strože kriterije – prema njima, osnovna frekvencija lakih drvenih međukatnih konstrukcija poslovnih objekata mora biti najmanje 15 Hz, a stambenih najmanje 14 Hz. Smith i Chui (1988.) preporučuju minimalnu osnovnu frekvenciju od 8 Hz, dok Allen i Pernica (1998.) za međukatne konstrukcije izložene ritmičkim aktivnostima preporučuju minimalne osnovne frekvencije navedene u tablici 1.

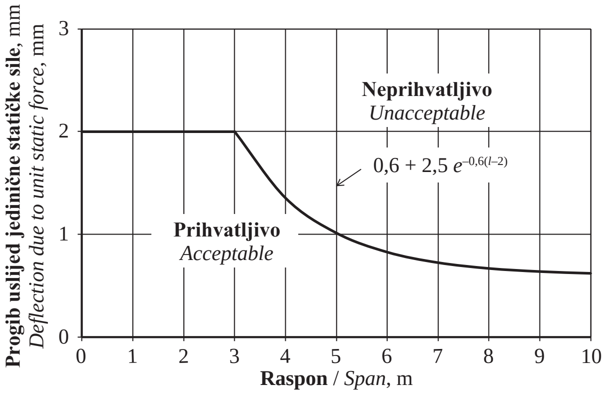
Iz svega navedenog može se zaključiti da je minimalna osnovna frekvencija vibriranja međukatne konstrukcije veća od 10 Hz sa stajališta graničnog stanja uporabivosti zadovoljavajuća.

2.2. Kriterij maksimalnoga dopuštenog progiba zbog jedinične statičke sile
2.2 Unit Load Deflection Limit

Allen i Pernica (1998.) predlažu da se pri projektiranju lakih međukatnih konstrukcija uzme u obzir i kriterij maksimalnoga dopuštenog progiba zbog jedi-

Tablica 1. Minimalne osnovne frekvencije vibriranja međukatnih konstrukcija (Hz)
Table 1 Minimum floor fundamental frequencies (Hz)

Ritmička aktivnost *Rhythmic activity*	**Čelične ili betonske međukatne konstrukcije** *Steel or concrete floor constructions*	**Lagane međukatne konstrukcije** *Lightweight floor structures*
restorani i plesne dvorane / *Restaurants and ballrooms*	5	10
dvorane za aerobik / *Aerobics halls*	9	13



Slika 1. Kriterij maksimalnog progiba zbog jedinične statičke sile (Allen i Pernica, 1998.)
Figure 1 Unit Load Deflection Limit (Allen and Pernica, 1998)

nične statičke sile i tako izbjegnu neprihvatljive vibracije konstrukcija koje su posljedica hodanja. Predloženi je kriterij prikazan na slici 1.

Maksimalni dopušteni progib zbog jedinične statičke sile u međukatnim konstrukcijama raspona manjeg od 3 m iznosi do 2 mm, a u međukatnim konstrukcijama raspona većeg od 3 m on eksponencijalno pada (sl. 1.). Progib od 0,6 mm zbog jedinične sile prihvatljiv je za sve raspone međukatnih konstrukcija.

3. MATERIJALI I METODE
3 MATERIALS AND METHODS

Analizirane su efektivne krutosti i osnovne frekvencije vibriranja za tri slobodno oslonjena međukatna CLT panela. Rasponi su varirani od 4,5 m do 6 m. Visina panela iznosila je 14 cm, a debljine lamela u poprečnom presjeku panela (sl. 2.) bile su 3 cm × 3,4 cm + 2 cm × 1,9 cm (P1), zatim 3 cm × 3 cm+2 cm × 2,5 cm (P2) i 5 cm × 2,8 cm (P3), (Kozarić *et al*., 2015.; Kozarić *et al*., 2016.).

Fizičko-mehanička svojstva uzdužnih i poprečnih lamela međukatnih panela prikazana su u tablici 2. Smicanje uzdužnih lamela se zanemaruje jer je odnos raspona i visine CLT panela veći od 30. Efektivne krutosti izračunane su Gamma metodom, K-metodom i Kreuzingerovom analogijom. Obujam drva bio je 480 kg/m^3, a Poissonov omjer (koeficijent) 0,3.

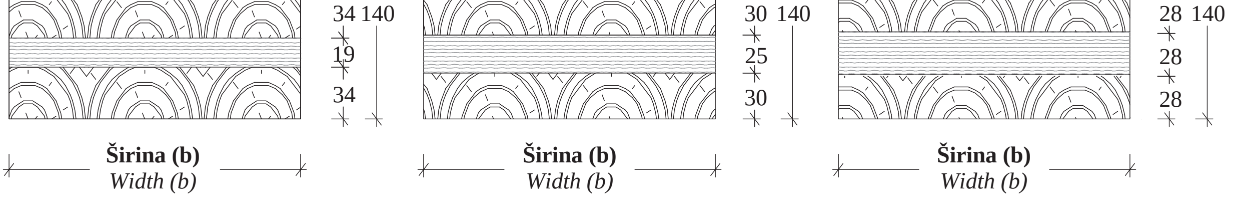
Vlastita frekvencija slobodno oslonjenoga međukatnog panela može se analitički izračunati uz pomoć jednadžbe:

$$f = \frac{\pi}{2l^2}\sqrt{\frac{(EI)_{ef}}{\gamma A}} \qquad (2)$$

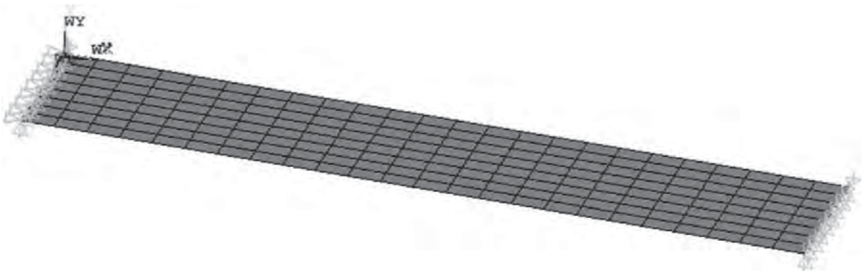
gdje je: l – raspon međukatne konstrukcije u m; $(EI)_{ef}$ – efektivna krutost panela širine 1 m u smjeru raspona izražena u Nm^2; γ – obujam drva u kg/m^3; A – površina poprečnog presjeka panela u m^2.

Tablica 2. Fizičko-mehanička svojstva uzdužnih i poprečnih lamela
Table 2 Physical and mechanical properties of the longitudinal and lateral laminates

Uzdužne lamele / *Longitudinal laminates*	**Poprečne lamele** / *Lateral laminates*
$E_0 = 11000$ MPa	$E_0 = 9000$ MPa
$E_{90} \approx \frac{E_0}{30} = \frac{11000}{30} = 367 \approx 370\,\text{MPa}$	$E_{90} \approx \frac{E_0}{30} = \frac{9000}{30} = 300\,\text{MPa}$
$G_0 \approx \frac{E_0}{16} = \frac{11000}{16} = 688 \approx 690\,\text{MPa}$	$G_0 \approx \frac{E_0}{16} = \frac{9000}{16} = 563 \approx 560\,\text{MPa}$
$G_R \approx \frac{G_0}{10} = \frac{690}{10} = 69\,\text{MPa}$	$G_R \approx \frac{G_0}{10} = \frac{560}{10} = 56\,\text{MPa}$



Slika 2. Geometrijska obilježja CLT panela P1, P2 i P3
Figure 2 Geometric characteristics of CLT panels P1, P2 and P3



Slika 3. Raspored čvorova i konačnih elemenata CLT panela P1 raspona 4,5 m
Figure 3 Arrangement of nodes and finite elements of CLT panel P1 with 4.5 m span

Maksimalni progib zbog jedinične statičke sile iskazan u mm može se odrediti iz jednadžbe:

$$d = \frac{1000Pl^3}{48\left(EI\right)_{ef}} \tag{3}$$

gdje je: $P = 1000$ N.

Metoda konačnih elemenata primijenjena je upotrebom kompjutorskog softvera Ansys 14.0. Međukatna konstrukcija modelirana je kao 2D laminatni ortotropni model sastavljen od slojeva – *layera* (međuslojeva), koji čine treću dimenziju modela (debljinu). Modeliranje konstrukcije provedeno je uz pomoć elemenata iz Ansysove knjižnice, i to putem 4-čvornoga dvodimenzionalnog elementa SHELL181. Upotrijebljen je kao 2D element debljine unutar koje se definira raspored i debljina *layera*, kao i njihova pojedinačna orijentacija. Element je definiran s četiri čvora i šest stupnjeva slobode u svakom čvoru te trima translacijama i trima rotacijama. Osnovni ulazni podatci za taj element jesu modul elastičnosti, Poissonov omjer (koeficijent) i obujam drva.

Konačni je element veličine 0,125 mm × 0,25 m (sl. 3.). Usvojena gustoća mreže određena je iterativnim postupkom tako da je progušćivana do trenutka kad se rezultati dvaju uzastopnih koraka nisu razlikovali manje od 1 %.

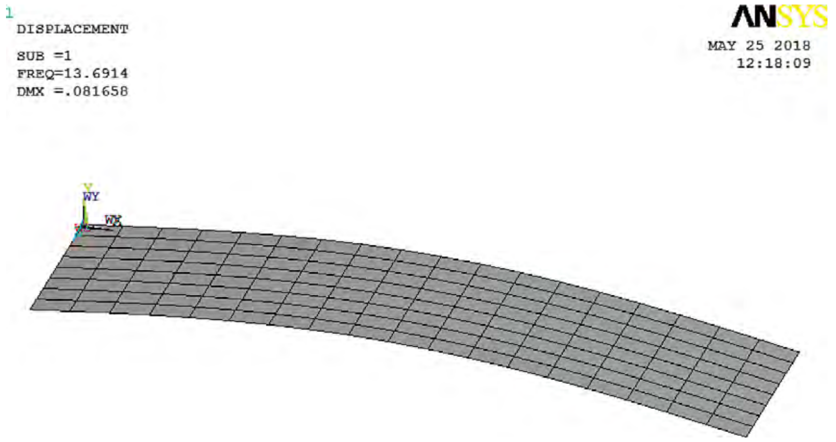
3. REZULTATI I RASPRAVA
3 RESULTS AND DISCUSSION

Osnovna vlastita frekvencija osciliranja i maksimalni progib zbog jedinične statičke sile analiziranih međukatnih CLT panela izračunani su analitički, uz pomoć jednadžbi (2) i (3), te numerički (metodom konačnih elemenata), modalnom i statičkom analizom u programskom paketu Ansys radi provjere dobivenih vrijednosti. Na slici 4. prikazan je prvi vlastiti oblik vibriranja međukatnog CLT panela P1 raspona 4,5 m.

Vlastite frekvencije vibriranja za sva tri međukatna CLT panela prikazane su u tablici 3., a maksimalni progib zbog jedinične statičke sile naveden je u tablici 4.

Uzimajući u obzir navedeni kombinirani kriterij predočen jednadžbom (1), koji uzima u obzir vrijednost osnovne frekvencije vibriranja, ali i vrijednost maksimalnoga dopuštenog progiba zbog jedinične statičke sile, u tablicu 5. uvrštene su prihvatljive vrijednosti za odgovarajuće međukatne CLT panele.

Dobiveni rezultati navedeni u tablici 3. pokazuju pad vrijednosti osnovne vlastite frekvencije vibriranja CLT panela s povećanjem njegova raspona, dok se njezina vrijednost neznatno mijenja s promjenom debljine lamela u križnim slojevima. Modalna analiza u programskom paketu Ansys potvrdila je analitički dobivene vrijednost, što upućuje na vrlo visoku preciznost analitičkih izraza. Ako bi se za potrebnu minimalnu osnovnu frekvenciju vibriranja lake međukatne konstrukcije usvojila vrijednost od 10 Hz, što odgovara strožim preporukama u dostupnoj literaturi, CLT paneli visine 14 cm i raspona do 5 m bili bi prihvatljivi sa stajališta graničnog stanja uporabivosti. Ali ako bi se kao minimalna potrebna osnovna frekvencija vibriranja CLT panela prihvatila vrijednost od 8 Hz (Smith i Chui, 1988.; Eurokod 5, 2009.), rasponi bi se mogli kretati i do 6 m.



Slika 4. Prvi vlastiti oblik vibriranja međukatnog CLT panela P1 raspona 4,5 m
Figure 4 First characteristic mode shape of CLT panel P1 with 4.5 m span

Tablica 3. Efektivna krutost i osnovna vlastita frekvencija vibriranja CLT panela
Table 3 Effective stiffness and fundamental frequency of CLT panels

CLT panel	**Metoda izračuna** *Calculation method*		**Efektivna krutost, kNm^2** *Effective stiffness,* kNm^2	f_{dop} = 10 Hz			
				Osnovna vlastita frekvencija *f*, Hz *Fundamental frequency f,* Hz			
				l = 4,5 m	l = 5,0 m	l = 5,5 m	l = 6,0 m
P1	analitički	γ-metoda	2087	**13,67**	**11,07**	9,15	7,69
		K-metoda	2218	**14,09**	**11,42**	9,43	7,93
		Kreuzinger	2218	**14,09**	**11,42**	9,43	7,93
	numerički (Ansys)			**13,69**	**11,15**	9,25	7,80
P2	analitički	γ-metoda	2069	**13,61**	**11,02**	9,11	7,66
		K-metoda	2082,88	**13,65**	**11,06**	9,14	7,68
		Kreuzinger	2082,88	**13,65**	**11,06**	9,14	7,68
	numerički (Ansys)			**13,21**	**10,77**	8,94	7,54
P3	analitički	γ-metoda	1990,60	**13,35**	**10,81**	8,94	7,51
		K-metoda	2006,41	**13,40**	**10,85**	8,97	7,54
		Kreuzinger	2006,41	**13,40**	**10,85**	8,97	7,54
	numerički (Ansys)			**12,95**	**10,56**	8,77	7,40

Tablica 4. Efektivne krutosti i maksimalni progibi CLT panela zbog jedinične statičke sile
Table 4 Effective stiffness and unit point load deflection of CLT panels

CLT panel	**Metoda izračuna** *Calculation method*		**Efektivna krutost, kNm^2** *Effective stiffness,* kNm^2	$d_{dop} \leq$ 1,15 mm	$d_{dop} \leq$ 1,01 mm	$d_{dop} \leq$ 0,09 mm	$d_{dop} \leq$ 0,82 mm
				Maksimalni progib uslijed jedinične statičke sile *d*, mm *Unit point load deflection d*, mm			
				l = 4,5 m	*l* = 5,0 m	*l* = 5,5 m	*l* = 6,0 m
P1	analitički	γ-metoda	2087	**0,91**	1,25	1,66	2,16
		K-metoda	2218	**0,86**	1,17	1,56	2,03
		Kreuzinger	2218	**0,86**	1,17	1,56	2,03
	numerički (Ansys)			**0,96**	1,29	1,68	2,16
P2	analitički	γ-metoda	2069	**0,92**	1,26	1,68	2,17
		K-metoda	2082,88	**0,91**	1,25	1,66	2,16
		Kreuzinger	2082,88	**0,91**	1,25	1,66	2,16
	numerički (Ansys)			**1,03**	1,38	1,80	2,30
P3	analitički	γ-metoda	1990,60	**0,95**	1,31	1,74	2,26
		K-metoda	2006,41	**0,95**	1,30	1,73	2,24
		Kreuzinger	2006,41	**0,95**	1,30	1,73	2,24
	numerički (Ansys)			**1,07**	1,43	1,87	2,39

Tablica 5. Kombinirani kriterij koji osigurava prihvatljivo dinamičko ponašanje CLT panela
Table 5 Combined design criterion that provides acceptable dynamic behavior of CLT panels

CLT panel	**Metoda izračuna** *Calculation method* *l* = 4,5 m		**Kombinirani kriterij /** *Combined design criterion* $\frac{f}{d^{0.7}} \geq 13$			
			l = 5,0 m	*l* = 5,5 m	*l* = 6,0 m	
P1	analitički	γ-metoda	**14,60**	9,47	6,42	4,49
		K-metoda	**15,66**	10,23	6,91	4,83
		Kreuzinger	**15,66**	10,23	6,91	4,83
	Ansys		**14,09**	9,33	6,43	4,55
P2	analitički	γ-metoda	**14,43**	9,37	6,34	4,45
		K-metoda	**14,58**	9,46	6,41	4,48
		Kreuzinger	**14,58**	9,46	6,41	4,48
	Ansys		**12,94**	8,60	5,92	4,21
P3	analitički	γ-metoda	**13,84**	8,95	6,07	4,24
		K-metoda	**13,89**	9,03	6,11	4,29
		Kreuzinger	**13,89**	9,03	6,11	4,29
	Ansys		**12,35**	8,22	5,66	4,02

Međutim, kriterij maksimalnoga dopuštenog progiba zbog jedinične statičke sile i kombinirani kriterij, čiji su rezultati prikazani u tablicama 4. i 5., znatno su stroži pri ocjenjivanju dinamičke prihvatljivosti CLT međukatnih panela. Prema tim kriterijima, samo paneli raspona do 4,5 m ne bi izazvali nelagodu u korisnika pri njihovim svakodnevnim aktivnostima.

Evidentno je da povećanje visine slabije nosivih lamela postavljenih u poprečnom smjeru ne utječe značajno na dinamičko ponašanje panela jer se vrijednosti kriterija s promjenom njihovih visina znatnije ne mijenjaju.

5. ZAKLJUČAK
5 CONCLUSIONS

Prikazani rezultati analiziranih međukatnih CLT panela pokazuju da se oni mogu vrlo uspješno primjenjivati u međukatnim konstrukcijama stambenih i poslovnih zgrada, uz uvjet da se provede adekvatan dinamički izračun.

Dobivene vrijednosti najčešće primjenjivanih kriterija za ocjenu dinamički prihvatljivih međukatnih konstrukcija pri dimenzioniranju CLT konstrukcija pokazuju da i sama ocjena je li međukatna konstrukcija prihvatljiva ili ne umnogome ovisi i o izboru kriterija. Kombinirani kriterij i kriterij maksimalnoga dopuštenog progiba zbog jedinične statičke sile daju slične rezultate, dok je kriterij minimalne vrijednosti osnovne frekvencije vibriranja znatno blaži. Stoga je preporučljivo da se pri dokazu graničnog stanja uporabivosti međukatne CLT konstrukcije sa stajališta prihvatljivoga dinamičkog ponašanja uzme u obzir kombinirani kriterij jer se njime kombinira vrijednost osnovne frekvencije vibriranja kao jedno od najbitnijih obilježja konstrukcije pri dinamičkom proračunu, ali i progib zbog jedinične statičke sile kao mjera deformabilnosti.

Buduća istraživanja vibracija međukatnih CLT panela u konstrukcijama stambenih i poslovnih zgrada bit će usmjerena na analizu utjecaja vrste, broja i rasporeda mehaničkih spojnih sredstava CLT međukatnih i zidnih panela na vibracije izazvane ljudskim djelovanjem.

6. LITERATURA
6 REFERENCES

1. Allen, D. E., 1990: Building vibrations from human activities. American Concrete Institute, Concrete International: Design and Construction, 12 (6): 66-73.
2. Allen, D. E.; Pernica, G., 1998: Control of floor vibration. Construction Technology, 22.
3. Dolan, J. D.; Murray, T. M.; Johnson, H.; Runte, D.; Shue, B. C., 1999: Preventing annoying wood floor vibrations. Journal of Structural Engineering, 15 (1): 19-24.
4. Hanes, R. M., 1970: Human sensitivity to whole-body vibration in urban transportation systems: A literature review. Applied Physics Laboratory, the John Hopkins University, Silver Springs, MD.
5. Jeleč, M.; Varevac, D.; Rajčić, V., 2018: Križno lamelirano drvo (CLT) – pregled stanja područja. Građevinar, 70 (2): 75-95. https://doi.org/10.14256/JCE.2071.2017.
6. Kozarić, Lj.; Prokić, A.; Bešević, M., 2015: Unakrsno lamelirani drveni elementi u savremenim drvenim konstrukcijama zgrada. Građevinski materijali i konstrukcije, 4: 51-69.
7. Kozarić, Lj.; Prokić, A.; Bešević, M.; Vojnić Purčar, M., 2016: Proračun ugiba unakrsno lameliranog drvenog međuspratnog panela. Zbornik radova Građevinskog fakulteta, 30: 63-72. https://doi.org/10.14415/zbornikGFS30.06.
8. Murray, T. M., 1991: Building floor vibrations. T.R. Higgins lectureship paper presented at the AISC National Steel Construction Conference, Washington, D.C.
9. Murray, T. M.; Allen, D. E.; Ungar, E. E., 2003: Steel Design Guide Series 11: Floor vibrations due to human activity. American Institute of Steel Construction (AISC), Chicago, USA.
10. Smith, I.; Chui, Y. H., 1988: Design of lightweight wooden floors to avoid human discomfort. Canadian Journal of Civil Engineering, 15: 254-262.
11. Wieruszewski, M.; Mazela, B., 2017: Cross Laminated Timber (CLT) as an Alternative Form of Construction Wood. Drvna industrija, 68 (4): 359-367. https://doi.org/10.5552/drind.2017.1728.
12. Wyatt, T. A., 1989: Design guide on the vibration of floors. SCI Publication 076: Steel construction Institute, Construction Industry Research and Information Association, UK.
13. ***EN 1995-1-1: 2004 Eurocode 5, Design of timber structures, Part 1-1: General – Common rules and rules for buildings.
14. *** 2013: Handbook cross-laminated timber. FPInnovations and Binational Softwood Lumber Council, USA.

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DRVO FARA (*Daniellia ogea* (Harms) Holland)

NAZIVI

Daniellia ogea (Harms) Holland naziv je drva botaničke vrste iz porodice *Leguminosae*. Trgovački su nazivi te vrste također: faro (Francuska, Njemačka, Italija, Velika Britanija, SAD, Šri Lanka); daniellia (Njemačka); heyedua, shedua, eye dua, eyele (Gana); ogea (Nizozemska, Njemačka, Velika Britanija; Gana); omugo, oziya (Velika Britanija, Nigerija), nsu (Kamerun, Ekvatorijalna Gvineja); santan (Senegal); bungbo (Siera Leone); whoe (Liberija); lonlaviol (Gabon); singa (Kongo); bolengu (Demokratska Republika Kongo).

PODRUČJE RASPROSTRANJENOSTI

Stabla *Daniellia ogea* Rolfe nalazimo u sjevernoj Africi; i to od Liberije, Sierra Leone, Obale Bjelokosti, Gane, Nigerije, Kameruna, Gabona, Konga, do Ekvatorske Gvineje. Raste u tropskim nizinskim kišnim šumama.

STABLO

Stablo doseže visinu od 35 metara. Čisto deblo dugo je do 20 (25) metara, a prsni mu je promjer od 0,6 do 1,3 (1,5) metara. Debla su valjkastog oblika. Kora drva je ispucana, svjetlozelena do svjetlosmeđa, debljine 0,5 – 2 cm.

DRVO

Makroskopska obilježja

Drvo je rastresito porozno. Bjeljika je bijelosiva do krem boje, a široka je 8 – 15 cm. Boja srži drva kreće se u rasponu od svjetlosmeđih do crvenkastih tonova. Tijekom stajanja potamni. Tekstura drva je jednolična i manje-više ukrasna. Granica goda je dobro uočljiva. Pore i drvni traci vidljivi su povećalom.

Mikroskopska obilježja

Traheje su pretežno pojedinačno raspoređene, ali mogu biti i u paru ili u grupama. Promjer traheja je 70…180…250 mikrometara, a gustoća im je 1…3…6 na 1 mm^2 poprečnog presjeka. Volumni udio traheja iznosi oko 10 %. Aksijalni je parenhim drva apotrahealno koncentričan, paratrahealno vazicentričan, paratrahealno oskudan.

Volumni udio aksijalnog parenhima iznosi oko 9 %. Staničje drvnih trakova je heterogeno. Drvni su traci katno raspoređeni, visoki su 330…370…430 mikrometara, odnosno do 20 stanica, a široki su 38…57…78 mikrometara, odnosno 4 stanice. Gustoća drvnih trakova je 10…12…14 na 1 mm. Njihov volumni udio iznosi oko 12 %. Drvna su vlakanca libriformska, a katkad su to i vlaknaste traheide. Dugačka su 1250…1660…2000 mikrometara.

Debljina staničnih stijenki vlakanaca iznosi 1,2…1,85…2,4 mikrometara, a promjeri njihova lumena 6,8…21,6…35,2 mikrometara. Volumni udio vlakanaca iznosi oko 69 %.

Fizička svojstva

Gustoća standardardno suhog drva, ρ_0	290…450 kg/m^3
Gustoća prosušenog drva, ρ_{12-15}	420...510…600 kg/m^3
Gustoća sirovog drva, ρ_s	800...875…900 kg/m^3
Poroznost	oko 70 %
Radijalno utezanje, β_r	3,5...4,2 %
Tangentno utezanje, β_t	5,6...8,2 %
Volumno utezanje, β_v	8,5...13,0 %

Mehanička svojstva

Čvrstoća na tlak	35…47 MPa
Čvrstoća na vlak, paralelno s vlakancima	oko 62 MPa
Čvrstoća na vlak, okomito na vlakanca	1,9...2,4 MPa
Čvrstoća na savijanje	70…86 MPa
Tvrdoća po Brinellu, okomito na vlakanca	oko 32 MPa
Modul elastičnosti	7,5…9,7 GPa

TEHNOLOŠKA SVOJSTVA

Obradivost

Drvo se dobro pili, lijepi, buši, brusi i polira.

Sušenje

Drvo se relativno brzo suši. Ima malu sklonost promjeni oblika i raspucavanju. U piljenicama većih debljina ipak se može pojaviti skorjelost i kolaps.

Trajnost i zaštita

Prema normi HRN 350-2, 2005, srž je vrlo slabo otporna na gljive uzročnice truleži (razred otpornosti 4

– 5) i osjetljiva na na napad termita (razred otpornosti S). Srž je slabo permeabilna (razred 2 – 3). Po trajnosti pripada razredu 1 i stoga se nezaštićena može koristi u interijeru.

Uporaba

Drvo se upotrebljava kao furnirsko drvo, a služi i za proizvodnju unutrašnjeg namještaja, dijelova namještaja te za izradu sanduka i kutija.

Sirovina

Drvo se isporučuje u obliku trupaca i piljenica.

Napomena

Drvo *Daniellia ogea* za sada nije na popisu ugroženih vrsta međunarodne organizacije CITES, niti je na popisu međunarodne organizacije IUCN. Gumozne tvari iz pukotina i rana na deblima iskorištavaju se za izradu lakova (zapadnoafrički kopal). Drvo sličnih svojstava imaju i vrste *Daniellia oliveri* (Rolfe) Hutch. & Dalziel, *D. thurifera* Benn., *D. klainei* A. Chev., *D.* spp.

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

Upute autorima

Opće odredbe

Časopis *Drvna industrija* objavljuje znanstvene radove (izvorne znanstvene radove, pregledne radove, prethodna priopćenja), stručne radove, izlaganja sa savjetovanja, stručne obavijesti, bibliografske radove, preglede te ostale priloge s područja biologije, kemije, fizike i tehnologije drva, pulpe i papira te drvnih proizvoda, uključujući i proizvodnu, upravljačku i tržišnu problematiku u drvnoj industriji.

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Upute

Predani radovi smiju sadržavati najviše 15 jednostrano pisanih A4 listova s dvostrukim proredom (30 redaka na stranici), uključujući i tablice, slike te popis literature, dodatke i ostale priloge. Dulje je članke preporučljivo podijeliti na dva ili više nastavaka. Tekst treba biti u *doc formatu*, u potpunosti napisan fontom *Times New Roman* (tekst, grafikoni i slike), normalnim stilom, bez dodatnog uređenja teksta.

Prva stranica poslanog rada treba sadržavati puni naslov, ime(na) i prezime(na) autora, podatke o zaposlenju autora (ustanova, grad i država) te sažetak s ključnim riječima (duljina sažetka približno 1/2 stranice A4).

Posljednja stranica treba sadržavati titule, zanimanje, zvanje i adresu (svakog) autora, s naznakom osobe s kojom će Uredništvo biti u vezi.

Znanstveni i stručni radovi moraju biti sažeti i precizni. Osnovna poglavlja trebaju biti označena odgovarajućim podnaslovima. Napomene se ispisuju na dnu pripadajuće stranice, a obrojčavaju se susljedno. One koje se odnose na naslov označuju se zvjezdicom, a ostale uzdignutim arapskim brojkama. Napomene koje se odnose na tablice pišu se ispod tablica, a označavaju se uzdignutim malim pisanim slovima, abecednim redom.

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

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

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

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

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

Slike je potrebno rasporediti na odgovarajuća mjesta u tekstu, trebaju biti izrađene u rezoluciji 600 dpi, crno-bijele (objavljivanje slika u koloru moguće je na zahtjev autora i uz posebno plaćanje), formata jpg ili tiff, potpune i jasno razumljive bez pozivanja na tekst priloga.

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

Naslovi slika i crteža ne pišu se velikim tiskanim slovima. Crteži i grafikoni trebaju odgovarati stilu časopisa (fontovima i izgledu). Slova i brojke moraju biti dovoljno veliki da budu lako čitljivi nakon smanjenja širine slike ili tablice. Fotomikrografije moraju imati naznaku uvećanja, poželjno u mikrometrima. Uvećanje može biti dodatno naznačeno na kraju naslova slike, npr. “uvećanje 7500 : l”.

Diskusija i zaključak mogu, ako autori žele, biti spojeni u jedan odjeljak. U tom tekstu treba objasniti rezultate s obzirom na problem postavljen u uvodu i u odnosu prema odgovarajućim zapažanjima autora ili drugih istraživača. Valja izbjegavati ponavljanje podataka već iznesenih u odjeljku *Rezultati*. Mogu se razmotriti naznake za daljnja istraživanja ili primjenu. Ako su rezultati i diskusija spojeni u isti odjeljak, zaključke je nužno napisati izdvojeno. Zahvale se navode na kraju rukopisa. Odgovarajuću literaturu treba citirati u tekstu, i to prema harvardskom sustavu (*ime – godina*), npr. (Bađun, 1965). Nadalje, bibliografija mora biti navedena na kraju teksta, i to abecednim redom prezimena autora, s naslovima i potpunim navodima bibliografskih referenci. Popis literature mora biti selektivan, a svaka referenca na kraju mora imati naveden DOI broj, ako ga posjeduje (http://www.doi.org) (provjeriti na http://www.crossref.org).

Primjeri navođenja literature

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

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

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

Primjeri

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

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

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Latin names shall be printed in italics and underlined.

Introduction should define the problem and if possible the framework of existing knowledge, to ensure that readers not working in that particular field are able to understand author's intentions.

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

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

The number of figures shall be limited to those absolutely necessary for clarification of the text. The same information must not be presented in both a table and a figure. Figures and tables should be numbered separately with Arabic numerals, and should be referred to in the text with clear remarks ("Table 1" or "Figure 1"). Titles, headings, legends and all the other text in figures and tables should be written in both Croatian and English.

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Example of references

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

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

Books:
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Examples:
Krpan, J. 1970: Tehnologija furnira i ploča. Drugo izdanje. Zagreb: Tehnička knjiga.
Wilson, J.W.; Wellwood, R.W. 1965: Intra-increment chemical properties of certain western Canadian coniferous species. U: W. A. Cote, Jr. (Ed.): Cellular Ultrastructure of Woody Plants. Syracuse, N.Y., Syracuse Univ. Press, pp. 551-559.

Other publications (brochures, studies, etc.):
Müller, D. 1977: Beitrag zur Klassifizierung asiatischer Baumarten. Mitteilung der Bundesforschungsanslalt für Forst- und Holzwirtschaft Hamburg, Nr. 98. Hamburg: M. Wiederbusch.

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

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