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Prediction of Optimum Veneer Drying Parameters with Artificial Neural Networks for Production of Plywood with High Mechanical Properties

Primjena umjetnih neuronskih mreža za predviđanje optimalnih parametara sušenja furnira za proizvodnju furnirske ploče visokih mehaničkih svojstava

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ABSTRACT • *Veneer drying is the manufacturing process in the plywood industry that most affects energy consumption and panel properties such as bonding and bending. Therefore, the veneer drying temperature and moisture content should be accurately adjusted. Moreover, the determination of veneer thermal conductivity is as important as these two parameters and the thermal conductivity values should also be specified when forming the drying programs. This study aimed to predict the optimum values of the veneer drying temperatures, moisture content and thermal conductivity, which gave the best mechanical properties, by artificial neural network (ANN) analysis. Poplar (Populus deltoidesI-77/51) and spruce (Picea orientalis L.) veneers and urea formaldehyde (UF) resin were used in the production of plywood. The thermal conductivity of veneer and the bonding, bending strength and elasticity modulus of the panels were tested by the relevant standards. The most accurate and reliable prediction models were obtained by analyzing the experimental data with ANN. The optimum veneer drying temperature, moisture content and thermal conductivity values that gave the best values for all three mechanical properties were 149 °C, 6.2 % and 0.02668 W/mK for poplar and 116 °C, 4.4 % and 0.02534 W/mK for spruce.*

KEYWORDS: *veneer drying temperature, moisture content, thermal conductivity, artificial neural network, plywood*

SAŽETAK • *Sušenje furnira proizvodni je proces u industriji furnirskih ploča koji najviše utječe na potrošnju energije i svojstva ploče kao što su čvrstoća lijepljenja i savijanja. Stoga je potrebno točno prilagoditi temperaturu sušenja i sadržaj vode u furniru. Nadalje, određivanje toplinske vodljivosti furnira jednako je važno kao temperatura sušenja i sadržaj vode, pa je pri izradi programa sušenja potrebno specificirati i vrijednosti toplinske vodljivosti. Cilj ovog istraživanja bio je primjenom umjetne neuronske mreže (ANN) predvidjeti vrijednosti optimalne temperature sušenja, sadržaja vode i toplinske vodljivosti furnira koje će rezultirati najboljim mehaničkim*

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svojstvima ploče. Za potrebe ispitivanja furnirske su ploče proizvedene od furnira topolovine (Populus deltoidesI-77/51) i furnira smrekovine (Picea orientalis L.) te su slijepljeni urea formaldehidnom smolom (UF). Prema odgovarajućim standardima ispitani su toplinska vodljivost i čvrstoća lijepljenja furnira te čvrstoća na savijanje i modul elastičnosti ploča. Najtočniji i najpouzdaniji modeli predviđanja dobiveni su analizom eksperimentalnih podataka uz pomoć umjetne neuronske mreže. Optimalne vrijednosti temperature sušenja, sadržaja vode i toplinske vodljivosti uz koje se postižu najbolja mehanička svojstva za furnirske ploče od topolovine iznosile su 149 °C, 6,2 % i 0,02668 W/mK, a za furnirske ploče od smrekovine 116 °C, 4,4 % i 0,02534 W/mK.

KLJUČNE RIJEČI: *temperatura sušenja furnira, sadržaj vode, toplinska vodljivost, umjetna neuronska mreža, furnirska ploča*

1 INTRODUCTION
1. UVOD

Plywood, one of the most traditional wood-based composite materials, is widely preferred in construction, interior design and furniture (Ferretti, 2021). The global plywood production market, which totaled $88.3 billion in 2017, is predicted to have a compound annual growth rate (CAGR) of 7.8 % between 2017 and 2022, and this market will reach $128.3 billion by 2022 (BCC Research, 2018). In the plywood industry, which has a very large market, it is extremely important to improve the production processes and integrate new technologies into the systems. Veneer drying process is the most important production process of veneer-based composite materials such as plywood (Guan *et al*., 2020). The efficiency of the veneer drying process is an issue that requires great attention both in terms of energy consumption and for improving the adhesion properties of the panels (Huang *et al*., 2011). The problems related to this process, in which the veneer is dried to the most suitable moisture content for adhesion, directly affect the adhesive properties such as curing and physical and mechanical properties of the panel (Bekhta *et al*., 2020). Moreover, the potential to cause an increase in both adhesive consumption and pressing and drying costs proves the economic importance of this process (Bekhta *et al*., 2014). It is a fact that the environment can be harmed in terms of global warming due to improper drying process, material properties and economic losses, as well as unnecessary energy consumption. Veneer drying in plywood production is one of the processes that consumes the most energy and 70 % of the total thermal energy consumption is due to this process (Han *et al*., 2015).

It is extremely important to set two parameters correctly in the veneer drying process. These parameters are the veneer moisture content and drying temperature. Aydin and Colakoglu (2005) stated that the veneer moisture content should not be above 7 % and that the veneers were dried up to 3 % moisture content. Furthermore, Bekhta *et al*. (2014) mentioned that, if the veneer moisture content is above (8±2) %, it can cause great disadvantages. According to FAO (1990), veneer drying temperatures between 90-160 °C were accepted as normal and it was stated that temperatures could be increased by about 175 °C for high temperature drying applications to shorten the drying time. High temperature drying can save up to 44 % of energy and reduce drying time by 25 % compared to normal drying (Theppaya and Prasertsan, 2004). In addition to these advantages, drying at high temperatures can adversely affect the surface, and thermal and chemical properties of veneers (Demirkir *et al*., 2016).

In the literature, there are few studies investigating the effects of the veneer moisture content (Aydin *et al*., 2006; Bekhta *et al*., 2020) and drying temperatures (Aydin and Colakoglu, 2005) on the technological properties of plywood panels. In addition to these studies in which experimental data were compared, there were some studies in which optimum results were achieved without further experimentation with the prediction models obtained successfully with artificial neural network (ANN) analysis. These optimization studies were mostly carried out on the veneer drying temperature, and optimum values were obtained for different wood species, giving the best mechanical properties (Demirkir *et al*., 2013; Ozsahin *et al*., 2019; Ozsahin and Aydin, 2014). In contrast, Demir and Aydin (2021) determined the effect of the veneer moisture content on the thermal properties of veneers with ANN prediction model.

In order to set the veneer drying programs correctly, the moisture content, drying temperature as well as the thermal conductivity of the veneer should be selected in the most appropriate way. It is known that the thermal conductivity is an important parameter used in developing drying models, determining the adhesive curing and heat transfer rate (Hassanin *et al*., 2018). Based on this, the lack of comprehensive optimization studies evaluating the veneer moisture content, drying temperatures and thermal conductivity parameters was seen in the literature. Therefore, this study aimed to predict the optimum values of the veneer moisture content, drying temperatures and thermal conductivity coefficients by ANN analysis for achieving the best mechanical strength properties.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Materials and plywood manufacture
2.1. Materijali i proizvodnja furnirskih ploča

In this experimental study, poplar (*Populus deltoidesI-77/51*) and spruce *(Picea orientalis L.*) veneers were used in the manufacture of plywood. While the poplar logs were peeled freshly, spruce logs were steamed for 12-16 hours before veneer production. After the peeling process, the veneers with 500 mm × 500 mm × 2 mm dimensions were obtained from the logs. The veneers were dried at 110, 130, 160, and 180 °C until 4 %, 6 % and 8 % moisture content. The veneers moisture content was continuously controlled with a magnetic moisture meter until it reached the specified moisture content levels. Three-layer-plywood panels, 6 mm thick, were manufactured by using urea formaldehyde (UF) with 55 % solid content. UF resin solution used in the plywood manufacturing was composed of 100 parts UF resin, 30 parts wheat flour and 10 parts NH_4Cl (with15 % concentration) as hardener, by weight. The glue was applied at a rate of 160 g/m^2 to every single veneer layer. The panel drafts belonging to the groups formed within the scope of the study were pressed by adjusting the press pressure to 8 kg/cm^2, the press temperature to 110 ºC and the press time to 6 minutes. Two panels produced from each group were kept in the climatization room at 20 °C and 65% relative humidity before the experiments.

The produced plywood panels bonding strength, bending strength and elasticity modulus were determined according to EN 314-1 (2004) and EN 310 (1993) standards, respectively. The samples manufactured with UF resin were tested after immersion in water at 20 °C for 24 h. Twenty-five and twelve specimens were used for the evaluation of bonding strength and bending strength tests, respectively. The thermal conductivity coefficients of the poplar and spruce veneers were measured in five replicates by the ASTM C 518 (2004) standard. The Lasercomp Fox-314 Heat Flow Meter was used for the determination of thermal conductivity. Its top and lower layers were set to 20°C and 40°C, respectively, for all specimens. The panels temperature during the measurement of the thermal conductivity was maintained to these constant temperatures.

2.2 ANN analysis
2.2. ANN analiza

In this study, Artificial Neural Network (ANN) analysis of the MATLAB Toolbox was used to determine the optimum veneer drying parameters. The experimentally obtained values of thermal conductivity, bonding, bending strength and elasticity modulus were used in the training phase and these values were predicted for the veneer drying parameters that were not used experimentally. First, the thermal conductivity model was determined from the prediction models, and then the prediction models for the mechanical properties were determined. The first prediction model used wood species, veneer drying temperature and veneer moisture content as the input variables, while other models additionally included thermal conductivity in input variables. The network structures of the models obtained from the training phase within the scope of this study are shown in Figure 1.

During the analysis, experimental data were divided into two groups as training and testing data. Training data, which contains approximately 67 % of the total data, was used in the development of prediction models, while the remaining data (approximately 33 %) was used to test the performance of the obtained models. The adjustments used in ANN trainings are given in Table 1.

At the end of the ANN analysis, some diagnostic tools were used to reveal the statistical relationship between the actual data and the predicted data in both training and testing data sets. These are the mean absolute percent error (*MAPE*), the root mean square error (*RMSE*) and coefficient of determination (R^2). The optimum veneer drying parameters were predicted by using ANN models determined using these tools.

Table 1 Adjustments used in ANN trainings
Tablica 1. Prilagodbe koje se primjenjuju u treninzima ANN-a

Type of ANN *Vrsta ANN-a*	Feed forward and backpropagation multilayer *višeslojno širenje naprijed i natrag*
Transfer function (hidden layers) *Funkcija prijenosa (skriveni slojevi)*	Hyperbolic tangent sigmoid function (tansig) *hiperbolična tangentna sigmoidna funkcija (tansig)*
Transfer function (output layers) *Funkcija prijenosa (izlazni slojevi)*	Linear transfer function (purelin) *linearna prijenosna funkcija (purelin)*
Training algorithm *Algoritam treninga*	Levenberg-Marquardt algorithm (trainlm) *Levenberg-Marquardtov algoritam (trainlm)*
Learning rule *Pravilo učenja*	Momentum gradient reduction backpropagation algorithm (traingdm) *algoritam povratnog širenja smanjenja gradijenta momenta (traingdm)*
Performance function *Funkcija izvedbe*	Mean square error (MSE) *srednja kvadratna pogreška (MSE)*

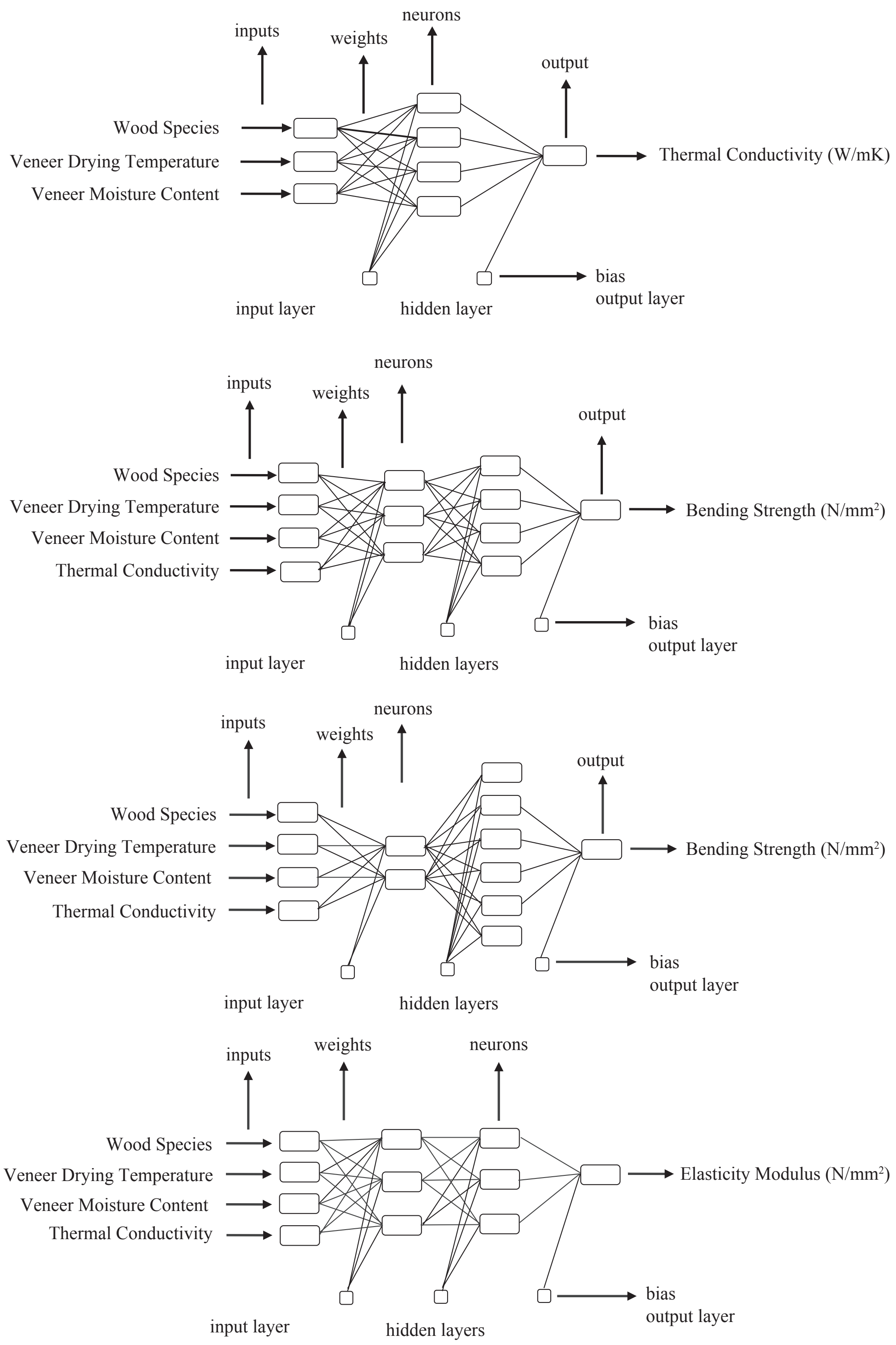


Figure 1 Structures of prediction models
Slika 1. Strukture modela predviđanja

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The predicted data with the experimental (actual) data are given in Tables 2 and 3 according to training and testing data sets, as well as the performance values of the prediction models. In the experimental results, it was observed that the veneer thermal conductivity values increased due to the increase in the veneer moisture content and the highest thermal conductivity values were obtained at 180 °C. The bonding values of the panels decreased, while the veneer drying temperature and moisture content values increased in both wood species. Furthermore, it was observed that the bending strength and elasticity modulus values of the plywood produced from poplar veneers were almost not affected

Table 2 Training data set used for thermal conductivity and mechanical strength and prediction model results
Tablica 2. Primijenjeni skup podataka za trening za toplinsku vodljivost i mehaničku *čvrstoću* te rezultati modela predviđanja

Wood species *Vrsta drva*	**Veneer drying temperature, °C** *Temperatura sušenja furnira,* °C	**Veneer moisture content, %** *Sadržaj vode u furniru*	**Thermal conductivity, W/mK** *Toplinska vodljivost,* W/mK			**Bonding strength, N/mm²** *Čvrstoća lijepljenog spoja,* N/mm²			**Bending strength, N/mm²** *Čvrstoća na savijanje,* N/mm²			**Elasticity modulus, N/mm²** *Modul elastičnosti,* N/mm²		
			Actual *Stvarna*	**Predicted** *Predviđena*	**Error, %** *Pogreška,* %	**Actual** *Stvarna*	**Predicted** *Predviđena*	**Error, %** *Pogreška,* %	**Actual** *Stvarna*	**Predicted** *Predviđena*	**Error, %** *Pogreška,* %	**Actual** *Stvarna*	**Predicted** *Predviđena*	**Error, %** *Pogreška,* %
Poplar *topolovina*	110	6	0.03034 *0.00009*	0.03022	0.41060	1.49 *0.13*	1.49	0.00	74.38 *7.89*	74.33	0.06	4316.39 *422.98*	4288.54	0.65
	110	8	0.03467 *0.00011*	0.03458	0.25742	1.87 *0.21*	1.87	0.07	83.43 *4.12*	83.26	0.20	5086.50 *337.70*	5084.56	0.04
	130	4	0.02712 *0.00008*	0.02714	-0.07575	1.47 *0.16*	1.47	-0.03	82.99 *7.76*	83.23	-0.28	3968.30 *486.03*	3979.95	-0.29
	130	8	0.03153 *0.00007*	0.03151	0.07664	1.34 *0,1*	1.34	0.06	79.06 *6.01*	79.17	-0.14	4865.91 *360.78*	4863.32	0.05
	160	6	0.02727 *0.00012*	0.02734	-0.25999	1.76 *0.27*	1.76	0.05	88.13 *6.99*	87.56	0.65	5145.32 *398.63*	5136.56	0.17
	160	8	0.03309 *0.00009*	0.03305	0.12185	1.33 *0.16*	1.33	-0.21	72.13 *6.66*	72.21	-0.12	4297.63 *490.04*	4311.25	-0.32
	180	4	0.03019 *0.00011*	0.03015	0.11737	1.47 *0.28*	1.47	0.05	78.05 *6.72*	77.83	0.28	4635.93 *294.48*	4612.14	0.51
	180	6	0.03108 *0.00008*	0.03108	0.00080	1.24 *0.23*	1.24	-0.06	85.23 *5.72*	84.85	0.44	4844.19 *214.08*	4857.71	-0.28
Spruce *smrekovina*	110	4	0.02488 *0.00005*	0.02479	0.37682	1.39 *0.23*	1.39	-0.11	74.52 *4.77*	74.66	-0.19	4485.44 *278.20*	4473.82	0.26
	110	8	0.02877 *0.00008*	0.02861	0.57112	1.29 *0,2*	1.28	0.84	64.38 *7.24*	64.38	0.00	4533.12 *217.17*	4573.67	-0.89
	130	4	0.02540 *0.00007*	0.02533	0.27914	1.34 *0.17*	1.34	-0.01	66.82 *7.92*	66.82	-0.01	4389.64 *323.56*	4434.17	-1.01
	130	6	0.02653 *0.00012*	0.02656	-0.09443	1.26 *0.16*	1.27	-0.74	60.03 *2.97*	60.07	-0.07	3057.93 *142.31*	3095.54	-1.23
	160	4	0.02578 *0.00006*	0.02583	-0.18449	1.36 *0.21*	1.36	-0.11	59.67 *5.14*	59.52	0.25	4550.55 *317.18*	4549.59	0.02
	160	8	0.02667 *0.00010*	0.02653	0.53174	1.24 *0.25*	1.26	-1.51	54.20 *3.97*	54.57	-0.69	3673.39 *180.02*	3701.88	-0.78
	180	6	0.02809 *0.00006*	0.02808	0.03055	1.27 *0.1*	1.26	0.84	62.88 *5.75*	63.04	-0.25	4234.94 *180.92*	4230.18	0.11
	180	8	0.02996 *0.00007*	0.03000	-0.11814	1.26 *0.19*	1.26	0.36	60.93 *3.47*	60.72	0.35	4916.41 *383.34*	4926.92	-0.21

Standard deviation values are shown in italic. / *Vrijednosti standardne devijacije otisnute su kurzivom.*

Table 3 Testing data set used for thermal conductivity and mechanical strength and prediction model results
Tablica 3. Primijenjeni testni skup podataka za toplinsku vodljivost i mehaničku *čvrstoću* te rezultati modela predviđanja

Wood species *Vrsta drva*	**Veneer drying temperature, °C** *Temperatura sušenja furnira,* °C	**Veneer moisture content, %** *Sadržaj vode u furniru*	**Thermal conductivity, W/mK** *Toplinska vodljivost,* W/mK			**Bonding strength, N/mm²** *Čvrstoća lijepljenog spoja,* N/mm²			Bending strength, N/mm² *Čvrstoća na savijanje,* N/mm²			**Elasticity modulus, N/mm²** *Modul elastičnosti,* N/mm²		
			Actual *Stvarna*	**Predicted** *Predviđena*	**Error, %** *Pogreška,* %	**Actual** *Stvarna*	**Predicted** *Predviđena*	**Error, %** *Pogreška,* %	**Actual** *Stvarna*	Predicted *Predviđena*	**Error, %** *Pogreška,* %	**Actual** *Stvarna*	**Predicted** *Predviđena*	**Error, %** *Pogreška,* %
Poplar *topolovina*	110	4	0.02981 *0.00009*	0.02967	0.45838	1.91 *0.26*	1.93	-0.82	87.27 *3.02*	86.37	1.03	4757.80 *440.41*	4601.75	3.28
	130	6	0.02832 *0.00007*	0.02738	3.31151	1.68 *0.23*	1.66	0.93	84.28 *5.09*	83.83	0.53	4681.47 *458.20*	4712.40	-0.66
	160	4	0.02630 *0.00005*	0.02645	-0.58552	1.46 *0.26*	1.38	5.60	81.71 *3.41*	80.20	1.85	4738.93 *315.28*	4733.70	0.11
	180	8	0.03534 *0.00012*	0.03528	0.16519	1.31 *0.18*	1.31	0.08	77.48 *6.82*	77.15	0.42	4771.69 *437.27*	4218.57	11.59
Spruce *smrekovina*	110	6	0.02660 *0.00005*	0.02674	-0.52975	1.38 *0.1*	1.31	4.94	67.33 *7.74*	66.28	1.56	4752.53 *294.21*	4667.60	1.79
	130	8	0.02747 *0.00006*	0.02764	-0.62730	1.23 *0.2*	1.26	-2.62	58.28 *3.67*	58.44	-0.28	3301.51 *139.74*	3121.57	5.45
	160	6	0.02660 *0.00007*	0.02612	1.81271	1.27 *0.09*	1.26	0.61	56.13 *4.79*	55.34	1.41	3925.54 *395.84*	3949.79	-0.62
	180	4	0.02705 *0.00006*	0.02661	1.61564	1.34 *0.2*	1.33	0.72	67.45 *3.50*	66.76	1.03	4662.68 *330.25*	4689.71	-0.58

Standard deviation values are shown in italic. / *Vrijednosti standardne devijacije otisnute su kurzivom.*

Table 4 Performance values of the best prediction models
Tablica 4. Vrijednosti svojstava najboljih modela predviđanja

Prediction models *Modeli predviđanja*	***MSE***	***R*²**	Data sets	MAPE	RMSE
Thermal conductivity *toplinska vodljivost*	0.00022287	0.9931	Training / *treniranje*	0.22%	0.0001
			Testing / *testiranje*	1.14%	0.0004
Bonding strength *čvrstoća lijepljenog spoja*	0.00038275	0.9856	Training / *treniranje*	0.32%	0.01
			Testing / *testiranje*	2.04%	0.04
Bending strength *čvrstoća na savijanje*	0.00018906	0.9983	Training / *treniranje*	0.25%	0.23
			Testing / *testiranje*	1.01%	0.84
Elasticity modulus *modul elastičnosti*	0.00046219	0.9459	Training / *treniranje*	0.43%	22.44
			Testing / *testiranje*	3.01%	215.69

by the increase in the veneer drying temperature and moisture content.

The best training performances and MSE values were realized as 0.00022287 in the 35th iteration for the thermal conductivity, 0.00038275 in the 19th iteration for the bonding strength, 0.00018906 in the 25th iteration for the bending strength and 0.00046219 in the 28th iteration for the elasticity modulus. The performance values of the best prediction models obtained by ANN analysis are given in Table 4.

MAPE, *RMSE* and R^2 parameters are mostly used to evaluate the performance of prediction models obtained by ANN (Yadav and Nath, 2017; Kucukonder *et al*., 2016). Yadav and Nath (2017) determined that the prediction performance of models with *MAPE* values below 10 % was quite good. Similarly, some researchers determined that the prediction abilities of the models were successful if the *RMSE* values were quite low and the R^2 values were close to 1 (Taspınar and Bozkurt, 2014; Ozsahin, 2012). In this study, the *MAPE* values for the thermal conductivity, bonding, bending strength and elasticity modulus were 0.22 %, 0.32 %, 0.25 %, 0.43 % for training and 1.14 %, 2.04 %, 1.01 %, 3.01 % for testing, respectively. The *RMSE* values were 0.0001, 0.01, 0.23, 22.44 for training and 0.0004, 0.04, 0.84, 215.69 for testing, respectively. Furthermore, the R^2 values were calculated as 0.9931, 0.9856, 0.9983 and 0.9459, respectively. The calculated values of these diagnostic tools proved the reliability and precision of the prediction models obtained from ANN analysis.

Thanks to the reliable and predictable ANN models, the output values corresponding to the intermediate input variables that are not used in the experiments can be predicted with high precision. In this study, high-precision predictions were made with the help of models for the veneer drying temperatures and moisture content, which were not used in the experiments. The effects of input variables on output variables are shown in Figures 2 and 3 according to wood species.

According to the data obtained from the ANN prediction models in Figures 2 and 3, it was determined that the veneer drying temperature and the veneer moisture content had a significant effect on the thermal conductivity, bonding strength, bending strength and elasticity modulus and these effects differed according to the wood species. In particular, it was clearly observed that the thermal conductivity coefficients increased depending on the increase in the veneer moisture content. The reason for this linear relationship could be shown as the fact that the water molecules, which increased with the increase in moisture, were more conductive than the air. According to the ISO 10456 (2007) standard, the thermal conductivity value (0.060 W/mK) of the water molecule was determined to be higher than the thermal conductivity value (0.025 W/mK) of the air. Sonderegger and Niemz (2009) worked on the effect of moisture content on the thermal conductivity of beech plywood and observed that the thermal conductivity values increased with the increase in moisture content. A similar relationship between the moisture content and thermal conductivity was also found in some studies on solid wood and wood-based panels in the literature (Taoukil *et al*., 2013; Troppová *et al*., 2015). Contrary to the veneer moisture content, nonlinear relationships were observed between the veneer drying temperature and thermal conductivity. However, the veneer drying temperature value, which gave the highest thermal conductivity values among the groups, was 180 °C in both wood species. Sonderegger and Niemz (2009) mentioned that the thermal conductivity values of wood materials increased depending on the increase in temperature.

It was determined that the bonding strength values obtained from the experiments and the predicted values were above the 1 N/mm² limit value specified in the EN 314-2 (1993) standard. The bonding values of the panels generally decreased, while the values of the veneer drying temperature and moisture content increased in both wood species. Aydin and Colakoglu (2005) stated that the veneer drying process at high temperatures could negatively affect the wettability of the wood surface with the adhesive, thus reducing the bonding strength. Similarly, Bekhta *et al*. (2020) mentioned that prolonged drying at a very high temperature could render the veneer surface ineffective, resulting in poor wetting of the veneer and thus poor adhesion. Furthermore, Aydin *et al*. (2006) investigated the effects of

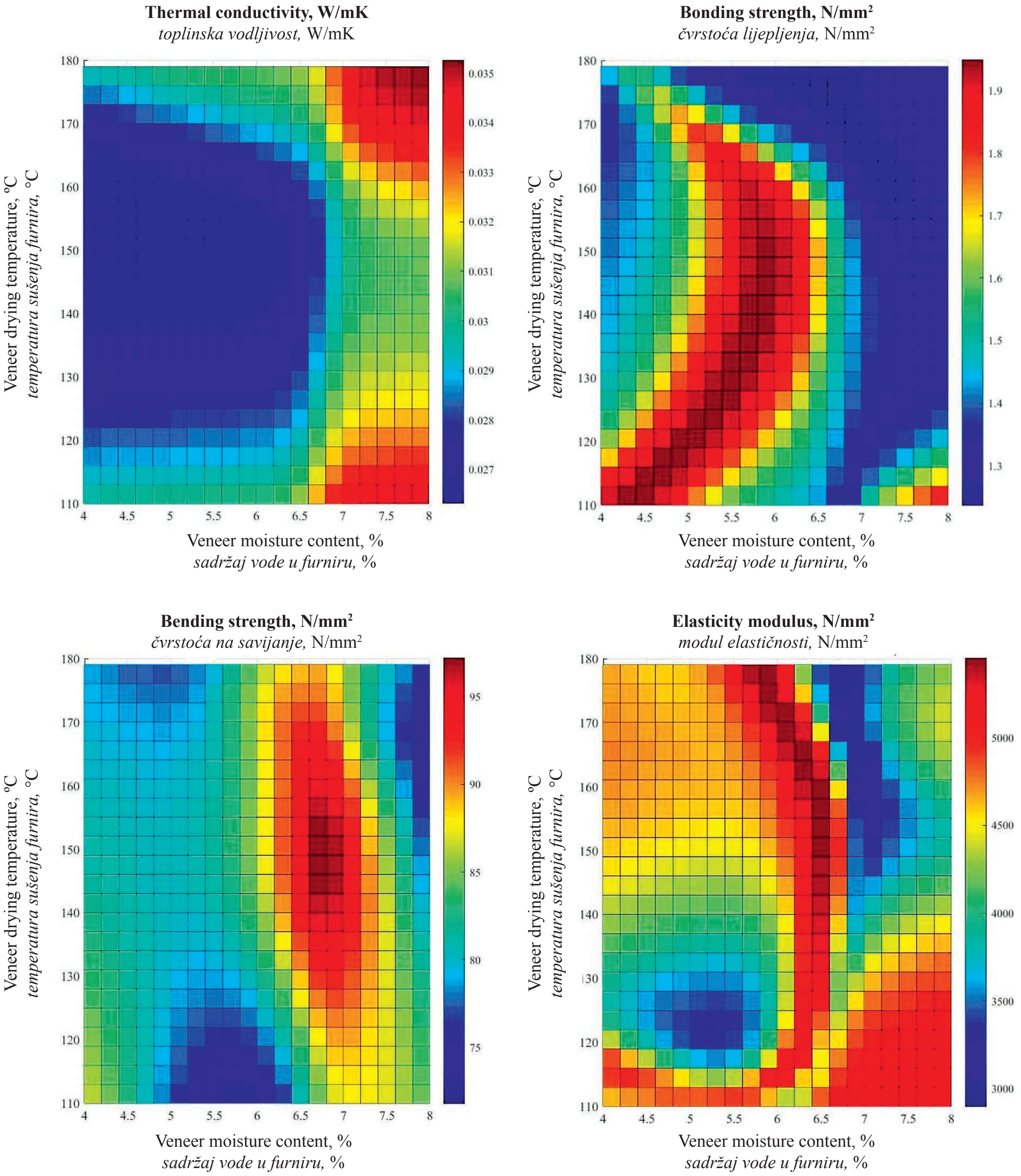
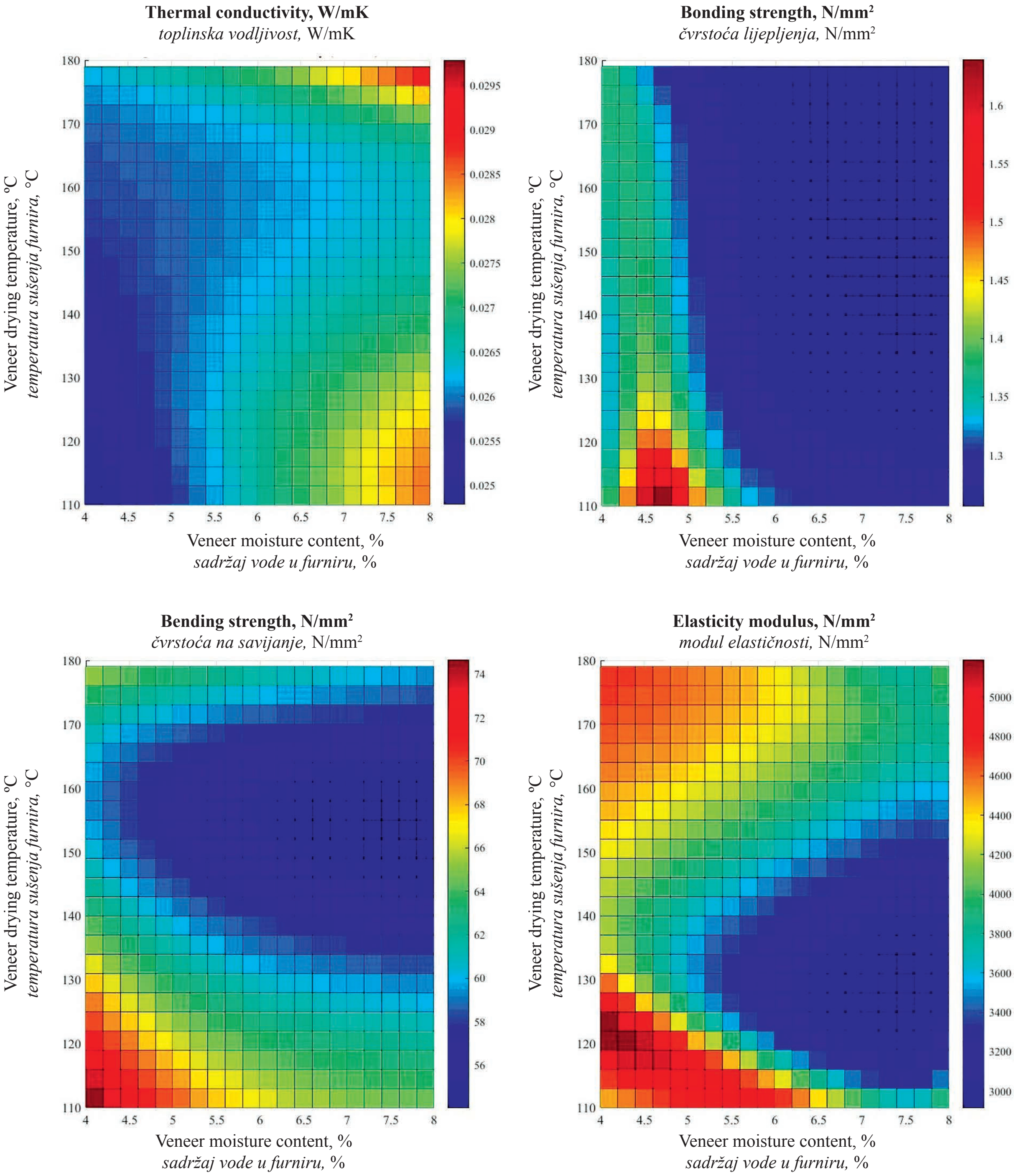


Figure 2 Effects of veneer drying temperature and veneer moisture content on thermal conductivity and mechanical strength values of poplar plywood panels
Slika 2. Učinci temperature sušenja i sadržaja vode u furniru na vrijednost toplinske vodljivosti i mehaničke čvrstoće furnirske ploče od topolovine

moisture content on the mechanical properties of plywood and found that the mechanical properties decreased with increasing veneer moisture content. However, the bending strength and elasticity modulus values of the plywood produced from poplar veneers were almost not affected by the increase in the veneer drying temperature and moisture content. In contrary, the highest bending strength and elasticity modulus values in the spruce plywood panels were obtained from the lowest values of veneer drying temperatures and moisture content.

By using the prediction models, optimum veneer drying temperature and moisture content values for wood species were determined and they are given in Table 5 according to output variables.

The veneer drying temperature values that gave the best mechanical properties of the plywood produced from poplar and spruce veneers are given in Ta-



Thermal conductivity, W/mK
toplinska vodljivost, W/mK

Bonding strength, N/mm²
čvrstoća lijepljenja, N/mm²

Bending strength, N/mm²
čvrstoća na savijanje, N/mm²

Elasticity modulus, N/mm²
modul elastičnosti, N/mm²

Figure 3 Effects of veneer drying temperature and veneer moisture content on thermal conductivity and mechanical strength values of spruce plywood panels
Slika 3. Učinci temperature sušenja i sadržaja vode u furniru na vrijednost toplinske vodljivosti i mehaničke čvrstoće furnirske ploče od smrekovine

ble 5. ANN optimization studies that could be used in veneer drying processes for the plywood industry were limited in the literature. Although the optimum values giving the best mechanical strength properties were determined for different wood species in a few studies on the veneer drying temperature, no optimization studies were found regarding the veneer drying moisture. Demirkir *et al*. (2013) worked on some manufacturing parameters such as the effect of veneer drying temperature on the bonding strength of the plywood produced from Scots pine, maritime pine and European black pine veneer and determined the veneer drying temperature that provides the best bonding strength with ANN. They found optimum values of the plywood produced with melamine urea formaldehyde (MUF) resin in the range of 110-125 ºC for the Scots pine veneers, 110-124 ºC for the maritime pine veneers and 110-112 ºC for the European black pine veneers (Demirkir *et al*.,

Table 5 Optimum veneer drying temperature, veneer moisture content and thermal conductivity results
Tablica 5. Rezultati optimalne temperature sušenja, sadržaja vode i toplinske vodljivosti furnira

Mechanical properties *Mehanička svojstva*	**Wood species** *Vrsta drva*	**Optimum values** / *Optimalna svojstva*			**Maximum strength values, N/mm^2** *Najveće vrijednosti čvrstoće,* N/mm^2
		Veneer drying temperature, °C *Temperatura sušenja furnira,* °C	**Veneer moisture content, %** *Sadržaj vode u furniru,* %	**Thermal conductivity, W/mK** *Toplinska vodljivost,* W/mK	
Bonding strength *čvrstoća lijepljenog spoja*	Poplar *topolovina*	128	5.4	0.02744	1.95
	Spruce *smrekovina*	110	4.6	0.02538	1.64
Bending strength *čvrstoća na savijanje*	Poplar topolovina	146	6.6	0.02791	97.23
	Spruce *smrekovina*	110	4	0.02479	74.67
Elasticity modulus *modul elastičnosti*	Poplar *topolovina*	164	6.2	0.02842	5454.98
	Spruce *smrekovina*	119	4	0.02505	5189.42

2013). In this study, the optimum results for spruce veneers, which was one of the coniferous wood species, were determined and the optimum veneer temperature value for bonding strength was determined as 110 °C. This result was found to be similar to the results found in the literature. Ozsahin *et al*. (2019) determined the optimum drying temperatures of alder and Scots pine veneers according to the results of mechanical properties and found that the highest values of bonding, bending strength and elasticity modulus were obtained from 190, 195 and 196°C in the alder veneers and from 165, 162 and 161°C in the Scots pine veneer, respectively. Moreover, Ozsahin and Aydin (2014) determined by the ANN analysis the optimum drying temperature values of 169 °C for UF and 125 °C for FF in beech veneers, 162 °C for UF and 151 °C for FF in spruce veneers. Similarly, the poplar veneers, which was one of the hardwood species, had higher optimum veneer temperature than spruce veneer, which was one of the coniferous wood species in this study. It can be seen in Table 5 that the optimum moisture content values of poplar veneers were higher than those of spruce veneers.

In addition to the veneer drying temperatures and the optimum veneer moisture content, the veneer thermal conductivity coefficients are given in Table 5. Figures 2 and 3 also show that the values of thermal conductivity coefficient increased with the increase of the moisture content of poplar and spruce veneers. Demir and Aydin (2021) obtained optimal results by modeling the experimental results of thermal conductivity with ANN according to the moisture content changes of beech, Scots pine and poplar veneer between 3 % and 15 % and determined that the veneers with high moisture content had high values of thermal conductivity.

According to the predicted results, the optimum values of veneer drying temperatures, moisture content and thermal conductivity of panels, which gave the best values for all three mechanical properties, were 149 °C, 6.2 % and 0.02668 W/mK for poplar and 116 °C, 4.4 % and 0.02534 W/mK for spruce.

4 CONCLUSIONS
4. ZAKLJUČAK

In this study, the optimum values of veneer drying temperature, moisture content and thermal conductivity, which gave the best mechanical properties of plywood panels, were determined by ANN analysis. While the experimental data were analyzed by ANN, the drying temperature and moisture content were used as input variables and the veneer thermal conductivity prediction model was first obtained. Then, the experimental thermal conductivity values were added in addition to the two input variables and the prediction models of mechanical properties were obtained. The accuracy and reliability of the ANN models were proven by the performance functions. In the testing phase, the *MAPE* values in the prediction models of the thermal conductivity, bonding, bending strength and elasticity modulus were 1.14 %, 2.04 %, 1.01 %, 3.01 %, whilst the *RMSE* values were 0.0004, 0.04, 0.84, 215.69, respectively. The R^2 values were 0.9931, 0.9856, 0.9983 and 0.9459.

The intermediate values that were not used in the experiments between 110 °C -180 °C veneer drying temperatures and 4 % - 8 % moisture content levels were predicted with high accuracy with the help of these models. Figures 2 and 3 show the changes in thermal conductivity and mechanical properties with these intermediate values. Furthermore, the optimum drying temperature, moisture content and thermal conductivity values that gave the best mechanical properties are presented in Table 5. The optimum veneer drying temperature, moisture content and thermal conductivity values that gave the highest bonding strength values were 128 °C, 5.4 % and 0.02744 W/mK for poplar, and 110 °C, 4.6 % and 0.02538 W/mK for spruce, respectively. The values for the bending strength were 146°C, 6.6% and 0.02791 W/mK for poplar, and 110 °C, 4 % and 0.02479 W/mK for spruce, respectively. These values for the elasticity modulus were 164 °C, 6.2 % and 0.02842 W/mK for poplar, and 119 °C, 4 % and 0.02505 W/mK for spruce, respectively. By using both the graphs and the table of optimum values, the mechanical properties of the plywood to be produced with poplar and spruce veneers can be predicted without further experimentation. It is thought that the findings of this study will be an important reference for veneer drying programs, which are extremely important for the plywood industry. If different wood species and adhesives are used, the precision of the prediction models in this study will be low and this is seen as the weakness of the study. Therefore, the optimization predictions can be carried out using different wood species of veneers and adhesives in future studies.

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