Prediction of Modulus of Rupture and Modulus of Elasticity of Heat Treated Anatolian Chestnut (*Castanea Sativa*) Wood by Fuzzy Logic Classifier

Predviđanje modula loma i modula elastičnosti toplinski obrađenog drva anatolskog kestena (*Castanea sativa*) modelom razvrstavanja *fuzzy* logikom

Original scientific paper • Izvorni znanstveni rad
Received – prispjelo: 25. 7. 2011.
Accepted – prihvaćeno: 9. 2. 2012.
*UDK: 630*812.463; 630*812.7; 632.25; 674.031*
doi:10.5552/drind.2012.1135

ABSTRACT • *In this study, test samples prepared from Anatolian chestnut (Castanea sativa) wood were first exposed to heat treatment at 130, 145, 160, 175, 190 and 205 ºC for 3, 6, 9 and 12 hours. Then the values of the samples of the modulus of rupture (MOR) and modulus of elasticity (MOE) were determined and evaluated by multiple variance analysis. The aim of this study was to establish the effects of heat treatment on the MOR and MOE values of wood samples by using fuzzy logic classifier. Secondly, input and output values and rule base of the fuzzy logic classifier model were built by using the results obtained from the experiment. The developed fuzzy classifier model could predict the MOR and MOE values of test samples at the accuracy levels of 92.64 % and 90.35 %, respectively. The model could be especially employed in manufacturing stages of timber industry.*

Keywords: *wood, heat treatment, fuzzy logic classifier, modulus of rupture, modulus of elasticity*

SAŽETAK • *U radu se prikazuju istraživanju u kojima su, prije svega, pripremljeni uzorci od drva kestena te izloženi zagrijavanju na temperaturama od 130, 145, 160, 175, 190 i 205 ºC tijekom 3, 6, 9 i 12 sati. Nakon toga uzorcima su određeni modul loma (MOR) i modul elastičnosti (MOE) te je napravljena analiza varijanci dobivenih vrijednosti. Cilj provedene studije bio je utvrditi učinak toplinske obrade drva na MOR i MOE vrijednosti drvnih uzoraka uporabom modela razvrstavanja neizrazitom (fuzzy) logikom. Ulazne i izlazne vrijednosti te osnovna pravila modela neizrazitog razvrstavanja definirani su uporabom rezultata dobivenih eksperimentom. Razvijeni model neizrazitog (fuzzy) razvrstavanja moguće je primijeniti za predviđanje MOR i MOE vrijednosti drvnih uzoraka s točnošću od 92,64 % i 90,35 %. Model može biti primijenjen u proizvodnim uvjetima, posebice u procesu proizvodnje piljene drvne građe.*

Ključne riječi*: drvo, toplinska obrada, model razvrstavanja fuzzy logikom, modul loma, modul elastičnosti*

[1] Authors are assistant professor and high graduate student at Technical Education Faculty, University of Karabük, Karabük, Turkey.
[1] Autori su profesor i student diplomskog studija Fakulteta tehničkog obrazovanja Sveučilišta u Karabüku, Karabük, Turska.

1 INTRODUCTION
1. UVOD

Heat treatment is one of the processes used to modify wood properties (Mazela *et al*, 2004). Heat treatment, which is a wood modification method, serves to improve the natural quality of the wood, such as dimensional stability and resistance to the effects of some corrosion and provide the wood material with new properties. The heat treatment process involves exposing wood to elevated temperatures ranging from 160 to 260 °C (Militz, 2002). The duration and temperature of heat treatment range from 15 min to 24 h and from 180 °C to 280 °C depending on the wood species, sample size, moisture content of the wood sample and the desired mechanical properties (Militz, 2002; Kandem *et al*, 2002). The heat treatment reduces certain mechanical properties of wood, but the dimensional stability and the durability of wood against biological attacks increase. Also, heat treatment results in favorable changes in the physical properties of the wood (Yıldız, 2002).

Wood is a natural and complex material constituted mainly of three biopolymers: lignin, cellulose and hemicelluloses. In addition to these polymeric components, wood may contain extractives in more or less large quantities including several classes of organic compounds like sugars, tannins, terpenes, fats or waxes (Nguila *et al*, 2006). Owing to heat treatment and thermal degradation, wood loses its weight. Weight loss depends on the heat treatment temperature and time, specimen size and prevailing circumstances during the heat treatment. The main targets for industrial heat treatment are increased biological durability, enhanced weather resistance and decreased shrinking and swelling of wood (Kandem *et al*, 2002). On the other hand, as a result of heat treatment, the wood becomes more fragile, and bending and tension strength decrease in relation to the level of heat treatment conditions (Kandem *et al*, 2002; Korkut *et al*, 2008; Bekhta and Niemz, 2003; Özçifçi *et al*, 2009).

There are some studies about the effects of heat treatment on mechanical and physical properties of wood, but the application of the fuzzy logic classifier in wood industry is very limited. Nevertheless, some researchers have focused on the fuzzy logic classifier model recently. Researchers suggested a fuzzy regression approach to estimate functional relationships (Kim and Park, 1998). Other researchers proposed another fuzzy regression approach, based on asymmetric triangular fuzzy coefficients, to model the functional relationships (Chen *et al*, 2004).

The use of non-linear programming to develop fuzzy regression models for the functional relationships was also proposed (Chen *et al*, 2005). Yapıcı *et al,* (2009) used fuzzy logic classifier model for predicting the modulus of rupture and modulus of elasticity of wood composite material, called the flake board. The model agreed well with the experimental results with maximum errors for modulus of rupture and modulus of elasticity at 5% and 3%, respectively (Yapıcı *et al*, 2009). Yapici and Gologlu (2009) also used fuzzy logic classifier model for predicting thickness swelling and weight increase on heat treated *Black Pine* (*Pinus Nigra*) wood. Their model was able to predict the thickness swelling and weight increase of test samples at the accuracy levels of 99.6 % and 86.05 %, respectively. Cha and Pearson developed two dimensional finite element models to predict the elastic tensile properties of a 3-ply model on LVL. The values of the predicted and experimental strains at maximum load (max. difference of 14.3 %) as well as the predicted and experimental stresses (max. difference of 7.7 %) matched acceptably (Cha *et al*, 1994).

The temperature and time used in the heat treatment process had different effects on the chemical, physical, and mechanical properties of wood material. Measuring of the effects of each parameter is too expensive and carrying out the experiments is also time-consuming. Fuzzy logic classifier is one of the powerful approaches to model these effects. In this study, heat treatment was applied to wood specimens. Test samples were prepared from Anatolian chestnut widely used in the shipbuilding industry. Then the MOR and MOE properties of the samples were determined experimentally. The results obtained experimentally were compared with the fuzzy logic classifier model for the accuracy.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The Anatolian chestnut (*Castanea sativa*) wood was chosen randomly from timber merchants of Bartın, Turkey. The selected specimens were cut for modulus of rupture (MOR) and modulus of elasticity (MOE) (20x20x360 mm), and they were exposed to heat treatment at 130, 145, 160, 175, 190 and 205 ºC for 3, 6, 9, 12 hours. After this process, the test samples were conditioned to constant weight at 65±5 % relative humidity and at a temperature of 20±2 °C until they reached a stable weight (TS 642 1997).

To determine MOR and MOE values of test samples, Zwick/Roell Z050 universal test device was used with the capacity of 5000 kg. In testing, the loading mechanism was operated with a velocity of 6 mm/min. MOR and MOE experiments were performed (TS 2474 1976).

2.1 Statistical analyses
2.1. Statističke analize

Data were statistically analyzed. The analysis of the variance (ANOVA) was used ($p \leq 0.05$) to evaluate the significance in the difference between factors and levels. When the ANOVA indicated a significant difference among the factors, Duncan's test was done for comparing these means.

2.2 Design of fuzzy logic classifier for predicting MOR and MOE
2.2. Izrada modela razvrstavanja *fuzzy* logikom za predviđanje MOR i MOE vrijednosti

Fuzzy logic was used for the first time in 1965 by Zadeh. In his approach Zadeh developed a new consideration instead of Aristotelian logic that contained two definite and different possibilities only 1-0. Fuzzy

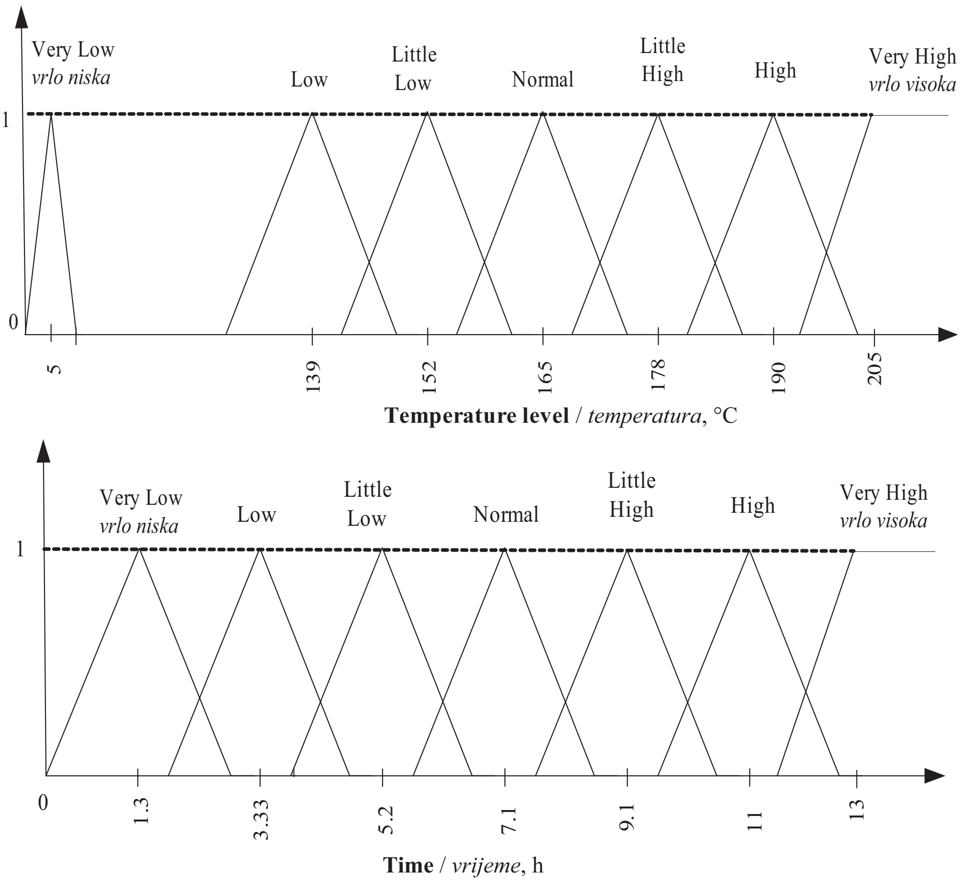

Figure 1 Input variables refer to both temperature level and time of the heat treatment process
Slika 1. Ulazne varijable koje pripadaju vrijednosti temperature i vremenu zagrijavanja

set theory provides a systematic calculus to deal with such information linguistically. Fuzzy performs numerical computation by using linguistic labels stimulated by membership functions (Zadeh, 1965). Input values contain all input parameters and information about them. Fuzzification converts each input data to degrees of membership by reference to one or more membership functions. Fuzzy rule base contains rules that include all possible fuzzy relations between input and outputs. Fuzzifier unit converts definite data in the input of the controller to the format of linguistic variables. Inference unit is a unit that performs fuzzy inference on fuzzy rules. Defuzzification unit converts the fuzzy values obtained from the output of the inference units to numerical values.

In this study, the fuzzy rules of the system were constructed according to the input and output variables, and their membership functions. Triangular membership functions were used because of the fact that it was widely preferred in the literature. The system has 71 rules.

Input variables used in the heat treatment process were designated as the value of heat treatment temperature and waiting times of the test samples. The degree of input variables refers to both temperature level and time of the heat treatment process, and they were designated as very low, low, little low, normal, little high, high, very high (see Figure 1). MOR and MOE values of test samples were used as output variables in membership function. Output variables were designated as very low, little low, low, normal, little high, high and very high, and they are presented in Figure 2.

The fuzzy logic controller model was developed by using MATLAB Simulink to predict MOR and MOE values of test samples. Input variables can be changed automatically or manually in this developed model. MOR and MOE values could be observed step by step in this model. The results obtained were simultaneously recorded to a file and to Matlab Workspace.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The variance analysis of MOR and MOE was conducted based on the heat treatment and time in the heat treatment process. Multiple variance analysis was used to determine the differences among the test samples. The results of variance are presented in Table1. According to the results of the variance analysis, it can be seen that the effects of waiting time and temperature levels on the MOR and MOE was meaningful at 95 % significance level. To identify the significance level of the differences among the other groups, Duncan test was done to establish whether it was significant or not. The results of Duncan test are presented in Table 2. It can be seen that the results obtained from experiments compared to the data predicted by fuzzy classifier were very successful.

The fuzzy logic classifier predicted the modulus of rupture and modulus of elasticity of samples with the average accuracy of 92.64 % and 90.35 %, respec-

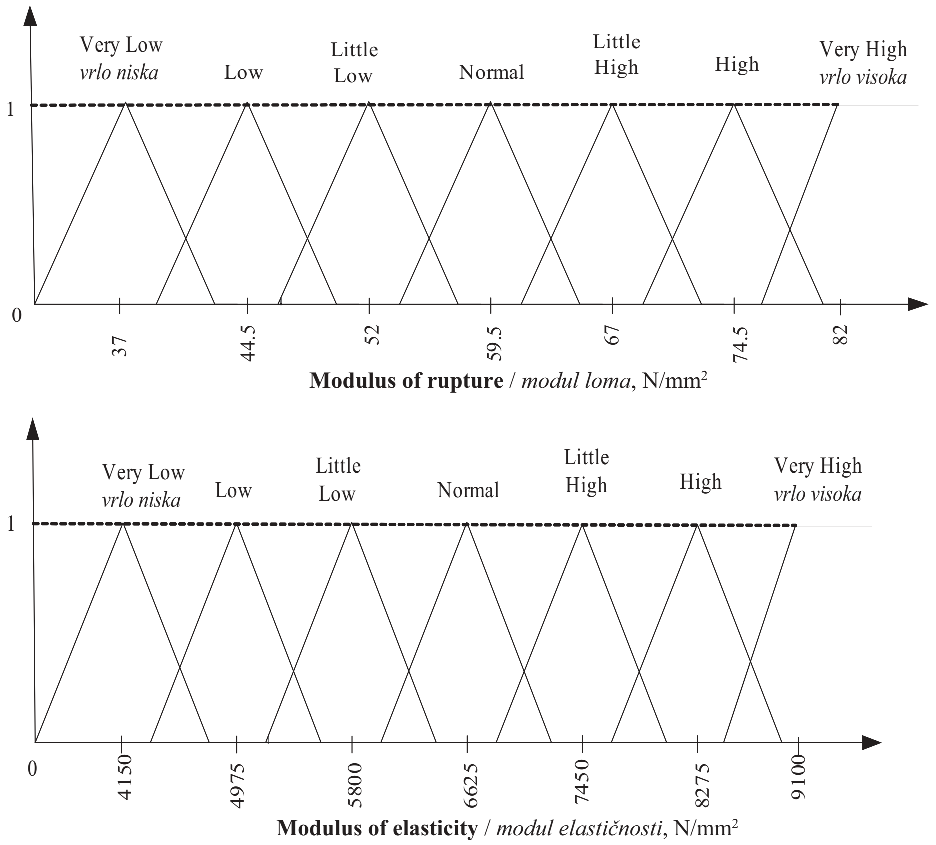

Fig. 2 Output variables refer to both modulus of elasticity and modulus of rupture
Slika 2. Izlazne varijable koje pripadaju modulu elastičnosti i modulu loma

tively. The MOR and MOE values obtained experimentally and predicted by classifier are presented according to heat treatment conditions in Table 3.

The changes of modulus of rupture and modulus of elasticity values of test samples according to condition of heat treatment are shown in Figure 3. As the temperature and time increase step by step between 0 and 205 °C, and from 0 to 12 hours, respectively, the changes of MOR and MOE values can be seen by fuzzy logic classifier model developed in this study.

Table 1 The results of variance analysis
Tablica 1. Rezultati analize varijance

	Source *Izvor*	**Type III Sum of Squares** *Zbroj kvadrata*	***df***	**Mean Square** *Kvadrat srednje vrijednosti*	***F***	**Significance** *Značajnost* (*p*<0.05)
Modulus of rupture *modul loma*, N/mm²	Corrected Model	67033.52	24	2793.06	14.33	0.00
	Intercept	1117883.18	1	1117883.18	5734.07	0.00
	Factor A	53975.45	5	10795.09	55.37	0.00
	Factor B	6309.17	3	2103.06	10.79	0.00
	A * B	4191.71	15	279.45	1.43	0.13
	Error	77981.81	400	194.95		
	Total	1456878.04	425			
Modulus of elasticity *modul elastičnosti*, N/mm²	**Source** *Izvor*	**Type III Sum of Squares** *Zbroj kvadrata*	***df***	**Mean Square** *Kvadrat srednje vrijednosti*	***F***	**Significance** *Značajnost* (*p*<0.05)
	Corrected Model	864704491	24	36029353,79	23.59	0.00
	Intercept	9885387195	1	9885387195	6472.44	0.00
	Factor *A*	789170216.2	5	157834043,2	103.34	0.00
	Factor *B*	15067481.64	3	5022493.88	3,29	0.02
	A * *B*	60456978.78	15	4030465.25	2.64	0.00
	Error	610921838.7	400	1527304.6		
	Total	13554815761	425			

Factor *A*: Temperature, ºC; Factor *B*: Time, h / *Činitelj A: temperatura, ºC; činitelj B: vrijeme, h.*

Table 2 Duncan test results
Tablica 2. Rezultati Duncanova testa

Heat treatment conditions *Uvjeti toplinske obrade*		**MOR**		**Heat treatment conditions** *Uvjeti toplinske obrade*		**MOE**	
Temperature *Temperatura* ºC	Time *Vrijeme* h	Average *Srednja vrijednost* N/mm²	HG	Temperature *Temperatura* ºC	Time *Vrijeme* h	Average *Srednja vrijednost* N/mm²	HG
205	12	32.14	A	205	9	3683.6	A
205	9	32.83	A	205	6	3824.32	AB
205	6	36.23	AB	205	12	3929.48	ABC
190	9	43.21	BC	205	3	4118.23	ABCD
190	12	44.25	BC	175	12	4232.52	ABCD
190	6	44.55	BC	190	3	4298.75	ABCD
175	12	46.02	BC	190	6	4355.02	ABCD
175	9	46.73	BCD	175	9	4356.77	ABCD
205	3	48.35	CD	175	3	4394.82	ABCDE
190	3	50.01	CDE	190	9	4401.31	ABCDE
175	6	53.52	CDEF	160	3	4507.21	ABCDE
175	3	56.81	DEFG	190	12	4539	ABCDE
145	12	58.88	EFG	160	12	4557.45	ABCDE
130	12	59.42	EFG	175	6	4803.35	BCDE
160	12	59.73	EFG	160	6	4869.5	CDE
145	9	60.5	EFG	160	9	5042.23	DE
145	3	63.83	FGH	0	0	5354.74	E
160	9	65.1	GH	130	12	6483.66	F
145	6	65.26	GH	130	9	6810.34	F
160	3	65.29	GH	145	6	6861.74	F
160	6	65.37	GH	145	9	6888.11	F
130	9	66.61	GH	145	12	6991.91	FG
0	0	67.58	GH	145	3	7154.24	FG
130	3	74.71	HI	130	3	7813.27	G
130	6	82.02	I	130	6	9008.27	H

HG – homogenous group / *HG – homogena skupina;* MOR – modulus of rupture / *modul loma;*
MOE – modulus of elasticity / *modul elastičnosti*

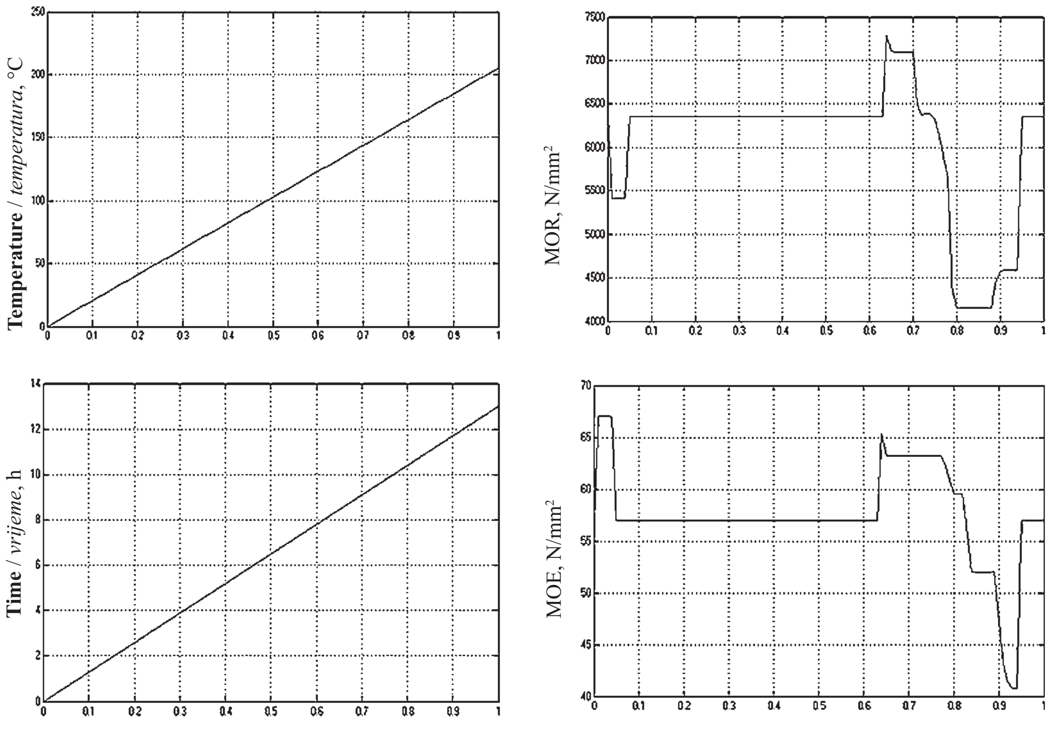

Figure 3 MOR and MOE values according to heat treatment conditions
Slika 3. MOR i MOE vrijednosti ovisno o uvjetima toplinske obrade

Table 3 Measured and prediction results
Tablica 3. Izmjereni rezultati i rezultati predviđanja

Experiment conditions *Uvjeti eksperimenta*		**Modulus of rupture** *Modul loma*, N/mm²			**Modulus of elasticity** *Modul elastičnosti,* N/mm²		
Temperature *Temperatura* °C	Time *Vrijeme* h	Experiment *Eksperiment*	Prediction *Predviđanje*	Accuracy level *Točnost* %	Experiment *Eksperiment*	Prediction *Predviđanje*	Accuracy level *Točnost* %
0	0	67.58	57	84.35	5354.74	6349	81.43
130	3	74.71	57	76.29	7813.27	6349	81.26
	6	82.02	58	70.72	9008.27	6410.5	71.16
	9	66.61	57	85.57	6810.34	6367.8	93.5
	12	59.42	58.3	98.11	6483.66	6421.7	99.04
145	3	63.83	67	95.04	7154.24	7040.3	98.41
	6	65.26	70.8	91.51	6861.74	6713.5	97.84
	9	60.5	63.3	95.38	6888.11	6721.6	97.58
	12	58.88	59.5	98.94	6991.91	6190.46	88.54
160	3	65.29	64.3	98.49	4507.21	5702.3	73.49
	6	65.37	67	97.5	4869.5	5639.1	84.2
	9	65.1	63.4	97.38	5042.23	6010.5	80.8
	12	59.73	59.5	99.62	4557.45	5934.3	69.79
175	3	56.81	59.5	95.27	4394.82	4538.6	96.73
	6	53.52	52	97.15	4803.35	4562.12	94.98
	9	46.73	44.5	95.22	4356.77	4176.3	95.86
	12	46.02	52	87.01	4232.52	4169.2	98.5
190	3	50.01	49.7	99.39	4298.75	4154.2	96.64
	6	44.55	41.4	92.93	4355.02	4210.4	96.68
	9	43.21	42.3	97.9	4401.31	4751.3	92.05
	12	44.25	40.8	92.2	4539	4581.4	99.07
205	3	48.35	48.3	99.9	4118.23	4160.3	98.98
	6	36.23	37	97.87	3824.32	4156.6	91.31
	9	32.83	36.9	87.61	3683.6	4165.7	86.91
	12	32.14	37.1	84.58	3929.48	4163.2	94.05
		Average accuracy: 92.64 % *Prosječna točnost: 92,64 %*			Average accuracy: 90.35 % *Prosječna točnost: 90,35 %*		

4 CONCLUSION
4. ZAKLJUČAK

Firstly, after the wood samples had been heat-treated, the MOR and MOE values were determined experimentally. It can be seen that MOR and MOE values were affected by both heat temperature and time of heat application. The results were used to build the fuzzy classifier system. Secondly, a model based on Fuzzy Logic was developed in Matlab Simulink in order to predict the values of MOR and MOE, which are among the most important mechanical features of solid wood. With the help of this model, the average MOR values were predicted to be 92.64 % accurate, while the average MOE values were predicted to be 90.35 % accurate. The MOR and MOE values of the samples could be found at any heat treatment conditions in very short time thanks to this model. Fuzzy logic classifier model can be used for prediction and optimization of mechanical and physical properties of solid wood.

5 REFERENCES
5. LITERATURA

1. Mazela, B., Zakrzewski, R., Grzes' Kowiak, W., Cofta, G., Bartkowiak, M., 2004: Resistance of thermally modified wood to basidiomycetes. Wood Tech. 7 (1), 253–262.
2. Militz H, (2002) Thermal treatment of wood: European processes and their background. In: 33rd Annual Meeting, 12–17 May, Cardi- Wales, IRG/WP 02-40241, 4, pp. 1–17.
3. Kamdem, DP., Pizzi, A., Jermannaud, A., 2002: Durability of heat-treated wood. Holz als Roh-und Werkstoff, 60, 1–6, http://dx.doi.org/10.1007/s00107-001-0261-1.
4. Yildiz, S., 2002: Physical,mechanical, technological and chemical properties of beech and spruce wood treated by heating. Ph.D. dissertation, Karadeniz Technical University, Trabzon, Turkey.
5. Nguila Inari, G., Petrissans, M., Lambert,J., Ehrhardt, JJ., Ge´rardin, P., 2006: XPS characterization of wood chemical composition after heat-treatment, Surf. Interface Anal., 38, 1336–1342, http://dx.doi.org/10.1002/sia.2455.
6. Korkut, S., Akgül, M., Dündar, T., 2008: The effects of heat treatment on some technological properties of Scots pine (Pinus sylvestris L.) wood, Bioresource Tech., 99, 1861–1868, http://dx.doi.org/10.1016/j.biortech.2007.03.038.
7. 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, http://dx.doi.org/10.1515/HF.2003.080.
8. Özçifçi, A., Altun, S., Yapıcı, F., 2009: Effects of heat treatment on technological properties of wood, 5th International Advanced Technologies Symposium (IATS'09), May 13-15, Karabuk, Turkey.

9. Kim, K., Park, T., 1998: Determination of an optimal set of design requirements using house of quality. Journal of Operations Management, 16, 569–581, http://dx.doi.org/10.1016/S0272-6963(97)00029-6.
10. Chen, Y., Tang, J., Fung, RYK., Ren, Z., 2004: Fuzzy regression-based mathematical programming model for quality function deployment. International Journal of Production Research, 42(5), 1009–1027, http://dx.doi.org/10.1080/00207540310001619623.
11. Chen, Y., Chen, L., 2005: A non-linear possibilistic regression approach to model functional relationships in product planning. International Journal of Advanced Manufacturing Tech., 28, 1175–1181, http://dx.doi.org/10.1007/s00170-004-2466-z.
12. Yapici, F., Ozcifci, A., Akbulut, T., Bayir, R., 2009: Determination of modulus of rupture and modulus of elasticity on flake board with fuzzy logic classifier, Mat. and Design, 6, 2269-2273, http://dx.doi.org/10.1016/j.matdes.2008.09.002.
13. Yapıcı, F., Göloğlu, C., 2009: Prediction of Thickness Swelling and Weight Increase on Heat Treated Black Pine (Pinus Nigra) Wood by Fuzzy Logic Classifier, 1st International Fuzzy Systems Symposium (FUZZYSS'09), Ankara, Turkey, October 1-2, 81-85.
14. Cha, JK., Pearson, RG., 1994: Stress Analysis and Prediction in 3-Layer Laminated Veneer Lumber: Response to Crack and Grain Angle. Wood and Fiber Sc., 26(1), pp. 97-106.
15. TS 642 ISO 554 1997: Standard atmospheres for conditioning and/or testing; Specifications TSE, Ankara.
16. TS 2474 1976: Wood - Determination of Ultimate Strength in Static Bending, T.S.E., Ankara.
17. Zadeh, LA., 1965: Fuzzy sets, Information and Control 8, 338–352, http://dx.doi.org/10.1016/S0019-9958(65)90241-X.

Corresponding address :

Assist. Prof. FATIH YAPICI, Ph.D.

University of Karabük, Technical Education Faculty
Department of Furniture and Decoration
Karabük / TURKEY
e-mail: fyapici@karabuk.edu.tr