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Optimization of Production Parameters of Densified Laminated Veneer Lumber Produced by Using Urea-Formaldehyde Resin

Optimizacija parametara proizvodnje ugušćene lamelirane furnirske građe proizvedene upotrebom urea-formaldehidne smole

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ABSTRACT • *This research aims to optimize densified laminated veneer lumber production parameters of compression ratio, press temperature, press time, and adhesive spread rate to maximize their mechanical properties. In the manufacturing process of densified laminated veneer lumber, I-77/51 American poplar clone (Populus deltoides) veneers and urea formaldehyde adhesive are used. The results showed that the compression rate and press time had the most significant impact on the mechanical properties of densified laminated veneer lumber. The optimal production conditions were determined as follows: 38 % compression, press temperature of 170 °C, press time of (10±3) minutes, and spread rate of 150 g/m^2. Modulus of rupture, modulus of elasticity, tensile shear strength, and tensile strength perpendicular to panels surface of densified laminated veneer lumbers produced under these conditions increased by 49 %, 8 %, 71 %, and 23 %, respectively, compared to the control group of laminated veneer lumber. So, it can be said that the production parameters of densified laminated veneer lumbers can be optimized safely and effectively using Taguchi method-based grey relational analysis.*

KEYWORDS: *densification, laminated veneer lumber, urea formaldehyde, processing parameters, Taguchi method based grey relational analysis*

SAŽETAK • *Cilj ovog istraživanja bilo je optimiziranje parametara proizvodnje ugušćene lamelirane furnirske građe: stupnja ugušćenja, temperature prešanja, vremena prešanja i količine nanosa ljepila kako bi se povećala mehanička svojstva lamelirane furnirske građe. U procesu proizvodnje lamelirane furnirske građe upotrijebljeni su furniri drva klona američke topole I-77/51 (Populus deltoides) i urea-formaldehidno ljepilo. Rezultati su pokazali da su stupanj ugušćenja i vrijeme prešanja imali najveći utjecaj na mehanička svojstva ugušćene lamelirane furnirske građe. Utvrđeni su ovi optimalni uvjeti: stupanj ugušćenja 38 %, temperatura prešanja 170 °C, vrijeme prešanja 10±3 min i količina nanosa ljepila 150 g/m^2. Modul loma, modul elastičnosti, smična čvrstoća i vlačna*

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čvrstoća okomito na površinu ploče ugušćene lamelirane furnirske građe proizvedene uz navedene uvjete povećali su se za 49 %, 8 %, 71 % odnosno za 23 % u usporedbi s kontrolnom skupinom lamelirane furnirske građe. Dakle, može se reći da se parametri proizvodnje ugušćene lamelirane furnirske građe mogu sigurno i učinkovito optimizirati uz pomoć sive relacijske analize utemeljene na Taguchijevoj metodi.

KLJUČNE RIJEČI: *ugušćivanje, lamelirana furnirska građa, urea-formaldehid, parametri procesa, siva relacijska analiza utemeljena na Taguchijevoj metodi*

1 INTRODUCTION
1. UVOD

The mechanical properties of wood, such as strength, hardness, and abrasion, can be improved by densification due to the compression perpendicular to grain under high temperature and pressure (Haller and Wehsener, 2004; Kollmann *et al*., 1975; Seborg *et al*., 1956; Ülker and Burdurlu, 2016). Thus, it is possible to use the wood of fast-growing species with low density and low mechanical properties as structural material instead of high-value wood (Kutnar and Sernek, 2007). Wood surface roughness is also reduced by densification, which provides lower press time, press pressure, press temperature, and less glue, especially in the production of laminated materials such as plywood and laminated veneer lumber (LVL) (Bekhta and Marutzky, 2007; Bekhta *et al*., 2012; Bekhta and Salca, 2018; Bekhta *et al*., 2018; Fang *et al*., 2012; Ugovšek *et al*., 2013; Ülker and Burdurlu, 2016).

In the literature, there are many studies on the production of laminated materials such as plywood and LVL from pre-densified veneer (Bekhta and Marutzky, 2007; Bekhta *et al*., 2012; Bekhta and Salca, 2018; Bekhta *et al*., 2018; Ugovšek *et al*., 2013; Ülker and Burdurlu, 2016). However, the densification of veneer as a separate step before lamination increases production time and cost.

Both densification and lamination require high press temperature and pressure. So, the production of laminated material by combining the densification and lamination in the same step may provide significant cost advantages. However, the vapor pressure, caused by the water in the adhesive, and wood moisture create the risk of blistering and blowing. A higher temperature (more than 100 °C) and pressure, which are needed for softening of wood, increase these risks even more (Wang and Dai, 2005). In contrast, spring-back and dimensional stability improve with increasing condensation temperature and time (Fang *et. al*., 2012; Kúdela *et al*., 2018). Therefore, it is necessary to apply the press pressure, press temperature, press time, and adhesive spread rate (SR) more carefully, if densification and lamination are used in the same step.

The Taguchi method is a powerful analysis method that reduces the number of experiments using orthogonal arrays to optimize production parameters. Several studies have used the Taguchi method to optimize the parameters such as press pressure, temperature, time, and adhesive amount in the production of composite materials. (Alade *et al*., 2022a; Alade *et al*., 2022b; Buddi *et al*., 2018; Hamzaçebi, 2016; Shafie and Zarea-Hosseinabadi, 2019).

Taguchi method allows for determining the effect of production parameters and optimizing them on a single product feature. However, it is often insufficient to evaluate the quality of a product by adhering to a single feature. In such cases, multi-response optimization techniques are used. In several studies, the Taguchi method and grey relational analysis (GRA) were successfully used together to determine the optimal production conditions for multiple quality features (Gupta *et al*., 2019; Kavimani *et al*., 2022; Khan *et al*., 2021; Kopparthi *et al*., 2021; Onyekwere *et al*., 2021; Velmurugan and Babu, 2020).

In this study, the effects of compression ratio, press temperature, press time, and adhesive spread rate on the mechanical properties of densified laminated veneer lumber (dLVL) were investigated. In this context, the parameter levels were determined using Taguchi-based GRA to maximize the modulus of rupture (*MOR*), modulus of elasticity (*MOE*), tensile shear strength (*TSS*), and tensile strength perpendicular to panel surface (*TSPS*) of dLVL.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The veneers to produce dLVLs were peeled from I-77/51 American poplar clone (*Populus deltoides*) logged at an altitude of 250 m in Düzce, Turkey. American poplar wood was chosen as wood of low value with lower mechanical properties (Candan *et al*., 2013) and with great potential of improvement by densification. The veneers were peeled in thicknesses of 1.8, 2.1, and 2.4 mm to produce dLVLs and 1.2 mm to produce LVLs for the control group. They were cut in dimensions 55 cm × 30 cm, conditioned at (20±3) °C and (65±1) % relative humidity until they reached a constant weight. Their equilibrium moisture content reached approximately 13 % before the production of panels. A commercial urea-formaldehyde (UF) adhesive (Poliure 2265, Polisan Kimya San. A.Ş., Kocaeli, Turkey) was used in the production of dLVLs. 10 % by weight hard-

Table 1 Production parameters of dLVLs and control group (non-densified) LVL
Tablica 1. Parametri proizvodnje dLVL-a i LVL-a kontrolne skupine (neugušćeno)

Parameters / *Parametri*		Level 1	Level 2	Level 3	Control
Compression rate / *Stupanj ugušćenja,* %		38	47	54	7*
Press temperature / *Temperatura prešanja,* °C		130	150	170	110
Press time, min *Vrijeme prešanja,* min	under 0.8 N/mm² / *pod tlakom 0,8* N/mm²	10	10	10	10
	under increased pressure / *pod povećanim tlakom*	3	5	7	-
Spread rate of adhesive, g/m² / *Količina nanosa ljepila,* g/m²		120	150	180	150

*Compression occurred at press pressure of 0.8 N/mm². / *Ugušćenje je postignuto primjenom tlaka prešanja od 0,8* N/mm².

ener (10 % NH_4Cl/water solution) and 20 % wheat flour by weight were added to prepare UF adhesive solution.

Equilibrium moisture content and air-dry density (*d*) were measured according to standards TS EN 322 (1999) and TS EN 323 (1999), respectively. The spring-back ratios (*SB*) of the produced test panels were calculated according to Eq. 1, respectively:

$$SB = \frac{t_{\mathrm{dLVL}} - t_{\mathrm{ms}}}{t_{\mathrm{ms}}} \cdot 100 \tag{1}$$

Where t_{dLVL} is the thickness of dLVL panels in air-dry condition, t_{ms} is the thickness of panels compressed state, i.e., of a mechanical stop.

MOR and *MOE* were determined according to TS EN 310 (1999), while *TSS* was determined according to TS EN 314-1 (1998) standard. For each experimental group, five samples were tested. The *TSPS* was determined according to the principles specified in TS EN 319 (1999) standard, and three samples for each experimental group were tested. The universal test machine with 50 kN capacity (UTEST 7012) was used to determine these mechanical properties of dLVLs.

2.1 Experimental design
2.1. Postavke eksperimenta

Parameter design is the first step of the Taguchi method. Here, the parameters that affect product quality and their levels are determined. As a result of the literature review and preliminary experiments, four production parameters, compression rate (*CR*), press temperature (*PT*), press time (*Pt*), and spread rate of adhesive (*SR*), and three levels of each suitable to L9 Taguchi orthogonal array were determined (Table 2). Parameter levels are determined by the low-normal-high principles. In addition, to compare the dLVLs, control group (non-densified) LVL panels were produced in conditions shown in Table 1.

2.2 Production of dLVLs
2.2. Proizvodnja ugušćene lamelirane drvne građe

The UF adhesive was applied to one side of the veneers of various thicknesses (1.8, 2.1 and 2.4 mm) to create nine layers of dLVL drafts with 16.2, 18.9, and 21.6 mm thicknesses, respectively. In the same way, 10.8 mm thick control group LVL drafts were created from 1.2 mm thick veneers. There are four main stages in the dLVL pressing process, as shown in Figure 1. Initially, the prepared drafts were cold-pressed under 0.5 N/mm² pressure for 1 minute. Subsequently, the panels were placed in the laboratory hot press with a capacity of 180 tons (Cemil Usta SSP 180 T) and pressed under a pressure of 0.8 N/mm² for 10 minutes to reach the desired temperature of all veneer sheets. In the compression stage, the press pressure was increased

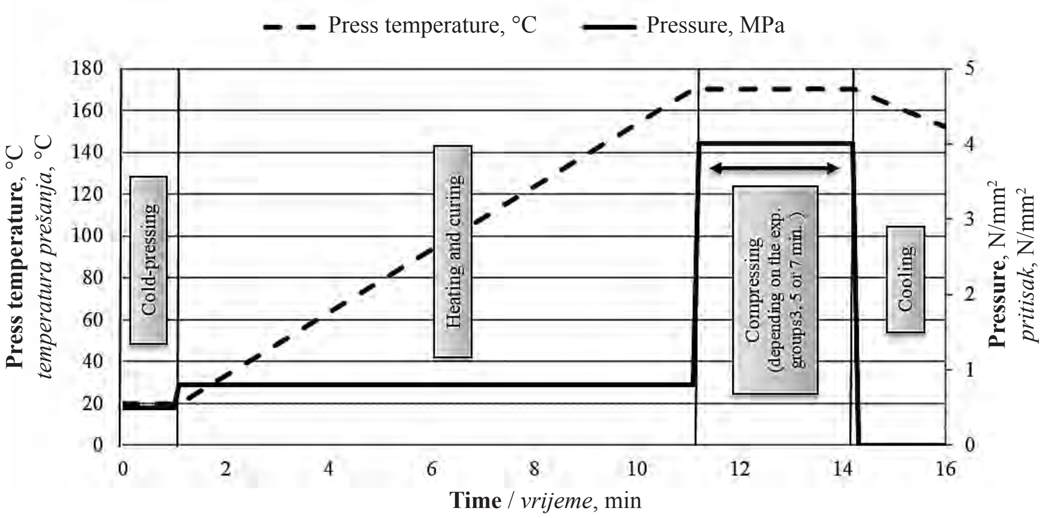

Figure 1 Schedule of dLVL pressing process
Slika 1. Raspored procesa prešanja ugušćene lamelirane drvne građe

to 4 N/mm^2 and the panels were brought to 10 mm. To ensure that all panels produced are of the same thickness, 10mm thick mechanical stops made of stainless steel were used. Thus, dLVLs were compressed at the rates of 38 %, 47 %, and 54 %. The compression step was not applied in the production of the control group LVL. The production parameters of the different experimental groups are presented in Table 2.

2.3 Single and multi-response optimization
2.3. Optimizacija s jednim i više odgovora

In this study, single responses are optimized by the Taguchi method, in which the functions called signal-to-noise ratio (*S/N*) are used and expressed in decibels (dB). The *S/N* for the *SB* was calculated according to the "smaller is better" principle using Eq. 2. In contrast, density, modulus of rupture (*MOR*), modulus of elasticity (*MOE*), tensile shear strength (*TSS*), and tensile strength perpendicular to panels surface (*TSPS*) were calculated according to the "larger is better" principle using Eq. 3, where $S/N_i(k)$: *S/N* of the i*th* experimental group for k*th* mechanical property, $y_i(k)$: test result of j*th* repetition for k*th* mechanical property, *n*: number of repetitions.

$$\left(S/N\right)_i(k) = -10\log_{10}\left[\frac{1}{n}\sum_{j=1}^{n} y_j(k)^2\right] \tag{2}$$

$$\left(S/N\right)_i(k) = -10\log_{10}\left[\frac{1}{n}\sum_{j=1}^{n}\frac{1}{y_j(k)^2}\right] \tag{3}$$

In both cases, the highest *S/N* calculated for each experimental group is considered as the best result. In addition, the contribution rates (*Cr*) and significance levels of the production parameters on mechanical properties were determined using analysis of variance (ANOVA) at a 95 % confidence interval. Taguchi-based experimental design and statistical analysis were performed using Minitab 18 software.

GRA was used to obtain optimal process parameters to maximize *MOR*, *MOE*, *TSS,* and *TSPS* at the same time. GRA was applied according to the following steps:

First, the results of *MOR*, *MOE*, *TSS*, and *TSPS* were normalized ($P_i(k)$) between the ranges from 0 to 1 to reduce the variability. The data are calculated according to Eq. 4.

$$P_i(k) = \frac{y_i(k) - \min y(k)}{\max y(k) - \min y(k)} \tag{4}$$

Then, the grey relational coefficient (ε_i) was calculated according to Eq. 5, where $\Delta_0(k)$ is the absolute difference between $P_i(k)$ and $P_i(k)$, $\Delta_{\min}(k)$ and $\Delta_{\max}(k)$ are the minimum and maximum value of absolute difference between $P_i(k)_{\max}$ and $P_i(k)$. ξ is the distinguishing coefficient and commonly assumed to be 0.5 (Kavimani *et al*., 2022; Kopparthi *et al*., 2021; Onyekwere *et al*., 2021; Velmurugan and Babu, 2020).

$$\varepsilon_i(k) = \frac{\Delta_{\min}(k) + \xi\Delta_{\max}(k)}{\Delta_0(k) + \xi\Delta_{\max}(k)} \tag{5}$$

In the fourth step, the grey relational degree (*GRD*) was calculated by summing the weighted grey relational coefficients (Eq. 6) and ranked as the largest best. In this study, equal weights *r(k)* are given for *MOR*, *MOE*, *TSS*, and *TSPS*.

$$GRD = \sum_{k=1}^{n}\frac{1}{r(k)}\varepsilon_i(k) \tag{6}$$

The grey relational degree (GRD) is a representation of the results of *MOR*, *MOE*, *TSS*, and *TSPS* as a single value. By using these values, Taguchi analysis was performed again to determine optimum process conditions. The dLVL for the confirmation test was produced in these optimum conditions. Finally, the mechanical properties of this dLVL and the control LVL produced under the standard conditions applied in industry were compared.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The air-dry density of the I-77/51 American poplar clone wood measured as 0.49 g/cm^3. The air-dry density, *DR*, *SB, MOR*, *MOE*, *TSS*, and *TSPS* of dLVLs and control group LVL are given in Table 2.

The densities of the dLVLs increased by 31 % to 43 % compared to American poplar wood and 17 % to 28 % compared to the control group LVL. When the response table for the *S/N* (Table 3a) is examined, it is seen that the most effective production parameter on density is the *CR* (45 %), as expected. However, it was observed that the increase in *CR* did not cause a significant increase in the densities of dLVLs (Figure 2a). This can be attributed to the increase in the *SB* of dLVLs, as the *CR* increases, which has the greatest effect on *SB* (Table 3b and Figure 2b). The higher *CR* increases internal stresses and causes an increase in the *SB* (Blomberg *et al*., 2006; Kutnar *et al*., 2009; Laine *et al*., 2016; Unsal *et al*., 2011). Additionally, the water in the adhesive evaporates due to the high temperature applied in pressing of dLVLs. As a result of the increased press pressure required to increase the density, this water vapor may be trapped in dLVL, which causes increased steam pressure. Therefore, the dLVLs may have tended to return to their original thickness and increased the *SB* when the press was opened. On the other hand, as the *SR* increased, an increase was observed in the density of dLVLs, because the used adhesive filled the cell lumens (Figure 2a).

Table 2 Experimental results of produced dLVLs and control group LVL
Tablica 2. Eksperimentalni rezultati proizvedene ugušćene lamelirane drvne građe i kontrolne skupine lamelirane drvne građe

Exp. Group	*CR*, %	*PT*, °C	*Pt*, min	*SR*, g/m²	*d*, g/cm³	*SB*, %	*MOR*	*MOE*	*TSS*	*TSPS*
							N/mm²			
1	38	130	10+3	130	0.68	9	122.56	14122	4.15	1.25
2	38	150	10+5	180	0.68	14	103.52	11476	6.77	1.47
3	38	170	10+7	150	0.70	9	104.11	11926	5.39	1.22
4	47	130	10+5	150	0.69	43	88.06	10429	5.25	1.51
5	47	150	10+7	130	0.69	38	97.52	10425	4.68	1.02
6	47	170	10+3	180	0.67	37	119.66	10821	5.23	1.51
7	54	130	10+7	180	0.67	45	78.97	7722	5.63	1.21
8	54	150	10+3	150	0.68	53	83.87	9391	5.33	1.27
9	54	170	10+5	130	0.64	43	71.16	6362	8.07	0.85
Control *Kontrolni uzorak*	7	110	10	150	0.55	1	82.77	10222	5.50	1.15

Table 3 Response tables for *S/N* of *d* (a), *SB* (b), *MOR* (c), *MOE* (d), *TSS* (e), and *TSPS* (f)
Tablica 3. Tablice odgovora za *S/N* od d (a), *SB* (b), *MOR* (c), *MOE* (d), *TSS* (e) i *TSPS* (f)

a)

Level	*CR*	*PT*	*Pt*	*SR*
1	-3.24	-3.31	-3.38	-3.46
2	-3.30	-3.33	-3.45	-3.43
3	-3.55	-3.45	-3.26	-3.20
Delta	0.32	0.14	0.19	0.29
Rank	1	4	3	2
Cr	45%	8%	14%	33%

Signal to noise: larger is better
Omjer signal/šum: veći je bolji

b)

Level	*CR*	*PT*	*Pt*	*SR*
1	19.79	11.87	11.82	12.36
2	8.17	10.26	10.47	10.77
3	6.53	12.36	12.20	11.35
Delta	13.26	2.11	1.72	1.59
Rank	1	2	3	4
Cr	96%	2%	1%	1%

Signal to noise: larger is better
Omjer signal/šum: veći je bolji

c)

Level	*CR*	*PT*	*Pt*	*SR*
1	41.07	39.80	40.86	39.75
2	39.99	39.44	38.71	39.90
3	37.80	39.61	39.28	39.20
Delta	3.27	0.36	2.15	0.70
Rank	1	4	2	3
Cr	66%	1%	28%	5%

Signal to noise: larger is better
Omjer signal/šum: veći je bolji

d)

Level	*CR*	*PT*	*Pt*	*SR*
1	82.14	80.57	81.25	79.96
2	80.34	80.22	79.16	79.85
3	77.70	79.39	79.77	80.38
Delta	4.45	1.17	2.10	0.53
Rank	1	3	2	4
Cr	79%	4%	16%	1%

Signal to noise: larger is better
Omjer signal/šum: veći je bolji

e)

Level	*CR*	*PT*	*Pt*	*SR*
1	14.02	13.81	13.68	14.36
2	13.99	14.55	15.87	14.98
3	15.55	15.21	14.01	14.23
Delta	1.56	1.40	2.20	0.75
Rank	2	3	1	4
Cr	24%	21%	51%	4%

Signal to noise: larger is better
Omjer signal/šum: veći je bolji

f)

Level	*CR*	*PT*	*Pt*	*SR*
1	2.13	2.83	2.41	0.11
2	2.33	1.67	1.68	3.24
3	1.31	1.28	1.68	2.42
Delta	1.02	1.55	0.72	3.13
Rank	3	2	4	1
Cr	25%	6%	14%	55%

Signal to noise: larger is better
Omjer signal/šum: veći je bolji

As seen in the response tables for the *S/N*, the most effective production parameters on *MOR* and *MOE* are *CR* and press time, respectively. While the contribution rates of *CR* and press time on *MOR* were 66 % and 28 %, those on *MOE* were 79 % and 16 %, respectively (Table 3c and 3d). The *MOR* and *MOE* values unexpectedly decreased due to the increase in *CR* (Figure 2c and 2d), although an increase in mechanical properties was expected (Kutnar and Sernek, 2007; Pelit *et al*., 2018; Yu *et al*., 2017). As a result, it is predicted that the highest *MOR* and *MOE* values will be obtained in dLVLs that are compressed at 38 % and pressed for (10±3) minutes.

As seen in Table 3e, the most effective production parameter on *TSS* was press time (51 %), followed by *CR* (24 %), press temperature (21 %), and *SR* (4 %). As known, it is possible to use lower press temperature, pressure, shorter pressing time, and less adhesive,

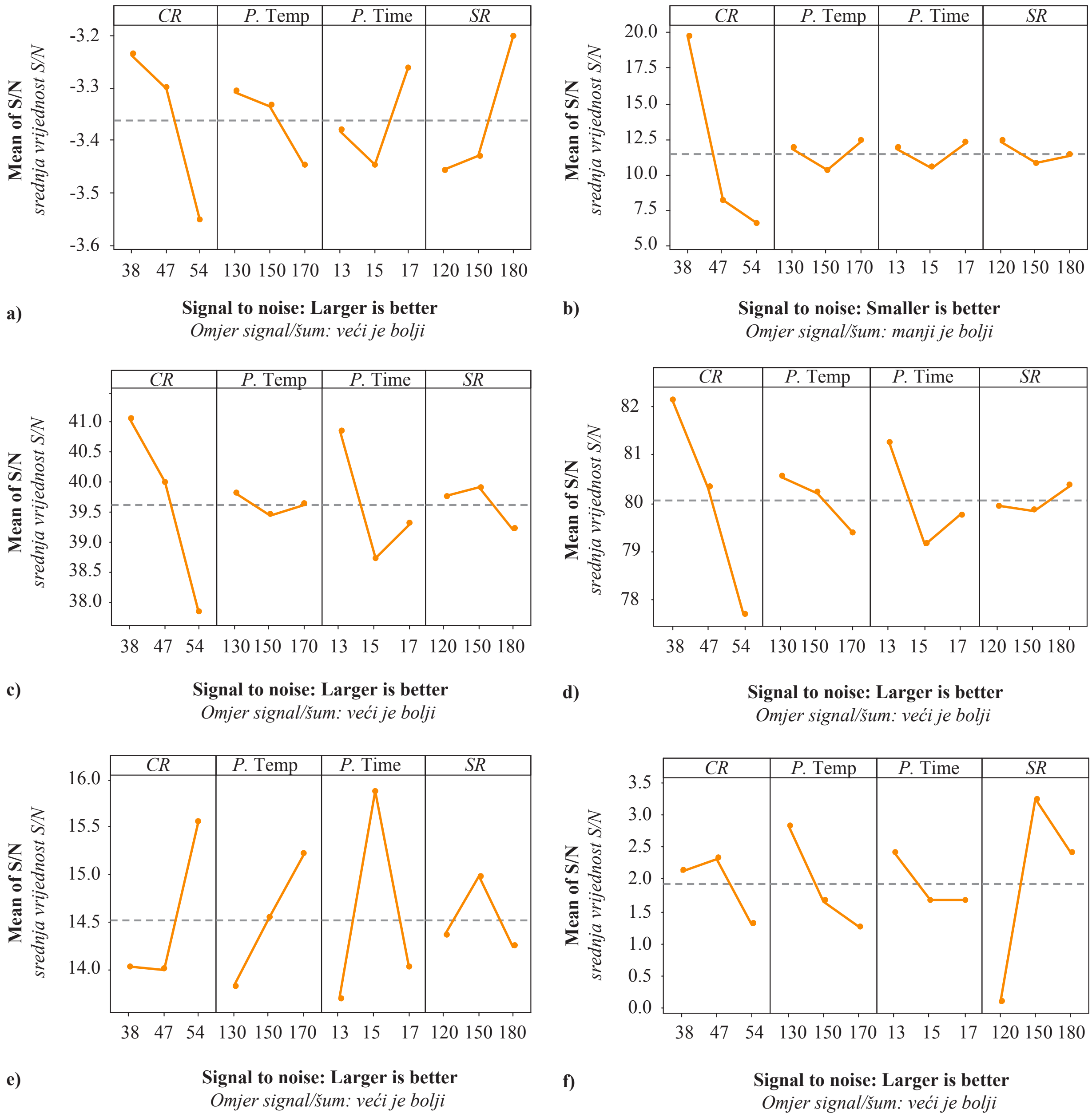

Figure 2 Main effect plots for *S/N* of d (a), *SB* (b), *MOR* (c), *MOE* (d), *TSS* (e), and *TSPS* (f)
Slika 2. Dijagrami glavnog učinka za *S/N* od d (a), *SB* (b), *MOR* (c), *MOE* (d), *TSS* (e) i *TSPS* (f)

as well as to increase mechanical properties by using densified veneer in the production of laminated materials (Bekhta and Marutzky, 2007; Bekhta *et al*., 2012; Bekhta and Salca, 2018). When the main effect plot for the *S/N* was examined, it was found that the highest *TSS* was obtained by dLVL densified by the highest compression rate of 54 % and at a temperature of 170 °C for (10±5) minutes (Figure 2e).

When the response table for the *S/N* (Table 3f) is examined, it can be seen that the most effective production parameters on the *TSPS* were the SR (55 %) and compression ratio (25 %), which made a statistically significant difference in *TSPS*. During the peeling process, cracks on the loose side of the veneer in the direction parallel to the fibers (lathe check) are inevitable (Huang, 2010). Furthermore, depending on the conditions, plastic deformation occurs during the densification, the cell lumens collapse, and the cell fractures develop (Bao *et al*., 2017; Blomberg and Persson, 2004). For these reasons, a decrease in *TSPS* can be expected. However, the adhesive used may have penetrated between these cracks and collapsed cell lumens, allowing them to repair. So, the highest *TSPS* was obtained at high SRs of 150 and 180 g/m^2, *CR* of 47 %, press temperature of 130 °C, and press time of (10±3) minutes (Figure 2f).

3.1 Multi-response optimization
3.1. Višestruka optimizacija mehaničkih svojstava

In this study, GRA, as a multi-response optimization method, was used to determine the optimum production conditions for *MOR*, *MOE*, *TSS*, and *TSPS* si-

Table 4 Calculated grey relational degree
Tablica 4. Izračunani sivi relacijski stupanj

Exp. Gr.	GRD	Orders
1	0.722	1
2	0.662	3
3	0.544	5
4	0.587	4
5	0.446	8
6	0.711	2
7	0.429	9
8	0.459	7
9	0.500	6

Table 5 Response tables for *S/N* of GRD
Tablica 5. Tablice odgovora za *S/N* GRD-a

Level	*CR*	*PT*	*Pt*	*SR*
1	-3.91	-4.93	-4.19	-5.29
2	-4.87	-5.78	-4.74	-4.63
3	-6.71	-4.76	-6.55	-5.56
Delta	2.80	1.02	2.37	0.93
Rank	1	3	2	4
Cr	48%	7%	38%	7%

*Signal to noise: larger is better / *Omjer signala i šuma: veći je bolji*

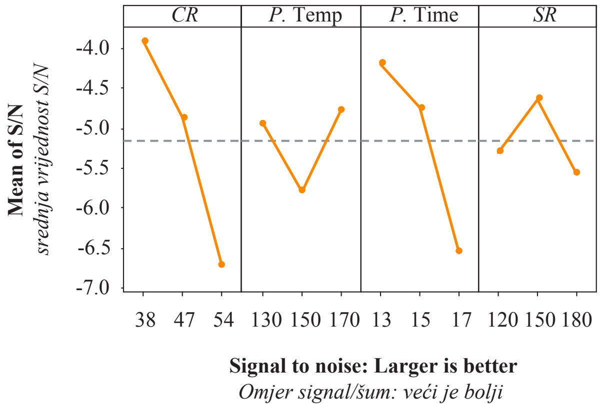

Figure 3 Main effect plots for *S/N* of GRD
Slika 3. Dijagrami glavnog učinka za *S/N* GRD-a

multaneously. The grey relational degrees (GRD) and the orders are shown in Table 4.

MOR, *MOE*, *TSS*, and *TSPS* were converted into a single response (GRD), and the effect of the production parameters on multiple performance was ordered by applying Taguchi method again. According to these results, the *CR* (48 %) and press time (38 %) had the highest effect on multiple performance of dLVLs (Table 5). The mechanical properties decreased with increasing compression ratio and pressing time (Figure 3).

3.2 Confirmation tests
3.2. Potvrdni testovi

At first, dLVL panels for confirmation were produced using optimum production conditions of 38 % compression, 170 °C press temperature, 10+3 minutes press time, and 150 g/m^2 *SR*, and their *MOR*, *MOE*, *TSS*, and *TSPS* were determined. It was found that the *MOR*, *MOE*, *TSS*, and *TSPS* of dLVLs produced under optimum conditions were 123.41, 11059, 9.40, and 1.42 N/mm^2, which is 49, 8, 71, and 23 % higher than control samples manufactured under standard conditions used in industry, respectively. The mechanical properties of dLVLs produced under optimum conditions were also compared with those of laminated materials produced with veneers of higher density, as published in literature (Table 6). As it can be seen, the dLVL may substitute LVL produced from high-value wood species and Taguchi-based GRA allows dLVL production parameters to be optimized safely and efficiently.

4 CONCLUSIONS
4. ZAKLJUČAK

The objective of this study is to determine the most suitable production conditions of compression ratio, press temperature, press time, and adhesive spread rate to maximize the mechanical properties of dLVL. The effects of the production parameters on the mechanical properties of *MOR*, *MOE*, *TSS,* and *TSPS* were also determined by using Taguchi and grey rela-

Table 6 Comparison of confirmation test results with control group and literature
Tablica 6. Usporedba rezultata potvrdnog testa s kontrolnom skupinom i literaturom

Comparison groups / *Grupe za usporedbu*		*MOR*	*MOE*	*TSS*	*TSPS*
		N/mm^2			
dLVL produced in optimum production conditions *dLVL proizveden u optimalnim proizvodnim uvjetima*		123.41	11059	9.40	1.42
Non-densified LVL (control group) / *neugušćeni LVL (kontrolna skupina)*		82.77	10222	5.50	1.15
Literature review *pregled literature*	Poplar LVL / *LVL od topolovine*	68.14[a]	6690[b]	4.24[c]	
	Beech LVL / *LVL od bukovine*	118.30[a] 95.41[b]	19512[a] 8773[b]	10.90[c]	-
	Beech plywood / *furnirska ploča od bukovine*	-	-	-	1.86[d]
	Eucalyptus LVL / *LVL od drva eukaliptusa*	94.90[a] 89.30[b]	9411[a] 9131[b]	-	-
	Oak LVL / *LVL od hrastovine*	-	-	8.94[c]	-

[a]Aydın *et al*., 2014; [b]Bal and Bektaş, 2012; [c]Uysal, 2006; [d]Réh *et al*., 2019

tionship analysis methods to optimize single- and multi-responses.

As *CR* increased, the density of dLVLs unexpectedly decreased due to the increase in *SB*. In addition, it caused an increase in density due to the fact that the adhesive used filled the cell spaces.

It was found that *CR* had the most significant impact on *MOR* and *MOE*, and contrary to expectations, dLVLs with 38 % compression showed the highest values. The most effective production parameters on *TSS* and *TSPS* were found to be press time and *SR*, respectively.

Multi-response optimization using grey relational analysis showed that the *CR* (48 %) and press time (38 %) had the most significant impact on the mechanical properties of dLVL. It has also been determined that the highest results will be obtained when the lowest *CR* of 38 % and the shortest pressing time of (10±3) minutes are applied. This combination may also reduce production costs.

Confirmation tests showed that the mechanical properties of dLVLs produced in optimum production conditions improved by 49 % (*MOR*), 8 % (*MOE*), 71 % (*TSS*), and 23 % (*TSPS*) compared to control group of LVL produced by traditional production method applied in wood product industry. So, it can be said that poplar dLVLs can be used as structural elements and the production parameters of dLVLs can be optimized safely and effectively using Taguchi-based GRA.

5 REFERENCES
5. LITERATURA

1. Alade, A. A.; Naghizadeh, Z.; Wessels, C. B.; Stolze, H.; Militz, H., 2022a: Adhesion performance of melamine-urea-formaldehyde joints of copper azole-treated *Eucalyptus grandis* at varied bonding process conditions. Construction and Building Materials, 314 (PA): 125682. https://doi.org/10.1016/j.conbuildmat.2021.125682
2. Alade, A. A.; Wessels, C. B.; Stolze, H.; Militz, H., 2022b: Improved adhesive-bond performance in copper azole and disodium octaborate tetrahydrate-treated *Eucalyptus grandis* laminates. International Wood Products Journal, 13:3, 139-147. https://doi.org/10.1080/20426445.2022.2058277
3. Aydın, I.; Çolak, S.; Çolakoğlu, G.; Salih, E., 2004: A comparative study on some physical and mechanical properties of laminated veneer lumber (LVL) produced from beech (*Fagus orientalis* Lipsky) and eucalyptus (*Eucalyptus camaldulensis* Dehn.) veneers. Holz als Roh- und Werkstoff, 62 (3): 218-220. https://doi.org/10.1007/s00107-004-0464-3
4. Bal, B. C.; Bektaş, I., 2012: The effects of wood species, load direction and adhesives on bending properties of laminated veneer lumber. BioResources, 7 (3): 3104-3112. https://doi.org/10.15376/biores.7.3.3104-3112
5. Bao, M.; Huang, X.; Jiang, M.; Yu, W.; Yu, Y., 2017: Effect of thermo-hydro-mechanical densification on microstructure and properties of poplar wood (*Populus tomentosa*). Journal of Wood Science, 63 (6): 591-605. https://doi.org/10.1007/s10086-017-1661-0
6. Bekhta, P.; Marutzky, R., 2007: Reduction of glue consumption in the plywood production by using previously compressed veneer. Holz als Roh- und Werkstoff, 65 (1): 87-88. https://doi.org/10.1007/s00107-006-0142-8
7. Bekhta, P.; Niemz, P.; Sedliacik, J., 2012: Effect of prepressing of veneer on the glueability and properties of veneer-based products. European Journal of Wood and Wood Products, 70: 99-106. https://doi.org/10.1007/s00107-010-0486-y
8. Bekhta, P.; Salca, E. A., 2018: Influence of veneer densification on the shear strength and temperature behavior inside the plywood during hot press. Construction and Building Materials, 162: 20-26. https://doi.org/10.1016/j.conbuildmat.2017.11.161
9. Bekhta, P.; Sedliačik, J.; Jones, D., 2018: Effect of short-term thermomechanical densification of wood veneers on the properties of birch plywood. European Journal of Wood and Wood Products, 76 (2): 549-562. https://doi.org/10.1007/s00107-017-1233-4
10. Blomberg, J.; Persson, B., 2004: Plastic deformation in small clear pieces of Scots pine (*Pinus sylvestris*) during densification with the CaLignum process. Journal of Wood Science, 50 (4): 307-314. https://doi.org/10.1007/s10086-003-0566-2
11. Blomberg, J.; Persson, B.; Bexell, U., 2006: Effects of semi-isostatic densification on anatomy and cell-shape recovery on soaking. Holzforschung, 60(3): 322-331. https://doi.org/10.1515/HF.2006.052
12. Buddi, T.; Singh, S. K.; Nageswara Rao, B., 2018: Optimum process parameters for plywood manufacturing using soya meal adhesive. Materials Today: Proceedings, 5 (9): 18739-18744. https://doi.org/10.1016/j.matpr.2018.06.220
13. Candan, Z.; Korkut, S.; Unsal, O., 2013. Thermally compressed poplar wood (TCW): Physical and mechanical properties. Drvna industrija, 64 (2), 107-111. https://doi.org/10.5552/drind.2013.1216
14. Fang, C. H.; Mariotti, N.; Cloutier, A.; Koubaa, A.; Blanchet, P., 2012: Densification of wood veneers by compression combined with heat and steam. European Journal of Wood and Wood Products, 70 (1-3): 155-163. https://doi.org/10.1007/s00107-011-0524-4
15. Gupta, A.; Vaishya, R.; Khan, K. L. A.; Walia, R. S.; Singh, H., 2019: Multi-response optimization of hybrid filler composition for pultruded jute fiber reinforced polymer composite. Materials Research Express, 6 (11): 1-14. https://doi.org/10.1088/2053-1591/ab4945
16. Haller, P.; Wehsener, J., 2004: Festigkeitsuntersuchungen an Fichtenpressholz (FPH). Holz als Roh- und Werkstoff, 62 (6): 452-454. https://doi.org/10.1007/s00107-004-0516-8
17. Hamzaçebi, C., 2016: Optimization of process parameters in oriented strand board manufacturing by Taguchi method. BioResources, 11 (3): 5987-5993. https://doi.org/10.15376/biores.11.3.5987-5993
18. Huang, C. L., 2010: Industry prospective of delamination in wood and wood products. In: Delamination in wood, wood products and wood-based composites, Bucur V. (ed.). Springer, Dordrecht, pp. 215-236. https://doi.org/10.1007/978-90-481-9550-3
19. Kavimani, V.; Gopal, P. M.; Sumesh, K. R.; Kumar, N. V., 2022: Multi response optimization on machinability of SiC waste fillers reinforced polymer matrix composite using Taguchi's coupled grey relational analysis. Silicon, 14 (1): 65-73. https://doi.org/10.1007/s12633-020-00782-x

20. Khan, M. U.; Abas, M.; Noor, S.; Salah, B.; Saleem, W.; Khan, R., 2021: Experimental and statistical analysis of saw mill wood waste composite properties for practical applications. Polymers, 13 (22): 1-19. https://doi.org/10.3390/polym13224038
21. Kollmann, F. F. P.; Kuenzi, E. W.; Stamm, A. J., 1975: Principles of Wood Science and Technology II: Wood Based Materials. Springer Verlag: Berlin, Heidelberg.
22. Kopparthi, P. K.; Kundavarapu, V. R.; Kaki, V. R.; Pathakokila, B. R., 2021: Modeling and multi response optimization of mechanical properties for E-glass/polyester composite using Taguchi-grey relational analysis. In: Proceedings of the Institution of Mechanical Engineers. Part E: Journal of Process Mechanical Engineering, 235 (2): 342-350. https://doi.org/10.1177/0954408920962592
23. Kúdela, J.; Rousek, R.; Rademacher, P.; Rešetka, M.; Dejmal, A., 2018: Influence of pressing parameters on dimensional stability and density of compressed beech wood. European Journal of Wood and Wood Products, 76 (4): 1241-1252. https://doi.org/10.1007/s00107-018-1298-8
24. Kutnar, A.; Kamke, F. A.; Sernek, M., 2009: Density profile and morphology of viscoelastic thermal compressed wood. Wood Science and Technology, 43 (1-2): 57-68. https://doi.org/10.1007/s00226-008-0198-1
25. Kutnar, A.; Sernek, M., 2007: Densification of wood. Zbornik Gozdarstva in Lesarstva, 82: 53-62.
26. Laine, K.; Segerholm, K.; Wålinder, M.; Rautkari, L.; Hughes, M., 2016: Wood densification and thermal modification: hardness, set-recovery and micromorphology. Wood Science and Technology, 50 (5): 883-894. https://doi.org/10.1007/s00226-016-0835-z
27. Onyekwere, O. S.; Oladeinde, M. H.; Edokpia, R. O., 2021: Multi-response optimization of bamboo fiber reinforced unsaturated polyester composites using hybrid Taguchi-grey relational analysis method. Journal of Industrial and Production Engineering, 38 (2): 98-107. https://doi.org/10.1080/21681015.2020.1848933
28. Pelit, H.; Budakçı, M.; Sönmez, A., 2018: Density and some mechanical properties of densified and heat post-treated Uludağ fir, linden and black poplar woods. European Journal of Wood and Wood Products, 76 (1): 79-87. https://doi.org/10.1007/s00107-017-1182-y
29. Réh, R.; Igaz, R.; Krišt'ák, L.; Ružiak, I.; Gajtanska, M.; Božíková, M.; Kučerka, M., 2019: Functionality of beech bark in adhesive mixtures used in plywood and its effect on the stability associated with material systems. Materials, 12 (8): 1298. https://doi.org/10.3390/ma12081298
30. Seborg, R. M.; Millet, M. A.; Stamm, A. J., 1956: Heat-Stabilized Compressed Wood (Staypak), Vol. 1580. Forest Product Laboratory, Madison, Wisconsin, pp. 1-20.
31. Shafie, M.; Zarea-Hosseinabadi, H., 2019: Eco-friendly laminated strand lumber from date palm rachis: Analysis of mechanical properties by Taguchi design of experiment. Drvna industrija, 70 (4): 359-367. https://doi.org/10.5552/drvind.2019.1843
32. Ugovšek, A.; Kamke, F. A.; Sernek, M.; Kutnar, A., 2013: Bending performance of 3-layer beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) Karst.) VTC composites bonded with phenol-formaldehyde adhesive and liquefied wood. European Journal of Wood and Wood Products, 71 (4): 507-514. https://doi.org/10.1007/s00107-013-0704-5
33. Ülker, O.; Burdurlu, E., 2016: Some mechanical properties of densified and laminated Lombardy poplar (*Populus nigra* L.). Wood Research, 61 (6): 959-969.
34. Unsal, O.; Candan, Z.; Buyuksari, U.; Korkut, S.; Chang, Y.-S.; Yeo, H.-M., 2011: Effect of thermal compression treatment on the surface hardness, vertical density profile and thickness swelling of eucalyptus wood boards by hot-pressing. Journal of the Korean Wood Science and Technology, 39 (2): 148-155. https://doi.org/10.5658/wood.2011.39.2.148
35. Uysal, B., 2006: Effects of the steam test on bonding strength of laminated veneer lumbers manufactured by using different adhesives. Journal of Applied Polymer Science, 99 (6): 2973-2977. https://doi.org/10.1002/app.22996
36. Velmurugan, G.; Babu, K., 2020: Statistical analysis of mechanical properties of wood dust filled jute fiber based hybrid composites under cryogenic atmosphere using the grey-Taguchi method. Materials Research Express, 7 (6): 1-11. https://doi.org/10.1088/2053-1591/ab9ce9
37. Wang, B. J.; Dai, C., 2005: Hot-pressing stress graded aspen veneer for laminated veneer lumber (LVL). Holzforschung, 59 (1): 10-17. https://doi.org/10.1515/HF.2005.002
38. Yu, Y.; Zhang, F.; Zhu, S.; Li, H., 2017: Effects of high-pressure treatment on poplar wood: Density profile, mechanical properties, strength potential index and microstructure. BioResources, 12 (3): 6283-6297. https://doi.org/10.15376/biores.12.3.6283-6297
39. ***TS EN 310:1999 Wood- Based panels- Determination of modulus of elasticity in bending and of bending strength.
40. ***TS EN 314-1:1998 Plywood-Bonding quality. Part 1: Test methods.
41. ***TS EN 319:1999 Particleboards and fibreboards- Determination of tensile strength perpendicular to the plane of the board.
42. ***TS EN 322:1999 Wood-based panels- Determination of moisture content.
43. ***TS EN 323:1999 Wood- Based panels- Determination of density.

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