Impact of Sawmill Processing on the Yield and Longitudinal Warping of Beech Blanks

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This study focused on the impact of the wood sawing pattern on 50 mm thick beech timber, followed by cross-cutting on the 3 m long, 50 × 50 mm beech blanks. The study analyzed two methods of cutting patterns of beech blanks (parallel to the surface of the timber and parallel to the grain fiber of the timber) regarding yield values and the size of longitudinal warping after air-drying. The yield values were higher (from 65.14 to 72.70 %) when producing long beech blanks using the method of sawing parallel to the timber's axis (B) compared to parallel to the edge of the blank (from 60.38 to 68.40 %). Results showed that a crucial factor for choosing the cutting method (A or B) is the taper of the logs. For blanks with a taper ≥ 1.3 cm.m^{-1}, it is more advantageous in terms of longitudinal warping and yield to use the method of sawing parallel to the timber's axis.

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INTRODUCTION

The primary aim of the sawmilling process is to achieve maximum yield from the original log while ensuring the desired structural properties of the sawn timber. The yield of the sawmilling process is influenced by factors such as sawing pattern, the thickness of sawn timber, cutting accuracy, and tapering stem. A comparison of different sawing technologies reveals that each method has its advantages and disadvantages in terms of material yield and structural properties of sawn timber (Popadić *et al.* 2009, 2014).

Previous studies (Todoroki and Budianto 2001; Missanjo and Magodi 2015) discovered that the taper of logs, log sawing patterns, and the interaction can significantly affect the volume production of lumber. Research by Missanjo and Magodi (2015) revealed a significant interaction between sawing method and the taper of logs. Two species of pine (*Pinus kesiya* Royle ex Gordon) and (*Pinus patula* Schiede ex Schltdl. and Cham.) were used for the cutting process. Results confirmed that different processing methods can produce different average lumber recovery with different degrees of log taper.

A strong negative relationship existed between lumber recovery percentage and log taper. The lumber recovery percentage decreased with an increase in log taper. The effects of taper and sawing methods on log yield were discovered in by Izekor *et al.* (2016). Results from the cited work showed that log diameter, taper, and length of the log have a positive relationship with lumber recovery efficiency. The study also discovered lumber recovery efficiency tends to increase with larger log diameter, short log length, and narrower taper. The interaction between sawing methods and log taper showed that different processing methods can average yield lumber recovery with different degrees of taper and consequently a reduction in the rate of wastes generated during production.

Next, researchers (Popadić *et al.* 2009, 2014) compared the quantitative and qualitative yields of beech logs sawn by the three methods (round, cant, and live or through and through sawing). The outcomes of live sawing were less favorable than the other two methods, producing similar results. In terms of quantitative yield, round sawing, and cant sawing of beech logs achieved approximately 60.5%, while live sawing resulted in a slightly lower yield of around 56.8%.

The method of drying can also significantly affect the volume production of lumber. Several authors focused on this issue (Vasileios *et al.* 2017; Kumar *et al.* 2022). The effect of drying method (air, kiln with slow or fast rate), wood quality, and lumber thickness, on the appearance of drying defects, for example, warping, checking, and discoloration), in Greek Macedonian fir (*Abies borisii-regis*) lumber, was examined (Vasileios *et al.* 2017). The results showed that the drying method, the lumber quality, and the lumber thickness strongly affected the appearance of defects, such as warping and checking on the dried lumber. The lower warping defects appeared in the lumber that was dried with the slow drying method, in the lumber of quality I, and of the small thickness. The higher warping appeared in the lumber that was dried with the fast kiln method, in the lumber of quality III, and of thickness 5 cm (Vasileios *et al*. 2017). Similar research (Frühwald 2007) focused on different larch species from three stands that were dried at high temperatures (80, 120, and 170 °C). The research investigated the effects of restraint during steaming, drying, and steaming on short-term twist reduction. Results discovered dependency of a twist on the distance to the pith. Specimens observed sawn close to the pith experienced reduced twist. The drying temperature did not remarkably influence the twist. In Yamamoto *et al.* 2021, the mechanical model was introduced to explain lumber warping based on beam theory. The numerical simulation using the introduced model examined how the amount and type of the residual stress distribution would affect the warps of the lumbers sawn from the four-sided cants with various sizes and shapes in their cross-sections, and how the different sawing patterns would affect the production efficiency of the straight lumber.

This research analyzed the impact of the sawmill processing method on the yield and longitudinal warping of the blanks of beech wood.

MATERIALS AND METHODS

Materials

European beech (*Fagus sylvatica* L.) was used as a test wood. It is the economically most significant wood species in the forests of Slovakia, and its occurrence is also substantial in Europe. Three logs with 480 and 515 mm central diameters and an average length of 3 m were used. The logs were harvested from the Kráľová nad Zvolenom area at an elevation of 784 m above sea level. The selection of logs was based on different values of the taper. Measurements of length and diameter were taken at the thinner end, middle of the length, and thicker end of each log. Diameter measurements were conducted in two perpendicular directions. The dimensions are provided in Table 1. The volumes and tapering of the logs were calculated from the measured dimensions.

Methods

Cutting

The sawing of logs into lumber was performed on a horizontal band saw, Mebor 1000, manufactured by Mebor d.o.o. Slovenija. All logs were sawn using the same sawing pattern, which was a through and through sawing, symmetrically from the axis of the log. The cutting thickness of the lumber, including allowances for drying, was 54 mm, and the width corresponded to the diameter of the chosen log segment and its position relative to the pith. After drying, the dimensions of the lumber were 50 × 50 mm with a length of 3000 mm. The sawing pattern used is shown in Fig. 1. The six pieces of lumber were cut from each log.

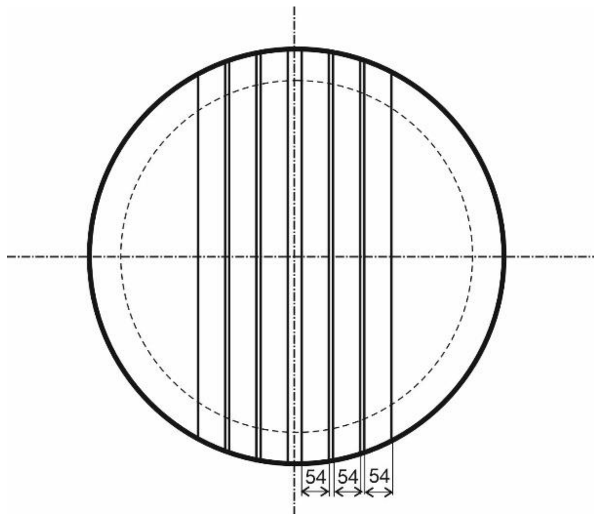

Fig. 1. Log-sawing patterns for beech logs

Each piece of lumber was cut into parts, as illustrated in Fig. 2. Two main principles of sawmilling boards were used for this research:

A) cutting parallel to the board's edge,
B) cutting parallel to the board's axis.

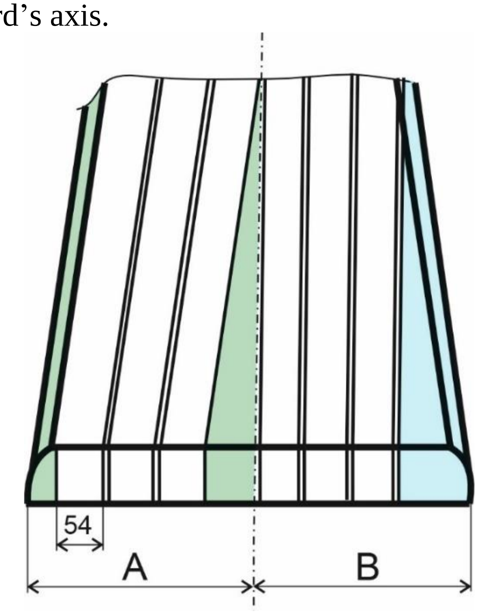

Fig. 2. Method of sawing timber into blanks: A – parallel to the edge of the blank, and B – parallel to the axis of the blank

Cutting parallel to the surface of the board has the advantage that valuable sapwood can be used precisely. The cutting is parallel to grains and the middle part of the board containing for example juvenile wood and pith is removed. Cutting parallel to the board's axis of the board is characteristic of a larger amount of blanks, but the edge part of the blank containing sapwood produces only short blanks of non-uniform width.

The dimensions of lumber and blanks were measured with an accuracy of 0.01 mm, and the quantitative yield of lumber was calculated according to Eqs. 1 to 3,

$$Q_{yt} = \frac{V_t}{V_l} \cdot 100 \tag{1}$$

where Q_{yt} is the quantitative yield of timber (%), V_t is the volume of timber (m^3), and V_l denotes the volume of log (m^3). The quantitative yield of blanks was calculated using Eq. 2, as follows,

$$Q_{yb} = \frac{V_b}{V_l} \cdot 100 \tag{2}$$

where V_b is the volume of blanks (m^3) and V_l is volume of logs (m^3). The quantitative yeild of blanks from timber (%) was calculated with Eq. 3,

$$Q_{ybt} = \frac{V_b}{V_t} \cdot 100 \tag{3}$$

where V_b is the volume of blanks (m^3) and V_t denotes volume of timber (m^3).

Drying of blanks

Both groups of blanks (A, B) were dried in the KS Mini hot air dryer from Katres Ltd., Czech Republic. The maximum drying temperature reached 62 °C. The total drying time was 405 h. The average initial moisture content of the sections was 78.3%, and the average final moisture content was 10.9%. The moisture content variation of the samples after drying was within 1%. To eliminate the negative impact of internal stresses during drying, a gentle drying regime with equalization and softening was applied. Figure 3 shows the course of drying, which exhibits a typical shape for hot air drying.

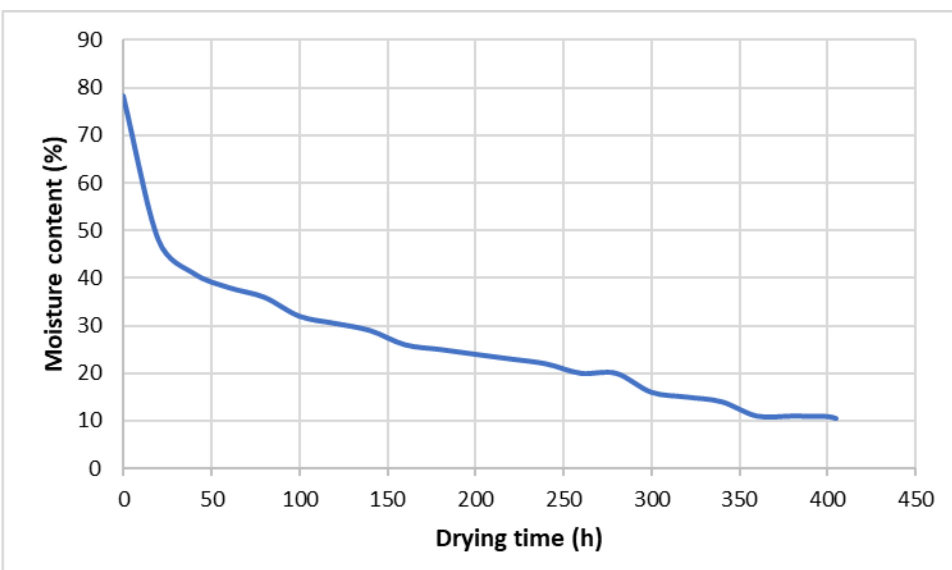

Fig. 3. The curve showing while drying

The drying mode was selected based on the ON 49 0651 standard. After a rapid decrease in moisture content (from 78.2% to 40%) at the beginning of drying, there was a slowdown in moisture content loss, reaching an average moisture content of 20% to 25%. This period corresponds to the evaporation of free water. The last phase is the evaporation of bound water, leading to the attainment of the final moisture content.

The measurement of the longitudinal warping

The measurement of the longitudinal warping of the blanks was performed using an optical method after drying. The lateral longitudinal warping was measured. Each sample was captured with high resolution. After image processing, the deviation from the ideal (original) shape - the zero optical axis - was measured. For the 3000 mm long logs, seven measurements of deviations from the zero optical axis were taken. Figures 4 and 5 illustrate the measurement points and the measured shape deviations from the zero axis.

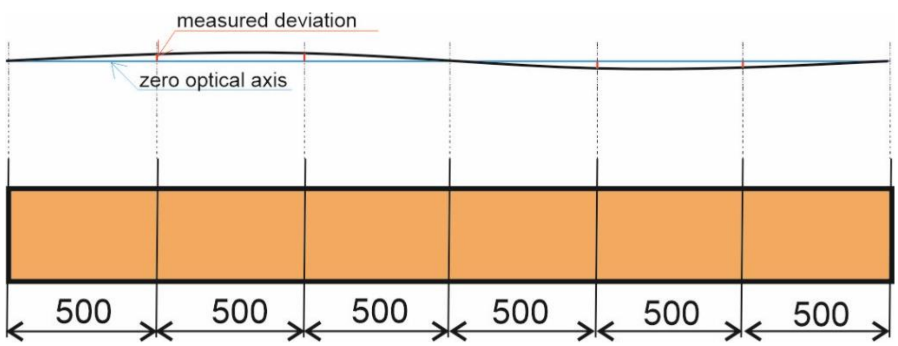

Fig. 4. Places and method of measuring the change in shape (longitudinal warping)

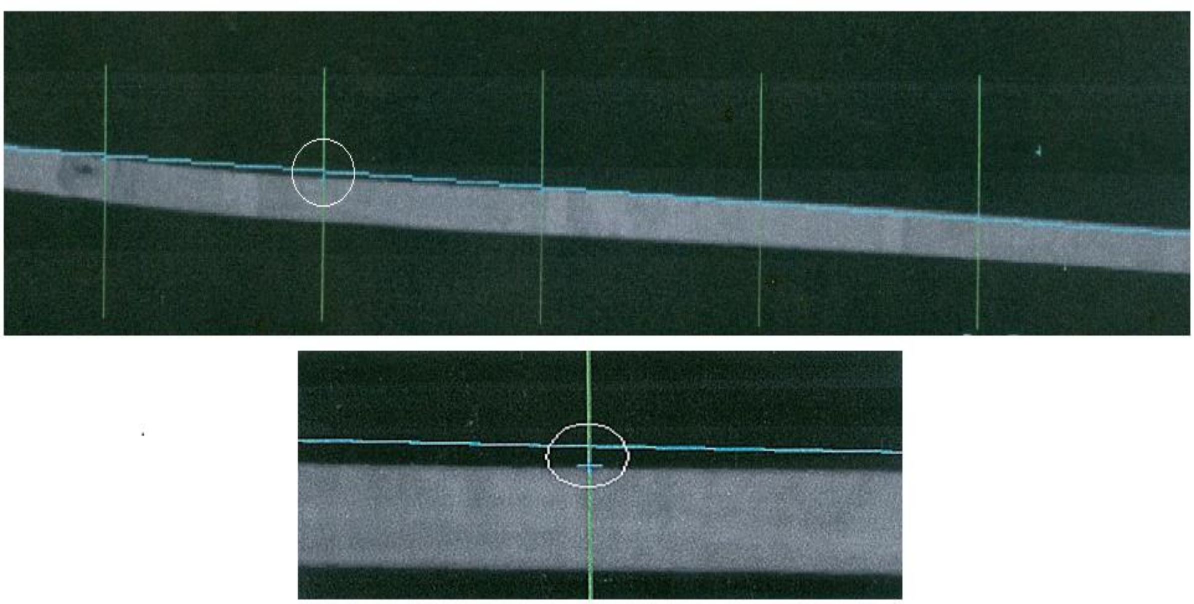

Fig. 5. Optical measurement of shape deviation from the zero axis

Shining 3D (*EinScan HX*) with a unique combination of blue LED light and blue laser was used for the measurements and was able to photograph beech blanks. The measurement accuracy was 0.01 mm. The program Solid Edge Shining 3D (Trial edition) was employed to evaluate the measured values. Other results, such as the comparison of the results of the longitudinal warping values, were evaluated through the Statistica 12 program (StatSoft, Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

The basic measured dimensions of the logs and the calculated values of the tapers are shown in Table 1.

Table 1. The Measured Dimensions and Taper of Beech Logs

Log	Diameter at the Thinner End (mm)			Diameter Average (mm)			Diameter at the Thicker End (mm)			Log Length (mm)	Taper ($cm.m^{-1}$)
	1	2	Ø	1	2	Ø	1	2	Ø		
1	500	500	500	530	500	515	540	540	540	3110	1.29
2	460	470	465	470	490	480	470	500	485	3020	0.66
3	470	500	485	500	530	515	580	700	640	3140	4.94

The diameters of the logs were measured at the thinner end, the middle, and the thicker end. The diameter was measured in two perpendicular directions. Log 1 had a symmetrical circular cross-section along its entire length, and its taper value was within the average range reported for beech wood. Log 2 had the lowest taper value and was slightly elliptical. The difference between diameters measured in perpendicular directions was 20 mm. This log (No. 2) had the smallest diameter among all the evaluated logs. Log 3 had a significantly elliptical shape, with a diameter difference of 120 mm at the thicker end. It was a section with a high tapering stem.

Table 2 shows the calculated values of quantitative yields for individual segments (logs, timber, and blanks as well). Yields for individual stages of processing were calculated according to Eqs. 1 to 3.

Table 2. Volume of Lumber and Logs and Calculated Quantitative Yield

Log	Volume of Logs (m^3)	Volume of Timber (m^3)	Timber Yield from the Log (%)	Method of Sawing	Total Blanks (Piece)	Volume of Blanks (m^3)	Yield of Blanks from Timber (%)	Yield of Blanks from Logs (%)
1	0.62	0.47	76.21	A	17	0.15	65.05	24.79
				B	19	0.17	**72.70**	**27.70**
2	0.52	0.41	78.63	A	16	0.14	68.40	26.89
				B	16	0.14	68.40	26.89
3	0.63	0.45	70.86	A	10	0.09	**47.69**	**14.58**
				B	18	0.16	65.14	26.24
Ø	0.59	0.44	75.03	A	14.3	0.13	60.38	22.9
				B	17.7	0.16	68.75	26.95

* **A** – parallel to the edge of the blank, **B** – parallel to the axis of the blank

The log 2 had the smallest volume. Logs 1 and 3 had almost the same volumes, but the quantitative yields were different. In log 1, the wood yield was 5.35% higher for timber yields, 12.5% for lumber yields, and 5.8% for raw material yields. Similar average yield values were also observed for log 2, where the lowest taper value of the section had a positive effect. In log 3, the lowest yield values were due to the highest taper value of the log (4.94 $cm.m^{-1}$). In similar works (Popadić *et al.* 2009, 2014), it was observed that the structure of products was strongly influenced by the choice of sawing patterns. These results showed most favorable in cant sawing, and least favorable in live (through and through) sawing.

When comparing the methods of producing lumber, higher yields were achieved for all logs when cutting parallel to the log axis (B). This method resulted in an average yield increase of 4.86% compared to method A (cutting parallel to the log surface). Method B also produced a higher number of lumber pieces. In log 1, using method B, the yield for raw material was 2.91% higher. The method of cutting did not significantly affect the yield for log 2. However, log 3 exhibited the highest difference in yields between the cutting methods. With method B (parallel to the log axis), the yield of lumber from log 3 was 11.7% higher compared to method A (parallel to the log surface). The difference in the number of lumber pieces produced was also significant. For this log and method A, 10 pieces were produced, while with method B, it resulted in 18 pieces. Log 3 had the largest diameter and volume among all evaluated sections.

These findings confirm that the choice of sawing patterns played a significant role in the final yield of blanks. Studies (Wang 1987; Popadić *et al.* 2009; Popadić *et al.* 2014; Missanjo and Magodi 2015) confirmed that there were significant ($p < 0.001$) differences between the sawing patterns and the resulting volume of lumber. Likewise, based on the results of Yamamoto *et al.* (2021) it was assumed that the production efficiency of the lumbers also differs depending on the sawing patterns.

The efficiency of its processing is the lowest, with the highest proportion of piecewise offcuts (waste). This is because the log had a highly elliptical shape and a high value of taper. The taper value of the logs is a more significant factor in terms of yield than the diameter of the section. The influence of taper becomes more significant when producing smaller elements from the log. For the log with high taper, the average yield value for the lumber was 56.2%, while for the lumber pieces it was 20.4% (with the lowest value being 14.6%). Likewise, a study (Izekor *et al.* 2016) affirmed that sawing methods play a significant role in the efficient yield of logs and minimizing the volume of waste. The results from previous studies (Missanjo and Magodi 2015) indicate there were significant ($p < 0.001$) differences between log taper on lumber recovery percentage with small taper having a higher recovery percentage than medium and large tapers.

Even when comparing yields with different methods of cutting lumber (A, B), the taper of the logs was found to be the decisive factor. For the log with the lowest taper (log 2), the yield values were the same for both methods of producing lumber pieces. The efficiency of producing lumber pieces by cutting parallel to the side of the section is significantly influenced by the taper of the log. This method of producing lumber pieces is not recommended for taper values ≥ 1.3 $cm.m^{-1}$. The elliptical shape of the sections had a smaller impact. Its influence on yields was between 1% to 1.5%. The work (Izekor *et al.* 2016) showed that the taper level of logs had a significant effect on the yield of lumber. The authors discovered minimum tapering ranged from 0.1 to 0.4 cm/m whilst the maximum ranged from 3.1 to 8.2 cm/m. Similarly, a study by Okai (1998) confirmed that among the factors that might affect the effective yield of logs are other things, even taper on logs.

After drying, the values of longitudinal warping of the lumber pieces were measured. The measured values were statistically processed for each log and method of cutting lumber pieces (A, B). Table 3 presents the basic statistical characteristics of the measured values of longitudinal warping for each log. Statistically significant differences in the influence of the cutting method on the values of longitudinal warping were also tested. Additionally, statistically significant differences in the size of warping between the logs and cutting methods were examined. Many researchers (Vasileios *et. al* 2017; Kumar *et. al* 2022) confirmed that the size of the change of shape of lumber could be affected, for example, the drying method, the lumber quality, and the lumber thickness. In Yamamoto *et al.* (2021), the warping of the sawn lumber was affected by the type and the amount of the inherent strain distribution or by the cross-sectional shape.

Table 3. Statistical Characteristics of Longitudinal Warping

Number of Logs	Method of Sawing Blanks	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Count
1	A	20.00	3.86	19.78	15.91	253.21	119
	B	12.29	1.13	11.18	4.93	24.31	133
2	A	19.84	2.63	16.09	10.51	110.41	112
	B	22.19	3.64	13.50	14.58	212.46	112
3	A	22.54	6.37	14.76	20.14	205.70	70
	B	14.31	2.01	13.01	8.51	72.39	126

Figure 6 shows the results of the statistical evaluation of the significance of the average values of the longitudinal warping between the logs in the used methods of sawing the blanks (A, B).

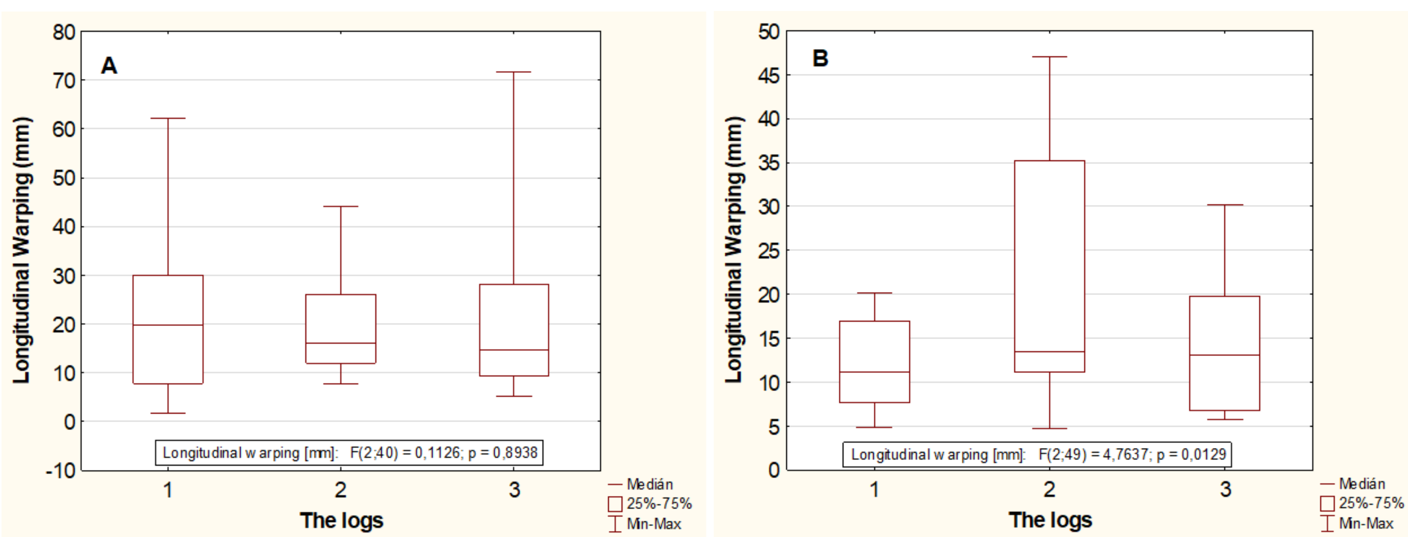

Fig. 6. Comparison of the statistical significance of the differences in longitudinal warping values (mean or median) A - parallel to the surface, B - parallel to the axis

For logs 1 and 3, the average values of warping were higher when cut parallel to the surface of the timber (Method A). For log 2, higher values were observed when cut parallel to the axis of the timber (Method B). This was influenced by the dimensions and taper of the logs. Log 2 had the smallest taper and a circular cross-section.

Statistically insignificant differences in the values of longitudinal warping were observed between the logs when cut using method A (parallel to the surface). This cutting method does not remarkably affect the size of warping, regardless of the taper, elliptical shape, or dimensions of the logs and timber. In this method of sawing (A), the cut is made parallel to the surface and, consequently, parallel to the fibers of the wood. Fiber cut-through is minimal, leading to similar values of longitudinal warping after drying. Results (Frühwald 2007) showed a clear dependency of a twist on the distance to the pith too. Specimens sawed close to pith experienced reduced twists. According to Straže *et al.* (2010) the twist was induced in most cases around the fiber saturation point. The radial position of boards had a significant influence on twists. End values of twist amounted from 10 and 20 °/m close to the pith and decreased to less than 4 °/m at 70 mm from the center of logs.

In the method of cutting parallel to the board axis (B), the differences in the warping values between the logs were statistically significant ($p = 0.0128$) (Fig. 6 B).

There was a statistically significant difference in the values of the longitudinal warping of the blanks between the cutting methods for logs 1 and 3 (Fig. 7). The highest (1B) and the lowest (3A) yield values were also calculated for these logs and methods of cutting blanks (Table 2). A statistically significant difference ($p = 0.0087$) was also measured between 1 and 2 logs and different methods of cutting blanks (1B and 2A) (Fig. 8).

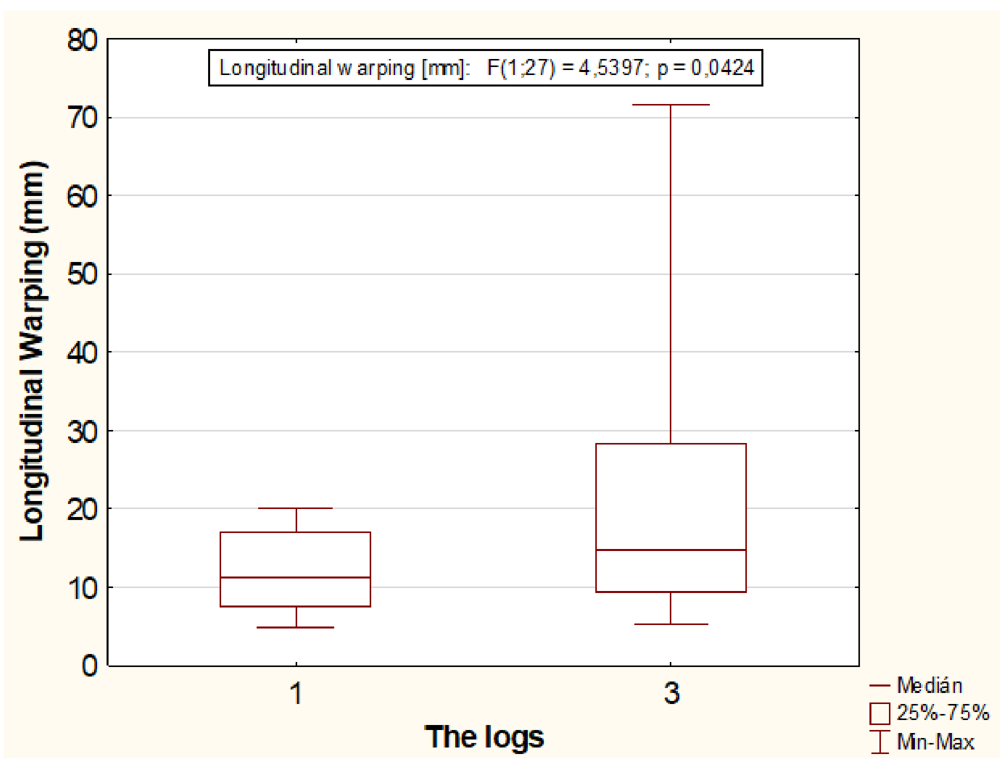

Fig. 7. Comparison of the differences in longitudinal waring with the log 1 and cutting method (B) and the log 3 and cutting method (A)

Figure 8 shows a statistically remarkable difference in longitudinal warping for the log 1 and cutting method (B) and the log 2 cutting method (A) (Fig. 8).

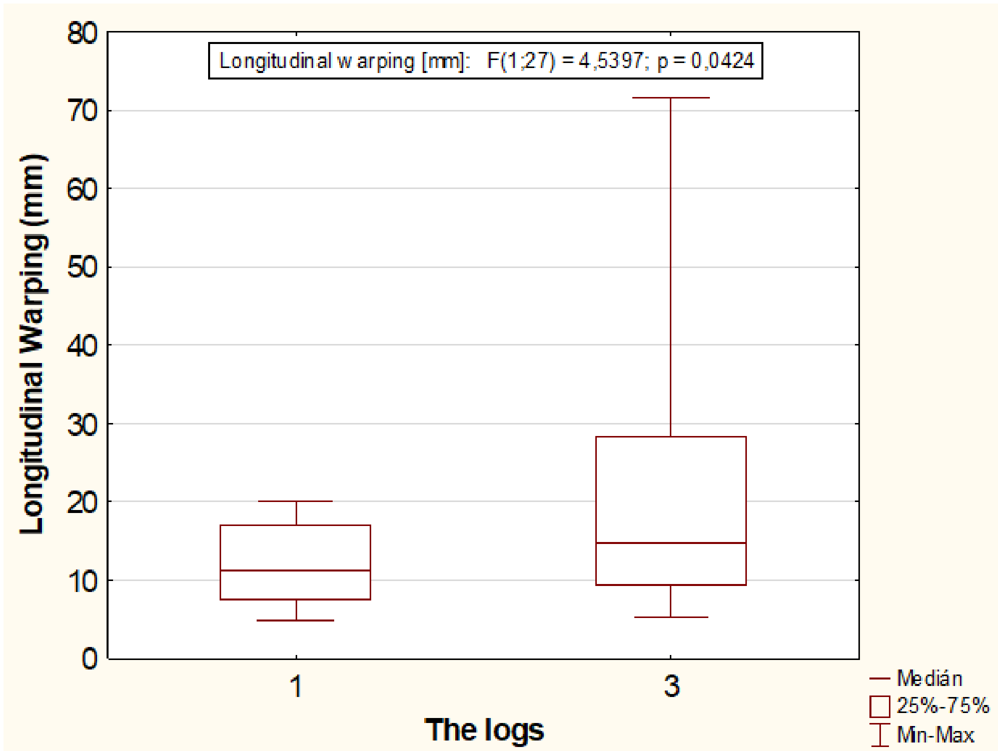

Fig. 8. Comparison of the differences in longitudinal warping with the log 1 and cutting method (B) and the log 2 and cutting method (A)

The value of the yield or lumber had the most significant influence on the values of yields and longitudinal warping of the produced blanks in the compared methods of cutting blanks (A, B). For cut-outs where the taper was small (log 2), both methods of producing blanks can be used from the point of view of longitudinal warping. There was no statistically significant difference between them.

CONCLUSIONS

The topic of the published article was to explore the impact of cutting patterns used in sawmill processing on the yield and longitudinal warping of beech blanks. Based on the results, the following conclusions can be made:

1. The yield values of blanks from timber were higher (from 65.1 to 72.7%) when producing long beech blanks using the method of sawing parallel to the timber's axis (B) compared to parallel to the edge of the blank (from 60.4 to 68.4%).

2. The yield values of blanks from logs were higher (from 26.2 to 27.7%) when producing long beech blanks using the method of sawing parallel to the timber's axis (B) compared to parallel to the edge of the blank (A) (from 14.58 to 26.89 %).
3. The yield was remarkably influenced by the taper of the log. A higher taper (from 1.3 to 4.94 cm.m^{-1}) resulted in a lower yield (log 3 = 14.58 %) when using the method of sawing parallel to the edge of the blank.
4. For the regular log with low taper (log 2), the yield values were the same for both cutting methods which we can attribute to the lowest taper of the log (0.66 cm.m^{-1}).
5. The impact of the sawing patterns on the size of longitudinal warping in the blanks was like its effect on yield. For blanks 2 (with a low taper), the longitudinal warping was lower when using the method of sawing parallel to the edge of the board (A).
6. For blanks with higher taper, the longitudinal warping values were lower when using the method of sawing parallel to the timber's axis.
7. The crucial factor for choosing the cutting method (A or B) is the taper of the logs. It has a significantly greater impact than the shape or diameter of the blanks. For blanks with a taper $\geq$ 1.3 cm.m^{-1}, it is more advantageous in terms of longitudinal warping and yield to use the method of sawing parallel to the timber's axis.

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