Effects of Beech Wood Dimensions and Quality on Edge-glued Boards Yield

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The production of edge-glued boards is one of the possibilities of using European beech wood for products with higher added value. European beech is highly abundant in the forests of Central Europe, but it is a wood species that has specific characteristics that affect the efficiency of processing. The dimensions and quality of the raw material are determined by the standard. This study analyzes the influence of the quality of European beech raw material on the quantitative and qualitative yield during the production of cross-sections used to produce edge-glued boards. Results show that the effect of class (raw material quality) on the quantity of timber produced is not remarkable. For classes III.B and III.C, the most prevalent factors diminishing yield were the quality and extent of red false heartwood, as well as cracks. This study confirmed that superior raw material quality has a positive impact on the yield of blanks with the highest quality.

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Keywords: Quality of raw material; European beech; Blanks; Red false heartwood; Reaction wood; Quantitative yield; Edge-glued boards

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INTRODUCTION

Wood product manufacturers face several significant challenges, particularly because of the high variability of raw materials. It is important to use high-quality logs to produce sawn blanks to reduce the number of trees that need to be cut down. Efficient utilization of wood extracted from the forest decreases waste generation. This leads to a higher yield of sawn blanks, contributing to the conservation of forest resources and overall environmental sustainability (Brunetti *et al.* 2020;de; Stragliotto *et al.* 2023).

Salim and Johansson (2016) proposed to examine the direct and indirect influences on the manufacturing process of the wood product industry in terms of productivity and efficiency. The direct influences (changeover, unpaid/paid break, meeting/training, *etc*.) aimed to examine the impact of consuming raw materials on the manufacturing process, while the indirect influences (quality of logs, *etc*.) examined process-related aspects affecting the material's influence on the manufacturing process. Two products were compared: Finger-joint Panels delivered to the customer with a moisture content of 8% to 10%, finger-jointed, knot-free, and only cover painted; and Solid Panels delivered to the customer with a moisture content of 16% to 18%, solid, knotty, and not surface finished. The first phase (direct influences) of the study discovered that there are pros and cons to both types of observed panels. Finger-joint raw material yields more "A quality" products. Furthermore, the dimensional stability of finger-joint panels remains more consistent than that of solid-wood panels over their use. The indirect influences have shown that material handling is one of the key process-related aspects that affect the material's influence on the manufacturing process.

The objective of Stragliotto *et al.* (2023)'s study was to evaluate the quality of logs and the sawn wood yield for export of the tropical species *Dinizia excelsa* Ducke, *Hymenolobium heterocarpum* Ducke, *Dipteryx odorata* (Aubl.) Willd., *Astronium lecointei* Ducke, and *Qualea paraensis* Ducke. The log quality parameters analyzed were conicity, flattening, curving, buttresses, cracks, heartwood percentage, and net volume. After sawing, the timber yield was determined. The species *D. odorata* exhibited the highest percentage of logs classified in the superior class. In the case of *D. odorata*, the average yield of sawn wood (35.2%) was statistically like that of *D. excelsa* (40.2%). *Hymenolobium heterocarpum* (30.5%) was different from the yields of other species. The lowest timber yield values for export were observed for species *A. Lecointei* and *Q. Paraensis.*

Several factors affect the quantitative and qualitative yield in the sawmills that process, with the main factors being the entrance quality of logs, storage in the storage yard, the type of equipment used (technology) in the cutting process, or the type of products of wood (Gerwing *et al.* 2001; Danielli *et al.* 2016; Melo *et al.* 2016; Klement *et al.* 2023; Rozas *et al.* 2023; Vilkovský *et al.* 2023).

Račko and Čunderlík (2006) focused on the qualitative and quantitative evaluations of the false heartwood in beech logs. The authors found that the lowest proportion of unseasoned heartwood was found in logs of quality class V. The limiting factors for this class are the diameter of the logs and other defects. Most logs with false heartwood were categorized in quality classes III/A and III/B. The analysis shows that the width and type of false beech heartwood are not restricting factors for categorizing logs into higher-quality classes. A newer study by Račko and Čunderlík (2013) compared the qualitative structure of beech logs sorted by the old and new Slovak technical standard STN 48 0056 (2007). The study showed that tightening sorting criteria, especially the middle diameter of logs, negatively impacts the qualitative structure of beech logs and reduces the yield from wood assortment sales. The analysis also indicated that limiting the frequency and size of red heartwood in beech logs can achieve a favorable qualitative structure and significantly increase the yield from the sale of produced assortments even the next studies by Straže *et al.* (2020) or Knoke (2003). The present observations are consistent with Majka *et al.* (2022), who showed that beechwood tends to have higher tangential shrinkage than other European hardwoods, making it more susceptible to warping and twisting. This is because it has a relatively high content of wood rays, which can influence its drying behavior and susceptibility to defects. Beechwood is also particularly prone to surface checks, especially during the initial drying stages. According to similar research by Ťavoda (1993), the main defect during the sorting of beech logs into individual classes is the false heartwood, while the proportion of the false heartwood significantly increases with increasing tree age. Based on economic analysis by Ťavoda (1993), the highest effectiveness of the round wood utilization (III.A and III.B quality class) is width group 30 to 39 and 40 to 49 cm.

The study by Lima *et al.* (2019) focused on the effect of species and log diameter on the volumetric yield of timber. Results discovered that the taper of logs has a significant influence on the yield of timber, and remarkable differences in the diameters of the thick and thin ends result in excessive material loss, as the sawn timber was obtained from the smaller diameter end. According to Vilkovský *et al.* (2024), among other things, even the spiral grain could remarkably influence the resulting quality of the lumber.

Muñoz *et al.* (2013) conducted a study to investigate the variation in sawing yield and create models to predict timber volume and class recovery. These models use easily measurable predictor variables of sawn logs to improve the efficiency and predictability of the timber production process.

The research used 82 logs, and the visual grading of logs resulted in the following quality classes: A: 9%, B: 34%, C: 37%, D: 13%, and below class D: 7%. Despite the variation in log classes, the total volumetric sawing yield was found to be 47.6%. Surprisingly, the log class did not significantly impact the sawing yield in the sample analyzed, even with logs ranging in diameter from 22 cm to 77 cm at the smallest end. However, the sawing pattern used did significantly affect the total sawing yield and the yield of structural planks. The study revealed that the sawing pattern had a significant impact on both the total sawing yield (F = 4.913; p-value = 0.001) and the yield for structural planks (F = 6.142; p-value = 0.0002). Specifically, radial sawing with one cut and live sawing of half logs provided the highest yields. These findings suggest that while the log class may not be a critical factor in determining sawing yield, the choice of sawing pattern is crucial for optimizing yield in timber production.

A similar paper by Tanušev *et al.* (2009) aimed to determine volume yield, timber value yield, and log value yield of common European beech (*Fagus sylvatica* L.) logs with smaller diameter and quality during their processing dimension stock and flooring components. European beech trees were harvested in Bosnia and Hercegovina. The object of the research was European beech logs divided into three groups with mid-diameters ranging from 18 to 20, 21 to 23, and 24 to 26 cm. Primary sawing of logs used a through-and-through sawing pattern on the band saw. All obtained sawn boards were sawn lip into dimension stock and flooring components by the cross-rip sawing method. The results showed that the best log volume yield in the form of blanks and flooring components showed logs with mid-diameters ranging from 24 to 26 cm. The results confirmed that the quality criteria of logs, dimensions of blanks, and flooring components that will be produced from that raw material are important. In this paper, the utilization of three very narrow diameter classes was also compared. It was established that the diameter of logs was not statistically significant.

The article by Popadić *et al.* (2014) presents the research of differences in quantitative and value yields, and structure of timber and residues, whose appearance is caused by different methods of sawing European beech logs with red heartwood. The authors used 45 logs in the research with lengths of about 4 m divided into three groups and the logs were sawn using three patterns: round, cant, and through-and-through sawing patterns. The quality class (I to III) was determined for unedged, edged, and red-heart timbers. Round sawing patterns were the dominant timber with the highest value (class I) and the lowest value (class II). The through-and-through sawing pattern had the lowest percentage share (about 23%) of the highest value (class I) and class II (about 3%). Live sawing resulted in less timber (edged and red heartwood boards) and smaller products compared to the other two methods, indicating a lower value yield. Results showed that methods of sawing have a noticeable impact on the quantity yield of small products (F = 28.188; p = 0.000). A similar result was also confirmed in the work of Vilkovský *et al.* (2023).

The main objectives of this study were to analyze the effect of raw material quality and to identify the relevance of dimensions and specific defects on product yield. This work provides new insights into how the stated specific properties of European beech raw material influence the technological process of producing edge-glued boards. More specifically, the study examines the impact of log quality on all types of products, from lumber production to long blanks and then to shorter blanks.

EXPERIMENTAL

Three groups of European beech logs were used for measurements, divided according to STN 48 0056 (2007) into three quality classes: III.A, III.B, and III.C. Quality class III was intended for sawmill processing into timber. Subclasses A, B, and C differed in the range of permissible wood defects (see Table 1) according to STN 48 0056 (2007). The minimum diameter for Class III hardwood raw material is 160 mm, and the length is 2000 mm. Material for investigation was obtained on the area of the Forests of the Slovak Republic district (Poľana, Považie, Tribeč).

This study used 92 logs of European beech cuttings of quality class III.A, 155 logs of class III.B, and 171 logs of class III.C. These logs were sawn into timber using through--and through sawing patterns, where the central part was sawn to a thickness of 55 mm and the side part to a thickness of 30 mm. The edges were milled and then used to process the agglomerated materials. Log sawing pattern is shown in Fig. 1. The log sawing pattern was made on an EWD 1800 bandsaw with a milling head PF 19.

The dimensions of each log were measured using an optical measuring system (Logeye-DE-700; Microtec, Bressanone, Italy), and the quality was visually assessed based on the criteria shown in Table 1. The average values and basic statistical characteristics of the European beech raw material used as input are presented in Table 2. All quality characteristics were analyzed by Statistica Software 7.0 (TIBCO Software, 7.0, Palo Alto, CA, USA).

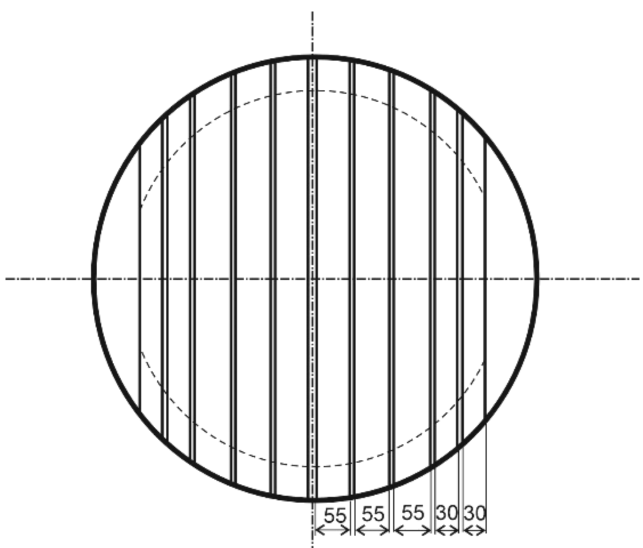


Fig. 1. Method of cutting beech logs to timber

The timber was then made into blanks by longitudinal-transverse sawing pattern (Fig. 2). During the production of the blanks, defects that are unacceptable for the final product - blanks were removed. These were cracks, knots, curvature, rounded sides of the timber, overgrown bark, red false heartwood, rot, *etc*.

Table 1. Classification of European Beech Raw Material in Quality Classes

Qualitative Characteristic		Qualitative Class		
		III.A	**III.B**	**III.C**
Knots	**closed**	up to 6 cm of diameter knot/ 2 knots are allowed/*cm; up to 1 cm of diameter knot are not taken into account	up to 10 cm of diameter knot/ 2 knots are allowed/*cm; up to 1 cm of diameter knot /are not taken into account	4 knots are allowed/*cm; without limit
	open	not allowed	not allowed	up to 8 cm of diameter knot/ 1 knot is allowed; for logs over 60 cm, 1 knot up to 15 cm diameter knot is allowed'
	overgrown	1 knot per/*cm is allowed	2 knots per /*cm is allowed	without limitation
Cracks	**shake**	not allowed	not allowed	not allowed
	pith	allowed straight and compound up to 1/4 of the diameter of the front	allowed straight and compound up to 1/2 of the diameter of the front	without limitation
	dry	The front ones are allowed up to 1/4 of the frontal diameter	The front ones are allowed up to 1/3 of the diameter of the front; side passing through shall be allowed up to 1/5 of the thickness of the front	The frontal are allowed without limitation; lateral transversions shall be allowed up to 1/3 of the thickness of the front
	frost	not allowed	1 crack without signs of rot is allowed	without limitation
Signs of stem growth	**curvature**	One-sided is allowed up to 3 cm/cm; up to 4 cm/*cm shall be allowed for logs over 6 m; multi-directional not allowed	One-sided is allowed up to 4 cm/*cm; up to 5 cm/cm shall be allowed for logs over 6 m; multi-directional not allowed	One-sided is allowed up to 5 cm/*cm; up to 6 cm/cm shall be allowed for logs over 6 m; multi-directional is allowed if it can be removed on a minimum length of 3 m of a logs that fulfil the conditions of unidirectional curvature.
	spiral grain	2 cm/*cm is allowed	4 cm/*cm is allowed	5 cm/*cm is allowed
	taper	allowed	allowed	allowed
	exc. pith	without limitation	without limitation	without limitation
	reaction wood	is not allowed	without limitation	without limitation
	ovality	without limitation	without limitation	without limitation
Signs caused by fungi	**colouring**	up to 1/3 of the front surface is allowed	up to 1/3 of the front surface is allowed	without limitation
	rot	not allowed	not allowed	Hard rot is allowed up to 1/3 of the frontal surface; soft rot is allowed up to 1/10 of the frontal surface'.
Red false heartwood		up to 1/3 of the frontal surface is allowed; a flame red core heartwood shall not be allowed'	up to 1/2 of the frontal area is allowed; a flame red core heartwood shall be allowed up to 1/3 of the frontal surface'.	without limitation; a flame red core heartwood is allowed up to 1/2 of the frontal surface'.
Wood decay degradation		not allowed	not allowed	up to 1/3 of the frontal surface is allowed
Insect damage		not allowed	surface up to a depth of 3 mm is permitted	without limitation
*Note: *cm : common metre*				

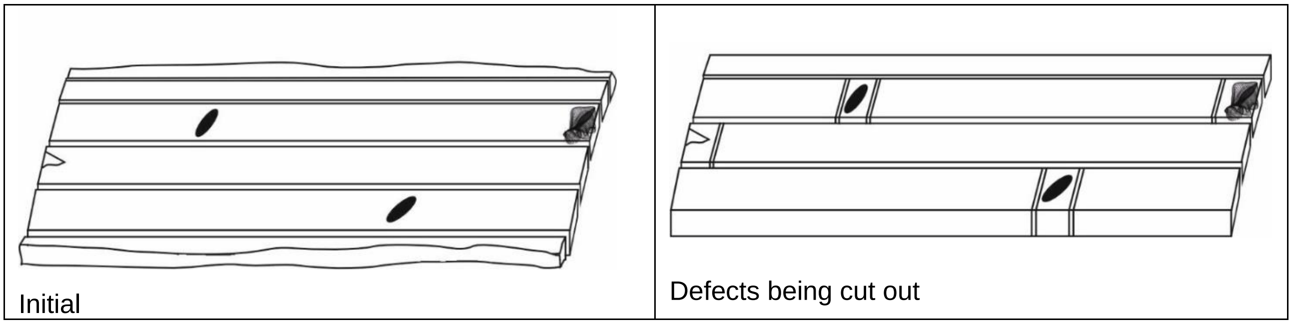


Fig. 2. The longitudinal-transversal method of manufacturing blanks from timber

The produced blanks were classified into quality classes AA, BB, AB, and CC based on their dimensions and aesthetic characteristics. Blanks in the AA class were of the highest quality and did not contain any red false heartwood or knots. They also had the exact required dimensions. Blanks in the BB quality class had red false heartwood on both the surface of the top and bottom or contained very small knots. Blanks AB class had one surface without defects and the other surface had a partial proportion of red false heartwood, which may have partially extended into the next surface. In class CC, the blanks were free of aesthetic defects, but the thickness or width was outside the allowable tolerance. These blanks can be used in the production of thinner glued boards, but processing is required.

RESULTS AND DISCUSSION

The average values and basic statistical characteristics of the European beech raw material used as input are presented in Table 2.

Table 2. Average Values and Basic Statistical Characteristics of European Beech Raw Material

Qualitative Class	Dimensions of Logs	Mean	Standard Error	Standard Deviation	Sample Variance	Minimum	Maximum	Count
III.A	Diameter at the thinner end (cm)	**42.33**	**0.61**	**5.86**	**34.29**	**33.00**	**61.00**	92
	Length (m)	5.22	0.11	1.7	1.14	3.00	7.00	
III.B	Diameter at the thinner end (cm)	46.34	0.64	8.1	64.15	35.00	74.00	155
	Length (m)	3.98	0.06	0.73	0.53	3.00	7.00	
III.C	Diameter at the thinner end (cm)	45.85	0.60	7.83	61.33	35.00	72.00	171
	Length (m)	3.89	0.03	0.35	0.12	3.00	6.00	

Figure 3 illustrates the distribution of logs by thickness class within quality classes III.A, III.B, and III.C. Figure 4 presents the categorization of logs by length and quality class.

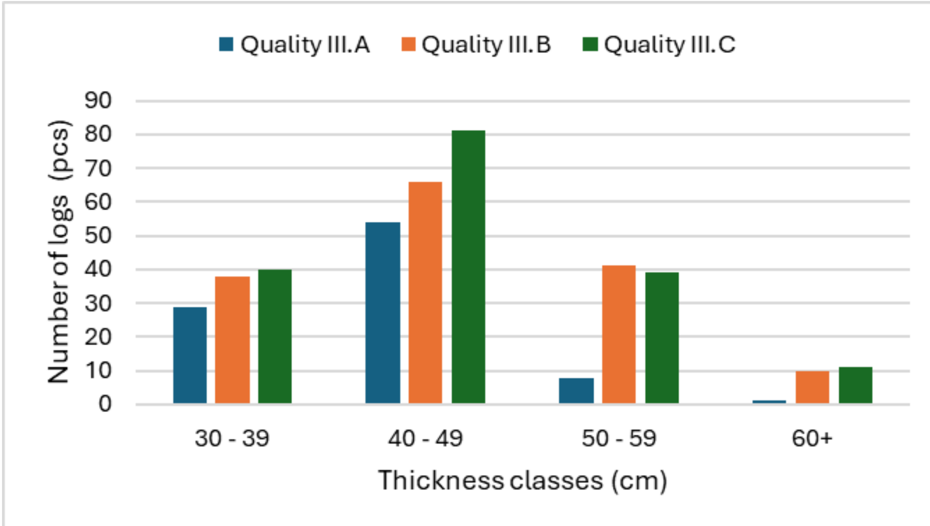


Fig. 3. Number of logs of quality classes in thickness classes

Most logs were classified as quality class III.C, while the fewest were categorized as III.A. All quality classes were almost equally represented in the 30 to 39 and 40 to 49 thickness classes. However, there was a noticeable difference in thickness in the 50 to 59 and 60+ classes, where class III.A was significantly less represented compared to the lower-quality classes. The impact of the 50 to 59 thickness class on the qualitative and quantitative yield values is somewhat limited due to the relatively small number of logs. However, the difference in the representation of quality classes in the 50 to 59 thickness class has a notable effect on some observed characteristics. Tanušev *et al.* (2009) showed a similar result. The authors used a through-and-through sawing pattern on the band saw and found that the greatest yield of beech blanks was achieved with the largest diameter from 24 to 26 cm, but the effect of the diameter of logs was not statistically significant. In contrast, Muñoz *et al.* (2013) discovered that the quality of logs did not significantly affect the yield of timber, even though logs had a wide range of diameters at the smallest end, ranging from 22 cm to 77 cm.

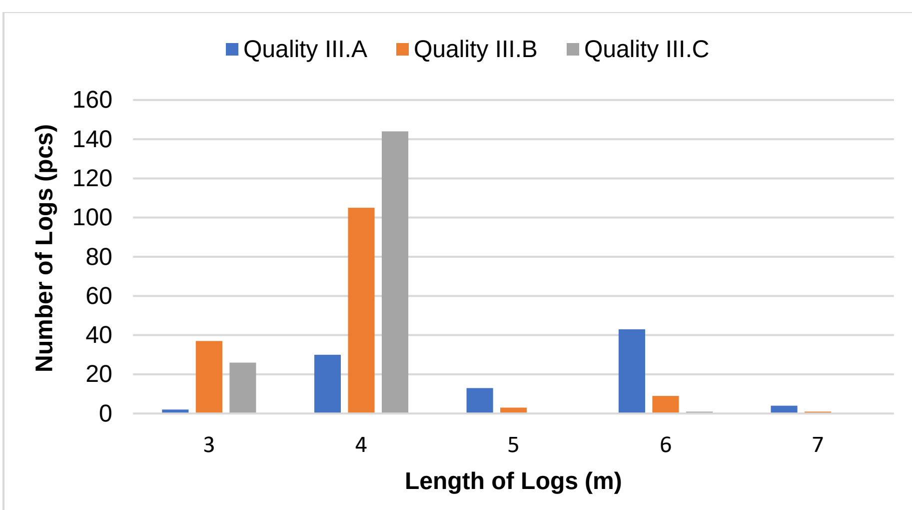


Fig. 4. Number of logs by length and quality classes

The highest number of processed logs for classes III.B and III.C had a length of 4 m. For quality class III.A, the highest number of processed logs was at a length of 6 m. When dealing with longer logs, the curvature of the log significantly affects the yield. It is worth mentioning that for the lowest class (III.C), log lengths of 5, 6, and 7 m were not found in this quality class at all.

Stragliottoa *et al.* (2023) examined how the quality of logs impacts the timber yield. Their results confirmed that the curvature of the log and other wood defects, such as conicity, cracks, and heartwood, are important factors.

The calculated values of the quantitative yield and the volumes of the main products from the raw material input to the final product are given in Table 3.

Table 3. Yield Values and Volumes of the Main Products for the Quality Classes of the Raw Material

Qualitative Class		Raw Material	Timber	Long Blanks	Blanks
III.A	Yield (%)	100.00	72.58	39.76	39.50
	Volume (m^3)	65.10	47.25	25.88	25.71
III.B	Yield (%)	100.00	75.32	40.72	38.03
	Volume (m^3)	100.67	75.82	40.99	38.28
III.C	Yield (%)	100.00	75.06	38.21	35.60
	Volume (m^3)	105.99	79.56	40.50	37.73

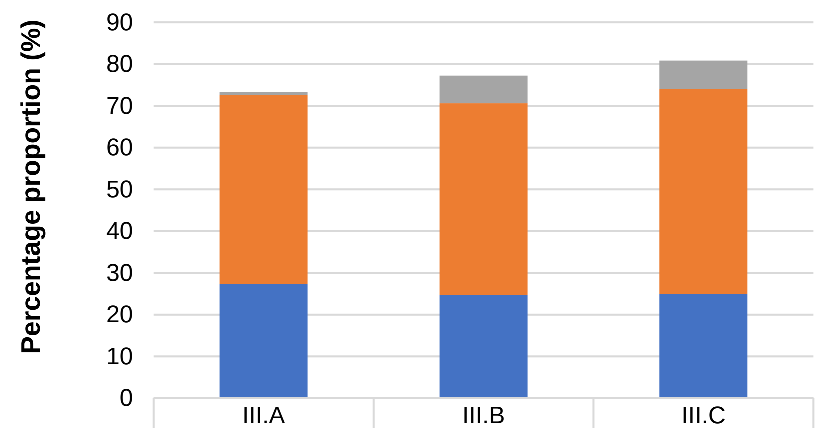
To produce timber, the average values of the quantitative yields were highest for the raw material quality class III.B, but the value was almost identical also for the quality class III.C. The logs of class III.A were discovered to exhibit the lowest yield. The lower yield was due to the higher quality of the raw material. Classes III.B and III.C had a higher proportion of log diameters in the 50 to 59 and 60+ thickness classes. In terms of log length, logs in class III.A were mainly longer, while classes III.B and III.C had the highest representation of shorter logs. According to the study by Lima *et al.* (2019) taper of logs has a significant influence on the yield of timber. Among other things, the authors found remarkable differences in the diameters of the thick and thin ends resulting in excessive material loss. According to the analysis by Račko and Čunderlík (2006), there could also be smaller red heartwood in beech logs that can achieve a favorable qualitative structure and significantly increase the yield of lumber.

The production of solid European beech timber by log sawing pattern through-and-through has the greatest effect on the value of quantity yield, which affects the diameter of the log, and the quantity of the produced timber. At this stage of production, quality attributes, such as the species and extent of red false heartwood, cracks, deformations caused by reaction wood, and the size and extent of knots, are not considered. For long logs, the yield may be reduced by the higher impact of the curvature of the log. The curvature of the logs has less effect on the yield values of timber in shorter logs.

The quality of the raw material affected the yields in the production of long blanks and final timber by longitudinal-cross-sawing. Longitudinal sawing of the timber into long blanks removed the rounded sides but also optimized the sawing process, reducing issues, such as red false heartwood, pith, cracks, and other damage. In this stage, the highest yield was in class III.B and the lowest was in class III.C. The highest quality raw material (class

III.A) had a yield almost at the level of class III.B. Similar results were confirmed even in other works by Stragliotto *et al.* (2016), Klement *et al.* 2023, and Vilkovský *et al.* (2023) where the quality of logs, and dimensions of blanks were remarkable factors that affected yield.

In the last stage of processing (production of the final blanks) by cross-cutting of long blanks, where unacceptable defects are removed, the highest yield was obtained from the best quality material III.A, and the lowest from quality class III.C. It can be concluded that with increasing classes of raw material processing, where the quality requirements of the product increase, the effect of the input quality of the raw material is greater than the effect of the dimensions. In Fig. 5, the percentages of secondary products that formed during processing were the chips that were produced when part of the taper zone of the logs was milled away, the sawdust from the sawing process, and the slab board from the longitudinal and transverse sawing of the blanks. The effects of the quality of the raw material were particularly evident in the production of the blanks.



	III.A	III.B	III.C
Blanks	0.65	6.61	6.83
Long blanks	45.22	45.94	49.09
Timber	27.42	24.68	24.94

Fig. 5. Percentages of secondary products for each quality class

At the highest raw material quality (III.A), the proportion of secondary products in the production of blanks was on average 0.65%, at the lowest quality III.C the proportion was almost 7%. The European beech blanks, after drying, will be used to produce edge-glued boards. These are products for which the mechanical, physical, and aesthetic attributes of the product are important. Additionally, tension wood in beech raw material significantly reduces its strength, durability, workability, and aesthetic appeal. Tension wood and red false heartwood have a lower tensile strength than normal wood, making it more susceptible to breakage and failure under stress. Additionally, tension wood is more likely to fracture without significant deformation. Beech red false heartwood and tension wood exhibit greater dimensional changes during drying and other processing stages, leading to warping, twisting, and surface checks (Majka and Sydor 2023). All information is in concordance with Vilkovská *et al.* (2024) where detection is also the fact that this zone of wood or individual pieces of timber with a large proportion of tension wood or red false heartwood may be removed from the other process. Removing this wood from processing at the start of production is important because the company then does not spend resources and money on processing it, which would lead to the production of an unusable semi-finished product, or product. Therefore, the produced blanks are divided into quality classes AA, BB, CC, and AB. The percentages of the blanks in the quality classes are shown in Fig. 6.

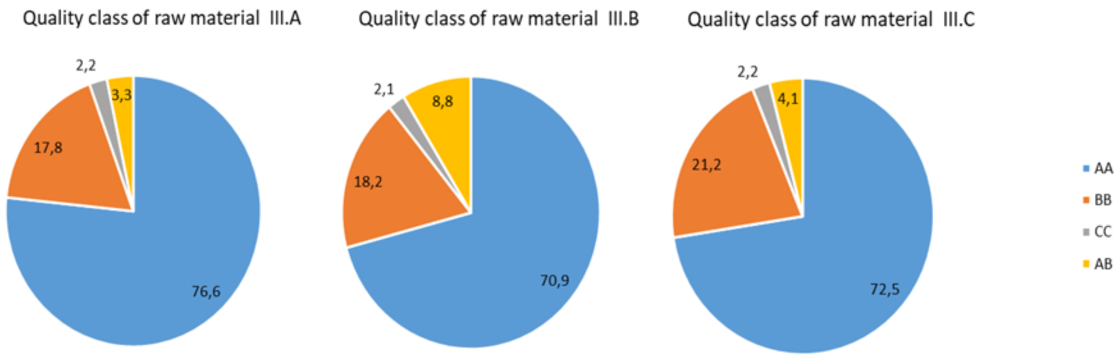


Fig. 6. Percentages of blanks produced from raw material classes

The largest proportion (76.6%) of the AA grade blanks was from the highest quality III.A raw material. The quality grade of the input raw material on the proportion of production of BB, CC quality logs was not significant.

CONCLUSIONS

The article analyzed the influence of the quality of European beech raw material on the quantitative and qualitative yield during the production of blanks used to produce glued boards. The processing of European beech wood was found to have specific properties that are determined by the characteristics of the wood itself. Typical features are, for example, red false heartwood, tension (reaction) wood, curvature, *etc*. The representation of this wood in Europe is high and its industrial use is important. The following conclusions can be made from this study:

1. In the production of unedged timber, the diameter of the logs has the greatest influence on the quantitative yield. The effect of diameter on yield is directly proportional. As the diameter increases, the yield increases. The effect of the length of the logs on the yield is inversely proportional. The yield decreases with increasing length, but the effect of length is less than the effect of log diameter. Although log length also affects yield, its impact is less pronounced and inversely proportional. Moreover, as determined by the qualitative class, raw material quality does not significantly affect timber production quantity. This indicates that prioritizing the selection and processing of logs with larger diameters could be a strategic approach to optimizing timber production efficiency.
2. The quality of the raw material significantly influences the yield and quality of the final product in the production of unedged timber. Higher quality raw material (III.A) generally leads to higher yields and a lower proportion of secondary products. Conversely, lower-quality raw material (III.C) results in lower yields and a higher proportion of secondary products. The impact of raw material quality on yield becomes

more pronounced in the later stages of processing, particularly when removing defects in the final planks. So, the quality of the raw material is a critical factor in determining the overall yield and quality of the final product in the production of unedged timber.

3. The study revealed that the quality and extent of red false heartwood and cracks are the primary factors limiting yield in lower-quality European beech logs (classes III.B and III.C). While tension wood is present in all quality classes, its distribution is relatively consistent and not significantly influenced by log dimensions. However, the impact of reaction wood on yield is more apparent after the drying process of the blanks. The occurrence of red false heartwood and tension wood in beech wood raw material is critical for the yield of edge-glued boards.

Research on the influence of raw material quality and the identification of the relevance of the effect of dimensions and specific defects on product yields is important. This allows optimization of raw material purchasing and modeling of the quality and proportion of primary and secondary product production.

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