Using Deciduous Branch Wood and Conifer Spindle Wood to Manufacture Panels with Transverse Structure

Alin M. Olarescu, Aurel Lunguleasa,* and Loredana Radulescu

The increasing demand on the wood market makes it necessary to use all secondary resources, including the wood branches and spindles. The properties of deciduous branches and softwood spindles were evaluated in order to create wood panels, highlighting the transverse texture with high value added. The research analyzed the properties of the wood from deciduous (beech, maple) branches and from conifer (spruce, fir) spindles. The methodology of obtaining panels with transversal structure was also presented. The production of minor wood (branches or spindles) was 254 m^3/ha/year in the case of beech (branches) and 109 m^3/ha/year in the case of spruce (spindles). The proportion of compression wood for spruce had an average value of 40.6%. A similar value of tension wood for beech was obtained. The modulus of elasticity for pine spindle wood was 71.7% lower than the modulus of elasticity for bending strength in the trunk. The quality index was 36.7% lower in the case of spindles than in the case of pine trunk, and the value of the quality ratio in branch maple wood was 2.61% lower than in trunk wood. Thus, even if it is not the only efficient solution, wood in the minor portions can be used to make high value-added panels such as those that highlight the transverse structure.

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Keywords: Cross section; Panel; Eco-design; MOR; MOE; Compression strength; Compression wood

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INTRODUCTION

The wood in the branches and spindles (called minor wood in this article) differs from the trunk in the macroscopic and microscopic structure as well as chemical composition. The differences in minor wood relative to trunks lead to different physical and mechanical properties and consequently to their different potential uses. Knowing the characteristics of wood from branches is important, as forestry creates an enormous number of minor woods that must be collected to use it efficiently. Differences in the anatomical features of wood in branches and trunks reflect the environmental conditions in which the tree grew (Kucera and Philipson 1977; Schweingruber 2009; Schweingruber *et al.* 2011; Shmulsky and Jones 2011). The branches are usually used as firewood and wood chips and fibers for chipboard and fiberboard factories. Therefore, creating new products from these secondary resources is a priority for the global wood industry.

First, it is necessary to evaluate the volume and mass of the minor wood from a felled tree. There are significant differences in relation to the species and type of product, for example, a cubage factor of 0.09 m^3/m ster for the branches from the trees harvested by regeneration cuttings and a cubage factor of 0.11 m^3/m ster for branches from trees harvested by care pruning (Chaffey 2019). The width of the annual rings is smaller for the wood in the branches than for the wood in the trunk. For example, in softwoods the width of the annual rings is 1.7 mm for the trunk and 0.7 mm for the spindles. For deciduous trees with scattered pores, it is 2.2 mm for the trunk and 1 mm for the branches, and for the deciduous trees with ring pores it is 2 mm for the trunk and 1 mm for branches (Hakkila 1989; Zhao *et al* 2018). Due to these differences, the density of the branches increases by 15 to 25% (Petrovici and Popa 1997; Vurdu and Bensend 1980). In deciduous species, the length of the fibers in branches is 25 to 35% shorter than the length of fibers in the trunk. Similar results were obtained for softwood (Petrovici and Popa 1997; Pulido-Rodríguez *et al*. 2020). For hardwoods, the fiber diameter, lumen diameter, cell wall thickness, and fiber length are smaller in branches than in the trunk. Hakkila (1989) showed that the diameter of the wood fibers in the branches was about 20% smaller than the diameter of the wood fibers in the trunk. After studying 22 deciduous species, they concluded that the average diameter of the fibers in the branches is 14.1 μm and the lumen of the fiber is 6.1 μm, both diameters being 15% smaller than in the wood in the trunk (Hakilla 1989).

The moisture content in the branches increases from the base to the top; however, the moisture content decreases with increasing branch diameter (Hakkila 1989). The density of wood in the branches is higher than in the trunk (Hakkila 1989). In spruce, the density of wood in the spindles is twice as high as the density of wood in the trunk. In deciduous wood, the difference in density between branches and trunk is smaller.

In terms of product eco-design, it is necessary to develop cleaner, greener products, which gives high added value. Therefore, the eco-design of products is a key element of competitiveness in contemporary society. Among the usual eco-design strategies (Brezet and van Hemel 1997), using secondary resources from biomass have been regarded as having little technical importance. Brass (1997) presented data about the life cycle of a product, its recovery, and the ecological design of an industrial product. Brezet and van Hemel (1997) provided data on green products, the concept of eco-design, and the sustainable design of industrial products. Zeng (2015) defined the product eco-design as a broad concept that aligns the project and the product with the environment. Nielsen (2002) analyzed the integration of environmental aspects in the design and ensuring a long product life cycle, thus increasing the competitiveness of products.

Suansa and Al-Mefarrej (2020) studied the wood branches of 3 species and found that they were of poor quality due to the increased number of vessels and woody parenchyma. It is recommended to use these branches mixed with wood from the trunk for wood composites or as biofuel and bioenergy. Ramage *et al*. (2017) showed how to maximize forestry production for trees and its by-products. Zao *et al*. (2014) studied the differences between branches and trunk for a type of poplar native to China, finding that the branches have the lowest density of 506 kg/m^3. The fibers were longer in the branches, but their walls were smaller. Gonçalves *et al.* (2019) found a computational model for ultrasonic characterization of the wood from the trunk and branches, in order to find some elastic properties. Hassanpoor Tichi (2021) made chipboard boards from poplar logs and branches. The composites obtained from 50% poplar and 50% citrus branches had the best mechanical properties. Luan and Yang (1992) predicted forest growth and wood quality using an index to quantify the growth of the annual ring of wood and branches. Jahan-Latibari and Roohnia (2010) studied the use of poplar branches in the production of wood chips. The characteristics of the boards that used branches were comparable (slightly more) to those that used mature trunks. Salem *et al.* (2016) studied the oily extracts obtained from the branches of a species native to Egypt, which can become sources of raw materials in the pharmaceutical and food industries. Wilsson (1986) studied the compression wood and the width of the annual rings in the white pine branches. Li *et al*. 2013 studied the formation of compression wood in the branches of *Pinus radiata* D, especially the characteristics of axial tracheid. *Hung et al.* (2017) made a comparison for tension wood and eccentricity between trunk and branch wood. The main idea of the study was that the functions of the branches are different from those of the trunk, hence leading to differentiation with respect to the optimal usage of the wood. Aiso-Sanada *et al*. (2018), concluded that the reaction wood of *Gnetum gnemon* branches is similar to that of other angiosperm species. Tsai *et al.* (2012) studied the reaction wood and eccentricity for broadleaf trunks and branches, starting from the hypothesis that the two parts of the tree have different physiological functions, but also collaborative. The distribution of gelatinous fibers was also studied. Pulido-Rodríguez *et al.* (2020) made a comparison between the anatomy of wood from branches and trunks for several tropical species in the dry zone, Colombia. Westing (1965) analyzed the formation and functionality of gymnosperm compression wood. Swift *et al.* 1976 studied the decomposition of wood from branches in a forest with an area of 1 hectare of deciduous species. 3 stages of decomposition were identified, with an annual rate of 17.1% at ground level, without major differences between the different wood species analyzed. Burgert and Jungnikl (2004) examined the branches of two woody species *Picea abies* and *Taxus baccata* in order to adaptively grow the trees of these species. Micromechanical and microscopic properties were examined, namely the angle of the microfibers in the secondary layer of the cell wall. Major differences were found between the different collection areas of the branches, respectively from the top, from the base and from the middle of the crown. Branches are a promise of a new resource on the secondary wood resources market (English 1994), beyond their use as decomposing soil fertilizer (Swift *et al.* 1976) or in the wood-based composites industry (Burgert and Jungnikl 2004; Hassanpoor Tichi 2021).

The bibliographic study, as described above, shows an abundance of works that presented the physical-mechanical properties of the branches, as the main element of capitalizing on the wood branches. Therefore, starting from the shortcomings or less analyzed problems and studies, the main objectives of the paper are channeled in two directions. A first direction will be based on the clarification of the microscopic and macroscopic aspects, the determination of the main physical-mechanical properties and the evaluation of the raw material resource from the branches of spruce, pine, beech and maple species. Based on beautiful texture and color (which easily accepts a good coloring in other colors than the natural one), the second direction will deal with the realization of a new ecological product with the highlighting of the transversal structure of branches in accordance with the requirements of the eco-design and of the sustainable development.

EXPERIMENTAL

Microscopy

Microscopic examinations were performed for wood from branches, spindles, and trunks. Deciduous and softwood species were obtained from Brasov Forest District, including beech (*Fagus sylvatica*), maple (*Acer platanoides*), spruce (*Picea abies*), and Scottish pine (*Pinus sylvestris*). The preparation of the samples consisted of cutting small cubes with a side of 20 mm, boiling for 24 h until saturation, cutting with a microtone the lamellae with a thickness of 25 µm, corresponding to the two cross sections. The sections were mounted with glycerin gel between glass slides by hot pressing. After positioning the coating slide, the preparations were allowed to cool for 12 h, after which the excess glycerin was removed by scraping. The slides were cleaned with an ethanol buffer. These preparations were examined under a Laboval microscope (Jena, Germany), equipped with a Nomarski contrast interference system and an image capture system. The images were taken at a magnification of 12.5 times, at which scale the optical network of the examination microscope was calibrated.

Compression Wood

The measurements were performed on three points of the specimens (300 mm length), making the arithmetic mean of the recorded values. The measurement method and the dimensions of the specimens are shown in Fig. 1. The cross section of the compression wood in the spruce branches was arranged in the form of a circular sector with an angle at the center between 110° and 165°.

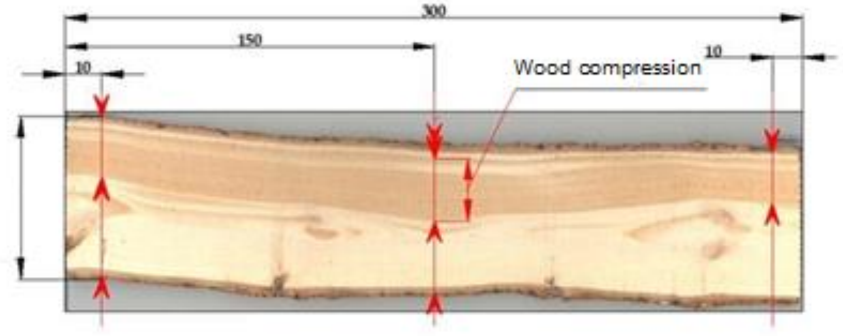


Fig. 1. The dimensions (in mm) of the specimens with compression wood from spruce branches

Branch Diameter and Bark Percentage

The thickness of the bark was measured on ten rounds cut transversely from beech branches (*Fagus sylvatica* L.) and another ten rounds of spruce (*Picea abies*) with bark and exterior diameter between 56 and 62 mm. The measurements were performed in two perpendicular directions, and the average value was calculated. The percentage of bark was calculated by determining within the cross section the area occupied by the bark, relative to the entire surface of the cross section of the analyzed samples. The outer diameter and the thickness of the bark were determined in two perpendicular directions. Taking into account the relation of the area of a circle according to its diameter, the proportion of the shell of the total surface was obtained with Eq. 1 (FAO 2022),

$$\boldsymbol{Bp} = \frac{\boldsymbol{D^2-d^2}}{\boldsymbol{D^2}} \cdot \mathbf{100}\ [\%] \tag{1}$$

where B_p is the bark surface (%), D is diameter of the branch with bark (mm), and d is diameter of the branch without bark (mm).

Resistance to Compression Parallel to the Fibers

The compressive strength tests were performed on specimens cut from branches and trunks from beech (*Fagus sylvatica*), maple (*Acer pseudoplatanus*), spruce (Picea abies) and Scottish pine (*Pinus sylvestris*). The dimensions of the specimens were 60 × 20 × 20 mm, using a minimum number of 10 specimens for each species and assortment, according to ISO 13061-17 (2017). According to the test standard, the samples were extracted from clean wood without defects, usually from the base of the branch where not many defects are found. The dimensions of the specimens were measured with a digital caliper, with a capacity of 150 mm, calibrated with a rod of 25 ± 0.1 mm.

Before the test, the density was determined for each specimen, and the average for each species and assortment was calculated. After the test, the moisture content of the specimens was determined, and the average value for each species and assortment was calculated. As the moisture content exceeded the value of 12%, the density was recalculated for this value according to ISO 13061-2 (2014). According to ISO 13061-17 (2017), the specimens must be cut so that the annual rings are oriented parallel to two opposite sides of the specimen. The specimens were cut from branches or spindles with a diameter of 100 to 120 mm. The test pieces in the trunk were cut according to ISO 13061-17 (2017).

A universal ESH servo-hydraulic tester (Zwick/Roell, Ulm, Germany) with a maximum load capacity of ± 100 kN, with the possibility of adjusting the load in four stages was used for testing at ± 10 kN, ± 25 kN, ± 50 kN, ± 100 kN. The load force of ± 25 kN was applied for the test, with a constant speed of 0.1 m/min. The compression strength parallel to the fibers was calculated for each specimen as a ratio between force and breaking force, and then data was averaged for each species and assortment of branches and trunks. At the time of testing, the specimens had different moisture content. To compare the values obtained, a recalculation for of 12% was used (Eq. 2) (ISO 13061-4: 2014),

$$\sigma_{12} = \sigma_{MC}[1 + 0{,}04(MC - 12)][MPa] \tag{2}$$

where σ_{12} is the compressive strength parallel to the fibers corresponding to the moisture content of 12% (MPa), σ_{MC} is the compressive strength parallel to the fibers corresponding to the moisture at which the test was performed (MPa), and *MC* is the moisture of the specimen at the time test (%).

The quality index was determined as the ratio between the strength and the density of the wood.

Modulus of Elasticity (MOE) and Resistance (MOR) to Static Bending

The tests were performed on specimens cut from branches, spindles, and trunks from the following species: beech, spruce, maple (*Acer pseudoplatanus*) and Scottish pine (*Pinus sylvestris*). The dimensions of the specimens were 300 × 20 × 20 mm, using 3 specimens for each species, assortment and type of test, according to EN 310 (1993). The samples were chosen from the base of the branch, without tension wood or other serious defects that would influence the resistance or elasticity. The dimensions of the specimens were measured with a digital caliper, with a capacity of 300 mm, calibrated with a 25 mm rod. Before the test, the density was determined for each specimen, and the average for each species and assortment was calculated. After the test, the moisture content of the specimens was determined, and the average value for each species and assortment was calculated. As the MC exceeded the value of 12%, the density was recalculated for this value according to ISO 13061-2 (2014).

The tests were performed with an Instron 4411 universal tester (Hudson, MA, United States) with a load capacity of ±5 kN. The loading force was applied constantly at a speed of 6.6 mm/min, and the diameter of the punch was 60 mm. The modulus of elasticity (MOE) at static bending and the resistance to static bending (MOR) according to EN 310 (1993) were calculated. At the time of testing, the specimens had different MC, but to compare the values obtained, the value of modulus of elasticity for 12% was recalculated, according to ISO 13061-4 (2014) (Eq. 7). For static bending strength, the MOR for MC of

12% was also recalculated. The calculation relation for the modulus of elasticity, modulus of resistance, modulus of elasticity for 12% moisture content, and modulus of resistance for 12% moisture content are presented in Eqs. 3 through 6 (ISO 13061-17: 2017),

$$E_m = \frac{l_1^3 \cdot (F_1 - F_2)}{4 \cdot b \cdot t^3 \cdot (a_2 - a_1)} \left[\frac{N}{mm^2}\right] \tag{3}$$

where l_1 is distance between bending supports (mm), b is width of sample (mm), t is thickness of sample (mm), (F_1 - F_2) is increment of force (N) on the linear portion (F_1=0.1×$F_{\max}$ and F_2=0.4×$F_{\max}$), $F_{\max}$ is maximum value of force (N), and (a_1 - a_2) is the increment of bending deformation (mm) corresponding to the difference of forces (F_1 - F_2).

$$\sigma_i = \frac{3 \cdot F_{max}}{2 \cdot b \cdot t^2} \left[\frac{N}{mm^2}\right] \tag{4}$$

where σ_{i} is the resistance to static bending (N/mm^2), l_1 is distance between supports (mm), b is width of sample (mm), t is thickness of sample (mm), and $F_{\max}$ is maximum value of force (N).

$$E_{m12} = \frac{E_m}{1 - 0.02(MC - 12)} \left[\frac{N}{mm^2}\right] \tag{5}$$

In Eq. 5, E_{m12} is the modulus of elasticity to static bending for MC=12% (N/mm^2), E_{m} is modulus of elasticity to static bending for a certain moisture content (N/mm^2), and MC is moisture content in time of testing (%).

$$\sigma_{i12} = \sigma_{iu}[1 + 0.04(MC - 12)][MPa] \tag{6}$$

In Eq. 6, σ_{i12} is resistance to bending strength for MC=12% (MPa), σ_{iu} is resistance to bending strength for a certain moisture content (MPa), and MC is moisture content in time of testing (%).

Branch and Spindle Resources

To establish the potential of the branches and spindles, it is necessary to determine the percentage of minor wood in the total volume of exploited trees. For each felled tree, the diameter and height of the tree and its volume were determined. From the cubage tables of the branches, but also for experimentally process for each tree, the percentage of branches was determined according to the diameter and height of the tree trunk. For deciduous trees this resource represented the spindle and the branches, and for softwoods only the spindle, as the branches are very thin. The volume of branches was calculated with Eq. 7,

$$V_b = \frac{V_s \cdot P_b}{100} [m^3] \tag{7}$$

where V_b is volume of branches (m^3), V_s is volume of trunk (m^3), and P_b is the percentage of branches (%), determined from cubage tables, related to diameter and height of trees at exploitability. In addition, the percentage of each dimensional assortment of beech branches was determined according to the species and the average diameter at exploitability.

Technology for Making Transverse Textured Panels

The finished product with transverse texture obtained from the branches has a high aesthetic level, because only in this way it becomes attractive to consumers. Even if the losses of wood material are minimal when the hexagonal or octagonal shape is used, the technological difficulties in obtaining and assembling them in the panel prompted the choice of the square shape.

There were two main stages in the use of wood from branches and spindles. During the primary exploitation and processing of such minor wood, the shaft formation site included the operations of exploitation, primary sorting, transport, final sorting, and ended with the realization of the raw material depot. The second stage included the processing of the minor wood and all technological operations necessary to transform the raw material into the finished product, namely to obtain cross textured eco-panels from the branches. The optimal technological variant for the manufacture of cross-textured eco-panels from softwood branches (Fig. 2) involves the following main operations:

- Drying the branches or spindles with bark to a moisture content of 12% (Fig. 2a).
- Cutting prisms from the minor wood (Figs. 2b, c, d, f). Cutting operations involve: straightening a face and an edge on the straightening machine, obtaining the technological working bases; obtaining the second face and the second edge by splitting at the circular saw; and thickening of the face and the edge obtained by splitting.
- Preparation of the prisms for the formation of the linear block (Fig. 2g). This preparation includes arranging and marking the prisms in descending order of their length.
- Apply the adhesive on the edge of the prisms (Fig. 2h). The adhesive can be applied manually with a spatula or brush, or mechanically on the roller adhesive applicator.
- Assemble the linear block by side tightening and top tightening of the prisms (Fig. 2i). The top clamping prevents the prisms from slipping between them, and the top clamping force is about half that of the side clamping force.
- Conditioning the linear block for 8 h at a temperature of 20 ± 2 °C and relative air humidity 60 ± 5% to complete the adhesion (Fig. 2j);
- Calibration or straightening and thickening of the linear block to remove the pressing defects (h, k), especially the achievement of a high flatness;
- Cutting the transverse friezes by cutting - sectioning the linear block (Fig. 2l, m). The operation is performed on a circular saw equipped with a blade for transverse cutting;
- Applying the adhesive on the edges of the transverse friezes by the same procedures as when applying the adhesive on the edges of the prisms (Fig. 2n);
- Assembling and pressing the transverse friezes in order to obtain the panel (Fig. 2o);
- Conditioning of the panels for 8 h at a temperature of 20 ± 2 °C and the relative humidity of the air 60 ± 5% (Fig. 2p);
- Calibration of the panel on the calibration machine (Fig. 2r);
- Formatting the panel on the circular saw to be formatted (Fig. 2t);
- Removal of defects (usually cracks) that appear on the surface of the panel (Fig. 2u).

The cutting efficiency of the prism from barked branches was obtained by Eq. 8 (ASTM D143-21:2021),

$$R_{dp} = \frac{4 \cdot l_m^2}{\pi \cdot d^2} \cdot 100[\%] \tag{8}$$

where R_{dp} is the cutting efficiency of the prism from barked branches (%), l_m is module side size (mm), and d is diameter of barked branch (mm).

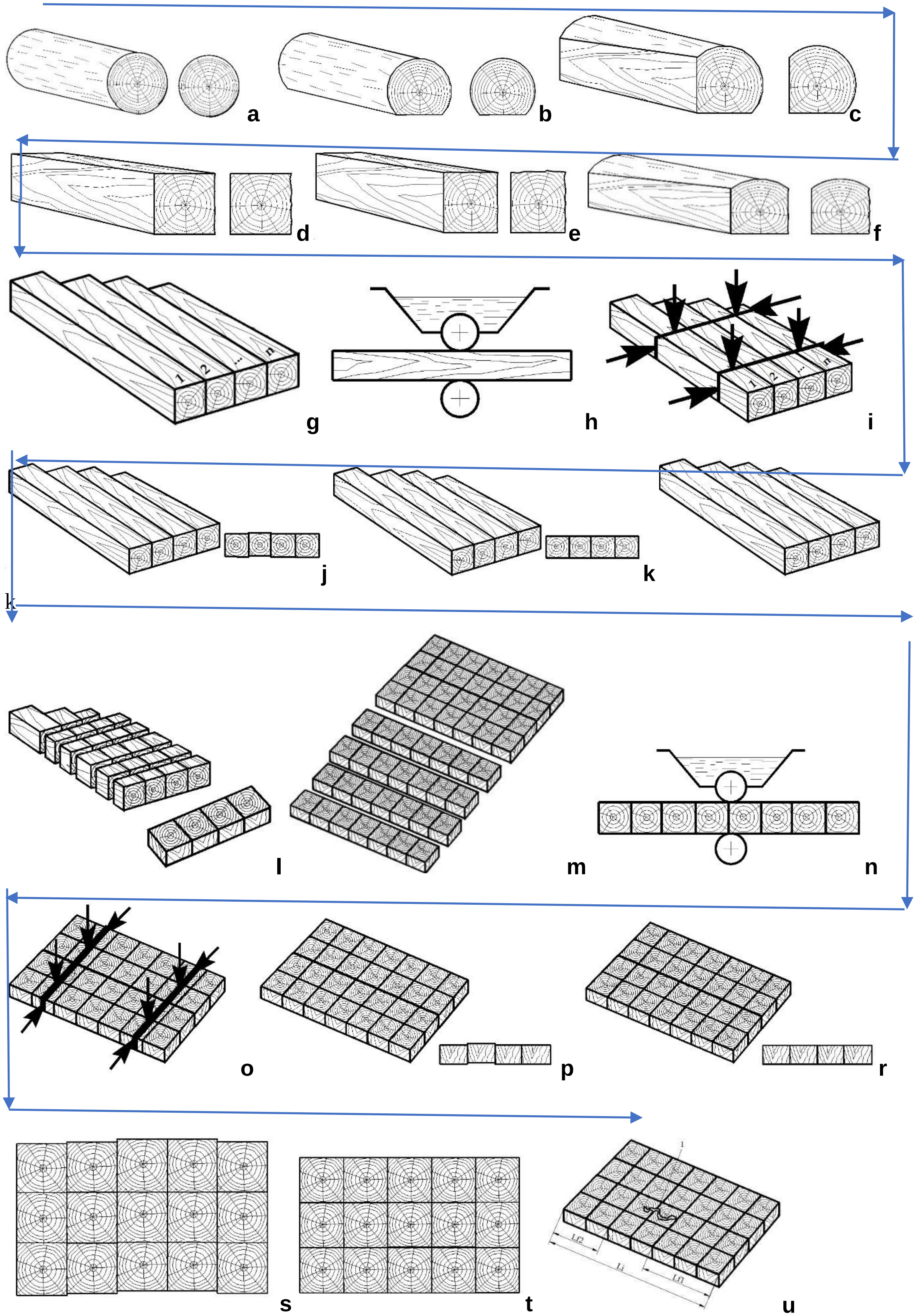


Fig. 2. Manufacturing flow of panel with transverse structures

Statistical Analysis

The arithmetic mean and the standard deviation were determined for each data series. The standard deviation for each group of values was posted. Minitab 18 statistical analysis software (State College, PA, USA) was used to obtain specific graphs. For all statistical analyses, a confidence interval of 95% was used, with an alpha error of 0.05.

RESULTS AND DISCUSSION

Branch Production

On the forest level, an average of 320 to 340 m^3/ha of logs was obtained, but they were 7 to 18 times smaller in branch volume by over 30 mm diameter (Schweingruber 2009). According to the developed algorithm, the annual production of the branches and spindles for 3 main species (beech, fir, and spruce) was calculated, depending on the diameter and the average height of the tree trunk at exploitability (Table 1). A higher quantity of minor wood was obtained when exploiting a beech log than the two softwoods (fir and spruce). In softwoods only their spindle (tip) is taken into account, and the branches are very thin (have insignificant dimension for obtaining panels with transverse texture).

Table 1. Annual Production of Beech, Spruce, and Fir Branches

Indicator	Species		
	Beech	Spruce	Fir
Medium diameter of trunk (cm)	36	40	36
Medium height of trunk (m)	26	36	26
Volume of trunk (m^3)	2.645	4.521	2.645
Percentage of branches and spindles (%)	16	4.2	5.8
Volume of branches and spindles (m^3)	0.423	0.182	0.153

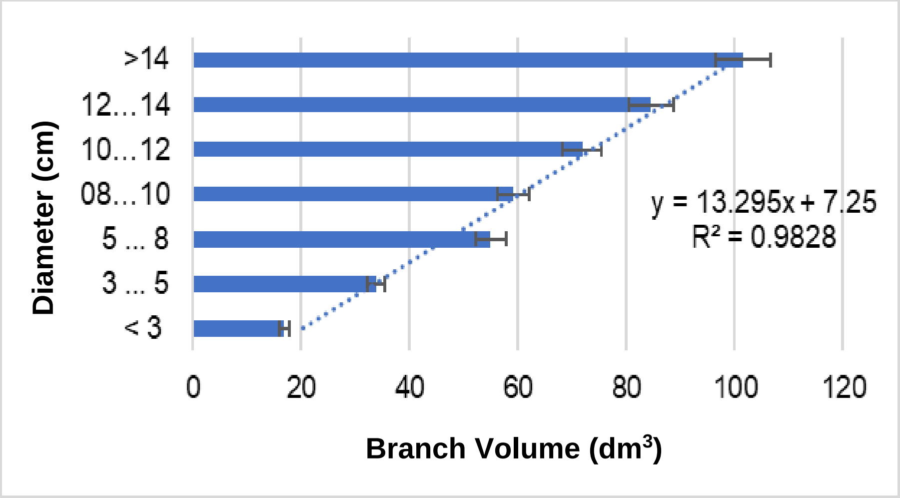


Fig. 3. Annual branch production depending on their diameter

In the case of beech forest exploitation, due to the diversity of the diameters, the annual production for various branch diameters was determined, as shown in Fig. 3. There was a constant increase in the volume of the branches, with the increase of their diameter. Considering that one hectare of forest contains on average about 600 trees, a forest production of 254 m^3/ha/year in the case of beech, of 109 m^3/ha/year in the case of spruce, and of 91.8 m^3/ha/year in the case of fir was obtained for forestry exploitation per year.

Technology of Cross-textured Panels and Efficiency Results

For spruce and fir, the percentage of spindles with a diameter over 3 cm was at least 10% higher than indicated previously (Shmulsky and Jones 2011). Following the primary sorting, approximatively 60% spindles over 3 cm in diameter and with 75% mechanically workable parts were obtained. The qualitative sorting by eliminating the defects made possible resulted in 75% sorts corresponding to the subsequent manufacturing process, and 25% sorts not conforming to the manufacturing process.

Regarding the drying of the wood branches, the experiments carried out on beech branches revealed that this operation can only be done for branches with bark and a conditioning time for a period of more than 200 h. Thus, it is not recommended to dry the branches in the form of prisms because there will be very large deformations, cracks, and deformations of the shape of the cross section. The conditioning time (16 h cumulated for the linear block and panel) represented 73.3% to 76.1% of the total working time in the manufacture of eco-panels with transverse sections. To remove this deficiency the press holding time of the linear block was increased by 1 h.

The total manufacturing yield of cross-textured cross-section panels from coniferous branches was directly proportional to the yield of obtaining prisms from bark branches. The correlation between the production efficiency of cross-textured eco-panels and the yield of prisms from barked-branches was modeled by a linear equation (Fig. 4).

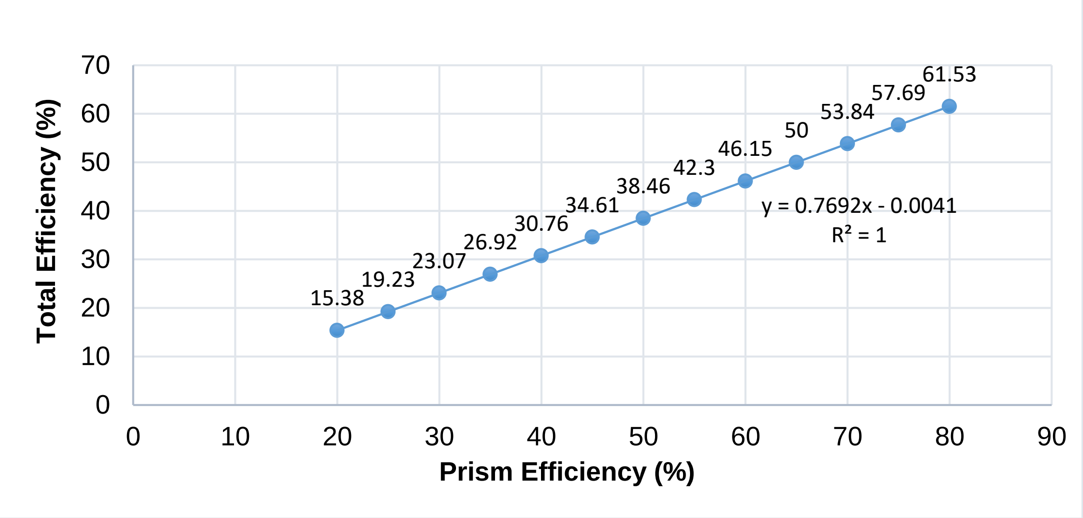
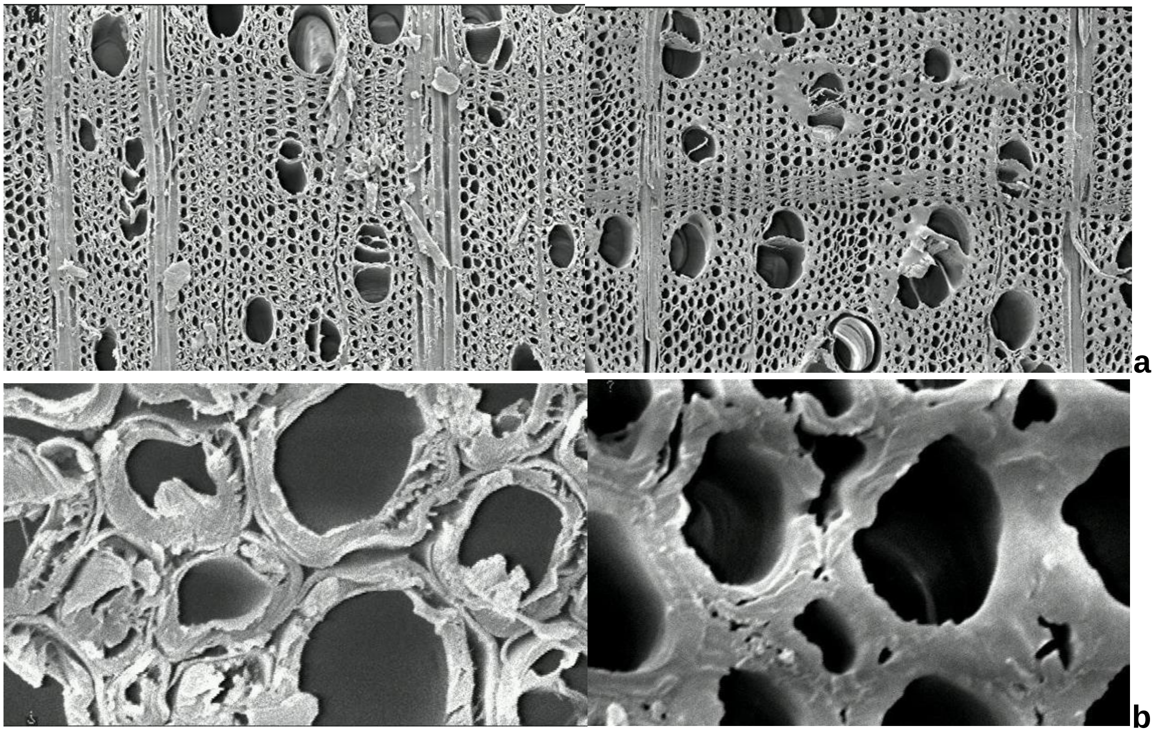


Fig. 4. Correlation between the cutting efficiency of prisms with the total production efficiency of panels

Microscopy Results

The cross sections of the 4 species (spruce, fir, maple, and beech) analyzed at the magnification of 153× and 2520× showed a finer structure in the branches than in the trunk, as shown in Fig. 5. There were fewer and smaller gaps for the wood in the trunk, as they have thicker cell membranes. Overall, this result suggests a denser structure, predicting a higher density of the wood in branches than in the trunk.

To measure the dimensions of the cells, a cross-sectional increase of 2,520 times was obtained. According to Schweingruber *et al.* (2011), the cell diameter, cell wall thickness, and lumen diameter for fibers and vessels of beech and maple tracheid for Scottish pine are smaller in wood from branchs compared to wood from the trunk, as shown in Fig. 5.



Acer branch **Acer trunk**

Fig. 5. Cross-sectional microscopic section of wood from branches (normal wood) and trunk for *Acer pseudoplatanus*: a-153×, b-2520×

For beech in the early wood, the average diameter of the vessels in the branches was 37.6% smaller than in the trunk, and in the late wood the average diameter of the vessels in the branches was smaller by 33.8% than in the trunk. For maple in early wood, the average diameter of the vessels in the branches was 18.8% smaller than in the trunk, and in the late wood the average diameter of the vessels in the branches was 37.7% smaller than in the trunk. In both species, the diameter of the vessels in the early wood of the branches was comparable in size to the diameter of the vessels in the late wood of the trunk. Contrary to data in the literature (Schweingruber *et al.* 2011), the number of vessels on a transverse surface of 243 mm^2 was higher in the wood in the branches than in the wood in the trunk, as follows: for beech by 27.4% and for maple with 25.2%. Although the diameter of the axial trachea and lumen was smaller in the branches, the average cell membrane size for axial tracheid pine trunks was 3.4% smaller than those of the trunk, which suggests a slight increase in the density of the branches relative to the trunk.

The Thickness of the Bark

The measurements made on 10 rounds cut transversely from fir spindles (*Abies alba*) showed that the diameter with bark was 59 to 75 mm, with an average diameter without bark of 59.8 mm. The average double-barked thickness was 8.44 mm, with an average bark diameter of 68.25 mm. Using Eq. 1, an average value of 23.2% for the transversal surface of the branch was obtained, while the proportion of the bark in the trunk did not exceed 8 to 10%. A slight increase in the thickness of the bark was observed with the increase in the diameter of the fir branch, on average by 0.25 mm for every 10 mm increase in diameter (Fig. 6). This connection was not observed in the case of the trunk, *i.e.*, with increasing in diameter the bark thickness significantly decreased (Schweingruber *et al.* 2011).

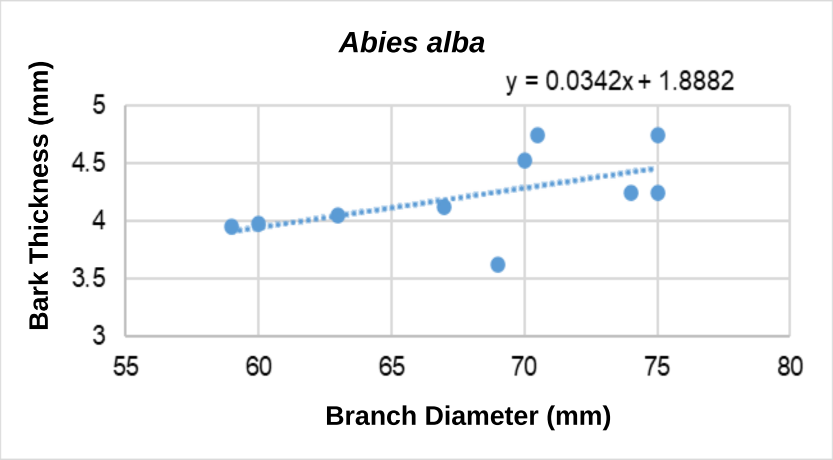


Fig. 6. The influence of branch diameter on bark thickness in the case of fir species

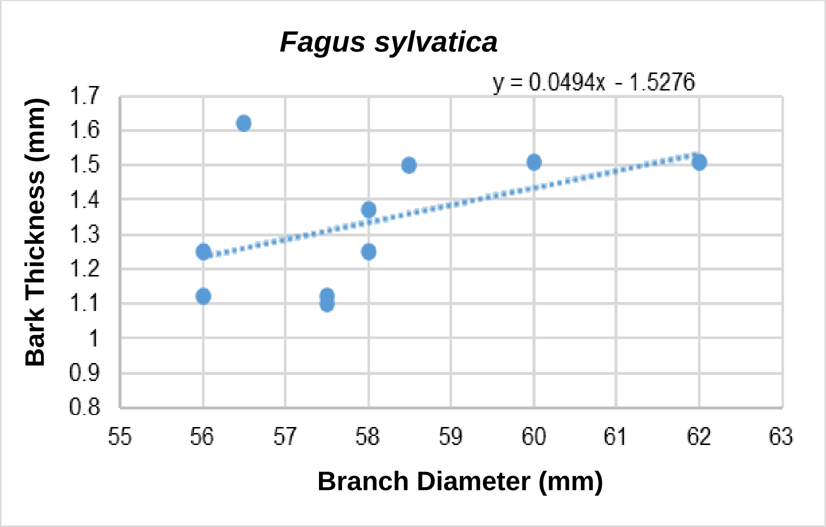


Fig. 7. Influence of branch diameter on beech wood bark thickness

In the case of *Fagus sylvatica* branches, the bark thickness was much smaller than that of the fir tree, with an average thickness of 1.33 mm for an average diameter of 58 mm (Fig. 7). Using Eq. 1, an average proportion of participation of the beech bark in branches was found to be 8.98%, which was 61.6% lower than in the fir tree. Because of the small thickness of the bark, the beech branches had a small increase in thickness depending on the increase in the diameter of the branch, with 0.54 mm of bark for every 10 mm increase in the diameter of the branch.

Compression Wood

In longitudinally cut strips from fir branches (*Abies alba*), with a diameter between 60 to 70 mm, the proportion of compression wood area ranged between 31 and 61%, with an average value of 40.6% (Table 2). Following the same work methodology as for compression wood, a similar value of tension wood was obtained for beech, 40.4%.

Table 2. Surface with Compression Wood in the *Abies alba* Spindles

Characteristics	Number of Samples				
	1	2	3	4	5
Length of sample (mm)	300	300	300	300	300
Medium width of whole sample (mm)	63.6	66.6	61	66	66.3
Medium width of compression wood (mm)	20.3	23	26.6	40.3	21.3
Total surface of samples(mm^2)	0.0191	0.02	0.0183	0.0198	0.0199
Total surface of compression wood (mm^2)	0.0061	0.0069	0.008	0.0121	0.0064
Proportion of compression wood (%)	31.937	34.5	43.7158	61.1111	32.1608
Medium proportion of compression wood (%)	40.6				

Resistance to Compression Parallel to the Fibers

In accordance with ASTM D143-21 (2021), the wood cut from the branches had a "brooming" behavior, *i.e.*, bending without breaking by shearing and sliding. This type of behavior of the specimens in the branches indicated a high elasticity of the wood. The test pieces cut from the wood in the trunk had a "shearing" behavior breaking by shearing and sliding. This type of behavior of the test pieces cut from the trunk indicates a low elasticity of the wood. Therefore, the wood from the branches showed a high elasticity compared to the wood from the trunk, at the same moisture content of 12%. The same results were found by other authors (Hakkila 1989; Petrovici and Popa 1997).

The quality of the wood, determined as a ratio between strength and density of minor wood and trunks were 75 and 92 in the case of maple, 61 and 74 in the case of beech and 64 and 96 in the case of Scots pine (Fig. 8). As these values increased, the wood was easier and more resistant, indicating superior quality. The wood in the branches is heavier and less resistant than wood in the trunk.

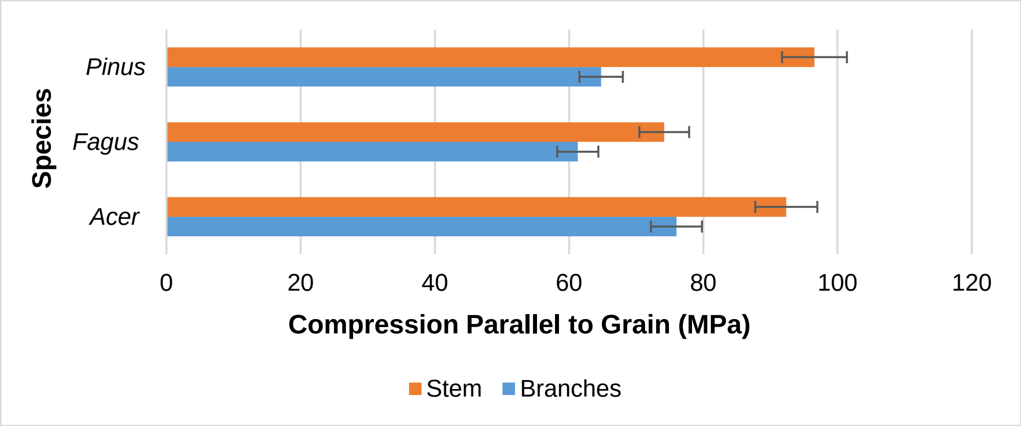


Fig. 8. Resistance to compression of minor wood and trunk

The resistance to parallel compression with the fibers for the minor wood was 6.68% lower for the maple than for the trunk, 0.5% lower for the beech than for the trunk, and 42.70% lower for the Scots pine in the trunk (Fig. 8). The "brooming - bending without breaking and slipping" behavior of the test specimens in the minor wood, when testing for compression parallel to the fibers, indicated a higher elasticity of the wood in the branches than in the trunk.

The compression strength parallel to the fibers of the minor wood of the pine was 42.7% lower than the resistance to parallel compression of the fibers of the trunk wood. The resistance to compression in the wood of the *Acer pseudoplatanus* branches was 0.5% lower than the resistance in the parallel compression in the wood in the *Fagus sylvatica*. The values obtained for the compressive strength of the test samples cut from the trunk were similar to those in the literature (Hakkila 1989). No correlation was found between density and resistance to compression parallel to the fibers in branches. Although the wood in the branches has a higher density than the wood in the trunk, it had a lower resistance to compression parallel to the fibers.

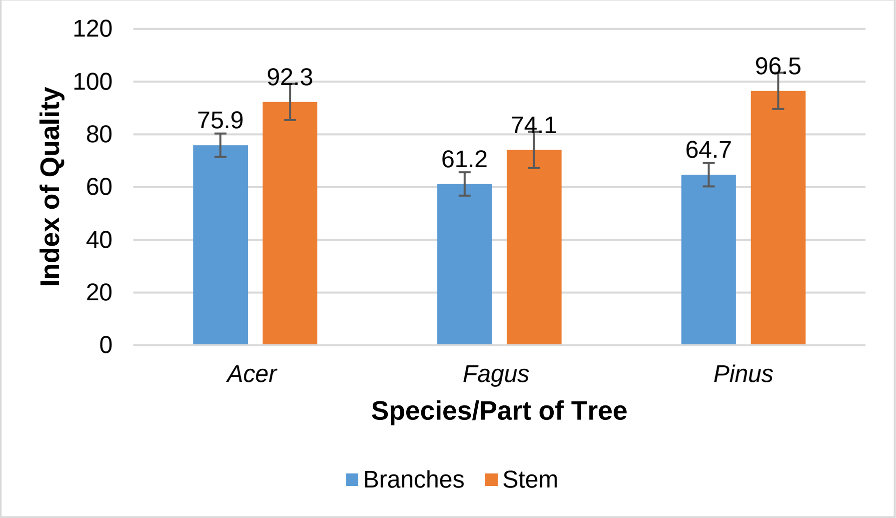


Fig. 9. The quality index of minor wood and trunk

Wood Density

According to Hakkila (1989) and experiments, the density of wood from maple branches was 11.8% higher than that from maple trunks. Contrary to the literature, the density of wood from pine spindles was 16.2% lower than the density of wood from pine trunks. Also, the density of wood from beech branches was 16.95% higher than the density of wood from beech logs. The wood in the branches (exception of the Scots pine), although this species had a higher density than the trunk, it had a lower mechanical strength than the trunk.

MOE and MOR to Static Bending

The way in which the maple specimens were broken showed the type characterized as "simple tension" (ASTM D143-21 2021). The maple twigs had a longer length than the shearing area of the logs in the trunk. The longer shearing area in the case of branches can be explained by an increased resistance to the tensile stress characteristic of wood from branches, which often have tension wood. The specimens cut from the *Scots pine* trunk were broken according to the "splintering" type, which illustrates a higher resistance to tensile stresses in the extended area, than in the case of branches. The higher elasticity of the wood in the branches is also demonstrated by the maximum bending arrow obtained during the tests. These values were higher in the case of branches with 1.86 times for maple and 2.76 times for pine, compared to the values of 9.49 mm and 10.91 mm for the trunk.

The quality index of the wood in the case of maple exhibited a value of 167 for branches and 172 for trunk, and 113 for spindles and 179 for trunk in the case of Scots pine (Fig. 10). The analysis of this ratio showed the following: for maple, the value of the ratio in branch wood was 2.61% lower than in trunk wood; for Scots pine, the value of the ratio in the wood of the spindles was 36.74% lower than the value in the trunk wood. This result indicated that the minor wood is inferior in quality to the wood in the trunk. In other words, the minor wood is denser and less resistant compared to the wood in the trunk.

Regarding the MOE and MOR of the minor wood compared with the wood from the trunk, several conclusions can be formulated. The MOR for maple wood was 13.92% lower than the bending modulus for maple wood. The MOR of maple wood was 9.63% higher than the MOR of maple wood. The MOE of Scots pine wood branches was 71.67% lower than the MOE of wood of pine trunks. The MOR of pine wood was 43.58% lower than the MOR of pine wood. The analysis of the quality ratio shows that the minor wood was inferior in quality to the trunk wood (Fig. 10).

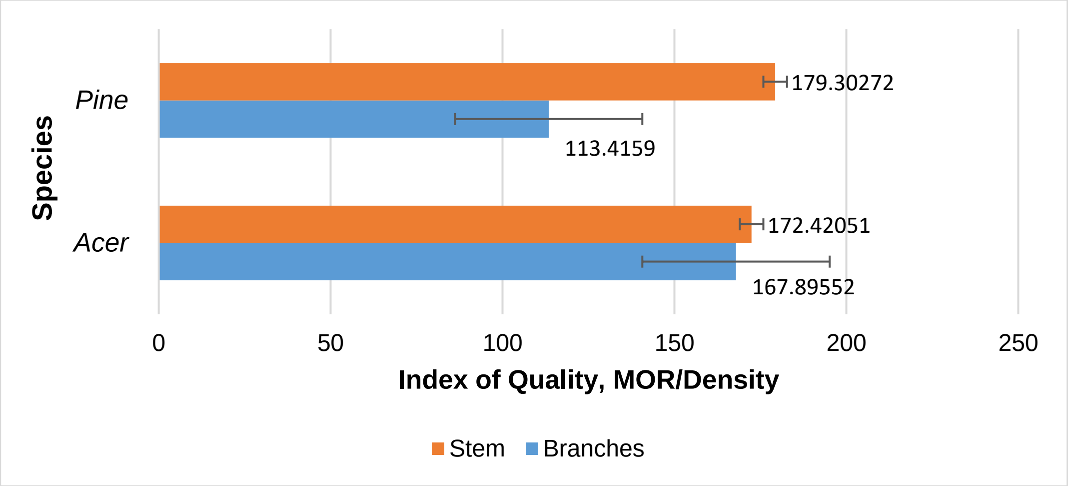


Fig. 10. Index of quality of wood for branches and trunk

The way of splitting the maple specimens presented the type characterized by "simple tension", with a longer length of the shear zone for the specimens in the branches. The most common form of breakage in the case of pine branches was "brash failure" typical of compression wood and mature wood. This type of rupture had a very low tensile strength in the pine area. The specimens cut from the pine trunk were broken by the splintering type, which illustrates a higher resistance to tensile stresses in the extended area than in the case of spindles (ASTM D143-21 2021).

The MOR of the wood from the maple branches was 9.63% higher than in the trunk, and for the Scots pine spindles was 43.6% lower than in the trunk, which denotes a different behavior of the softwood from those of deciduous trees. The MOR of the wood from the branches was 13.9% lower for the maple than for the trunk, and for the pine by 71.7% lower than the trunk. The rupture of the maple specimens showed the "simple tension" type, characterized by a longer length of the shear zone in the branch specimens compared to the trunk specimens. The longer shearing area in the case of branches can be explained by an increased resistance to the tensile stress characteristic of wood from branches, which often have tension wood. The most common form of breakage in the case of wild pine branches was "brash failure" typical of compression wood and mature wood. This type of rupture corresponds to a very low resistance of the tensile stress in the wide area, which also explains the low strength values compared to the strength in the wood trunk.

Bark Thickness

The thickness of the bark and its proportion for the beech branches were analyzed on an Empirical Cumulative Distribution Function (eCDF) graph (Fig. 11), which shows an average value of the bark percentage of 8.97%, with a standard deviation of ± 1.17%. Considering the 95% confidence interval, an optimal interval of the bark quantity of 6.6311.31% was obtained.

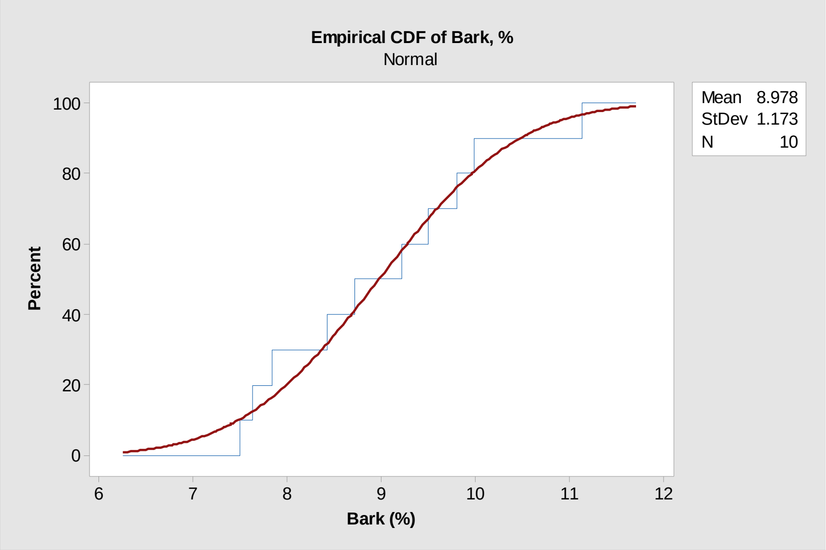


Fig. 11. Curve eCDF for the bark percentage from beech branches

The yield obtained experimentally when cutting prisms from softwood spindles was 53.3%. This value was 1.4% higher than the theoretically value. Also, both theoretically and experimentally values were comparable to the efficiency of timber cutting (Shmulsky and Jones 2011; FAO 2022). According to the technology of manufacturing panels with transverse texture from branches, the raw material went through three major phases, defining for the finished product: prisms cut from branches, transverse friezes, and panel.

Eco-panels with a transverse texture of softwood branches can be made industrially in a small or medium enterprise. The implementation costs are low because in the manufacture process, classic and small capacity woodworking machines are used.

CONCLUSIONS

1. Microscopic analysis of the cross section showed a denser structure in branches and spindles than in trunks, with high dimensional un-stability of wood and consequence different uses.
2. The production of branches and spindles was more than double in deciduous trees than in softwoods, but only 16% from wood trunk for *Fagus sylvatica* and 5.8% for *Abies alba*.
3. Large differences were found in the behavior of static bending resistance for maple and pine, due to the different behavior of compression wood.
4. The index quality analysis showed that the wood from the branches is inferior in quality to the wood from the trunk, which presupposes a special attention to the processing and drying of the wood from the branches.
5. From the analysis of the sorting and of the processing efficiency of the branches, 75% assortments corresponding to the manufacturing process of the cross-textured eco-panels has resulted and 25% assortments not conforming.
6. A total yield of 44.1% in the manufacture of cross-textured eco-panels from coniferous branches was obtained.
7. The differences in the physical and mechanical properties of wood from the branches and trunks suggest that they have different optimal uses.

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