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Computed Tomography as a Tool for Quantification and Classification of Roundwood—Case Study

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Abstract: The first goal of this paper is to verify the accuracy of four calculation methods of log volume. The tool to achieve this goal is to compare the results of the calculation of the log volume with the real log volume obtained from the three-dimensional reconstruction obtained by computed tomography. The second goal of this paper is to determine the effectiveness of displaying the qualitative features of wood in three-dimensional models of selected pieces of logs of oak, beech, and spruce, which were obtained using computed tomography. It is possible to state that each of the tested calculation methods of wood log volume are applicable in practice. The tested methods achieve excellent accuracy in determining the volume of spruce logs with a small variance of values, and conversely, in the case of beech wood, the tested methods are the most inaccurate with the largest variance of values. When determining the volume of wood logs, we recommend using the calculation method STN 48 0009, because it achieves the best results. Qualitative analysis based on CT scans of internal features can be described as a completely new level of approach to the evaluation of log quality. The performed analysis showed great potential for automatic detection of internal qualitative features in the tested spruce log. In this wood, wood defects are distinguishable by computed tomography. In the case of deciduous oak and beech, the situation is more complicated. The internal structure of these trees overlaps the internal qualitative features of the wood. To accurately detect internal errors in these trees, it will be necessary to perform many comparative tests to achieve optimal results.

Keywords: wood log; CT scanner; wood qualitative feature; volume log; quality class; tomography

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1. Introduction

The trend of pressure to reduce operating costs together with the optimization of production processes to make the best use of the input raw material was not bypassed even by the wood processing industry. We are on the threshold of the fourth industrial revolution and there is a transformation in established processes [1]. There is no doubt that the breadth and depth of these changes will result in the transformation of entire production and management systems [2,3]. When processing logs in the wood processing industry, innovative technologies are essential. For the wood processing industry to be competitive in the future, the priority must be to reach the technological level of industry leaders [4].

Philp H. Steele addressed the conditions and contexts that influence the use of sawlogs in 1984 [5]. He identified the main factors influencing the final yield of sawlogs. Increasing the yield of sawlogs due to log rotation has been discussed in detail by Lundahl & Grönlund (2010) [6]. They state that the implementation of the cutting plan in the correct position of the log results in an increase in the sawn timber yield by 4.5%. Extensive work dealing with the optimization of log cutting was also presented by Lindner et al., (2015) [7]. The authors describe individual types of cutting plans, and methods of their implementation, define the factors that influence the choice of cutting plan, and describe the basic mathematical model for the program for creating log cutting plans [8]. Geerts (1984), Lin et al., (2011), and Meier & Rukki, (2001) [9–11] have also addressed the optimization of cutting plans and the creation of programs for this purpose.

Today, various types of scanners are available for the wood-processing industry. The simplest ones are scanners for the presence of metals in logs. Higher-level scanners are combined with an optical or laser scanner to scan the surface of the log [12]. 2D stationary X-ray scanners are available for information on internal log wood features [13]. The latest technology is 3D CT log scanners, which are used to create an accurate three-dimensional model of the scanned log [14,15]. Algorithms for wood qualitative features detection are applied to this model [16]. By combining software for creating log cutting plans with an accurate 3D model of the log with identified features, it is possible to achieve a better evaluation of the input raw material [17,18]. The importance of innovation is based on forecasts of future developments in log prices [19] and requirements to ensure the sustainability of the sector [20].

Based on the extent to which they damage the evaluated material, we divide them into destructive, semi-destructive, and non-destructive. In the wood processing industry, of course, non-destructive methods of wood evaluation are most often used. These can be described as identifying the physical and mechanical properties of a material without altering its end-use. Based on the identified properties, a decision is made on its appropriate applications [21]. The main reasons for using non-destructive methods according to the authors (Schimleck, et al., 2019) [21] are the protection of investments in wood raw material, potential reduction in wood processing costs, easier use in field measurements, fast real-time data collection, ability to identify the most suitable measurement applications and reduce the variability of product classes [22].

Non-destructive wood evaluation technologies work on various physical principles. Acoustic, ultrasonic, optical, laser, X-ray and microwave are most often used. In the past, non-destructive methods were used to evaluate very valuable trees (e.g., exotic). Today, these methods are increasingly being introduced (for their speed, accuracy, and affordability) in modern wood processing enterprises, but also in forestry to assess the quality of forest stands.

Scanning technologies allow for different levels of non-destructive evaluation. Based on the publication (Österberg, 2009) [23], the individual scanning technologies were compared with each other in Table 1. Table 1 compares the level of technology procurement costs, the level of applicability, safety, and suitability of selected wood properties. The evaluation ranges from - - - (then the technology is completely inappropriate) to + + + (then the technology is suitable for determining the mentioned properties). In the gray field, we present the results of commercially known technologies.

It can be deduced from the table that the X-ray method is the most suitable for the evaluation of most parameters. These devices are less widespread due to their high prices. In Europe, there are only 4 industrial CT scanners located in France, Sweden, and Germany in terms of the closest distance (Table 1). Other types of technologies are laser and image ones. Considering that these two technologies are combined in most industrial devices, we can also consider them very suitable for wood evaluation. Laser, image, and also acoustic methods are therefore the most used in industrial practice. Their great advantage is the affordability as well as advanced computer vision technology for image analysis. This results in the possibility of accurate evaluation at high speeds, applicable in fast automated production. Laser, image, and acoustic methods, often combined with IR radiation, are used in all large, automated sawmills in Europe. Gradually, however, they started to be used in medium-sized sawmills.

Logs are a part of trees that are to be used for the production of wood products such as lumber, veneer, and plywood. In today's competitive environment, it is important that the determination of log volume and log quality is accurate and provides a good basis for revenue estimation. An important factor is also the simplicity of determining the log volume from the user's point of view.

Table 1. Evaluation of individual technologies according to their possibilities.

	Visible Light	IR Radiation	Laser	Acoustics	X-ray	µ-Waves	Radio Frequencies
Cost	+++	++	++	+++	---	+	+
Applicability	+++	-	+++	++	+	++	-
Safety	+++	+++	-	++	--	+	++
Performance:	+++	+++ [2]	+++	---	+++	--	---
3D-shape	+++ [2]	+	---	++	+++	--	-
Rot and decay	+++ [2]	---	---	---	---	---	--
Colour defects	+ [2]	-	---	+	+++	+	+
Compression and tension wood	+++ [2]	+	++ [1,2]	++	++	+	-
Cracks and splits	--	-	++ [1,2]	--	++	+	-
Resin pockets	---	---	---	+	+++	++	++
Foreign objects	+++ [2]	+	+++ [1,2]	-	+++	++	+
Knots	+	-	---	++	+++	++	+
Wood density	+	+	---	+	+++	+	+
Strength	+++ [2]	-	++ [1,2]	---	+	---	---
Annual ring width	++ [2]	---	+++ [1,2]	---	++	++	+
Grain orientation	---	+	---	-	++	++	+
Moisture content	+++	--	++ [1]	---	+++	---	---
Bark content	+	---	---	---	+	---	---

[1] when combined with image analysis, [2] is not thermography, i.e., no spectral content is utilized, --- the technology is completely unsuitable for determining the mentioned characteristics, +++ the technology is suitable for determining the mentioned characteristics, Gray color - Commercially known techniques.

When exporting Roundwood logs, it is necessary to create a record of each piece, which lists the external parameters (dimensions, quality, and volume) of logs, the type of tree species, or the harvesting location. Several standardized methods are used around the world to measure dimensions and determine log volume. A large number of methods bring confusion to the international timber trade, which creates inconsistencies in the detection of log volume. For the Slovak timber trade, it is recommended to use the standard STN EN 1309-2 Round and sawn timber method of measurement of dimensions. Part 2: Round timber; requirements for the measurement and volume calculation rules [24]. The standard STN 48 0009 volume tables of round timber without bark according to the mean diameter measured in bark is also commonly used to calculate the volume of a log [25].

The log volume calculation rules try to estimate the total wood volume without taking into account the expected form of followed processing (there are exceptions). Using different calculation methods, significant differences arise in the determination of log volume. Most calculations are based on the assumption that the stem corresponds to the geometric shape of a cylinder, cone, or paraboloid and that the stem has a circular diameter. The length of the log is given as a nominal value and not a rounded value. This causes further inaccuracies in determining the volume of the log because in some cases the shape of the cutout deviates considerably from the ideal geometric shape [26].

Depending on the location, state, and business practices, different systems for measuring log volume have become extinct over the years. Examples are:

1. Rules for determining the volume of logs for Japan, Korea, Chile
2. Log volume rules for Indonesia, Malaysia and the Philippines
3. Rules for determining the volume of logs for British Columbia
4. Rules for determining the volume for Russia

We present some commonly used formulas for calculating the volume of logs, which result in a volume in m^3 [26].

$$\text{Smalian } V = f \times (ds^2 + dl^2) \times L/2 \quad (1)$$

$$\text{Bruce's butt log } V = f \times (0.75 \times ds^2 + 0.25 \times dl^2) \times L/2 \quad (2)$$

$$\text{Huber } V = f \times dm^2 \times L \quad (3)$$

$$\text{Sorenson } V = f \times (ds + 0.05 \times L)^2 \times L \quad (4)$$

$$\text{Newton } V = f \times (ds^2 + 4 \times dm^2 + dl^2) \times L/6 \quad (5)$$

$$\text{Subneiloid } V = f \times [(ds + dl)/2]^2 \times L \quad (6)$$

$$\text{Two-end conic } V = f \times (ds^2 + ds \times dl + dl^2) \times L/3 \quad (7)$$

where:

f = 0.00007854
V = volume in cubic meters
d_s, d_m, d_l = top, middle and butt end diameter in centimeters
L = length in meters (Figure 1)

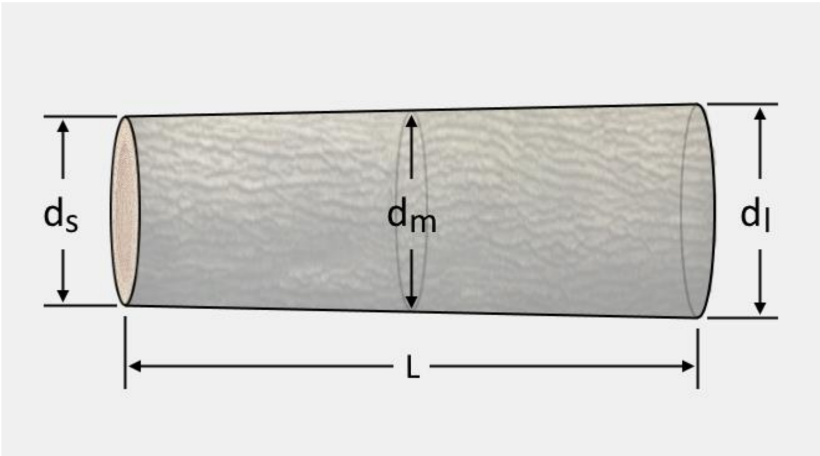

Figure 1. Scheme of determining parameters for the calculation of log volume.

All of the above relationships calculate the volume of the log as a function that increases steadily with increasing thickness and length of the log. The length of the log is given as a nominal value, and not a rounded value. These assumptions cause inaccuracies in determining the volume of the log, because in some cases the shape of the log has significant deviations from the ideal geometric shape. A Smalian formula is legal in British Columbia. It is based on the assumption that the strain has a paraboloid shape and therefore has a tendency to overestimate. The Huber formula assumes that the average flat cross-section of a log is at its center, this assumption does not always apply, and measuring at the center of a log without bark is impractical. The Sorenson formula is derived from the Huber formula, with the difference that the volume of the log is calculated based on the diameter of the thinner end of the log, assuming that the conicity of the log is a maximum of 1 inch per 10 feet of log length. This measurement is more practical than measuring the diameter of a log without bark in the middle. Newton's formula is the most accurate but requires measuring the diameter of the thinner and thicker end of the log and even in the middle of the log. Due to its time and impracticality, it is used to a limited extent. The Subneiloid formula is similar to the Smalian formula. The two-end conic formula is based on the assumption that the strain has a conical shape. These facts can bring several problems in practice, which can be eliminated by determining the volume of logs by the digital method [27].

At present, various digital systems for the quantification and qualification of Roundwood logs are being developed, most often based on image and laser scanning technology. These scanners are fast, accurate, and can create a computer model thanks to the three-dimensional reconstruction of the scanned object image, which can be further worked with, for example, dimensions, volume, shape, and, to a limited extent, surface qualitative features of wood logs.

Image and laser scanning technology, combined with X-ray defectoscopy such as computed tomography, allows the exact volume of wood logs to be displayed with internal qualitative features.

These scanners are usually large stationary devices that, using a system of cameras and laser measuring systems, evaluate the external parameters of the log. Devices of this type are commercially available. They are manufactured, for example, by WEINIG Gruppe (CombiScan + model), Innovativ Vision (morel WoodEye 5), and Microtec (Goldeneye series) [28,29].

The first goal of this paper is to verify the accuracy of four calculation methods of wood log volume. The tool to achieve this goal is to compare the results of the calculation of the log volume with the real log volume obtained from the three-dimensional reconstruction obtained by computed tomography.

The second goal of this paper is to determine the effectiveness of displaying the qualitative features of wood in three-dimensional models of selected pieces of logs of oak, beech, and spruce, which were obtained using computed tomography.

2. Materials and Methods

2.1. Materials

Nine pieces of wood logs were selected for the experiments. The test set was made from tree species of beech, spruce, and oak from each of three pieces. Non-coniferous logs were based on the standard STN EN 1316-1 Hardwood round timber. Qualitative classification: part 1: Oak and beech [30] are classified in class D. Coniferous logs based on the standard STN EN 1927-1 Qualitative classification of softwood round timber. Part 1: Spruces and firs [31] are classified in class C. In these classes, we classify logs in the case that we do not know the purpose of their use.

The measurement of dimensional characteristics of selected log pieces was carried out on 11 May 2022 using the forestry caliper and the measuring band. A worker equipped with this equipment first measures the length of the log and then measures the thickness at the ends and middle of the log according to the established methodology. The measured data are recorded in a table.

The following Table 2 shows the dimensional characteristics of selected pieces of logs that enter into the calculation of the log volume using selected methods.

Table 2. Dimensional characteristics of selected wood logs.

Log Mark	Log Length (m)	Middle Diameter over Bark (cm)	Middle Diameter under Bark (cm)	Thinner End Diameter According Guo Biao Method 4814-84 (cm)	Thinner end Diameter according to JAS Method JAS (cm)
SP 1	3.945	27.5	25.5	24	24
SP2	3.923	33.5	31	28	28
SP 3	3.932	30	28.5	26	26
BE 1	4.035	38	37.5	36	34
BE 2	4.055	33	33	30	30
BE 3	4.175	34	33.5	32	32
OA 1	4.205	29.5	28	24	24

Table 2. *Cont.*

Log Mark	Log Length (m)	Middle Diameter over Bark (cm)	Middle Diameter under Bark (cm)	Thinner End Diameter According Guo Biao Method 4814-84 (cm)	Thinner end Diameter according to JAS Method JAS (cm)
OA 2	4.085	31.5	30	28	27
OA 3	4.215	29	26.5	26	24

The designation of wood species was carried out according to EN 13556 (2003) Round and sawn timber—Nomenclature of timbers used in Europe adapted with permission from Ref. [32], 2003 European Committee For Standardization (SP—spruce, BE—beech, OA—Oak).

2.2. Methods

2.2.1. Quantitative Analysis

In order to demonstrate the differences in the calculation of the wood log volume according to different calculation models, the volumes of selected logs were calculated. Four calculation methods were used:

- STN 48 0007 (Tables of Roundwood volume according to the mid-diameter),
- STN 48 0009 (Volume tables of round timber without bark according to the mean diameter measured in bark),
- Guo Biao GB 4814-84 (Standards for China Market Access),
- JAS (Japanese Agricultural Standard).

In order to compare the accuracy of determining the volume of wood logs, using selected calculation methods, a three-dimensional model of wood logs was reconstructed using computed tomography, on the basis of which the actual volume of tested wood logs is precisely determined. Scanning of nine selected pieces of logs was performed on 20 February 2022, using a three-dimensional CT scanner of wood logs. CT scans of the log were performed using equipment CT Log of the manufacturer Microtec.

3D models of real logs are created from a selected set of wood logs of commonly traded assortments of economically important tree species. The log passing through the scanner is illuminated by X-rays. Different values of absorption of this radiation determine the density of different points of the wood. The Tomographic Inversion algorithm displays an image with a density of the scanned section for each section. The result is a 3D model of a log. The CT scanner resolution is limited (10 mm in the longitudinal direction and 2×2 mm in the transverse direction). The brightness value of a pixel in the black and white spectrum (gray levels) is called the DN value in the CT image, which represents the attenuation of the X-rays, which depends on the amount of absorbed X-ray energy. For lower material densities, pixels are represented by a lower brightness value (displayed as darker shades of gray) in the CT image, and vice versa. The density of wood in the cross-section of the log shows significant changes depending on the structure of the annual rings and the presence of qualitative features such as knots, cracks, and rot [28].

The output of the CT scan is an image in TIFF format (Figure 2), which contains individual cross-sections of the wood log, in steps every 10 mm. This means that when scanning a wood log with a length of 4000 mm, the created image consists of 400 sections.

Subsequently, a three-dimensional log model is constructed from these sections. A sequence of slices is imported into the specialized 3D slicer software [33,34], then a 10 mm thickness is defined for each slice and a three-dimensional log model is created by the volume rendering function (Figure 3). This model consists of voxels with dimensions of $2 \times 2 \times 10$ mm.

When calculating the volume of a 3D log model, we use the segment statistics function, which calculates the volume of the 3D model segment from the number of voxels and their dimensions [34]. In this case, we divide the 3D log model into two segments, the bark and the rest of the log (Figure 4). We then compare the determined volume of the log balance segment with selected calculation models of the wood log volume.

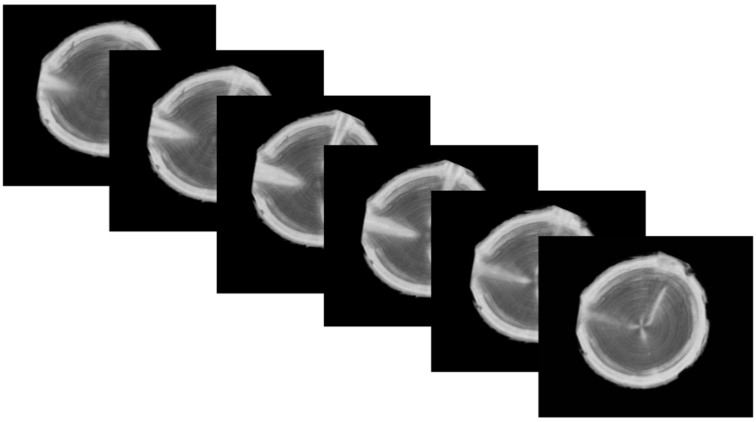

Figure 2. Output image of the spruce log from CT scanning.

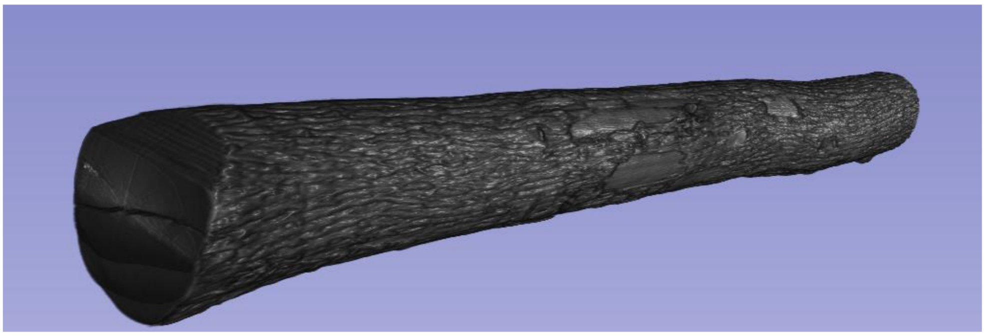

Figure 3. Three-dimensional model of a real oak log.

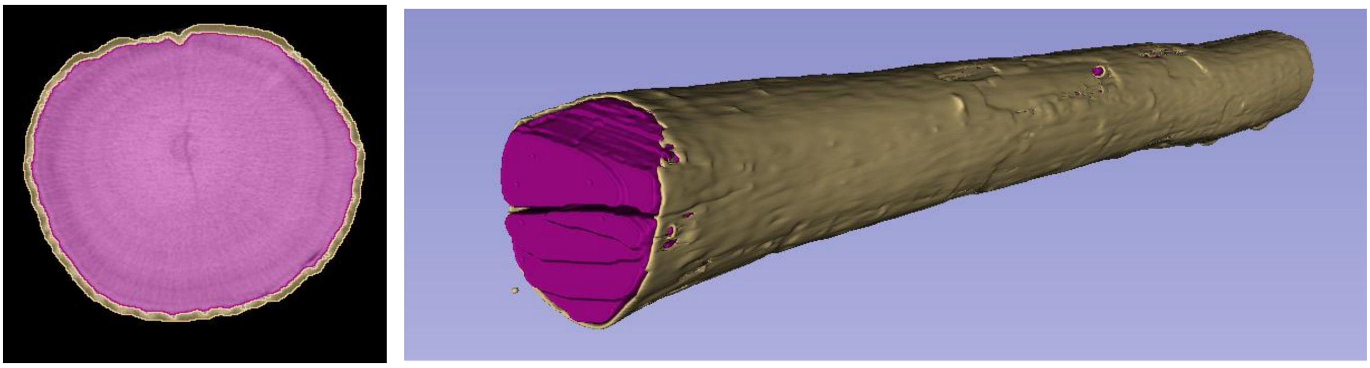

Figure 4. Real model of wood logs divided into bark segments and the rest of the logs.

Roundwood Volume according to STN 48 0007

This calculation model has been most often used in the Czech Republic and the Slovak Republic since 1959. This standard applies to the determination of numerical values of volumes of all types of raw wood logs, on which it is possible to measure the thickness without bark in the middle of the log length. The computational model is based on a stereometric formula [35].

$$V = 0.7584 \times L \times D^2/10{,}000 \tag{8}$$

where:

L—Log length (m)

D—Middle diameter (cm).

Roundwood Volume according to STN 48 0009

In the Czech Republic and the Slovak Republic, the STN 48 0009 standard was introduced in 1975, based on which the volume of wood logs is determined according to the central thickness measured with the bark. This means that STN 48 0009 solves the determination of the log volume of wood based on the main groups of tree species progressively, which have approximately the same course of thickness (Table 3). The calculation model is based on the following formula [25]:

$$V = (((d - (P0 + P1 \times d^{P2}))^2/pi \times L)/40{,}000) \tag{9}$$

where:

L—Log length (m)

d—Middle diameter (cm).

P0, P1, P2—coefficients from Table 4, selected on the basis of the main tree species groups.

Table 3. Tree species groups adapted with permission from Ref. [25], 1975, Slovak Office of Standards, Metrology and Testing.

I.	raggedrightspruce, fir
II.A	raggedrightPine bark, Eastern white pine, Douglas fir
II.B	raggedrightPine bark, European larch
III.	raggedrightbeech, maple, hornbeam, European mountain ash, lime, European aspen, sycamore, plum-tree, wild cherry, pear, European crabapple
IV.	raggedrightoak, Turkey oak, elm, ash, black locust, birch, horse chestnut, alder, aspen, walnut, willow

Table 4. Function parameters based on tree species groups adapted with permission from Ref. [25], 1975, Slovak Office of Standards, Metrology and Testing.

Tree Species	**Function Parameters**		
	P0	**P1**	**P2**
I.	0.577230	0.006897	1.312300
II.A	0.250170	0.901915	1.786600
II.B	1.701500	0.008762	1.456800
III.	−0.040877	0.166340	0.560760
IV.	1.247400	0.042623	1.062300

Roundwood Volume with Bark according to Guo Biao GB 4814-84

This calculation model was proposed by the Ministry of Forestry of the People's Republic of China, a special group for the drafting of basic standards for wood in 1984. This model is mainly used in the People's Republic of China to calculate the log volume of all tree species. When using this method, it is important to note its specific details:

The method calculates the volume of the log from the thickness of the thinner end. Two thickness measurements must be made across the narrow axis and the wide axis, and the resulting log thickness is determined as the arithmetic mean of the values from these two measurements, rounded to the nearest even integer [36]. Examples of rounding directions are given in the following Table 5 examples.

Table 5. Examples of the Guo Biao method of determining the final diameter of wood logs adapted with permission from Ref [36], 1984, Ministry of Forestry of the People Republic of China.

Narrow Diameter	Vertical Wider Diameter	Average Diameter	Resulting Record Diameter
20	21	20.5	20
20	22	21	22
20	23	21.5	22
20	24	22	22
20	25	22.5	22
20	26	23	24
20	28	24	24
26	27	26.5	26
26	28	27	28
26	29	27.5	28
26	30	28	28
26	31	28.5	28
26	32	29	30

To calculate the volume of a log with a thickness of 4 to 12 cm:

$$V = 0.7854 \times L \times (D + 0.45L + 0.2)^2/10{,}000 \quad (10)$$

To calculate the volume of a log with a thickness of more than 14 cm:

$$V = 0.7854 \times L[D + 0.5 \times L + 0.005 \times L^2 + 0.000125 \times L \times (14 - l)^2 \times (D - 10)]^2/10{,}000 \quad (11)$$

In the case of special-purpose logs whose length exceeds the standard lengths given in the tables, the log volume is calculated as follows:

$$V = 0.8 \times L(D + 0.5 \times L)^2/10{,}000 \quad (12)$$

where:

L—Log length (m),

D—thinner end diameter (cm).

The calculated volume of logs with a diameter of 4 to 6 cm is given to four decimal places, and in the case of logs with a thickness greater than 8 cm, is given to three decimal places.

Roundwood Volume with Bark according to JAS (Japanese Agricultural Standard)

It is one of the most widely used methods of calculating log volume, especially in Japan, Chile, East Asia, and Oceania. This calculation method was developed in Japan in the late 1940 and requires recording the thickness of the thinner end of the cut to determine the volume of the log. When using this method, it is important to note its specific details [37]:

- For logs with a thickness at the thinner end of less than 14 cm, the resulting diameter of the thin end of the log is determined as the thickness of the narrower axis of this end.
- For logs with a thin-end thickness of more than 14 cm, two narrow-axis and wide-axis thickness measurements must be made, and the resulting log thickness is determined as the average of these two measurements, rounded down to the nearest even whole number. Subsequently, the computational model is applied in two modes, namely for logs shorter than 6 m and logs equal to or longer than 6 m.
- For logs shorter than 6 m:

$$V(m^3) = (D^2 \times L)/10{,}000 \quad (13)$$

- For logs equal to or longer than 6 m:

$$V(m^3) = (D + [L' - 4]/2)^2 \times (L/10{,}000) \quad (14)$$

where:
D—Diameter on thinner end (cm), determined according to above rule
L—Length (m)
L′—length in meters rounded down to the nearest whole number

2.2.2. Qualitative Analysis

The three-dimensional log model was created as in Section 2.2.1. In this analysis, we deal with the representation of the internal structure of the analyzed log. The brightness value of a pixel in the black and white spectrum (gray levels) is called the DN value in the CT image, which represents the attenuation of the X-rays, which depends on the amount of absorbed X-ray energy. For lower material densities, pixels are represented by a lower brightness value (displayed as darker shades of gray) in the CT image, and vice versa. The density of wood in the cross-section of the log shows significant changes depending on the structure of annual rings, the presence of white, core, bark, and the presence of features such as knots, cracks, and rot.

A CT scan of a wood trunk usually contains four groups of brightness levels (gray levels), which represent the heartwood, sapwood, knots, and local holes in the log. The following factors affect the variations in the different gray levels observed in the CT images of the strain:

- Structure of annual rings—The log (temperate tree species) is composed of circular layers (annual rings) of early and late wood. Late-wood is made up of smaller cells and is denser, so it appears in lighter shades of gray (higher brightness) on the CT image. On the contrary, it is exactly how the human eye (negative) perceives the annual circles.
- Sap and heart wood—Some woods (oak, black locust, ash, elm, pine) are characterized by a distinction between sap and heart wood. Sapwood (younger) has a higher density due to higher moisture content. Because water has a higher density than wood, areas of sapwood appear lighter in CT scans of the log.
- Knot—is the part of the branch ingrown in the trunk of the tree. Nodes tend to deform annual circles. Their characteristic feature is a higher density compared to the surrounding wood. On CT images, they are displayed in a lighter shade of gray (higher brightness). The nodes usually have an elliptical shape in the cross-section of the tree trunk.
- Local pockets—There are areas of high water concentration (pockets) in the wood. These areas appear lighter shades of gray (higher brightness) on CT scans because water has a higher density than wood [28].

3. Results

3.1. Results of Quantitative Analysis

The following Table 6 shows the calculated log volumes using selected calculation methods.

In the following Table 7, the volumes of wood logs are determined from a three-dimensional model, made by computed tomography.

Table 6. Calculated volumes of wood logs using selected calculation methods.

Log Mark	Log Volume according to STN 48 0007 (m^3)	Log Volume according to STN 48 0009 (m^3)	Log Volume according to Guo Biao (m^3)	Log Volume according to JAS (m^3)
SP 1	0.19	0.22	0.222	0.227
SP2	0.29	0.32	0.295	0.308
SP 3	0.24	0.26	0.257	0.266
BE 1	0.43	0.43	0.492	0.466
BE 2	0.33	0.33	0.349	0.365
BE 3	0.36	0.36	0.408	0.428
OA 1	0.25	0.24	0.239	0.242
OA 2	0.28	0.27	0.309	0.298
OA 3	0.22	0.23	0.278	0.243

Table 7. Logs of wood determined from real CT scans of logs.

Log Mark	Log Volume with Bark Determined by CT Scanner (m^3)	Log Volume without Bark Determined by CT Scanner (m^3)
SP 1	0.226	0.218
SP2	0.336	0.322
SP 3	0.269	0.264
BE 1	0.439	0.412
BE 2	0.364	0.347
BE 3	0.409	0.394
OA 1	0.272	0.252
OA 2	0.303	0.275
OA 3	0.261	0.237

The following comparison was made in Statistica [38]. The following Figure 5 shows a comparison of the average log volume difference calculated using the four calculation methods with the actual log volume. The comparison is independent of the type of wood tested. The calculation methods STN 48 0007 and STN 48 0009 underestimate the volume of the tested log and the Gua Biao and JAS methods overestimate the volume of the tested log. The most accurate volume determination results are achieved by the STN 480009 method, in which the average difference in the volume of the log from the actual volume is less than 0.01 m^3. Methods STN 48007, Guo Biao, and JAS achieve an average difference in the volume of the log from the actual volume in the range of 0.01 m^3 to 0.02 m^3. The Guo Biao method records the largest variance of log volume difference values.

The following Figure 6 shows a comparison of the average log volume difference calculated using the four calculation methods with the real log volume. The comparison is shown for each tree species tested. All computational models tested were the most accurate in determining spruce volume. When determining the volume of beech by the Guo Biao and JAS method, the largest differences from the actual log volume were recorded. In all four tested methods, the largest variance of the values of log volume differences from reality was recorded for beech.

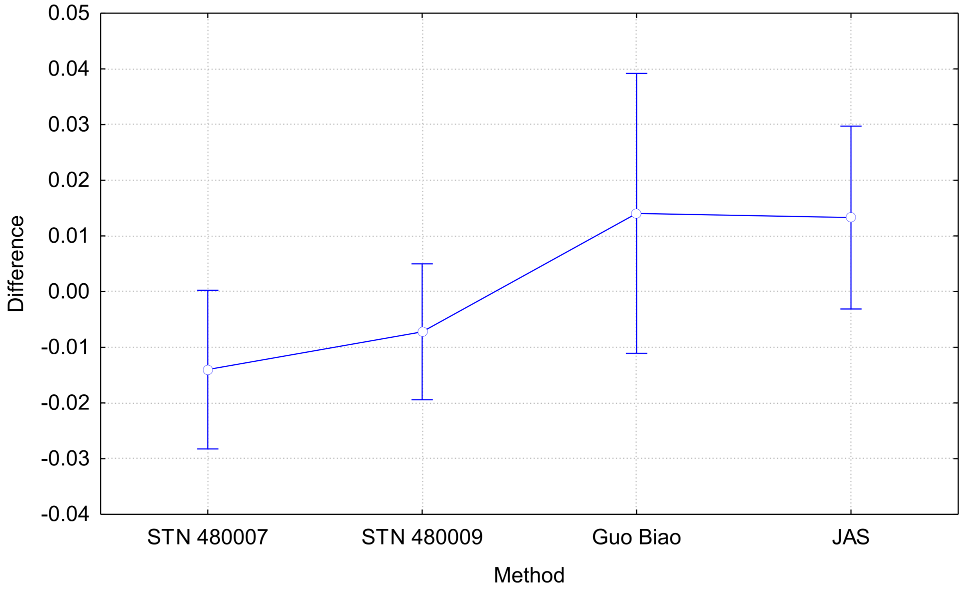

Figure 5. Comparison of averaged differences between the real volume and the calculated log volume.

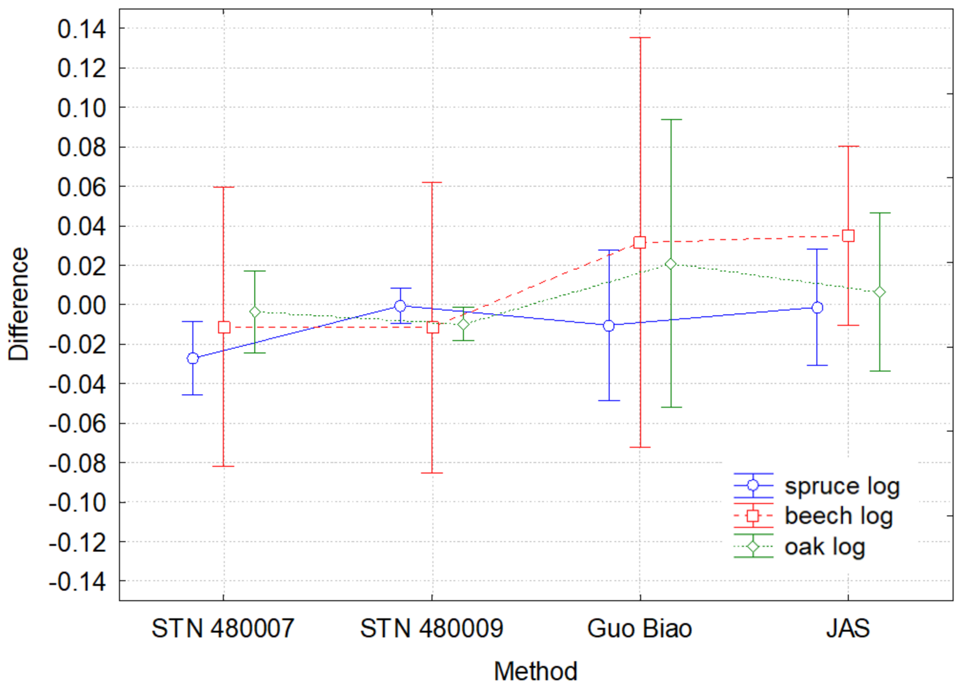

Figure 6. Comparison of differences between the real volume and the calculated log volume according to tree species.

3.2. Results of Qualitative Analysis

The following Figures 7–9 show the internal structure and wood qualitative features of the scanned spruce, oak and beech logs. On the left side, one cross-section in shades of gray through a specific log is shown, and on the right side, a three-dimensional model of a specific log is shown, with the internal structure shown in longitudinal section. The part of the log with the lowest density is shown in blue. With the increasing density of the log structure, the color display changes from green to shades of orange. Identified wood qualitative features are displayed in red.

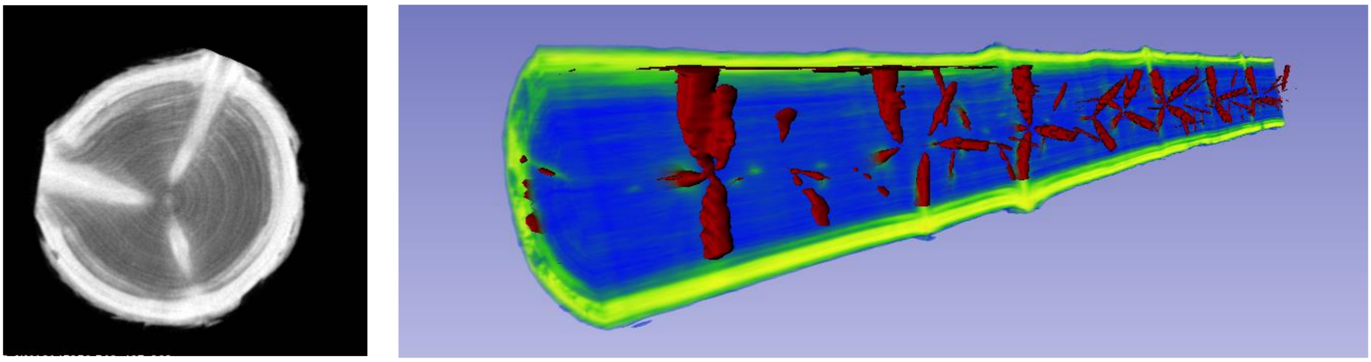

Figure 7. The internal structure of wood qualitative features on spruce.

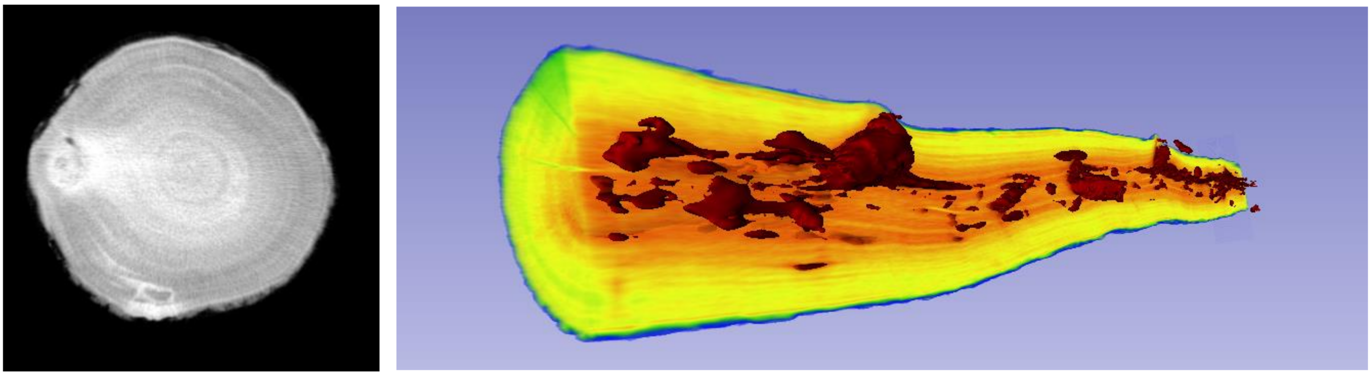

Figure 8. The internal structure of wood qualitative features on oak.

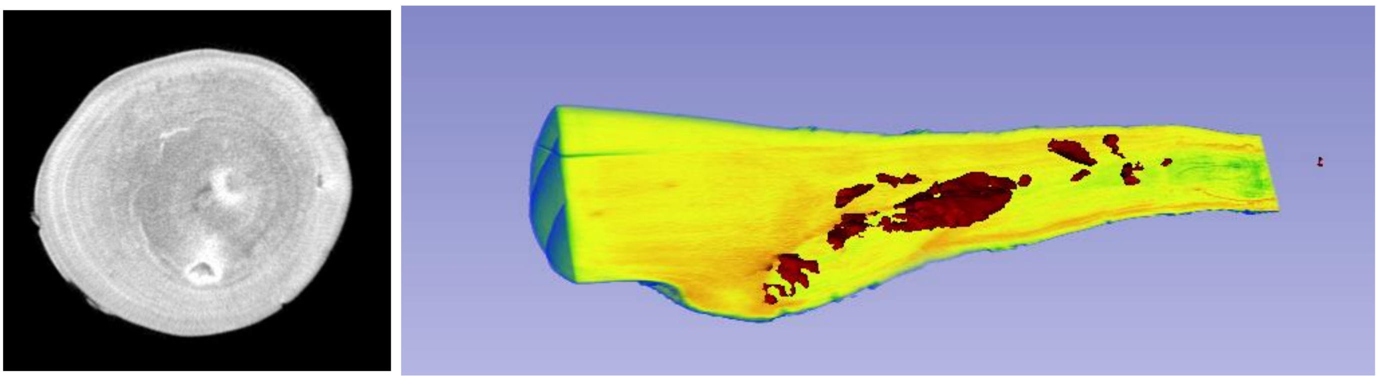

Figure 9. The internal structure of wood qualitative features on beech.

From a three-dimensional representation of the internal structure of spruce, oak and beech logs, we can observe significant differences in the internal structure between these trees. The most significant difference in structure is when comparing coniferous and non-coniferous logs.

In the case of spruce, higher-density sap wood is clearly distinguishable from lower-density heart wood. The individual knots in the middle wood are clearly distinguishable because they have a significantly higher density. The problem is to distinguish the knots in the sap wood, because it is visible from the CT images that they have the same density. For the overall representation of the knots in the spruce wood passing through the white part, it will be necessary to calculate this part of the knot representation based on the geometric shape.

In the case of oak, the clearly distinguishable bark of the log is shown in blue as the part with the lowest density. Heart wood as wood with a higher density is shown in shades of orange. The low difference in density between heart wood and wood qualitative features complicates their detection. Wood qualitative features are not displayed individually, but as interconnected areas of undefined shape.

In the case of beech, the clearly distinguishable bark of the log is shown in blue as the part with the lowest density. Heart wood is not visible. Rot is shown as an area with a green color bordered by a thin strip of wood with a higher density—orange. The low difference in density between healthy wood and wood qualitative features complicates their detection. Wood qualitative features are not displayed individually, but interconnected areas of undefined shape.

4. Discussion

The use of computed tomography in the quantitative and qualitative analysis of logs is a highly topical issue today. This is evidenced by the number of literary sources that have emerged in recent years. In Lowe et al. the authors analyze the effect of infestation of spruce wood by common insects on the mechanical properties of such wood. The computed tomography technique was used to correctly assess the extent of damage and cut out the test specimens [39]. Authors Boscaini et al. represent a new method for efficient localization of defects in CT scans of logs of valuable wood assortments [40]. This paper also demonstrates the need for a different approach to the detection and classification of hardwood defects. The issue of economic efficiency of the introduction of CT scanning was addressed by Pernkopf et al., specifically developed a simulation model to calculate the return on investment in CT scanning technology in the environment of a woodworking company [41]. Authors Gazo et al. and Cao et al., developed a method for detecting logs from real-time CT scans. The algorithm has proven to be suitable for industrial applications in hardwood saws [16,42]. The publication by Wei et al., presents the possibilities of computed tomography in determining the volume of logs, wood moisture, and localization of internal wood qualitative features. Finally, they compare the advantages and disadvantages of different types of scanners in the woodworking industry [43]. J.C. Ellis dealt with the comparison of the accuracy of the calculation of the volume of pine and Douglas fir logs using the JAS model and the Guo Biao model. [44]. An interesting direction of research possibilities is described in the work: "Using X-ray CT Scanned Reconstructed Logs to Predict Knot Characteristics and Tree Value". The authors describe the possibilities of creating a predictive model for estimating the value of a tree based on information about the internal structure of individual trees obtained by computed tomography [45].

5. Conclusions

It is possible to state that each of the tested calculation methods of wood log volume is applicable in practice. In the tested cases, the comparison of the calculated log volume with the real log volume (determined by computed tomography) recorded a difference in the log volume in the range from -0.015 m^3 to 0.014 m^3 (from -4.8% to 4.7%). With the total amount of logs traded on the world market, the amount of undervalued or overvalued logs is significant.

Accurate calculation of the log volume by the tested methods can be achieved only if the methodical procedure for determining the thickness of the tested log is followed. Experience has shown that to meet this assumption, the technician must determine the thickness of the log entering the calculation to determine with maximum accuracy. In practice, such a precise determination of the thickness of the log is time-consuming and technically demanding, because it is necessary to handle a log that is several hundred kg and repeatedly stored in a pile with a minimum amount of handling space. The introduction of log scanning technology eliminates the need for lengthy manual measurements and at the same time eliminates the human factor in this activity.

In conclusion, it is possible to state that the tested methods achieve excellent accuracy in determining the volume of spruce logs with a small variance of values and, conversely, for beech wood, the tested methods are the most inaccurate with the largest variance of values. When determining the volume of wood logs, we recommend using the calculation method STN 48 0009, because it achieves the best results. This method can be described as the most complicated because it is based on the thickness of the log determined in the middle, calculated as the arithmetic mean of two perpendicular measurements with the bark. Subsequently, the specified coefficients are applied to subtract the bark volume.

Qualitative analysis based on CT scans of internal features can be described as a completely new level of approach to the evaluation of log quality. The performed analysis showed great potential for automatic detection of internal qualitative features in the tested spruce log. In this wood, the wood qualitative features are distinguishable using computed tomography. In the case of non-coniferous oak and beech, the situation is more complicated. The internal structure of these trees overlaps the internal wood qualitative features. To accurately detect internal features in these trees, it will be necessary to perform many comparative tests to achieve optimal results.

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References

1. Vrchota, J.; Pech, M. Readiness of Enterprises in Czech Republic to Implement Industry 4.0: Index of Industry 4.0. *Appl. Sci.* **2019**, *9*, 5405. [CrossRef]
2. Halse, L.L.; Jæger, B. Operationalizing Industry 4.0: Understanding Barriers of Industry 4.0 and Circular Economy. In Proceedings of the IFIP International Conference on Advances in Production Management Systems (APMS), Austin, TX, USA, 1–5 September 2019.
3. Müller, F.; Jaeger, D.; Hanewinkel, M. Digitization in wood supply—A review on how Industry 4.0 will change the forest value chain. *Comput. Electron. Agric.* **2019**, *162*, 206–218. [CrossRef]
4. Gergeľ, T.; Bucha, T.; Gejdoš, M.; Vyhnáliková, Z. Computed tomography log scanning–high technology for forestry and forest based industry. *Cent. Eur. For. J.* **2019**, *65*, 51–59. [CrossRef]
5. Steele, P.H. *Factors Determining Lumber Recovery in Sawmilling*; FPL-39; US Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 1984; pp. 1–8.
6. Lundahl, C.G.; Grönlund, A. Increased yield in sawmills by applying alternate rotation and lateral positioning. *For. Prod. J.* **2010**, *60*, 331–338. [CrossRef]
7. Grundberg, S.; Grönlund, A. Simulated grading of logs with an X-ray log scanner-grading accuracy compared with manual grading. *Scand. J. For. Res.* **1997**, *12*, 70–76. [CrossRef]
8. Lindner, B.G.; Vlok, P.J.; Wessels, C.B. Determining optimal primary sawing and ripping machine settings in the wood manufacturing chain. Southern Forests. *J. For. Sci.* **2015**, *77*, 191–201.
9. Geerts, J. Mathematical solution for optimising the sawing pattern of a log given its dimensions and its defect core. *N.Z.J. For. Sci.* **1984**, *14*, 124–134.
10. Lin, W.; Wang, J.; Thomas, E. Development of a 3D log sawing optimization system for small sawmills in central Appalachia, US. *Wood Fiber Sci.* **2011**, *43*, 379–393.
11. Meier, P.; Rukki, H. *Saekavade Koostamine ja Arvutamine: Õppematerjal*; Tallinna Tehnikaülikooli Kirjastus: Tallinn, Estonia, 2001; pp. 1–39.
12. Chiorescu, S.; Grönlund, A. The fingerprint approach: Using data generated by a 3D log scanner on debarked logs to accomplish traceability in the sawmill's log yard. *For. Prod. J.* **2004**, *54*, 269–276.

13. Bhandarkar, S.M.; Faust, T.D.; Tang, M. CATALOG: A system for detection and rendering of internal log defects using computer tomography. *Mach. Vis. Appl.* **1999**, *11*, 171–190. [CrossRef]
14. Giudiceandrea, F.; Ursella, E.; Vicario, E. A high speed CT scanner for the sawmill industry. In Proceedings of the 17th International Non-Destructive Testing and Evaluation of Wood Symposium, Sopron, Hungary, 14–16 September 2011.
15. Correa, C.A.; Maldonado, M.R.; Lozano, D.M.; Carrasco, C.A. 3D optimization of cutting patterns for logs of Pinus Radiata D. don with cylindrical defective core. In Proceedings of the 10th International Conference on Modeling, Optimization and Simulation-MOSIM'14, Nancy, France, 5–7 November 2014.
16. Gazo, R.; Vanek, J.; Abdul_Massih, M.; Benes, B. A fast pith detection for computed tomography scanned hardwood logs. *Comput. Electron. Agric.* **2020**, *170*, 105–107. [CrossRef]
17. Stängle, S.M.; Brüchert, F.; Heikkila, A.; Usenius, T.; Usenius, A.; Sauter, U.H. Potentially increased sawmill yield from hardwoods using X-ray computed tomography for knot detection. *Ann. For. Sci.* **2015**, *72*, 57–65. [CrossRef]
18. Longo, B.L.; Brüchert, F.; Becker, G.; Sauter, U.H. Validation of a CT knot detection algorithm on fresh Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) logs. *Ann. For. Sci.* **2019**, *76*, 28. [CrossRef]
19. Gejdoš, M.; Lieskovský, M.; Giertliová, B.; Němec, M.; Danihelová, Z. Prices of raw-wood assortments in selected markets of central Europe and their development in the future. *BioResources* **2019**, *14*, 2995–3011.
20. Ross, R.J. *Nondestructive Evaluation of Wood*, 2nd ed.; General Technical Report; Forest Service: Madison, WI, USA, 2019; p. 169.
21. Schimleck, L.; Dahlen, J.; Apiolaza, L.A.; Downes, G.; Emms, G.; Evans, R.; Moore, J.; Pâques, L.; van den Bulcke, J.; Wang, X. Non-destructive evaluation techniques and what they tell us about wood property variation. *Forests* **2019**, *10*, 728. [CrossRef]
22. Potkány, M.; Gejdoš, M.; Debnár, M. Sustainable Innovation Approach for Wood Quality Evaluation in Green Business. *Sustainability* **2018**, *10*, 2984. [CrossRef]
23. Österberg, P. Wood Quality and Geometry Measurements Based on cross Section Images. Ph.D. Thesis, Tampere University of Technology, Tampere, Finland, 2009; p. 192.
24. *STN EN 1309-2*; Round and Sawn Timber. Method of Measurement of Dimensions. Part 2: Round Timber. Requirements for Measurement and Volume Calculation rules. European Committee for Standardization: Brussels, Belgium, 2007.
25. *STN 480009*; Tabul'ky Objemu Gul'atiny bez Kôry Podl'a Stredovej Hrúbky Meranej v Kôre [Tables of log Volume without Bark According to the Mean Thickness Measured in the Bark]. Slovak Office of Standards, Metrology and Testing: Bratislava, Slovakia, 1975.
26. Tewari, V.P.; Singh, B. Comparison of Bruce's formula and other Methods for Log Volume Estimation. *Indian For.* **2005**, *131*, 917–924.
27. Lippke, B.R.; Zobrist, K.W.; Mason, C.L. Rural Technology Initiative. In *Measurement of Logs*; Ruraltech Technology Initiative: Washington, WA, USA, 2007; Volume 1, pp. 1–24.
28. Gergel', T.; Sedliak, M.; Ondrejka, V. *3D Zobrazovacie Technológie Pre Detekciu Chýb Dreva*; Národné Lesnícke Centrum: Zvolen, Slovakia, 2021; pp. 53–58.
29. Ondrejka, V.; Gergel', T.; Bucha, T.; Pástor, M. Innovative methods of non-destructive evaluation of log quality. *Cent. Eur. For. J.* **2020**, *66*, 3–13. [CrossRef]
30. *STN EN 1316-1*; Hardwood Round Timber. Qualitative Classification. Part 1: Oak and Beech. European Committee for Standardization: Brussels, Belgium, 2012.
31. *STN EN 1927-1*; Qualitative Classification of Softwood Round Timber. Part 1: Spruces and Firs. European Committee for Standardization: Brussels, Belgium, 2008.
32. *EN 13556*; Round and Sawn Timber-Nomenclature of Timbers Used in Europe. European Committee for Standardization: Brussels, Belgium, 2003.
33. 3D Slicer Image Computing Platform. Available online: https://www.slicer.org/ (accessed on 31 May 2022).
34. Fedorov, A.; Beichel, R.; Kalpathy-Cramer, J.; Finet, J.; Fillion-Robin, J.-C.; Pujol, S.; Bauer, C.; Jennings, D.; Fennessy, F.; Sonka, M.; et al. 3D Slicer as an Image Computing Platform for the Quantitative Imaging Network. *Magn. Reson. Imaging* **2012**, *30*, 1323–1341. [CrossRef]
35. *STN 480007*; Tabul'ky Objemov Gul'atiny Podl'a Stredovej Hrúbky [Tables of Log Volumes by Mean Thickness]. Slovak Office of Standards, Metrology and Testing: Bratislava, Slovakia, 1998.
36. *GB4814-84*; Anon. Log Volume Table People's Republic of China. The Standardization Administration of the People's Republic of China: Beijing, China, 1984.
37. *No. 1841*; New Standards for Softwood and Hardwood Logs. Japanese Ministry of Agriculture, Forestry and Fisheries: Tokyo, Japan, 1967.
38. STATISTICA CZ; [Softwarový Systém na Analýzu Dat], Verzia 7. Statsoft, Inc.: Tulsa, OK, USA. 2004. Available online: www.statsoft.cz (accessed on 30 May 2022).
39. Löwe, R.; Sedlecký, M.; Sikora, A.; Prokůpková, A.; Modlinger, R.; Novotný, K.; Turčáni, M. How Bark Beetle Attack Changes the Tensile and Compressive Strength of Spruce Wood (*Picea abies* (L.) H. Karst.). *Forests* **2022**, *13*, 87. [CrossRef]
40. Boscaini, D.; Poiesi, F.; Messelodi, S.; Younes, A.; Grande, D.A. Localisation of Defects in Volumetric Computed Tomography Scans of Valuable Wood Logs. In Proceedings of the International Conference on Pattern Recognition, Milan, Italy, 10–11 January 2021.
41. Pernkopf, M.; Riegler, M.; Gronalt, M. Profitability gain expectations for computed tomography of sawn logs. *Eur. J. Wood Wood Prod.* **2019**, *77*, 619–631. [CrossRef]

42. Cao, Y.; Wang, D.; Wang, Z.; Tian, L.; Zheng, C.; Tian, Y.; Liu, Y. Research on Tree Pith Location in Radial Direction Based on Terrestrial Laser Scanning. *Forests* **2021**, *12*, 671. [CrossRef]
43. Wei, Q.; Leblon, B.; Rocque, A. On the use of X-ray computed tomography for determining wood properties: A review. *Can. J. For. Res.* **2011**, *41*, 2120–2140. [CrossRef]
44. Ellis, J.C. A log volume formula for exporters. *N. Z. J. For.* **2011**, *56*, 20–26.
45. Ji, A.; Cool, J.; Duchesne, I. Using X-ray CT Scanned Reconstructed Logs to Predict Knot Characteristics and Tree Value. *Forests* **2021**, *12*, 720. [CrossRef]