

Article

Differences in Timber Volume Estimates Using Various Algorithms Available in the Control and Information Systems of Harvesters

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Abstract: Timber is the most important source of revenue in forestry and, therefore, is necessary to precisely estimate its volume. The share of timber volume produced by harvesters is annually growing in many European countries. Suitable settings of harvesters will allow us to achieve the most accurate volume estimates of the produced timber. In this study, we compared the different methods of log volume estimation applied by control and information systems of harvesters. The aim was to analyze the price categories that can be set up in the StanForD standard and to determine the differences between the algorithms used for log volume estimations. We obtained the data from *.STM files collected from March 2017 until June 2018 on a medium-size harvester. We analyzed price categories and found seven different algorithms used to estimate the log volumes. Log volume estimates according to Algorithm A2 were considered as standard because these estimates should be closest to the true log volumes. Significant differences, except the difference between Algorithm A2 and Algorithm A3, were found between log volumes estimated by different algorithms. After categorization of logs to assortments, the results showed that significant differences existed between algorithms in each assortment. In the roundwood assortment, which contains the most valuable logs, a difference of more than 6% was found between the log volumes estimated by Algorithm A5 and Algorithm A2. This is interesting because Algorithm A5 is widely used in some Central European countries. To obtain volumes closest to the true volumes, we should use Algorithm A2 for the harvester production outputs. The resulting differences between the algorithms can be used to estimate the volume difference between harvester outputs using the different price categories. Understanding this setting of harvesters and the differences between the price categories will provide users useful information in applied forest management.

Keywords: bucking; log; StanForD; stem file; tree measurement; TimberMatic; CTL method

1. Introduction

Timber is the most important source of revenue in forestry. Besides grade, which affects the price per unit, it is necessary to precisely estimate volume and weight to quantify the amount of merchantable timber. Incorrect estimates of timber quantity affect the economic vitality of enterprises and forest owners. Besides the effects of the accuracy of the estimates on revenue, they also have a function on a societal level, serving as inputs into records and being used in industrial statistics.

There are many different ways of measuring timber. Measurements can be manual or automatic, depending on the logging method and technology. Timber can be scaled based on diameter measured either over or under bark [1]. For automated measurements that are rapid and accurate, there is no reason not to scale immediately after felling. In fact, it enables precise record keeping in forestry and reduces risk of losing timber during handling.

The use of manual, semiautomatic or automatic measurement is closely related to logging methods. Pulkki [2] describes five logging methods used around the world. He distinguishes between cut-to-length (CTL), tree-length, full-tree, whole-tree, and complete-tree logging methods. These methods differ in the form and size of logs hauled from the forest immediately after logging [3]. The CTL logging method can be described as a series of operations, in which standing trees are converted to timber assortments directly at the stump [4]. The assortments are produced during forest harvesting to increase net revenue early in the production chain [5,6]. The frequency that the CTL method is used varies between countries. Almost all logging in Sweden, Finland, and Norway is carried out by the CTL method [7,8]. The CTL method plays an important role in other European countries as well; in Estonia, 80% of all timber is logged by the CTL method, whilst in Latvia, 70%; Germany, 65%; Spain, 60%; and Italy, 60% [8]. Similarly, the share of the CTL method in the total amount of annual logging is increasing over the long term in countries such as the Czech Republic [9] and Poland [10], mainly due to the popularity of harvester technology. The reason for the increasing usage of harvester technology is that mechanized harvesting increases productivity and reduces costs and damages compared to motor-manual harvesting [11]. In the Czech Republic, the share of the CTL method reached 34% of total annual logging in 2017 [12], though this proportion may continue to grow to at least 50% [13].

Harvesters automate the measurement of log dimensions and subsequent volume estimation. If a machine is properly calibrated and set up, the outputs from its control and information system can be accepted as an accurate estimate of the amount of harvested timber by that machine. Although the harvesters are capable of measuring lengths with the accuracy in centimeters and diameters in millimeters [14], Czech forestry is lacking a standard that would govern the acceptance of these measurements by official records. This is also true for Germany and other European countries [15]. On the other hand, the outputs from harvesters can be affected by measurement errors, practices used, and bucking procedures [6]. For harvester outputs to be considered trustworthy in forestry record keeping, it is necessary for the forestry community to become familiar with the functioning of control and information systems.

Machine manufacturers supply the harvesters equipped with control and information system suites, often containing several separate software products. This software provides means of communication with the measuring sensors placed on the harvester head and converts the measured data (pulses and voltages) into metrics (lengths and diameters). Diameters of a log are recorded every 1 to 10 cm of its length—this distance depends on the control and information system and the standard file type. The measured data are stored in a unified data format, according to the StanForD standard. This communication standard allows data transfer between harvesters from different producers without problems. It was developed and is maintained by Skogforsk, the Forestry Research Institute of Sweden. The original StanForD was developed in 1988, and in 2011, an updated version was published. The updated version was named StanForD 2010 and the original was renamed to StanForD Classic [16]. In the Czech Republic, most of the harvesters still use StanForD Classic, which specifies data in more than 20 standard file types, such as *.KTR files for control measurement data, *.PRD files for production data, *.STM files for stem information, *.APT for bucking instruction data, and so on [17]. The StanForD offers a selection of 14 different price categories [18]. The price category defines the algorithm for volume estimation from the measured data (diameters and lengths) and also determines which diameter of the log (midspan or top-end) determines the inclusion of the log into individual assortments [19].

To enable the efficient use of any technology, we must study all relevant characteristics connected to it. Several aspects of using the harvester technology were studied, such as the damage to logs by feed roller spikes [20–22], the impact of heavy machinery on soil [23], harvester efficiency and performance [24,25], bucking optimization [26], harvester productivity [27–29], time consumption analysis [30–32] and harvester operators [33]. However, one key aspect of the harvester technology has been largely neglected in the scientific literature: the control and information systems and standards connected with their settings to achieve the most accurate volume estimates of the produced timber.

Therefore, this study compares the different methods of log volume estimation applied by the control and information systems of harvesters in conjunction with different price categories. The aim of this study was to analyze the price categories and to determine the differences between the algorithms used for log volume estimations. The algorithms use different parameters and calculation procedures to estimate the log volume. Therefore, we expect them to provide significantly different estimates of log volume, regardless of the assortment considered. It is important to consider this in the forestry practice, as even a seemingly minuscule error in volume estimation (e.g., due to using an inappropriate algorithm) can have a severe effect on the timber production in large-scale harvesting operations. Errors in volume estimation directly affect revenues, because they manifest in the amount of timber supplied to the market. This is especially true for roundwood, the most valuable assortment produced. Understanding this setting of harvesters and the differences between the price categories will provide users useful information in applied forest management.

2. Materials and Methods

2.1. Data Collection

The data were collected from March 2017 until June 2018 on a medium-size John Deere 1270E harvester. The machine was equipped with the TimberMatic control and information system and with a Waratah 480C harvester head. In the Czech Republic, the vast majority of harvesters use StanForD Classic. Therefore, a harvester using this standard was selected for this study. The harvester was owned by a private forest company. Harvests included mainly final felling and took place in Central Bohemia, South Bohemia, Vysočina and South Moravia Regions of the Czech Republic (Figure 1).

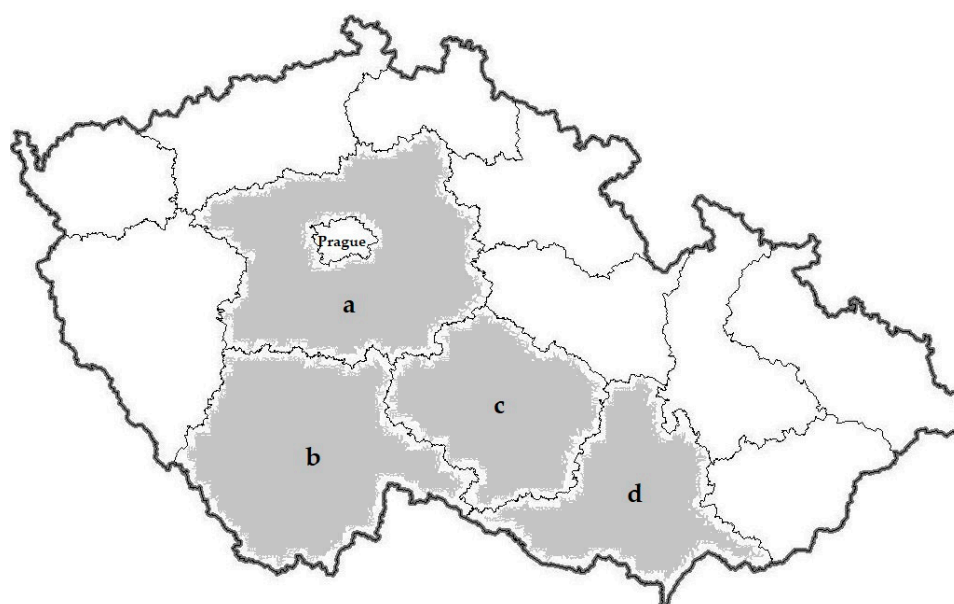


Figure 1. Map of the Czech Republic showing the Regions from where the harvester data originated. These regions are marked in gray: (a) Central Bohemia Region; (b) South Bohemia Region; (c) Vysočina Region; (d) South Moravia Region.

We dealt with *.STM files that contained lengths and diameters along 10 cm length increments of each recorded stem. For the purpose of this study, a total amount of 40,930 *.STM files were used. In this study, we analyzed Norway spruce (*Picea abies* [L.] Karst.) timber. Data from *.STM files represent a total amount of 231,196 spruce logs. To ensure the accuracy of the measured lengths and diameters, a control measurement was performed at the beginning of each working day. In the control measurements, the harvester felled from three to five trees, which were processed into logs. The harvester recorded the log lengths and diameters and created the *.STM control tree files. Subsequently, the harvester operator imported the *.STM data from the control and information system of the harvester into the Haglöf Digitech Professional II digital caliper with Kermit communication, equipped with the Digitech Tape and remeasured the logs. The caliper was set to automatic and used Skalman 6.11 software (Haglöf Sweden AB: Långsele, Sweden). In this setting, the harvester operator was guided for measurement locations by audio alerts of the caliper. When the control measurements were finished, the caliper created a *.KTR file. This file contains deviations between the log lengths and diameters as measured by the harvester and the caliper. If more than 20% of the diameters differed by more than 4 mm or more than 20% of the lengths differed by more than 2 cm, the harvester measuring device was calibrated. The calibration was realized by transferring the *.KTR file from the digital caliper to the harvester on-board computer. The TimberMatic software (1.19, Deere & Company: Moline, Illinois, USA) allows for the performance of automatic calibration of length and diameter gauges in the harvester head from the *.KTR file according to StanForD Classic.

2.2. Price Categories and Volume Estimation Algorithms

The TimberMatic software had 14 price categories pre-set. The description of each price category contained information about the algorithm used for the log volume estimation and also information about the diameter used for sorting the logs to individual assortments [18]. Some price categories differed only in using a different diameter to determine the assortment of the log, and their algorithm for the calculation of the log volume estimate remained the same. If some price categories were not described in detail [18], they were excluded. Two price categories were excluded from this study. They were the Board feet price category, which is not defined in the standard due to the very large number of different calculation methods that exist [18], and the M3sB price category, where the bulk volume is calculated with the default diameter and length of the bundle [34]. Other price categories were divided into groups according to the algorithm used to estimate the log volume. Price categories that contained the same algorithm for the log volume estimate were merged. This way, we ended up with seven different algorithms for the calculation of log volume estimates according to StanForD (Table 1).

Table 1. Seven algorithms (A1–A7) for log volume estimations according to StanForD. Price categories were merged to algorithms based on the log volume estimating algorithm.

Algorithm	Name of the Price Category
A1	M3to (code 1); M3tos (code 14)
A2	M3s (code 2); Log (code 3)
A3	M3sNO (code 4); LogNO (code 11)
A4	M3tobutt (code 5)
A5	M3toDE (code 6); M3miDE (code 7)
A6	M3smimi (code 8); M3sm (code 10)
A7	M3sEST (code 13)

All log diameters were measured over bark. Log volumes were estimated in m³ over bark and from the required length (nominal log length) instead of the total length (bucked length). Price categories were described in detail by Skogforsk [18].

Log volume according to Algorithm A1 was estimated by top-end diameter (TD) in millimeters and required length in centimeters. The TD measurement was always performed at the end of the required log length, i.e., 0 cm from the top end. The volume was estimated according to Equation (1):

$$V_{A1} = [\pi \times (TD/1000)^2] / 4 \times (RL/100) \quad (1)$$

where: V_{A1} is the log volume (m^3 over bark), $\pi = 3.14$, TD is the top-end diameter (mm), RL is the required length (cm).

The log volume estimate according to Algorithm A2 included price categories M3s and Log. Skogforsk [18] states that the volume estimated by the M3s is closest to the true volume of a log, because it measures the over bark diameter at each end of a 10 cm long section of the log. These measurements are then averaged, thus approximating the section as a cylinder. As the feeding rollers move the stem through the measurement devices, the machine adds up the volume of all sections calculated through Huber's formula until it reaches the threshold diameter for smallwood of the set price category [35]. For the last section, which is shorter than 10 cm, the real length is used in volume estimation. The total volume of the log is then calculated as the sum of all section volumes. This reduces the possible deviation from the true volume to a minimum. Total log volumes according to Algorithm A2 were taken from the *.STM file where they are automatically recorded.

Other algorithms use various measured or calculated diameters and required length of the log to calculate volume estimates. These algorithms were added to the StandForD standard to meet the requirements of key timber producers and make the outputs of harvesters and other scaling methods compatible in forestry record-keeping.

Log volume according to Algorithm A3 was estimated based on the calculated theoretical midspan diameter of the log (TMD) and the required length. The required length in decimeters was used for estimating the log volume. Therefore, the length measured in centimeters was rounded down to the nearest whole decimeter. The registered diameter measured at a distance of 10 cm from the top of the log (TD_{10}) was used for calculating the theoretical midspan diameter (TMD). The TD_{10} measured in millimeters was rounded down to the nearest whole centimeter. Equation (2) was used to calculate the log midspan diameter:

$$TMD = TD_{10} + (RL/2/10) + 0.5 \quad (2)$$

where: TMD is the theoretical midspan diameter (cm), TD_{10} is the diameter at a distance of 10 cm from the top of the log (cm), and RL is the required length (dm).

Then, the log volume was calculated in dm^3 according to Equation (3):

$$V_{A3} = (TMD/10)^2 \times \pi/4 \times RL \quad (3)$$

where: V_{A3} is the log volume (dm^3 over bark, subsequently converted to m^3 for volume comparisons), TMD is the theoretical midspan diameter (cm), $\pi = 3.14$, and RL is the required length (dm).

Log volume according to Algorithm A4 was estimated based on diameters measured at a distance of 10 cm from the top of the log and at a distance of 10 cm from the log butt end. In the case of a butt log (stem base), a second diameter was measured at a distance of 50 cm from the log butt end. Log volume was calculated according to the following Equation (4):

$$V_{A4} = \pi/4 \times RL/100 \times [a \times (BD_{10(50)}/1000)^2 + (1 - a) \times (TD_{10}/1000)^2] \quad (4)$$

where: V_{A4} is the log volume (m^3 over bark); $\pi = 3.14$, RL is the required length (cm); a is the parameter assigned according to the length and top end diameter of the log [18]; BD_{10} or BD_{50} is the diameter at a distance of 10 cm from the log butt end (mm) or at a distance of 50 cm from the butt end in the case of a butt log; and TD_{10} is the diameter at a distance of 10 cm from the top of the log (mm).

Log volume according to Algorithm A5 was estimated based on the midspan diameter and the required length. For volume estimation, the midspan diameter was rounded down to the nearest

whole centimeter according to the Handelsklassensortierung (sorting of merchantable wood; further in text HKS) method [18,36]. The total log volume was calculated according to Equation (5):

$$V_{A5} = \pi \times (MD^2/4/10,000) \times RL/100 \quad (5)$$

where: V_{A5} is the log volume (m^3 over bark), $\pi = 3.14$, MD is the midspan diameter (cm), and RL is the required length (cm).

Log volume according to Algorithm A6 was estimated based on the midspan diameter and the required length. The midspan diameter was measured in millimeters and was not rounded. The total log volume was calculated according to Equation (6):

$$V_{A6} = \pi \times (MD^2/4/1,000,000) \times RL/100 \quad (6)$$

where: V_{A6} is the log volume (m^3 over bark), $\pi = 3.14$, MD is the midspan diameter (mm), and RL is the required length (cm).

Log volume according to Algorithm A7 was estimated based on the top-end diameter of the log. The volume was calculated according to Equation (7):

$$V_{A7} = [TD^2 \times RL \times (a_1 + a_2 \times RL) + a_3 \times RL^2]/10,000 \quad (7)$$

where: V_{A7} is the log volume (m^3 over bark), TD is the top-end diameter (mm), RL is the required length (dm) with at least one decimal, $a_1 = 0.07995$ is the tree species dependent conic factor for spruce, $a_2 = 0.000161$ is the tree species dependent conic factor for spruce, and $a_3 = 0.04948$ is the tree species dependent conic factor for spruce (a_1 , a_2 and a_3 factors are by Skogforsk [18]).

2.3. Stem Files Analysis

Data stored in the *.STM files were transferred to the MS Excel spreadsheets using the STeMa application. The variables obtained from the *.STM files were the following: (i) tree species (SP), (ii) assortment (AS), (iii) total length (TL), (iv) required length (RL), (v) log volume according to M3s (A2), and (vi) top-end diameter (TD). Other variables necessary for log volume estimation by particular algorithms were calculated during the iteration of each single *.STM file by analysis of the StanForD variable that contains the taper curve of the produced stem and allows for the extraction of variables that are not a direct part of the saved *.STM file by using a suitable algorithm. This way, the following variables were obtained: (i) midspan log diameter (MD), (ii) diameter at a distance of 10 cm from the top end of the log (TD_{10}), (iii) diameter at a distance of 50 cm from the log butt end (BD_{50}), and (iv) diameter at a distance of 10 cm from the log butt end (BD_{10}). After the batch processing of the *.STM files was finished, the data were saved in the *.CSV format. This format allows for easy conversion to the *.XLSX format, which is suitable for further data analysis. Data in the *.XLSX format were subsequently used for estimation of the log volumes according to the individual algorithms.

2.4. Assortment Categorization

The stem of the felled tree was cut into individual logs by the harvester. Each log represented an assortment, meeting the tree species, dimensions, and quality requested by the customer. The harvester operator determined the tree species and grade; the machine software then suggested the assortment to be produced based on the quantitative parameters. We distinguished the logs into three assortments: (i) firewood (FW), the lowest grade of timber intended for energy use; (ii) pulpwood (PW), timber intended for production of wood pulp products; and (iii) roundwood (RW), the highest grade of timber intended for industrial processing, such as for veneer logs, timber for the production of musical instruments, sawn wood, poles, etc.

2.5. Data Analyses

First, we calculated the absolute (in m³ over bark) and the relative (in %) differences between the log volumes estimated by each algorithm and Algorithm A2. We also calculated the relative differences between the log volume estimates for the seven different algorithms, differentiated by assortment categorization. Then, we used general linear models (GLM), specifically ANOVA for repeated measurements, to test differences in log volume estimates among the algorithms, both for all timber together and categorized according to assortments. The post-hoc tests (Tukey HSD) were used to find out differences between the log volumes estimates according to the respective algorithms. For all statistical tests, the $\alpha = 5\%$ level of significance was set. All tests were conducted in the Statistica 13 package (TIBCO Software Inc.: Palo Alto, CA, USA).

3. Results

Altogether, 231,196 logs were measured, and seven volume estimates were calculated (Table 2).

Table 2. Measured timber parameters and estimated log volumes.

Timber Parameter	All Logs		Assortments					
			Roundwood		Pulpwood		Firewood	
	<i>n</i> = 231,196		<i>n</i> = 93,129		<i>n</i> = 114,474		<i>n</i> = 23,593	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
TL (cm)	294.9	126.7	430.0	83.5	211.3	27.0	167.2	64.1
RL (cm)	288.6	122.3	418.4	81.4	208.1	26.8	167.2	64.1
MD (mm)	207.4	102.0	278.8	79.7	171.0	86.1	101.9	56.4
TD (mm)	193.2	98.8	261.8	78.8	157.9	83.1	93.7	55.1
TD ₁₀ (mm)	194.1	98.9	262.6	78.8	158.8	83.3	94.3	55.4
BD ₅₀ (mm)	217.8	106.8	295.3	83.0	177.8	87.4	105.2	57.2
BD ₁₀ (mm)	222.0	107.6	299.4	83.9	182.4	88.6	108.0	58.0
V _{A1} (m ³)	0.1251	0.1443	0.2431	0.1508	0.0517	0.0647	0.0149	0.0300
V _{A2} (m ³)	0.1453	0.1650	0.2830	0.1694	0.0597	0.0725	0.0170	0.0333
V _{A3} (m ³)	0.1452	0.1636	0.2845	0.1663	0.0582	0.0682	0.0178	0.0334
V _{A4} (m ³)	0.1413	0.1594	0.2744	0.1637	0.0585	0.0696	0.0175	0.0330
V _{A5} (m ³)	0.1370	0.1560	0.2659	0.1608	0.0571	0.0708	0.0164	0.0323
V _{A6} (m ³)	0.1417	0.1593	0.2740	0.1633	0.0596	0.0720	0.0176	0.0332
V _{A7} (m ³)	0.1420	0.1629	0.2781	0.1689	0.0570	0.0686	0.0174	0.0328

N = number of logs, TL = total length, RL = required length, MD = midspan diameter, TD = top-end diameter, TD₁₀ = diameter at a distance of 10 cm from the top of the log, BD₅₀ = diameter at a distance of 50 cm from the log butt end, BD₁₀ = diameter at a distance of 10 cm from the log butt end, V_{A1} = log volume estimate according to Algorithm A1, V_{A2} = log volume estimate according to Algorithm A2, V_{A3} = log volume estimate according to Algorithm A3, V_{A4} = log volume estimate according to Algorithm A4, V_{A5} = log volume estimate according to Algorithm A5, V_{A6} = log volume estimate according to Algorithm A6 and V_{A7} = log volume estimate according to Algorithm A7.

The absolute log volumes estimated by the different algorithms were always lower than the log volumes estimated by Algorithm A2 (Table 3). Algorithm A1 provided log volume estimates which differed the most from those provided by Algorithm A2. The second highest difference was recorded by using Algorithm A5. On the other hand, the smallest difference was recorded using Algorithm A3.

Table 3. Absolute and relative differences between the log volume estimates by seven different algorithms according to StanForD Classic. Differences were related to Algorithm A2.

Algorithm	Total Volume of Logs	Absolute Difference from Algorithm A2	Relative Difference from Algorithm A2
	(m ³ over Bark)	(m ³ over Bark)	%
A1	28,914.92	−4674.31	−13.92
A2	33,589.22	0	0
A3	33,577.46	−11.76	−0.04
A4	32,662.77	−926.46	−2.76
A5	31,684.32	−1904.90	−5.67
A6	32,753.76	−835.46	−2.49
A7	32,835.02	−754.20	−2.25

The relative differences between the log volume estimates were also determined for the seven different algorithms differentiated by assortment. Out of 231,196 logs, 40.3% of logs were roundwood assortments, 49.5% of logs were pulpwood assortments and 10.2% of logs were firewood assortments (Table 4). The total volume of the logs according to Algorithm A2 was 33,589.22 m³ over bark, out of which roundwood assortments accounted for 78.5%, pulpwood assortments for 20.3%, and firewood assortments for 1.2%.

Table 4. Relative differences between the log volume estimates by seven different algorithms according to the assortment's categorization (roundwood, pulpwood, firewood). Differences were related to Algorithm A2.

Algorithm	Assortments					
	Roundwood		Pulpwood		Firewood	
	Total Volume of Logs	Relative Difference from Algorithm A2	Total Volume of Logs	Relative Difference from Algorithm A2	Total Volume of Logs	Relative Difference from Algorithm A2
	(m ³ over Bark)	%	(m ³ over Bark)	%	(m ³ over Bark)	%
A1	22,643.54	−14.08	5919.51	−13.38	351.87	−12.51
A2	26,353.27	0	6833.77	0	402.18	0
A3	26,495.77	0.54	6661.30	−2.52	420.39	4.53
A4	25,554.26	−3.03	6696.71	−2.01	411.80	2.39
A5	24,759.89	−6.05	6537.43	−4.34	387.00	−3.78
A6	25,519.29	−3.16	6819.89	−0.20	414.91	3.16
A7	25,895.78	−1.74	6528.71	−4.46	410.53	2.08

There were significant differences in the mean log volume estimates among the algorithms (Figure 2a). Algorithm A2 estimated the highest mean log volume and was similar to Algorithm A3. The smallest log volume was estimated by Algorithm A1. Calculations according to assortments followed similar patterns with minor differences (Figure 2b). For the roundwood assortment, the highest log volume was estimated by Algorithm A3, followed by the lower log volume estimated by Algorithm A2. Algorithm A1 provided the smallest log volumes estimates and was followed by Algorithm A5. For the pulpwood assortment, the highest log volume was estimated by Algorithm A2, followed by the significantly lower log volume estimated by Algorithm A6. The smallest log volume was estimated by Algorithm A1 and the second lowest log volume was estimated by Algorithm A5. For the firewood assortment, the highest log volume was estimated by Algorithm A3, which was followed by Algorithm A6. The smallest log volume was also estimated by Algorithm A1 and the second lowest volume was estimated by Algorithm A5.

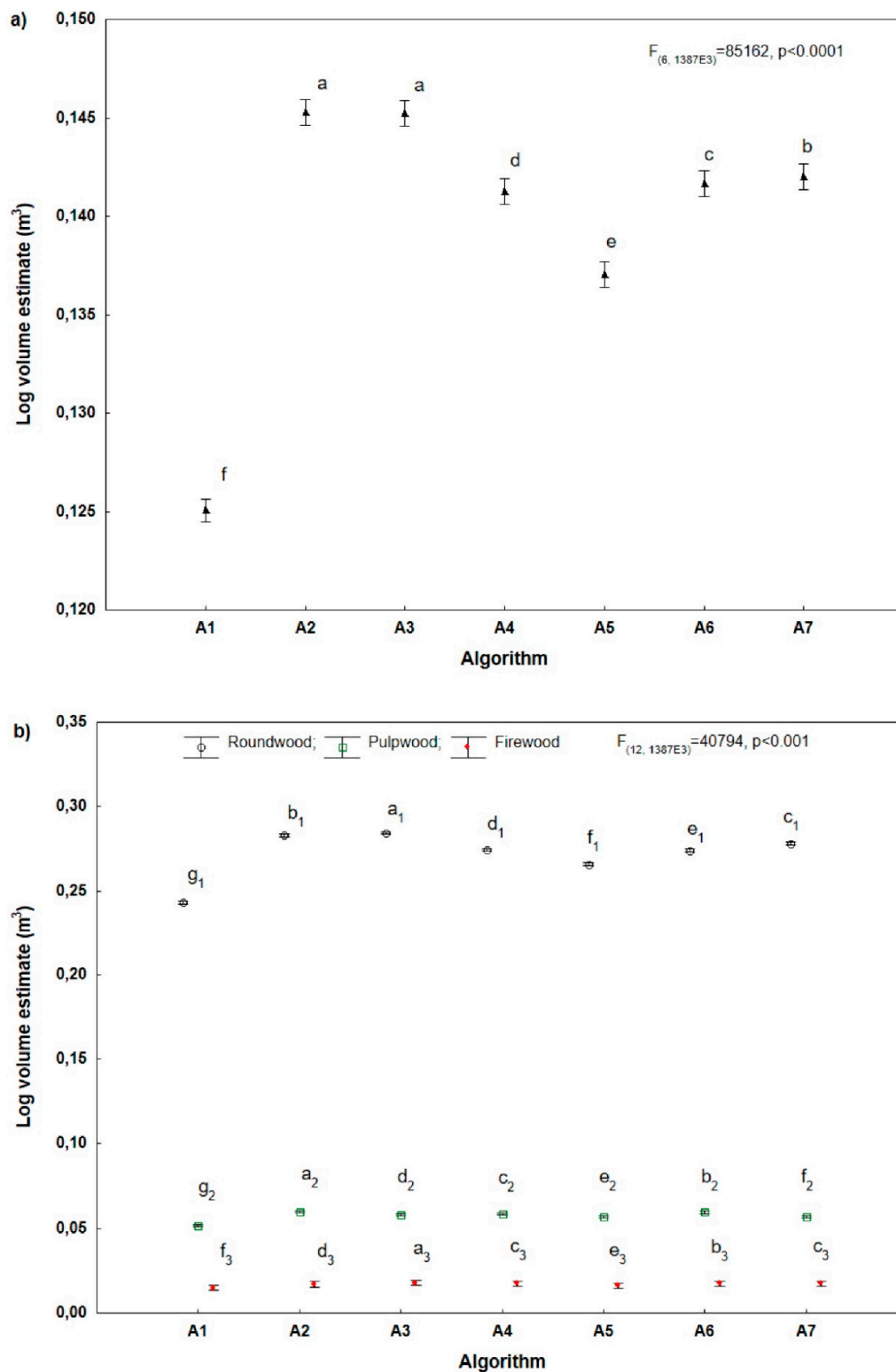


Figure 2. Differences in mean volume estimates per log by different algorithms (a) of all logs together, (b) according to assortments. Different letters indicate significant differences revealed by post-hoc Tukey HSD tests ($\alpha = 0.05$); assortments were tested separately. The error bars indicate a 0.95 confidence interval. There were no significant differences only between Algorithms A2 and A3 in the group of all logs together (a-a) and between Algorithms A4 and A7 in the firewood assortment (c₃-c₃).

4. Discussion

The results showed significant differences between the log volumes estimated by different algorithms used in the control and information systems of harvesters. A comparison of the obtained results with other studies could not be carried out because we were unable to find suitable scientific literature dealing with the evaluation of volume differences according to the price categories of StanForD. Differences between the volumes estimated by the individual algorithms were related to Algorithm A2. As Skogforsk [18] states, the volume estimated by the Algorithm A2 should be closest to the true volume of the log. However, even this volume estimation algorithm is not absolutely precise; as Hohmann et al. [15] state, harvesters underestimate the log volume by -0.45% on average, compared to the water immersion technique.

The large difference between Algorithm A2 and Algorithm A1 can be explained by the parameters they use to estimate the volume. Algorithm A1 is based on cylindrical volume to estimate the log volume and uses the top-end diameter as the diameter value. Naturally, the top-end diameter is the smallest value that can be used and will result in a substantial underestimation of the log volume, so it is inappropriate for detecting the true log volume. However, it can be assumed that Algorithm A1 was never intended to provide a true log volume, but apparently to provide a value reflecting the volume available for full-length sawn products.

The second largest difference was found between Algorithm A2 and Algorithm A5. According to Algorithm A5, the log volume is estimated based on the measured midspan diameter. However, its value is always rounded down to the nearest whole centimeter. This is in accordance with the HKS method [35] described in detail by Wojnar [37]. Thus, if Algorithm A5 is used to determine the volume of harvester timber production, this cannot be considered as a true timber volume which is felled and hauled from the forest. The large difference was interesting because Algorithm A5 is used in the M3toDE and M3miDE price categories that are used in Central European countries such as Germany, the Czech Republic, Austria, Slovakia, and Hungary. For example, in the Czech Republic, these price categories are recommended because they ensure that the timber volume reported by the harvester will be comparable to the timber volume determined according to the Recommended Rules for Timber Measurement and Sorting in the Czech Republic 2008 [37]. Thus, we deliberately significantly underestimate the volume of timber production.

It is also very interesting to compare the volume results according to Algorithm A5 and Algorithm A6. These two methods differ in one key aspect: Algorithm A6 does not require rounding down the midspan diameter because it is not based on the HKS method. Therefore, the directly measured midspan diameter, in millimeters, is used for the volume estimation. Estimating the volume based on precise midspan diameter halved the margin of error to 3.18% (1069.44 m^3). Therefore, we recommend working with the accuracy of diameter measurements harvesters provide [14] and not round the measured diameters for volume estimation.

Both Algorithm A4 and Algorithm A7 showed a difference in estimated log volumes of less than 3% compared to Algorithm A2. Algorithm A4 uses Equation (4) that contains the “a” parameter, the value of which varies with the log length and top-end diameter. The values of the “a” parameter are listed in [18]. Also, Algorithm A7 uses Equation (7) for log volume estimation. The log volume is estimated by using the top-end diameter of the log and the conic factors whose value depends on the tree species [18]. Thus, the difference from Algorithm A2 could be different if we were to estimate the log volumes of tree species other than the Norway spruce.

Algorithm A3 proved to estimate the volume closest to the benchmark Algorithm A2. This difference was the lowest one and was the only statistically insignificant difference. Algorithm A3 estimated the log volume based on a cylinder with a theoretical midspan diameter of the log and the measured log length rounded down to the nearest whole decimeter. However, the diameter used to estimate the theoretical midspan diameter was actually measured 10 cm from the top of the log. This measured diameter is always rounded down to the nearest whole centimeter. The calculation of the theoretical midspan diameter is based on a standard stem taper that is 1 cm diameter per 1 m

length. Such a standard taper is in accordance with what is stated in [38] for sawlogs. Then, 0.5 cm is added to the calculated theoretical midspan diameter for compensation of the previous rounding. Then, the Huber's equation [35] is used to calculate the log volume. Equation (3), used to calculate the volume according to Algorithm A3, thus appears to be the best alternative to Algorithm A2. However, if we focused on individual assortments, we found that there were significant differences between these two algorithms, though the lowest difference between these two algorithms was in the roundwood assortment. This could be due to the fact that the equation of Algorithm A3 uses the theoretical midspan diameter that is calculated based on the principle of standard stem taper of 1 cm diameter per 1 m length. This stem taper is referred to as the standard for sawlogs, which largely represents the roundwood assortment. On the contrary, pulpwood and firewood assortments contained mainly butt and top logs, which can taper differently than the standard rate [38].

When we compared the differences in the assortments, it was interesting to focus especially on differences in the roundwood assortment that contained not only the highest volume of the logs but also the best economically valued logs. In the roundwood, the results showed that a significant difference occurred between the log volume estimates for each algorithm pair. As compared with the overall difference, the difference between Algorithm A5 and Algorithm A2 increased by 0.38 percentage points. This result was interesting because it showed an increase in the volume difference in the most valuable timber. In some Central European countries, Algorithm A5 is used for harvester production outputs of roundwood. If we would like to use these outputs for selling timber, we would sell more than 6% less timber than what the true volume is. In the case where this underestimation is not reflected in the timber price, this would bring a significant economic loss to the seller, even if the machines were properly maintained and calibrated. We should require credible outputs not only for timber sales, but also for credible timber production records.

Log volumes estimated by Algorithm A2 were the highest in the pulpwood and the second highest in the roundwood. However, in the firewood assortment, the volume estimated by Algorithm A3, Algorithm A4, Algorithm A6, and Algorithm A7 was higher than that estimated by Algorithm A2. This can be due to the fact that the firewood grade contained logs of small dimensions. Procedures for estimating the log volume of firewood logs according to some algorithms are not entirely appropriate for these small dimensions and therefore overestimate the true log volume.

This study was focused only on spruce stems. Generally, cutting and processing coniferous trees is preferred for harvesters. The influence of tree species cannot be ignored when discussing mechanized harvesting [25]. There are still problems when harvesting broadleaved trees by machines associated with delimbing [39], taller stumps in coppice stands [40], and also larger shavings of the bark and the lateral surface of processed assortments [41]. Defects on stems and large branches, which are particularly common in some broadleaved tree species, can cause measurement errors for both the log length and diameter [42]. These errors can significantly affect the precision of volume estimations through various algorithms.

It is necessary to perform regular control measurements of harvester measuring systems and, if necessary, to calibrate the harvester. Regular calibration improves the accuracy of the harvester measurement system [43] and ensures that the volume outputs are credible. Different methods can be used for manual control measurements. In this study, a digital caliper equipped with a digital tape was used. The combination of a digital caliper and a digital tape is faster, more accurate, and more efficient than conventional analog measuring devices. We strongly recommend using this method to calibrate the measuring system of harvesters. Performing regular control measurements and calibration of the machine measuring system secures sufficient measurement accuracy of the timber volume production.

For these results, it is also necessary to note that the log volume estimates in this study were expressed as volumes in m^3 over bark. In this manner, volumes are free from potential inaccuracies caused by the estimation of volume under bark. Marshall et al. [44] dealt with the effects of bark thickness estimates. It is important to note that the resulting volumes compared in this study cannot be compared with the true total volume of logs because timber volumes in this study do not include the

volume of the allowance to the required length and the cutting window volume. The length allowance means the addition of length to some assortments for cross-cutting or other processing, and the cutting window is an addition to the length for ensuring a cut-point tolerance of the harvester measuring sensors, which increases the performance of the machine. In the Czech Republic, the recommended allowance is 2% of the required log length, and the recommended cutting window is within a range from 0 cm to a maximum of 4 cm [19]. The total volume of harvested timber also differs from the volume of standing timber because it does not contain a share of logging residue volume estimates [45].

5. Conclusions

In this study, we revealed significant differences between the log volumes estimated by different algorithms used in the control and information systems of harvesters. The results showed that if we want to use harvester production outputs for timber sales and record keeping, it is necessary to distinguish how the log volumes were estimated. Algorithm A1 proved to be an inappropriate algorithm for estimating the true log volume. There was no significant difference between the log volumes estimated by Algorithm A3 and Algorithm A2. In the roundwood assortment, a difference of more than 6% was found between the log volumes estimated by Algorithm A5 and Algorithm A2. This is an interesting result, especially for some Central European countries, where Algorithm A5 is preferred in harvester production outputs.

To obtain volumes closest to the true volumes, we should use Algorithm A2 for timber production outputs of harvesters. These conclusions are true if the goal is to obtain the most accurate total timber volume that can be used for timber sales and for precise forestry record-keeping. If the measurement would have a different goal, e.g., to estimate the amount of timber for board production, using a different algorithm could be appropriate.

However, the outputs of timber production are useful only if credible. Therefore, it is necessary to perform regular control measurements of the harvester measuring systems and, if necessary, to calibrate the machine. The resulting differences between the algorithms can be used to estimate the volume difference between harvester outputs using different price categories. Further research could be focused on what share of timber is not registered in harvester production outputs due to the length allowance and the cutting window of logs.

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References

1. Edwards, P.N. *Forestry Commission Booklet 49- Timber Measurement: A Field Guide*; HMSO: Edinburgh, UK, 1998; p. 64, ISBN 0-85538-403-4.
2. Pulkki, R. Cut-to-length, tree-length or full tree harvesting? *Cent. Woodl.* **1997**, *1*, 22–27.
3. Rebula, E. Tehnologija u šumarstvu na početku idućeg tisućljeća. *Mehanizacija šumarstva* **1988**, *13*, 31–40.
4. Malinen, J.; Kilpeläinen, H.; Wall, T.; Verkasalo, E. Variation in the value recovery when bucking to alternative timber assortments and log dimensions. *For. Stud.* **2006**, *45*, 89–100.
5. Faaland, B.; Briggs, D. Log Bucking and Lumber Manufacturing Using Dynamic Programming. *Manag. Sci.* **1984**, *30*, 245–257. [[CrossRef](#)]

6. Marshall, H.D. An Investigation of Factors Affecting the Optimal Output Log Distribution from Mechanical Harvesting and Processing Systems. Ph.D. Thesis, Oregon State University, Corvallis, OR, USA, 2005.
7. Gellerstedt, S.; Dahlin, B. Cut-to-length: The next decade. *Int. J. For. Eng.* **1999**, *10*, 17–25.
8. Lundbäck, M.; Häggström, C.; Nordfjell, T. Worldwide Trends in the Methods and Systems for Harvesting, Extraction and Transportation of Roundwood. In Proceedings of the 6th International Forest Engineering Conference “Quenching our thirst for new Knowledge”, Rotorua, New Zealand, 16–19 April 2018; pp. 1–3.
9. Natov, P.; Dvořák, J.; Sedmíková, M.; Löwe, R.; Ferenčík, M. Srovnání vyrobeného objemu dříví harvestorem se zásobou porostu stanovenou objemovými tabulkami. *Zprávy Lesnického Výzkumu* **2017**, *62*, 1–6.
10. Bembenek, M.; Mederski, P.S.; Karaszewski, Z.; Łacka, A.; Grzywiński, W.; Węgiel, A.; Giefing, D.F.; Erler, J. Length accuracy of logs from birch and aspen harvested in thinning operations. *Turk. J. Agric. For.* **2015**, *39*, 845–850. [[CrossRef](#)]
11. Spinelli, R.; Lombardini, C.; Magagnotti, N. The effect of mechanization level and harvesting system on the thinning cost of Mediterranean softwood plantations. *Silva Fenn.* **2014**, *48*, 1–15. [[CrossRef](#)]
12. MZe. *Zpráva o Stavu Lesa a Lesního Hospodářství České Republiky v Roce 2017*; Ministry of Agriculture: Prague, Czech Republic, 2018; p. 116, ISBN 978-80-7434-477-0.
13. Dvořák, J.; Bystrický, R.; Hošková, P.; Hrib, M.; Jarkovská, M.; Kováč, J.; Krilek, J.; Natov, P.; Natovová, L. *The Use of Harvester Technology in Production Forests*, 1st ed.; Lesnická práce s.r.o.: Kostelec nad Černými lesy, Czech Republic, 2011; p. 156, ISBN 978-80-7458-018-5.
14. Sládek, P.; Neruda, J. Analysis of volume differences in measuring timber in forestry and wood industry. In Proceedings of the Austro 2007/FORMEC’07: Meeting the Needs of Tomorrows Forests—New Developments in Forest Engineering, Wien, Austria, 7–11 October 2007; pp. 1–11.
15. Hohmann, F.; Ligocki, A.; Frerichs, L. Harvester Measuring System for Trunk Volume Determination: Comparison with the Real Trunk Volume and Applicability in the Forest Industry. *Bull. Transilv. Univ. Braşov* **2017**, *10*, 27–34.
16. Skogforsk the Forest Research Institute of Sweden. StanForD. Available online: <https://www.skogforsk.se/english/projects/stanford/> (accessed on 19 March 2019).
17. Skogforsk the Forest Research Institute of Sweden. Standard for Forest Data and Communications. 27 March 2007, p. 10. Available online: https://www.skogforsk.se/cd_48e53b/contentassets/b063db555a664ff8b515ce121f4a42d1/stanford_maindoc_070327.pdf (accessed on 19 March 2019).
18. Skogforsk the Forest Research Institute of Sweden. Appendix- Standard for Forest Data and Communications. 18 April 2012, p. 32. Available online: https://www.skogforsk.se/cd_48e53b/contentassets/b063db555a664ff8b515ce121f4a42d1/appendix1_eng_120418.pdf (accessed on 19 March 2019).
19. Natov, P.; Dvořák, J. *Doporučená pravidla pro elektronický příjem dříví harvestory v ČR 2018*; Produkce BPP s.r.o.: Litomyšl, Czech Republic, 2018; p. 136, ISBN 978-80-906874-7-9.
20. Nuutinen, Y.; Väättäin, K.; Asikainen, A.; Prinz, R.; Heinonen, J. Operational efficiency and damage to sawlogs by feed rollers of the harvester head. *Silva Fenn.* **2010**, *44*, 121–139. [[CrossRef](#)]
21. Gerasimov, Y.; Seliverstov, A.; Syuney, V. Industrial Round-Wood Damage and Operational Efficiency Losses Associated with the Maintenance of a Single-Grip Harvester Head Model: A Case Study in Russia. *Forests* **2012**, *3*, 864–880. [[CrossRef](#)]
22. Karaszewski, Z.; Łacka, A.; Mederski, P.S.; Bembenek, M. Impact of season and harvester engine RPM on pine wood damage from feed roller spikes. *Croat. J. For. Eng.* **2018**, *39*, 183–191.
23. Marusiak, M.; Neruda, J. Dynamic Soil Pressures Caused by Travelling Forest Machines. *Croat. J. For. Eng.* **2018**, *39*, 233–245.
24. Apăfăian, A.I.; Proto, A.R.; Borz, S.A. Performance of a mid-sized harvester-forwarder system in integrated harvesting of sawmill, pulpwood and firewood. *Ann. For. Res.* **2017**, *60*, 227–241. [[CrossRef](#)]
25. Mederski, P.S.; Bembenek, M.; Karaszewski, Z.; Pilarek, Z.; Łacka, A. Investigation of Log Length Accuracy and Harvester Efficiency in Processing of Oak Trees. *Croat. J. For. Eng.* **2018**, *39*, 173–181.
26. Labelle, E.R.; Huß, L. Creation of value through a harvester on-board bucking optimization system operated in a spruce stand. *Silva Fenn.* **2018**, *52*, 1–22. [[CrossRef](#)]
27. Glöde, D.; Sikström, U. Two felling methods in final cutting of shelterwood, single-grip harvester productivity and damage to the regeneration. *Silva Fenn.* **2001**, *35*, 71–83. [[CrossRef](#)]
28. Spinelli, R.; Hartsough, B.R.; Magagnotti, N. Productivity Standards for Harvesters and Processors in Italy. *Prod. J.* **2010**, *60*, 226–235. [[CrossRef](#)]

29. Strandgard, M.; Walsh, D.; Acuna, M. Estimating harvester productivity in *Pinus radiata* plantations using StanForD stem files. *Scand. J.* **2013**, *28*, 73–80. [[CrossRef](#)]
30. Nurminen, T.; Korpunen, H.; Uusitalo, J. Time consumption analysis of the mechanized cut-to-length harvesting system. *Silva Fenn.* **2006**, *40*, 335–363. [[CrossRef](#)]
31. Szewczyk, G.; Sowa, J.M. The accuracy of measurements in a time study of harvester operations. *New Zealand J. For. Sci.* **2017**, *47*. [[CrossRef](#)]
32. Pajkoš, M.; Klvac, R.; Neruda, J.; Mishra, P.K. Comparative Time Study of Conventional Cut-To-Length and an Integrated Harvesting Method—A Case Study. *Forests* **2018**, *9*, 194. [[CrossRef](#)]
33. Purfürst, F.T. Learning Curves of Harvester Operators. *Croat. J. For. Eng.* **2010**, *31*, 89–97.
34. Arlinger, J. (Skogforsk, Upsalla Science Park, Upsalla, Sweden). Personal communication, 13 August 2018.
35. Husch, B.; Beers, T.W.; Kershaw, J.A., Jr. *Forest Mensuration*, 4th ed.; John Wiley and Sons: New York, NY, USA, 2003; p. 443, ISBN 978-0-471-01850-6.
36. BW-HKS. *Gesetzliche Handelsklassensortierung für Rohholz (Forst-HKS) mit Ergänzungsbestimmungen für BadenWürttemberg*; Ministerium für Ländlichen Raum, Ernährung, Landwirtschaft und Forsten: Stuttgart, Germany, 1983; p. 25.
37. Wojnar, T. *Doporučená pravidla pro měření a třídění dříví v ČR 2008*, 2nd ed.; Lesnická práce s.r.o.: Kostelec nad Černými lesy, Czech Republic, 2007; p. 147, ISBN 978-80-87154-01-4.
38. Hamilton, G.J. *Forestry Commission Boklet No. 39—Forest Mensuration Handbook*; HMSO: London, UK, 1975; p. 274, ISBN 0-11-710023-4.
39. Labelle, E.R.; Soucy, M.; Cyr, A.; Pelletier, G. Effect of Tree Form on the Productivity of a Cut-to-Length Harvester in a Hardwood Dominated Stand. *Croat. J. For. Eng.* **2016**, *37*, 175–183.
40. Spinelli, R.; Magagnotti, N.; Schweier, J. Trends and Perspectives in Coppice Harvesting. *Croat. J. For. Eng.* **2017**, *38*, 219–230.
41. Karaszewski, Z.; Łacka, A.; Mederski, P.S.; Noskowiak, A.; Bemberek, M. Damage caused by harvester head feed rollers to alder, pine and spruce. *Drewno* **2016**, *59*, 77–88.
42. Strandgard, M. Evaluation of Manual Log Measurement Errors and Its Implications on Harvester Log Measurement Accuracy. *Int. J. For. Eng.* **2009**, *20*, 9–16. [[CrossRef](#)]
43. Nieuwenhuis, M.; Dooley, T. The effect of calibration on the accuracy of harvester measurements. *Int. J. For. Eng.* **2006**, *17*, 25–33. [[CrossRef](#)]
44. Marshall, H.D.; Murphy, G.E.; Lachenbruch, B. Effects of bark thickness estimates on optimal log merchandising. *For. Prod. J.* **2006**, *56*, 87–92.
45. Gendek, A.; Wezyk, P.; Moskalik, T. Share and accuracy of estimation of logging residues in the total volume of harvested timber. *Sylvan* **2018**, *162*, 679–687.



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