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Accuracy of Double Bark Thickness Estimation Methods Used in Spruce—(*Picea abies* L. Karst) Timber Production in Czechia

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Abstract: The accurate estimation of bark thickness is important for foresters for several reasons. It is crucial for timber volume estimation and can help improve the quality of forestry records, and bark has a growing commercial importance as a high-value bioresource. The problem is that models such as the Czech Cubic Tables (CCT) polynomial model are frequently unique. Furthermore, the official method requires rounding down the midspan over-bark diameter (DOB) to the nearest centimetre to estimate the double bark thickness (DBT) and merchantable timber volume. Therefore, we verified the significance of the effects of rounding down the midspan DOB on DBT using a dataset of 438 recently harvested Norway spruce (*Picea abies* L. Karst.) logs from the Central Bohemian region. The correlation analysis showed that for measured data without rounding down the diameters, the variability of the DBT was able to explain only 8% of the DOB variability. As for the rounded-down data, the coefficient of determination was slightly higher, reaching 9%. The paired-samples T-tests showed a significant difference between the DBT as calculated directly from measured data and that from the rounded-down over-bark diameters ($p < 0.05$). The polynomial and linear models underestimated the DBT (2.24 and 1.75 mm on average, respectively) on measured data. In contrast, for data from the rounded-down DOB, the models overestimated the DBT (2.70 or 3.18 mm on average, respectively).

Keywords: diameter over bark; diameter under bark; Norway spruce; midspan diameter; diameter rounded down

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1. Introduction

The bark of a tree is a protective layer [1,2] necessary for the tree's survival [3]. It forms between the cambium and the outer part of the tree trunk [2,4,5] and protects the tree from a broad spectrum of abiotic and biotic factors injurious to the tree and its tissues [6,7]. Among the most important protective functions are the protection against mechanical injuries [8], fire [9–12], frost [9], and other abiotic factors. Similarly, it protects against pests and plant diseases such as fungi, insects, and other biotic pathogens [8,13]. The inner side of the bark ensures sap flow [14], water storage [15], exchange of water and gasses [16] and other vital physiological functions [17]. Bark formation is highly variable between tree species, be it from a thickness perspective, texture, color, and other parameters [18]. However, bark thickness does not vary only between species [18]. Due to different climates, the stages of evolution, and ecological conditions. such as the slope and aspect of habitat or type of soil [18]. Indeed, Muhairwe et al. [19] state that bark thickness varies depending on the species, age, size, genotype, site quality, growth rate, stand density, and position along the stem. The thickness of the bark must be assessed at the species level because it can account for a large proportion of the total wood volume. The proportion of bark ranges from 4% to 30%, depending on the tree species [20]. Heath et al. [21] state that tree bark amounts to 12%–20% of the total wood volume in North America, depending on the tree species. Another study reports that for most species, bark volume represents 10–20% of the total stem volume [22].

Accurate estimation of bark thickness is important for foresters [23]. It is crucial for timber volume estimation [23] because roundwood, the globally most important part of the forest value chain, is typically supplied with bark, but the merchantable timber volume is estimated under the bark [24,25]. Therefore, an inaccurate estimation of bark thickness has negative economic impacts on either the seller or the buyer [26]. Another reason bark thickness should be accurately estimated is the growing commercial importance of bark [27] as a high-value bioresource with a unique chemical composition, which makes it suitable for producing specialty products or solid biofuels, such as briquettes or pellets [28,29]. On the other hand, despite the growing desirability of bark, inaccurate bark thickness estimations can lead to a loss of up to 11% of the value of sold timber [30]. Finally, improving the accuracy of double bark thickness estimation will lead to improved quality of forestry records, which will serve as a basis for reporting to statistical bureaus and international institutions, such as FAOSTAT.

Albeit calculating the merchantable volume of timber presumes an exact measurement of bark thickness [31], measuring it on each log or stem is time- and labour-intensive. Therefore, many authors have developed models or formulas to convert over-bark diameters to under-bark diameters for many tree species [2,23,29,32,33]. Most of these models have limited application in practice for several reasons, e.g., tree species, regionality, age, and many more. The simplicity of use, sufficient accuracy, and wide acceptance among practitioners are just some of the challenges that forest research must overcome when addressing changes in merchantable timber volume estimation.

The double bark thickness estimation methods that are used in practice are often country-specific. They are based on historical developments in those countries and tackle the regional needs of practitioners, thus approaching the problem from a specific, often narrow perspective. The Swedish perspective is based on linear bark thickness modeling based on the midspan over-bark diameter of a log [34]. On the other hand, the German perspective is based on deducting the bark as a constant within certain midspan diameter bands (intervals) [35]. Yet, another approach can be seen in Czechia, where foresters use a polynomial function based on the log midspan diameter over bark to estimate the double bark thickness [36]. The midspan over-bark diameter is measured using two perpendicular measurements. Each outcome is rounded down to the nearest centimetre, the average is calculated, and the mean value is again rounded down to the nearest centimetre. The value then represents the midspan over-bark diameter, from which the double bark thickness is deducted based on a selected bark thickness deduction method. Thus, the under-bark diameter is estimated, which serves as an input for merchantable timber volume estimations.

The polynomial functions used to estimate the double bark thickness are based on the Czech cubing tables (CCT) found in the ČSN 48 009 technical standard [37]. In practical wood procurement, the volume of merchantable timber is estimated by subtracting the double bark thickness (estimated from the log over-bark midspan diameter, Equations (1) and (2) from the over-bark midspan diameter data as inputs in Huber's formula (Equation (3)) to calculate the under-bark log volume.

$$\mathrm{DBT} = \mathrm{p_0} + \mathrm{p_1} \times \mathrm{DOB}^{\mathrm{p_2}} \tag{1}$$

$$\mathrm{DBT} = \alpha + \beta \times \mathrm{DOB} \tag{2}$$

$$\mathrm{V_{UB}} = \frac{\pi}{4} \times (\mathrm{DOB} - \mathrm{DBT})^2 \times \mathrm{l} \times 10^{-4} \tag{3}$$

DBT represents the double bark thickness (mm); p_0, p_1, and p_2 are parameters of the polynomial function for Norway spruce, which are as follows: p_0 = 0.57723, p_1 = 0.006897, and p_2 = 1.3123; α is the intercept of the linear function; β is the parameter of the univariate linear function; DOB is diameter over bark (mm); V_{UB} is volume under bark (m^3); l is log length (m).

The presented double bark thickness estimation methods are problematic for several reasons. Some are connected to measurement procedures or the static nature of the underlying data, whereas others are related to the models used. First, the measurement procedures in many countries were developed for manual measurement methods that require rounding down the mean midspan diameter to the nearest centimetre [38].

Across Europe, the share of mechanized logging is increasing. In Estonia, harvesters log 80% of timber; in Latvia, they log around 70%; in Germany, 65%; in Spain, 60%; and in Italy, 60% [39,40]. In the Czech Republic, the share of the CTL method (connected to harvester technology) reached 34% of the total annual logging in 2017 [40,41] and is expected to grow to at least 50% [40,42]. With the rise of fully mechanized harvesting technologies, the share of timber that needs to be manually measured has decreased. Harvesters use different measurement procedures, and if appropriately calibrated, can measure diameters in millimetres with an error between 1% and 2% [43]. Thus, the need to round down the measurements to the nearest centimetre is unnecessary.

The problem with the models' static nature is that the data used for calibrating the practical models for bark thickness estimations are often outdated. For example, the official Czech polynomial model is based on CCT [37], which was constructed in 1977 (the data predate the tables). The only official linear bark thickness estimation model [44] is even older; it was constructed in 1972. Similarly, the German HKS standard for scaling and grading timber (Forst-HKS, 1983) [45], which is still used in Germany, is also quite old (40 years). Even though Germany introduced a newer scaling and grading system in 2009, the so-called RVR (Rahmenvereinbarung für den Rohholzhandel [35], it has not caught on substantially as of yet. Sweden also uses an outdated linear model from Zacco [34] (1974) in the official StanForD documentation to deduct bark from over-bark data in harvesters. While these double bark thickness estimation methods are not mandatory, and the contract parties can agree on using whatever method they see fit, they are used frequently because of their convenience. Often, the age of the data does not pose a problem. However, climate change and other factors have caused trees to grow under conditions different from those several decades ago. Temperatures have risen, winters are milder, weather is more unstable, and more carbon is in the atmosphere to "fuel" photosynthesis than before [46,47]. The fact that Norway spruce trees in Baden-Würtemberg produce less bark than before was confirmed by Stängle et al. [48], while Pellegrini [49] states that trees in areas with moisture stress and drought seasons generate more bark in savannas and forests. This warrants verification of whether a large-scale recalibration of the double bark thickness estimation methods used around Europe is necessary.

Yet another problem of what models to use relates to smaller markets (e.g., Czechia) that use models incompatible with those used in larger markets (e.g., Germany, Sweden, Austria). This incompatibility then translates to the forest machine systems' (typically incorporating the models used in large markets) incompatibility with the local scaling standards. Harvesters use linear modeling as the primary method of bark thickness estimation, though they can also use the German deduction method based on diameter bands described in Forst-HKS [50]. However, the Czech polynomial model cannot be input into the forest machine systems, thus presenting the need to either localize the methods from different countries or continue measuring all timber manually. To remedy this problem, Jankovský et al. [51,52] have linearized the standard polynomial bark deduction models for all main species groups into the so-called LinBark function, thus enabling the use of automated timber scaling by harvester forest machine systems in Czechia.

Albeit the linearization of polynomial models has resolved the incompatibility issue, problems with measurement procedures and the use of outdated data remain. Therefore, we aim to verify the significance of the effects of rounding down the midspan over-bark diameter data on double bark thickness estimation using a dataset of recently harvested Norway spruce logs from the Central Bohemian region. We also hypothesize that the polynomial model (derived from the CCT) and linear model estimates differ significantly from the double bark thickness measured at the midspan of the required length of Norway spruce logs from the Central Bohemian region.

2. Materials and Methods

The measurements took place at the University Forest Enterprise of the Czech University of Life Sciences Prague (UEF) conversion depot, located near Kostelec and Černými lesy, Czechia (49.9818572° N, 14.8262892° E). The UEF manages approximately 5.5 thousand ha of forests, with a high abundance of Norway spruce (*Picea abies* L., Karst—55%), followed by Scots pine (*Pinus sylvestris* L.—15%), European Beech (*Fagus sylvatica* L.—11%), and other species. Overall, coniferous species account for over 75% of all tree species in the UEF forests. According to the latest forest management plan issued for the area, the total timber stock was 275 m^3 per hectare of forest. According to the internal data of the UEF, the use of CTL harvesting technologies has increased over the years, reaching roughly half of the total harvests in 2022. The remainder of the timber was harvested by the tree-length harvesting method, using motor-manual felling and skidding. Both short and long timber of higher grades were trucked to the conversion depot, where they were processed further and fed into the sawmill operated by the UEF.

The measurements focused on Norway spruce logs sorted and bucked at the conversion depot, i.e., those harvested by the tree-length harvesting method. The sample size was calculated using Cochran's sample size formula [53] (Equation (4)). According to the results, the minimal sample size was 385.

$$N = \frac{z^2 \times \hat{p}(1 - \hat{p})}{\varepsilon^2} \quad (4)$$

where N = sample size, z = z score according to confidence interval (1.96 in our case by 95% confidence interval), p = population proportion (0.5 in our case), and ε = is the margin of error (0.05 in our case).

The sorting and processing line was fed with spruce logs of at least 15 cm in diameter at the small end, and the stems were bucked to a required length between 3 and 6 m. The processing line operator added a 2% length allowance to the required length for crosscutting and shrinkage. After bucking, the logs were conveyed and released into appropriate hoppers based on the small-end diameter, with a 2 cm diameter increase threshold. From these hoppers, a front loader gathered a batch of logs for measurements over bark, with an assignment to, if possible, evenly select logs from all hoppers. After the over-bark measurements were completed, the loader gathered the measured logs and put them into a machine debarker. After the logs were debarked, the loader collected them and placed them on the ground for the underbark measurements.

Each log collected from the hoppers was inspected for faults or growth irregularities. Logs with scraped or missing bark at measurement points, severe growth irregularities that could lead to inconsistent data, or other characteristics that could affect the reliability of the dataset were excluded from the measurements. All logs deemed fit for the measurements were marked with a unique identifier and measured. We measured the log-specific characteristics first over bark and subsequently under bark, according to [54]. The measured characteristics were as follows: (i) total length of the log; (ii) midspan diameter over bark (DOB); (iii) midspan diameter under bark (DUB). The total length was measured using a logger's tape with a one-centimetre scale from Bahco company (Enköping, Sweden). After deducting the 2% allowance, we calculated the required length of each log. The over- and under-bark diameters were measured at the midspan of the required length of the logs using a precision calliper with a millimetre scale from Nestle company (Waldfreund, Dornstetten, Germany). Two perpendicular measurements were made at each measurement point to limit the effect of the log cross-sectional shape. The calliper positioning was marked on the large end of each log to limit the effect of the shape on the measurement accuracy between the DOB and DUB measurements.

Double bark thickness was calculated as (i) the difference between the over- and under-bark diameters as they were measured (DBT ED) and (ii) the difference between diameters over bark rounded down to the nearest centimetre and diameters under bark as they were measured (DBT RD) [54]. The latter method, which uses rounded-down over-bark diameter data, is the standard method used for timber volume estimation in Czechia. Additionally, we also used the commonly used polynomial function (Equation (1)) and linear function (Equation (2)) to estimate the DBT and compare the estimation results to the measured data. A detailed flowchart of the study can be found in Supplementary Material Figure S1.

After processing the data into a dataset, we performed statistical analyses in Statistica program (Version 14, StatSoft, Hamburg, Germany). First, we assessed whether the over- and under-bark diameter data were normally distributed using the Shapiro–Wilk test. We then tested the relationship between the measured over- and under-bark diameters via regression and correlation analysis. After verifying the relationship between the diameter variables, we conducted univariate regression and correlation analyses between the measured over-bark diameter and double bark thickness and between the rounded-down over-bark diameter and the double bark thickness calculated from the rounded-down diameter data. Finally, we used a series of paired-samples *t*-tests between (i) the measured and rounded-down double bark thickness and (ii) the polynomial and linear model estimates and measured and rounded-down double bark thicknesses to confirm our hypotheses.

3. Results

We measured the data on 438 Norway spruce logs with the required lengths of 3 m (0.67%), 4 m (73.26%), 5 m (19.10%), and 6 m (6.97%) to create the dataset (Figure 1). The measured over-bark diameter values ranged from 163 to 492 mm (mean 295 mm). After the machine debarking, the under-bark diameters ranged between 155 and 476 mm (mean 281 mm). Table 1 shows that both linear and polynomial models underestimated the double bark thickness compared to the measured values (both exact and rounded down).

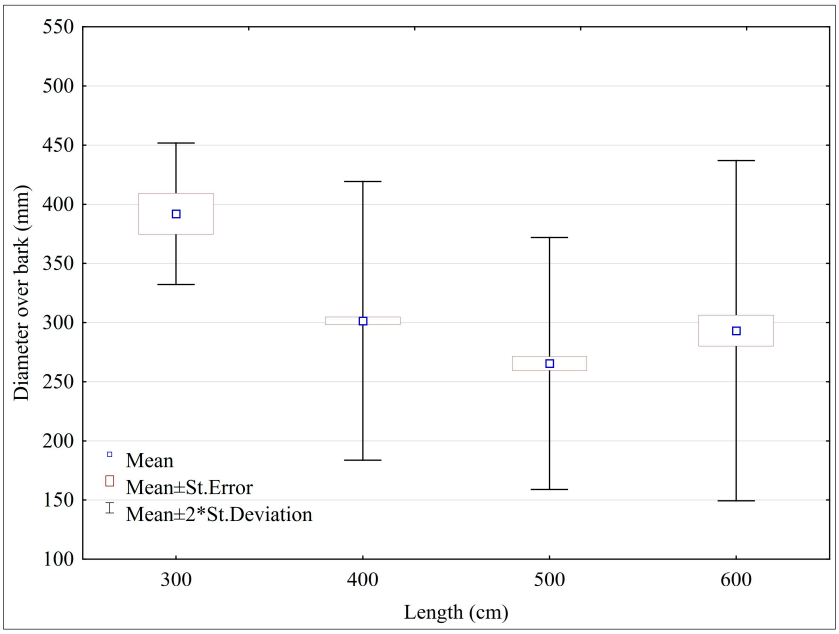

Figure 1. Measured diameters over bark in particular required length categories.

Table 1. Descriptive statistics of measured and calculated variables.

Variable	Descriptive Statistics						
	Valid N	**Mean**	**Median**	**Minimum**	**Maximum**	**Std. Dev.**	**Coef. Var.**
DOB (mm)	438	294.8	290.5	163.0	492.0	60.7	20.6
DUB (mm)	438	280.8	278.2	155.0	476.0	59.3	21.1
DBT ED (mm)	438	13.9	13.0	1.5	38.0	6.1	43.6
DBT LB (mm)	438	12.1	12.0	8.6	17.4	1.6	13.4
DBT P (mm)	438	11.6	11.5	8.4	17.2	1.6	13.7
DBT RD (mm)	438	8.8	8.5	−6.5 *	37.5	6.8	77.9
DBT RD LB (mm)	438	11.6	12	8	17	1.6	14.1
DBT RD P (mm)	438	11.2	11	8	17	1.6	14.7

DOB = Diameter over bark; DUB = Diameter under bark; DBT ED = Double bark thickness—exact (measured) diameter; DBT RD = Double bark thickness—rounded down; DBT LB = Double bark thickness—linear function; DBT P = Double bark thickness—polynomial function. * The negative figures were caused by the rounding down procedure, e.g., if the measured midspan over-bark diameter was 219 mm, the rounded down midspan over-bark diameter was 210 mm. If in reality, the bark thickness was small, e.g., 2 mm, then the exact under-bark diameter was 217 mm. The calculated DBT was then as follows: DBT = DOB RD-DUB = −7 mm.

The next step in our study was to observe the relationship between the over- and under-bark diameters (mm) (Figure 2). The analysis showed that the relationship between the variables was extremely strong, with a correlation coefficient reaching r = 0.99, r^2 = 0.98, and a significant *p*-value of 0.0000. The relationship was represented by a regression Equation (5):

$$DUB = -5.0385 + 0.9711 \times DOB \quad (5)$$

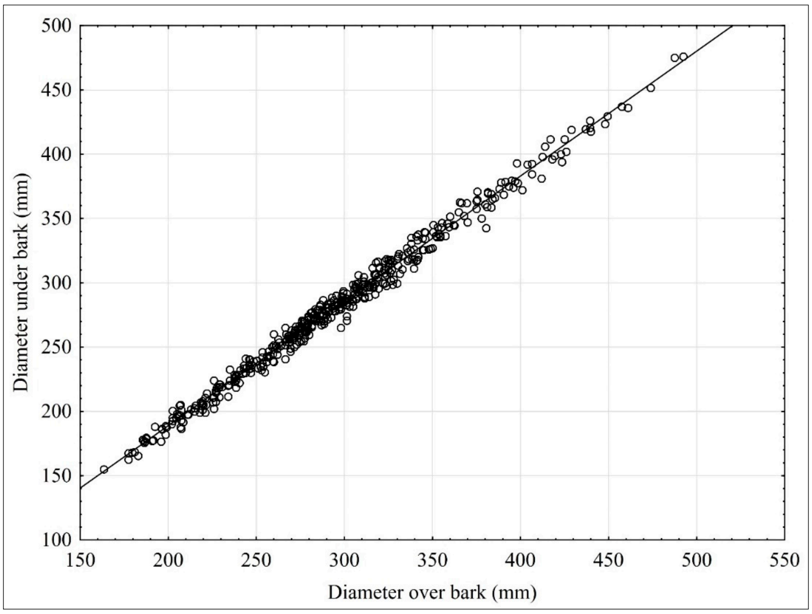

Figure 2. Regression and correlation analysis between diameter over bark (mm) and diameter under bark (mm).

The analysis of the relationship between the measured over-bark diameter and the double bark thickness (Table 2, Figure 3) showed that, although significant, the relationship between the two variables was relatively weak, with r = 0.28. Figure 3 also shows the effects of estimating the double bark thickness using linear and polynomial models. The models underestimated the double bark thickness compared to the measured values, and the widely used polynomial model underestimated more than the linear model. The different results were achieved when the rounded-down diameter data were used (Figure 4). The relationship between the rounded-down over-bark diameters and the related double bark thickness was slightly stronger, with an r = 0.30. Regression and correlation analyses (Table 3) showed that 9% of the variability of the double bark thickness calculated from the rounded-down diameter data could be explained by the variability of the rounded-down over-bark diameter. The double bark thickness estimated using the linear and polynomial models from the rounded-down data showed an overestimation of the double bark thickness, as calculated from rounded-down data. With increasing diameters, the overestimation decreased. The results showed that the current estimation method underestimated double bark thickness compared to the measured data (non-rounded-down) on the logs in the Central Bohemian region. The figure highlights the effects of data manipulations used in practical forestry, which results in simplified and more uniform datasets.

Table 2. Regression summary between DBT ED (mm) and DOB (mm), bold type = statistical significance.

N = 438	Regression Summary of Dependent Variable: DBT ED (mm) R = 0.28 R^2 = 0.08; F(1436) = 39.715; $p < 0.00000$; Std. Error of Estimate: 5.8179					
	b*	**Std. Err. of b***	**b**	**Std. Err. of b**	**t(436)**	***p*-Value**
Intercept			**5.404130**	**1.379508**	**3.917432**	**0.000104**
DOB (mm)	**0.288937**	**0.045849**	**0.028884**	**0.004583**	**6.301970**	**0.000000**

DOB (mm) = diameter over bark; DBT ED (mm) = double bark thickness exact diameter; R = correlation coefficient, R^2 = coefficient of determination; *p*-value = serves as an alternative to rejection points to provide the smallest level of significance at which the null hypothesis would be rejected; b* = parameter estimates from the model in which we would standardize all regressors so that their mean is equal to zero.

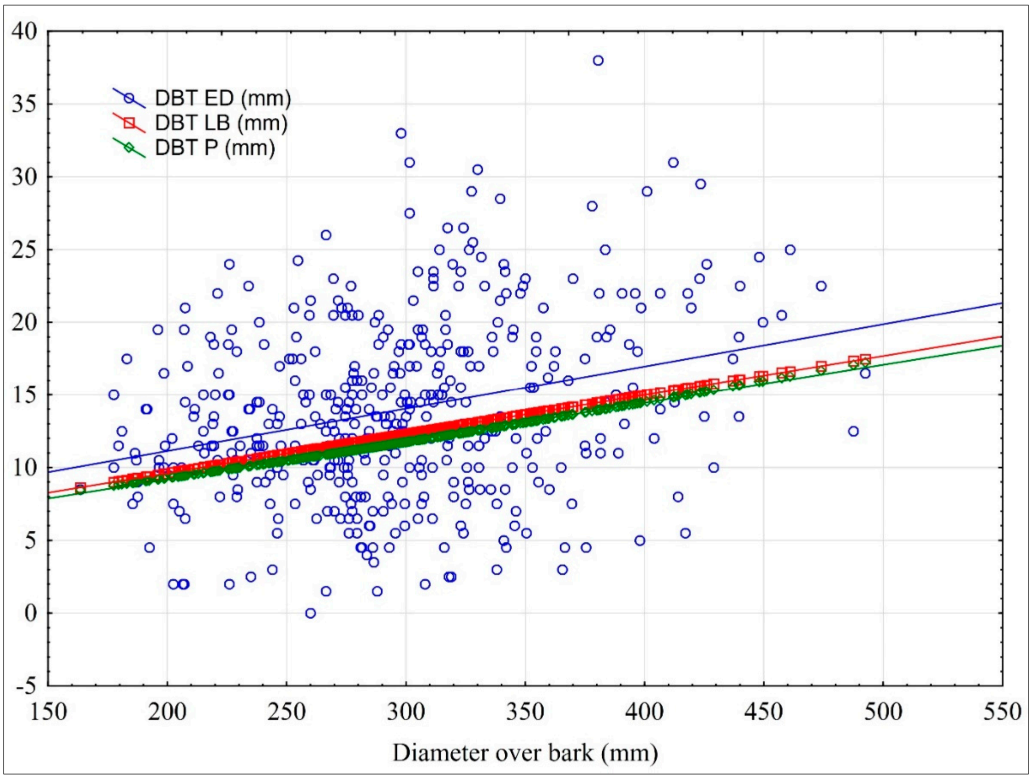

Figure 3. Scatterplot representing the relationship between the diameter over bark and double bark thickness. The scatterplot includes the estimates provided by the polynomial and linear models from measured over-bark diameter data (DBT ED: measured diameter data; DBT LB: linear function; DBT P: polynomial function).

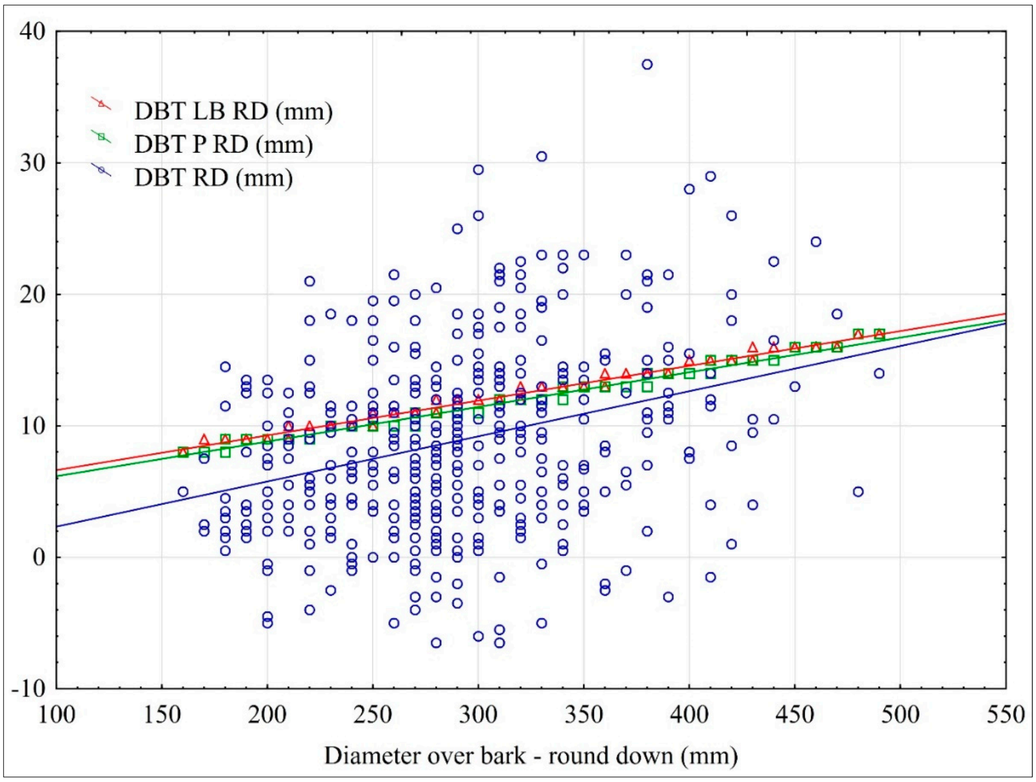

Figure 4. Scatterplot representing the relationship between the diameter over bark and double bark thickness. The scatterplot includes the estimates provided by the polynomial and linear models from rounded-down over-bark diameter data. (DBT RD: rounded down diameter data; DBT LB RD: linear estimation based on rounded down data; DBT P RD: polynomial estimation based on rounded down data).

Table 3. Results of the regression and correlation analysis between DBT RD (mm) and DOB RD (mm), bold type = statistical significance.

N = 438	**Regression Summary for Dependent Variable: DBT RD (mm)** **R = 0.30 R^2 = 0.09; F(1436) = 44.440; *p* < 0.00000; Std. Error of Estimate: 6.5675**					
	b*	**Std. Err. of b***	**b**	**Std. Err. of b**	**t(436)**	***p*-Value**
Intercept			−1.11161	1.525205	−0.728829	0.466498
DOB RD (mm)	**0.304135**	**0.045623**	**0.03434**	**0.005152**	**6.666316**	**0.000000**

DOB RD (mm) = diameter over bark round down; DBT RD (mm) = double bark thickness round down; R = correlation coefficient, R^2 = coefficient of determination; *p*-value = serves as an alternative to rejection points to provide the smallest level of significance at which the null hypothesis would be rejected; b* = parameter estimates from the model in which we would standardize all regressors so that their mean is equal to zero.

To compare the differences between the measured and rounded-down data, and the differences between measured double bark thickness and model estimates, we used paired-samples T-tests (Table 4). The tests confirmed statistically significant differences between the measured and rounded-down double bark thickness values and between the measured double bark thickness and those estimated from the measured data by both models. The differences can also be seen in Figure 5. The box plot shows the differences between the non-rounded data (Figure 5a,b) and rounded-down data (Figure 5c,d). For the non-rounded data, the models underestimate bark thickness, whereas, for the rounded-down data, they overestimate bark thickness. Considering the estimation errors, (Table 5), the polynomial model exhibited larger errors for the measured data, whereas, for the rounded-down data (the intended use case), the linear model predicted larger errors. On the other hand, even though the differences seem substantial in Figure 5 or Table 5, they were quite small in reality, reaching only a couple of millimetres. Rounding down slightly worsens the accuracy of estimations.

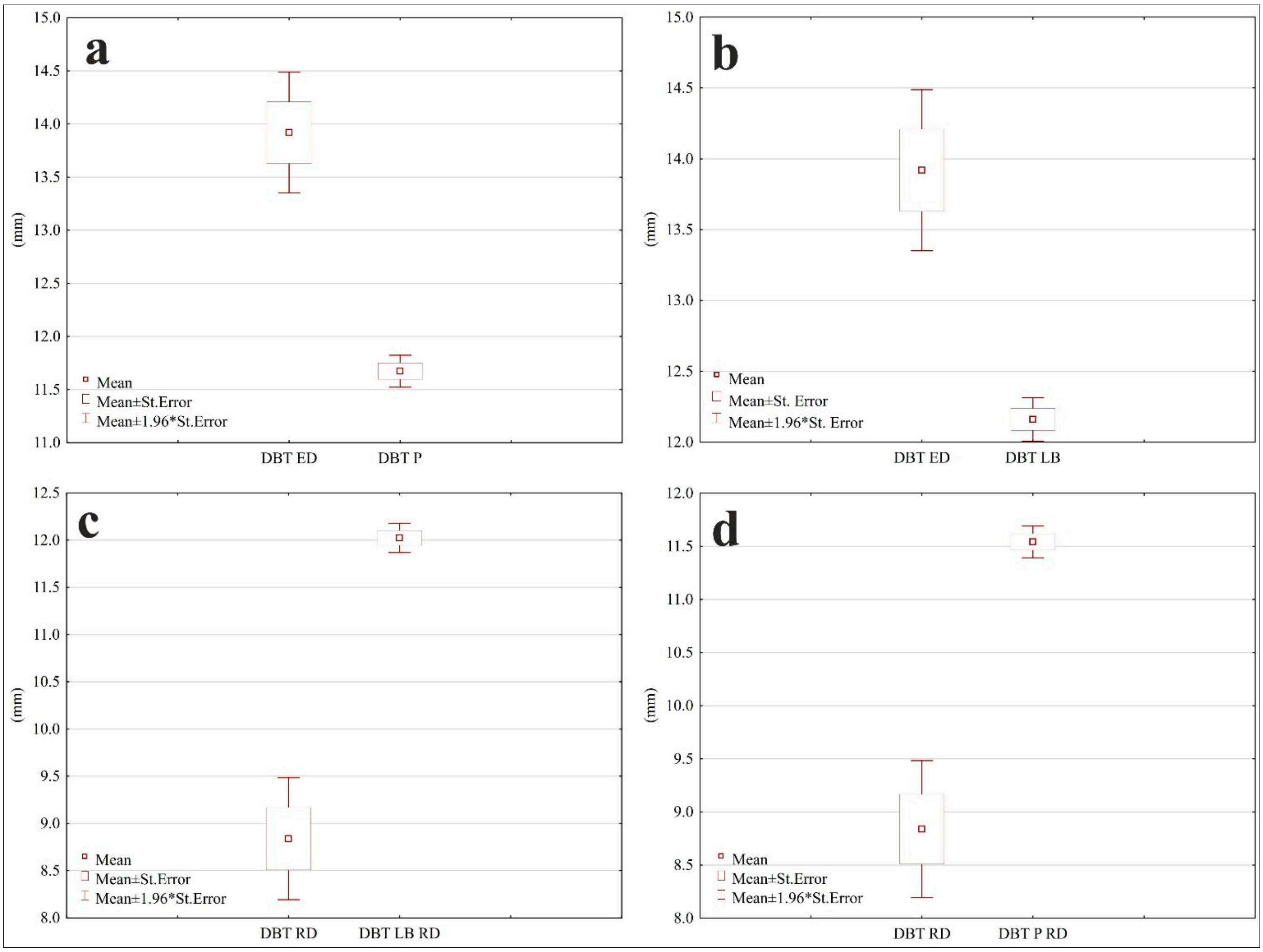

Figure 5. Box plots for comparisons of rounded-down (DBT RD) and non-rounded-down (DBT ED) data with relevant polynomial (DBT P or DBT P RD) and linear (DBT LB and DBT LB RD) estimates.

Table 4. Paired-samples T-test outcomes for the comparisons between the measured and rounded-down double bark thickness (DBT ED and DBT RD, respectively); DBT ED and the linear model (DBT LB), DBT ED and the polynomial model (DBT P) estimates; DBT RD and DBT LB RD and DBT RD and DBT P RD, i.e., the rounded-down data and model estimates.

Paired-Samples *t*-Test Differences Are Significant on a Level of $p < 0.05000$										
Variables	**Mean**	**SD**	**N**	**Difference**	**SD Differences**	**t**	**SV**	***p***	**CI −95.0%**	**CI +95%**
DBT ED (mm)	13.919	6.070								
DBT RD (mm)	8.838	6.886	438	5.081	2.883	36.87	438	0.00	4.810	5.351

Table 4. *Cont.*

Paired-Samples *t*-Test Differences Are Significant on a Level of $p < 0.05000$										
Variables	**Mean**	**SD**	**N**	**Difference**	**SD Differences**	**t**	**SV**	***p***	**CI −95.0%**	**CI +95%**
DBT ED (mm)	13.919	6.070								
DBT LB (mm)	12.160	1.633	438	1.759	5.812	6.33	437	0.00	1.213	2.304
DBT ED (mm)	13.919	6.070								
DBT P (mm)	11.672	1.599	438	2.247	5.810	8.09	437	0.00	1.701	2.792
Paired-Samples *t*-Test Differences Are Significant on a Level of $p < 0.05000$										
Variables	**Mean**	**SD**	**N**	**Difference**	**SD Differences**	**t**	**SV**	***p***	**CI −95.0%**	**CI +95%**
DBT RD (mm)	8.838	6.886								
DBT LB RD (mm)	12.023	1.640	438	−3.185	6.575	−10.13	437	0.000	−3.802	−2.567
DBT RD (mm)	8.838	6.886								
DBT P RD (mm)	11.541	1.597	438	−2.703	6.578	−8.59	437	0.00	−3.320	−2.085

DBT ED = double bark thickness exact diameter; DBT RD = double bark thickness rounded down; DBT LB = double bark thickness linear estimation; DBT P = double bark thickness polynomial estimation; DBT LB RD = double bark thickness rounded down liner model estimates, DBT P RD = double bark thickness rounded down polynomial model estimates; SD = standard deviation; N = size of the statistical sample; t = test criterion; SV = degrees of freedom; *p*-value = serves as an alternative to rejection points to provide the smallest level of significance at which the null hypothesis would be rejected; CI = Interval of confidence.

Table 5. Model output error characteristics for measured and rounded-down data.

Dataset	**Error Metric**	**DBT P (mm)**	**DBT LB (mm)**
DBT ED (mm)	MAE[(a)]	4.835932	4.777381
	MBE[(b)]	−2.24719	−1.7591
	MAPE[(c)]	46.13819	47.04241
	RMSE[(d)]	6.223826	6.066472
Dataset	Error metric	DBT P RD (mm)	DBT LB RD (mm)
DBT RD (mm)	MAE[(a)]	5.720047	5.89026484
	MBE[(b)]	2.702997	3.185274
	MAPE[(c)]	65.19454385	68.8024884
	RMSE[(d)]	7.105576	7.29973099

DBT ED = over-bark diameter data; DBT P = polynomial estimates for measured over-bark diameter data; DBT LB = linear estimates for measured over-bark diameter data; DBT RD = rounded-down diameter data; DBT LB RD = linear estimation based on rounded-down data; DBT P RD = polynomial estimation based on rounded-down data; MAE[(a)] = mean absolute error; MBE[(b)] = mean bias error; MAPE[(c)] = mean absolute percentage error; RMSE[(d)] = root mean square error).

4. Discussion

The results showed a practically functional relationship between the over- and under-bark midspan diameters of the measured logs. As a result, there was little chance of another variable explaining a substantial portion of under-bark diameter variability, as documented by the weak relationship between the double bark thickness and diameter variables. Authors Berndt et al. [55] state a similar conclusion that the double bark thickness was not significantly affected by the diameter over bark, although the research was conducted on Scots pine (*Pinus sylvestris*, L.) in northeastern Germany. Neuman and Lawes [56] in their study state that when using over-bark diameter measurements, the bark volume is overestimated by up to 40%.

The literature suggests that other variables can be successfully used to improve the accuracy of double bark thickness estimations. A study by Wilms et al. [20] shows that diameter at breast height (DBH) and tree height significantly affect the bark thickness of Scots pine trees. Gordon [57] also show that DBH has a strong influence, whereas tree height has a weak influence on the bark thickness of Radiata pine (*Pinus radiata* D. Don.). Music et al. [29] found that the bark thickness of Norway spruce correlates with the diameter at breast height very strongly (r = 0.76) and the bark thickness of spruce increases with the increase in the mean diameter of Roundwood. Laasasenaho et al. [23] conducted research on spruce bark from the fifth National Forest Inventory (NFI) data, which was carried out during the years 1968–1971 and represented Finland. They reported a strong correlation (0.76) between bark thickness and diameter at breast height. They stated that other variables besides diameter at breast height, such as tree age and stem tapering, further improved the relationship strength. Stängle et al. [58] also observed the double bark thickness and its relationship with multiple variables as follows: (i) diameter of the section; (ii) diameter at breast height; (iii) relative height and determination, and they were able to reach an R^2 of 0.76. Sonmez et al. [59] observed the effects of various factors on double bark thickness and derived prediction models for *Picea orientalis* (L.). Diameter over bark at breast height explain 50% of the double bark thickness variability at breast height on shady aspects and 68% of the variations in double bark thickness on sun-exposed aspects. According to Sonmez et al. [59], in addition to age and diameter, the aspect of tree growth should be taken into account to estimate the amount of merchantable timber and bark. Several factors, therefore, need to be considered when constructing accurate double bark thickness estimation models.

Thus, we can see that although the literature provides evidence that bark thickness correlates with diameter, most authors report that it depends on multiple factors, both tree-specific and those related to the site. Estimating the double bark thickness using one variable (in our case the midspan over-bark diameter) can, therefore, lead to inaccuracy in the estimation of the volume of merchantable timber. Based on these results, it is apparent that diameter at breast height can indeed serve as a variable that increases the accuracy of double bark thickness estimation. However, in practice, many cases occur when the diameter at breast height is not available for the scaler, e.g., at a log yard where stems or logs are further bucked, and their volume needs to be estimated. Therefore, this approach can lead to inconsistencies in timber scaling when multiple methods are used by different actors.

To showcase the effects of rounding down the over-bark midspan diameter on double bark thickness, we verified the accuracy of the standard polynomial and the relatively new linear models that can be used for double bark thickness estimations in Czechia. Jankovský et al. [51] found that the polynomial model underestimated the double bark thickness. Similarly, we also found that the models underestimated the double bark thickness for measured data compared to the measurement results, although we can state this only for logs within the range of the used dataset, i.e., those with a midspan diameter over bark between 163 and 492 mm, while the models were created for an interval between 100 mm and 1000 mm. The diameter interval used in this study reflects the typical size of timber supplied to operations producing sawn timber in Czechia. Typically, logs with smaller diameters are graded as pulpwood and supplied to pulp and paper mills, whereas logs with (large end) diameters larger than 43 cm [60] are supplied to processing facilities specifically designed to process oversized timber. Therefore, research is needed to verify the models' applicability for timber outside the log diameter interval we studied.

Rounding down the diameter measurements, as required by the standard measurement method in Czechia (and other countries, such as Germany or Austria) [54] had little effect on improving the strength of the relationship between the diameter over bark and double bark thickness because the coefficient of determination increased only by 0.01. It, however, did change the double bark thickness estimations using the polynomial and linear functions. Both models overestimated the double bark thickness when it was rounded down to the nearest centimetre. In contrast, the models underestimated bark thickness when the exact double bark thickness, as measured on the logs, was used. Although statistically significant differences were found between the rounded-down and exact double bark thickness measurements, we think that the differences between the two measurement methods were insubstantial from a practical perspective. Considering the increasing share of fully mechanized logging, rounding down the over-bark measurements can be omitted without substantial effects on scaling practices other than their simplification. Considering that, in Czechia, the share of fully mechanized harvesting technologies is approximately 40%, and other countries report that the majority of the timber is harvested by machines [40,61], which would substantially improve the accuracy and reliability of forestry records. One challenge connected to such a step is that the method of timber scaling is a process negotiated by contract parties, so both parties must agree on the measurement procedures to be used. Another challenge is specific to scenarios in which manual measurements are carried out. In these instances, human factors still play a role and introduce stochasticity or systemic errors in the process of estimating the volume of merchantable timber.

5. Conclusions

We found that for logs with a thickness between 163 and 492 mm harvested in Central Bohemia, the double bark thickness had a weak relationship with over-bark midspan diameter. Furthermore, both our hypotheses were confirmed: (i) rounding down the over-bark midspan diameters to the nearest centimetre significantly affected the double bark thickness estimation, and (ii) the polynomial and linear model estimates significantly underestimate the double bark thickness compared to the measurement results. Nevertheless, in the current conditions, accurate estimation of the volume of merchantable timber is important for foresters, as it is directly linked to the revenues of foresters on the one hand and customers' costs on the other. The methods used in Czechia were developed decades ago, and the double bark thickness estimation was based on a standard issued in 1977. Moreover, these methods do not reflect technical innovations that enabled the automated measurement of log parameters by forest machines and include procedures meant to address the potential of human error in measurements (such as rounding down the diameter measurement data), which are not necessary for automated timber scaling. The limitations of our study are in the size of the dataset, the fact that we analyzed the timber size for mechanical processing—logs of smaller or larger diameters were not considered—and the fact that only Norway spruce timber from 5.5 thousand ha of forests in Central Bohemia was considered. However, to make such a profound decision, further study of the relationship between the double bark thickness and diameter data is needed, which would cover a larger range of diameters, all main tree species, and multiple biogeographic regions in Czechia.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14051026/s1, Figure S1: Technical flowchart of the study method.

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