ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 10 N° 3 2015
pp. 11-20

REPLACING OUTLYING WOOD ANATOMY IN THE EVALUATION OF PROCESSING ROUGHNESS DATA AT SANDING

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Abstract:

Anatomical irregularities should be removed from the evaluation if a reliable processing roughness is to be evaluated. In order to get only measures of processing, wood anatomy can be removed with a method based on the Abbot-curve, which separates the core data from outliers by means of an upper and a lower threshold. Although researchers agreed on the need of separating the processing roughness from anatomical roughness, there was no study on the most appropriate method of replacing the missing data in the roughness profiles.

This paper examined three methods of replacing the oulying data and their effect on roughness parameters calculated on sampling lengths, as instructed by ISO 4287 (1998) and on evaluation length. The Zero method replaced outliers with zero values disregarded in further calculations, the Predicted method replaced the missing data by cubic spline interpolation and Total removal method removed completely wood anatomical features up to the profile mean line.The results showed that Zero method is the best choice when roughness parameters are calculated on the evaluation length. Compared to Predicted method it has the advantage of using real data giving similar results.Total removal method dramatically reduces the number of profile valleys in the evaluation biasing the roughness parameters.

Key words: *processing roughness; wood anatomy; separation; roughness parameters.*

INTRODUCTION

A proper evaluation of the quality of sanding requires anatomical irregularities to be excluded from the roughness data (Westkämper and Riegel 1993, Gurau *et al.* 2007). The Abbot-curve defined in ISO 13565-2 (1996) is the most appropriate starting point for devising a separation method since it is a straightforward tool for calculating the distribution of the profile heights. The method of separating the processing roughness from wood anatomy was described in detail by Gurau *et al.* (2005). The Abbot-curve is constructed by sorting the profile data in descending order. Statistically outlying peaks and valleys appear as non-linear regions in the Abbot-curve, and can be excluded. The upper and lower points of abrupt change in the local curvature of the Abbot-curve are identified by monitoring the variation of its second derivatives (Fig. 1). These points are taken to mark the thresholds for the core data (Fig. 3).

The upper and lower thresholds define the range of core data, which should represent the sanding marks. Data points above the upper threshold represent the fuzziness, while those below the lower threshold represent the anatomical features that exist on the surface independently of the sanding process.

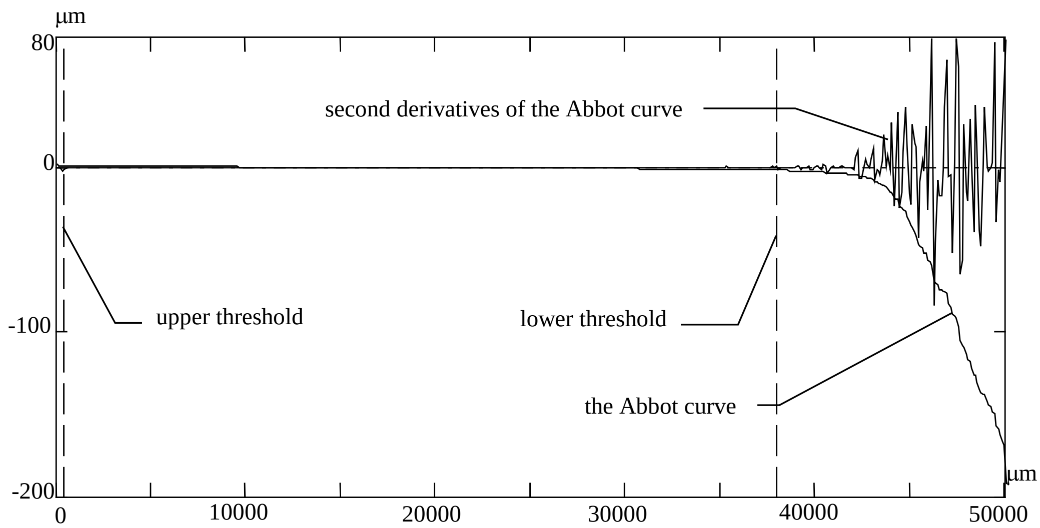

Fig. 1.
Use of the Abbot curve to find threshold values to delimit the processing, oak sanded with P1000.

Although many researchers agreed about the necessity of separating wood anatomy from processing, there are few studies where the outlying values are identified and replaced. Few different approaches were found in the literature: replacing the data points with zeros, which are disregarded in further calculations (Fujiwara *et al*. 2003, Gurau 2004, Hendarto *et al*. 2005), compacting the profile without replacing the outliers with values (Schadoffsky 2000, Hendarto *et al.* 2005), replacing the datapoints with the threshold value (Hendarto *et al.* 2005) or replacing them with a cubic curve fitted between the boundaries of the data points which are to be removed (Fujiwara *et al.* 2001).

The methods that will be investigated in this paper are based on those approaches from the literature.

Furthermore, ISO 4288 (1996) makes recommendations regarding the choice of the sampling length and evaluation length as a function of the expected range of variation for some roughness parameters such as *Ra*, *Rz* and *RSm* (ISO 4287:1998). However, Westkämper and Schadoffsky (1995) stated that the recommendations are not reliable for a heterogeneous material like wood. When wood anatomy is kept in the evaluation of wood surface roughness, an evaluation length should be sufficiently long to include both, the macro and microstructure of wood (Ostman 1983, Gurau 2004). However, it is not clear if the processing roughness left in the profile after removal of wood anatomy can or cannot be reliably calculated on sampling lengths, according to the requirements of ISO 4287 (1998).

OBJECTIVES

This paper aims to compare by means of roughness parameters, the effect of replacing wood anatomical data in the processing roughness profiles using three methods: replacing outliers with zero values which are disregarded at calculations, replacing outliers with predicted values and total removal of outlying data up to the profile meanline. The reliability of calculating the roughness parameters on sampling lengths as instructed by ISO 4287 (1998) is also examined.

METHOD, MATERIALS AND EQUIPMENT

a) Replacing with zeroes – Zero method

This method consists of replacing outlying data points with zeroes, which will be disregarded in the calculation of roughness parameters. Fig. 2 shows the roughness profile of an oak surface sanded with P1000, where outliers caused by wood anatomy, deeper than the sanding marks, lie below the lower threshold. In Fig. 3, the anatomical data crossed by the lower threshold is replaced by zero values in the processing roughness profile resulted after the separation. This method has the advantage that every data point is kept in its original place so that a visual examination of the real surface by image analysis remains possible. However, it maybe that replacing outliers with zeroes will create less data points in the evaluation and that might affect the values of some roughness parameters within the processing roughness, especially when calculating them on sampling lengths, too short for wood surfaces. This assumption is investigated in this study, roughness parameters calculated when outliers are replaced with zeroes will be compared with parameters obtained with a method where they are replaced with predicted values.

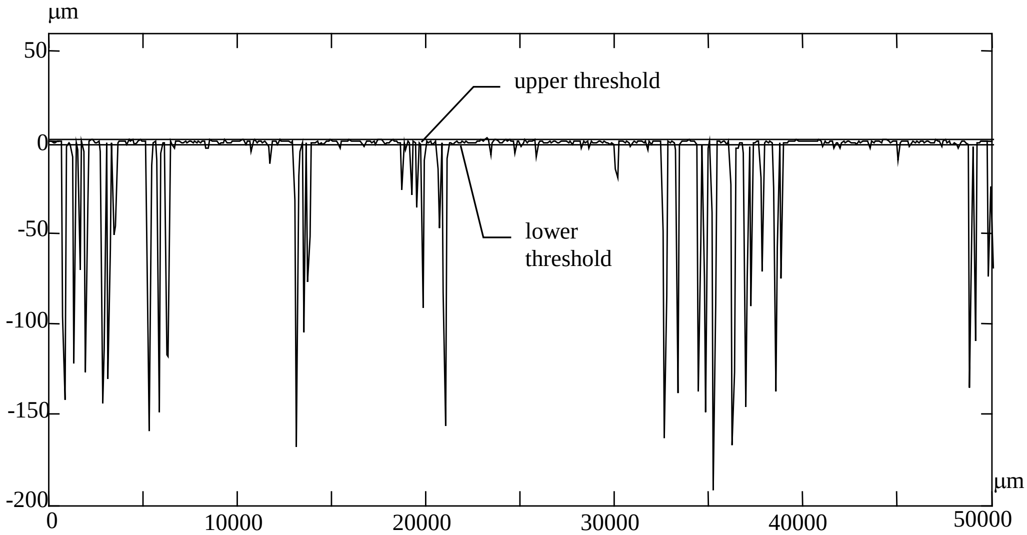

Fig. 2.
Core roughness data delimited by thresholds at oak sanded with P1000. Outlying anatomical data appears below the lower threshold.

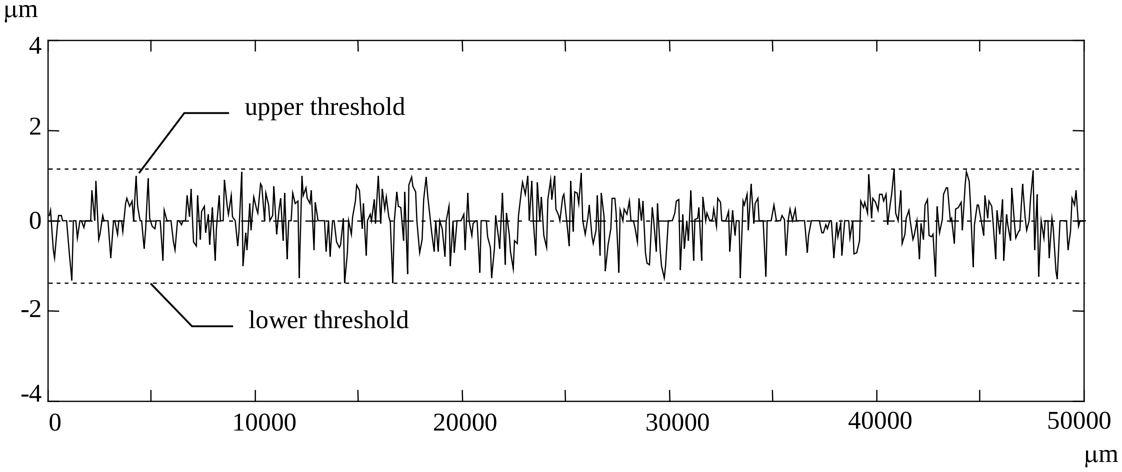

Fig. 3.
Processing roughness of an oak surface sanded with P1000 obtained by replacing outlying anatomy with zero values (Zero method).

An alternative to the Zero method is to replace the outliers with mean or median of values between the mean line and the lower or upper threshold respectively.or even to replace them with the value of the threshold itself (Hendarto *et al*. 2005). The advantage is that it maintains the same number of data points in the profile (compared with the Zero method). However, they do not introduce real data, can artificially increase some roughness parameters, as *Ra* and *Rq* in the study of Hendarto *et al*. (2005) and therefore, affect the reliability of the results.

b) Compacting the profile

In this method the outliers are not replaced with values; instead the profile is shortened. This method, called here the Compacting method, does not introduce bias by replacing the outliers with some unreal value, but it does produce different length profiles from a single measured area (Fig. 4). Roughness parameters calculated on the evaluation length should have identical values for Compacting method and Zero method. However, the calculation of roughness parameters on sampling lengths is more difficult and since data points move from their original location, an image analysis becomes impossible.

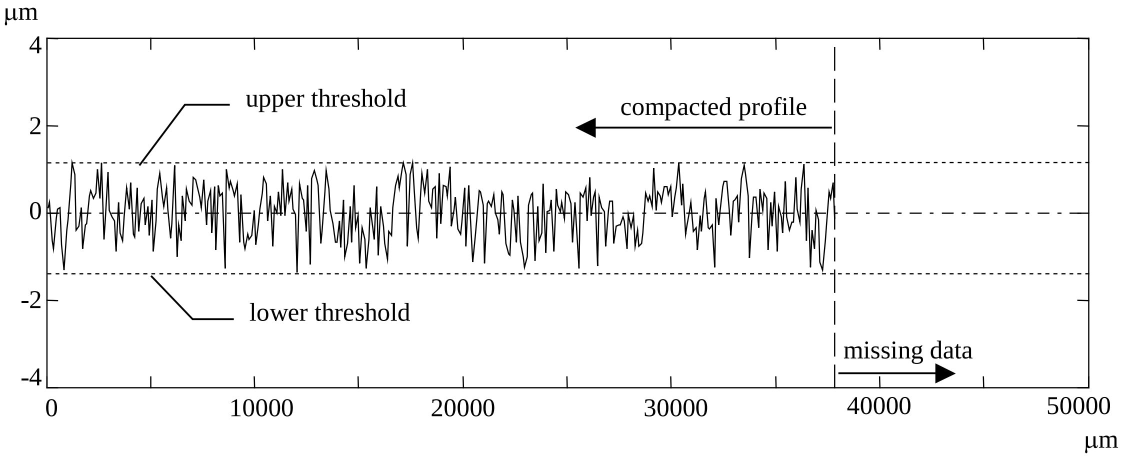

Fig. 4.
Processing roughness of an oak surface sanded with P1000 obtained by compacting the profile where anatomical outliers were removed (Compacting method).

c) Replacing with predicted values – Predicted method

To avoid the limitations of the Compacting method a modification can be sought to keep the same length for all measured profiles. MathCAD 2000 - Reference Manual provides a prediction function, which can use coefficients calculated from the last *m* data points of the original profile to compute coordinates of the missing data points. Having the prediction coefficients, the function uses the last *m* points to predict the coordinates of the *m* + 1 point, in effect creating a moving window that is *m* points wide. The prediction algorithm is based on Burg's method (Press *et al.* 1992). If there are *n* missing data points, then the prediction equation can be given by (1).

$$P = predict(C, m, n) \tag{1}$$

P - predicted vector of data points
C - compacted vector of data points
m - length of vector C
n - number of data points to be predicted

The results for the Predicting method for oak can be seen in Fig. 5. The first part is identical to the Compacting method (Fig. 4), but predicted data has been added to the ends of the profiles to restore the original profile length. Although this modified method allows the analysis of sampling lengths, any image analysis remains impossible.

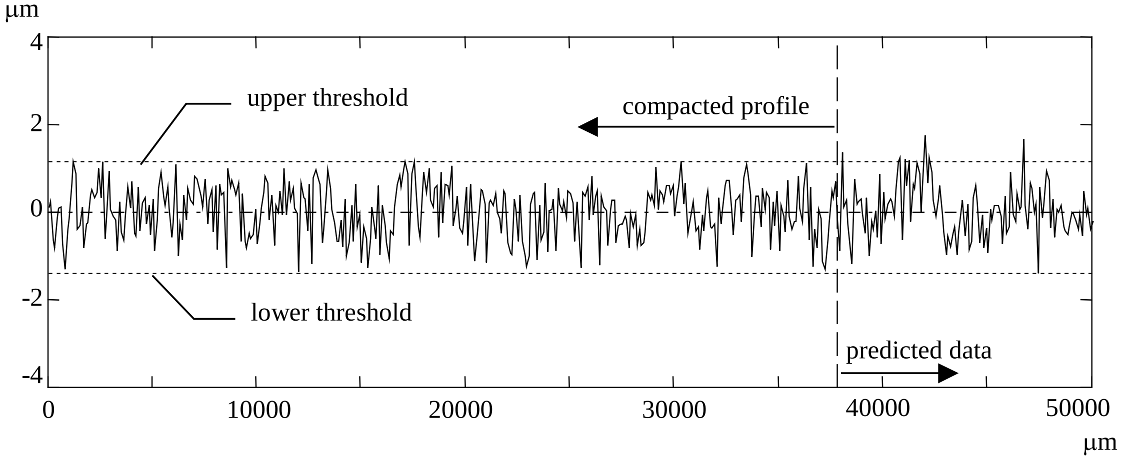

Fig. 5.
Processing roughness of an oak surface sanded with P1000, compacted in areas where the anatomical outliers were removed and completed with predicted datapoints.

To make image analysis possible there is an alternative to the Predicted method. Instead of adding predicted values to the end of a compacted profile, and so changing the real location of original data points, the predicted values can be located in place of outlying data (Fig. 6). MathCAD provides a function, which returns the vector of coefficients of a cubic spline with cubic ends. Cubic spline passes a curve through a set of three adjacent points so that the first and second derivatives of the curve are continuous across each point.

$$F = cspline(vx, vy) \tag{2}$$

F - vector of spline coefficients.
vx- vector of indices in ascending order, which indicates the length of the processing roughness profile without outliers.
vy- ordinate values of processing roughness data with no values in place of the outliers

The cubic spline coefficients are further used as arguments of an interpolation function, which interpolates the values from the spline coefficients.

$$I = interp(vs, vx, vy, x) \tag{3}$$

I- vector of processing roughness with outliers replaced by cubic spline interpolation.
vs- vector of spline coefficients supplied by cspline function.
vx- vector of indices in ascending order, which indicates the length of the processing roughness profile without outliers.
vy- ordinate values of processing roughness data with no values in place of the outliers
x- vector of indices in ascending order, which indicates the length of the processing roughness with outlying values replaced by interpolated values ($x > vx$).

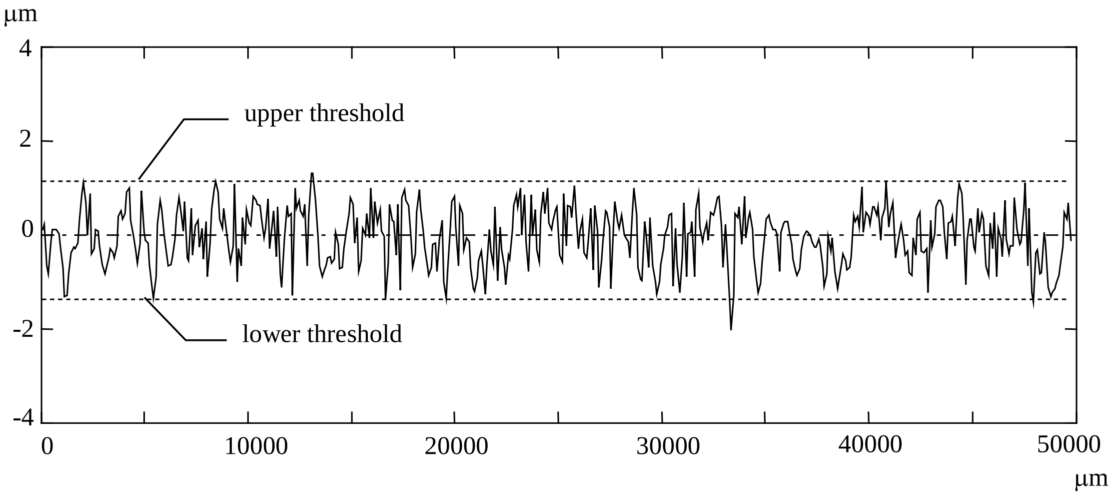

Fig. 6.
Processing roughness of an oak surface sanded with P1000 when outlying anatomical values are replaced with data predicted with cubic spline interpolation (Predicted method).

From Fig. 5 and Fig. 6 it can be seen that both predicting methods have introduced some isolated values, which are outside the threshold limits. This can influence some roughness parameters sensitive to isolated peaks or valleys, such as the skewness, *Rsk* and the height paraleter *Rt* as will be seen in the analysis that follows. This leads to a general assumption that predicting values is less reliable than using existing real data.

d) Total removal of outlying features – Total removal method

The separation method presented in the Introduction, does not completely remove the data points associated with the pores. Data points in the sides of the pores that are between the mean line and the lower threshold are retained. An algorithm was developed to remove these points completely by replacing them with zeroes up to the mean line, so that their influence on some roughness parameters could be compared with the Zero method. The location of data points in the profile is checked in relation to the lower threshold. Anatomical features intersecting the lower threshold are identified, their shape is reconstructed up to the mean line (shaded areas in Fig. 7) and corresponding values replaced with zeros, which are disregarded in further calculation of roughness parameters.

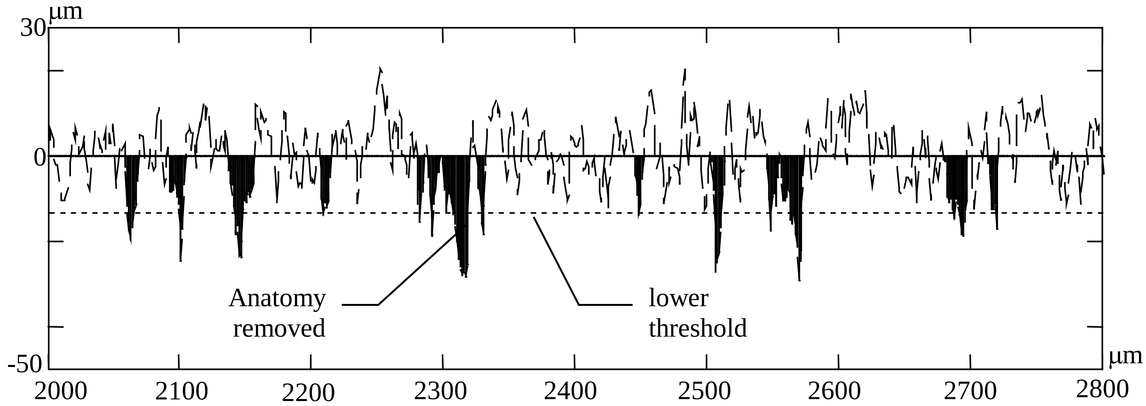

Fig. 7.
Identification of the anatomical roughness (black areas), when the roughness profile (dashed line) is intersected by the lower threshold (dotted line), at an oak surface sanded with P120.

From Fig. 7 it appears that the number of peaks remained in the processing roughness profile is much greater than the number of valleys and this method reduces the number of data points left in the profile for evaluating roughness parameters even more than the Zero method. Large wood pores obscure the grit marks to such an extent that few valleys are left in the roughness profile after the total removal of outlying features.

e) Experimental data

The following study contains a comparison of roughness parameters calculated on sampling lengths and evaluation lengths from profiles obtained with the Zero method. Although the Predicted method with cubic spline interpolation is based on predicted data added to the original profile, it is used in comparisons because the number of data points within the profile is the same as in the total roughness profile. The difference between roughness parameters calculated on sampling lengths and on evaluation lengths with the Predicted method can be taken as a reference for the same parameters, calculated with Zero method, although slight differences are inevitable due to the additional predicted data in the Predicted method. The comparison includes the Total removal method, in order to evaluate the impact on roughness parameters of a much lower number of real data in comparison with the other two methods.

Specimens of oak, beech and spruce were sanded parallel to the grain with P1000 grit paper. Such a fine grit size represents an extreme case of sanding, where the height variation due to processing is minimized in comparison with wood anatomy.

Measurements were carried out using a stylus with 2μm tip radius and 90° tip angle. Three profiles 50 mm long of each species were recorded at a lateral resolution of 100μm. The data was stored in ASCII format and processed with algorithms written in MathCad™.

Form errors were removed according to the profile method of ISO 3274 (1996) with a second order polynomial regression, which proved to be the best fit for the initial data.

The total roughness profiles, which contain both processing roughness and wood anatomy, were obtained by filtering the surface with the Robust Gaussian Regression Filter from ISO/TS 16610-31 (2010). A cut-off length of 2.5mm was used for beech and spruce and 8mm for oak in order to produce undistorted profiles (Gurau *et al.* 2006).

The separation of processing roughness from the other irregularities of the surface followed the method that uses the Abbot-curve (Gurau 2004). In a first set of data, the outlying peaks and valleys were replaced with zeros, which were neglected when the roughness parameters were calculated. The method is known here as Zero method.

Another set of data replaced the outlying values with predicted data by using a cubic spline as described in the Predicted method.

Finally, a third set of data removed outlying data completely up to the mean line as described in the Total removal method.

For each set of data, roughness parameters were calculated: *Ra*, *Rq*, *Rt*, *Rsk*, *Rku* from ISO 4287 (1998) and *Rk*, *Rpk* and *Rvk* from ISO 13565-2 (1996). Their calculation was performed on sampling lengths and evaluation lengths for Zero method and Predicted method and only on the evaluation length for Total removal method. The reduced number of datapoints remained in the profile with Total removal method, makes calculation on sampling lengths unreliable.

The sampling length is numerically equal to the characteristic cut-off length of the profile filter. Therefore, for oak, a cut-off length of 8mm was used, that allowed 6 sampling lengths to be evaluated. For beech and spruce, a 2.5mm cut-off length, divided the length of profile in 20 sampling lengths. An average parameter value was calculated by taking the arithmetic mean of the parameters from all the individual sampling lengths. Further, a mean value was calculated for all profiles measured for each species. Mean values were calculated also for the set of parameters calculated on evaluation lengths.

RESULTS

Processing roughness parameters calculated when outlying data was replaced with the three methods are evaluated on sampling lengths and evaluation lengths and are contained in Table 1. Their comparison is continued in Fig. 8, Fig. 9 and Fig. 10.

Table 1

Processing roughness of three species sanded with P1000 after removal of wood anatomy with three methods: replacement of data with zero values, with predicted data or total data removal with no replacement. Processing parameters are mean values (in μm) calculated on sampling lengths (SL) and evaluation lengths (EVL)

		Replacement with zero values		Replacement with predicted data		Total removal of outliers
		SL	EVL	SL	EVL	EVL
Ra	Oak	0.586	0.493	0.500	0.500	0.261
	Beech	0.468	0.345	0.352	0.349	0.174
	Spruce	1.647	1.05	1.004	1.005	0.655
Rq	Oak	0.680	0.588	0.601	0.603	0.412
	Beech	0.482	0.424	0.431	0.430	0.292
	Spruce	1.600	1.325	1.233	1.273	1.013

Rsk	Oak	-0.259	-0.247	-0.103	-0.042	0.362
	Beech	0.305	0.368	0.470	0.450	1.250
	Spruce	-0.650	-0.831	-0.721	-0.740	0.756
Rku	Oak	1.738	2.309	2.439	2.463	3.972
	Beech	1.773	2.474	2.568	2,698	4.631
	Spruce	2.128	3.038	2.987	3.035	4.765
Rk	Oak	1.455	1.492	1.455	1.532	0
	Beech	0.755	1.061	-	1.042	0
	Spruce	-	2.821	-	2.800	0.374
Rpk	Oak	0.304	0.304	0.345	0.391	0.422
	Beech	0.299	0.357	-	0.402	0.308
	Spruce	-	0.670	-	0.765	1.406
Rvk	Oak	0.585	0.526	0.562	0.517	1.045
	Beech	0.495	0.373	-	0.384	0.645
	Spruce	-	1.838	-	1.623	2.312
Rt	Oak	-	2.526	-	3.14	2.423
	Beech	-	1.759	-	2.468	1.754
	Spruce	-	5.953	-	6.071	5.894

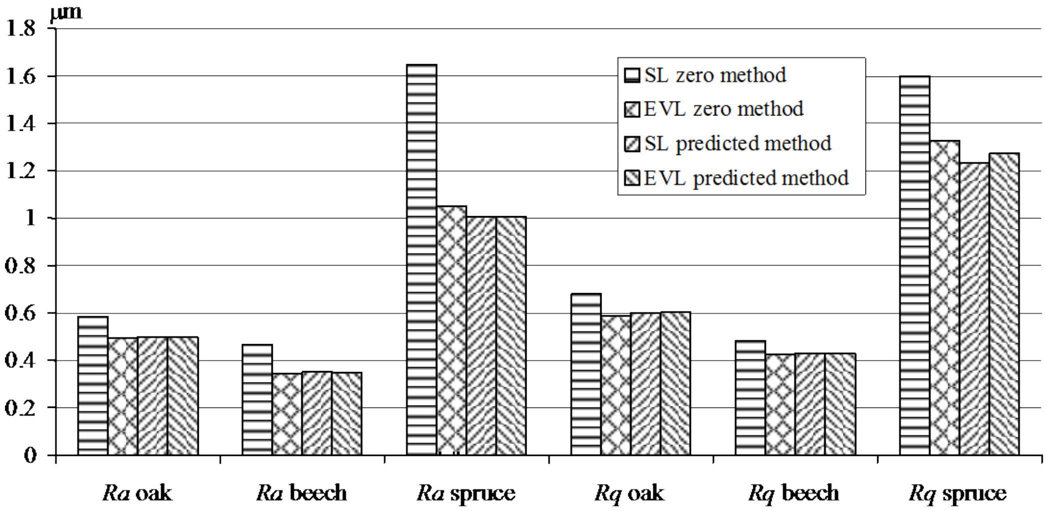

Fig. 8.
Comparison of processing mean parameters Ra and Rq when replacing the anatomical data using the Zero method and the Predicted method. SL - sampling length. EVL - evaluation length.

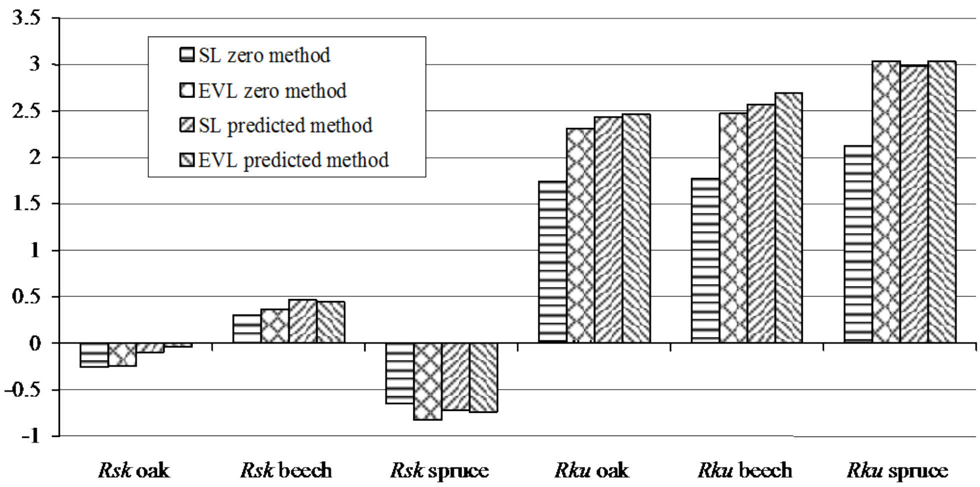

Fig. 9.
Comparison of processing shape parameters Rsk and Rku when replacing the anatomical data using the Zero method and the Predicted method. SL - sampling length. EVL - evaluation length.

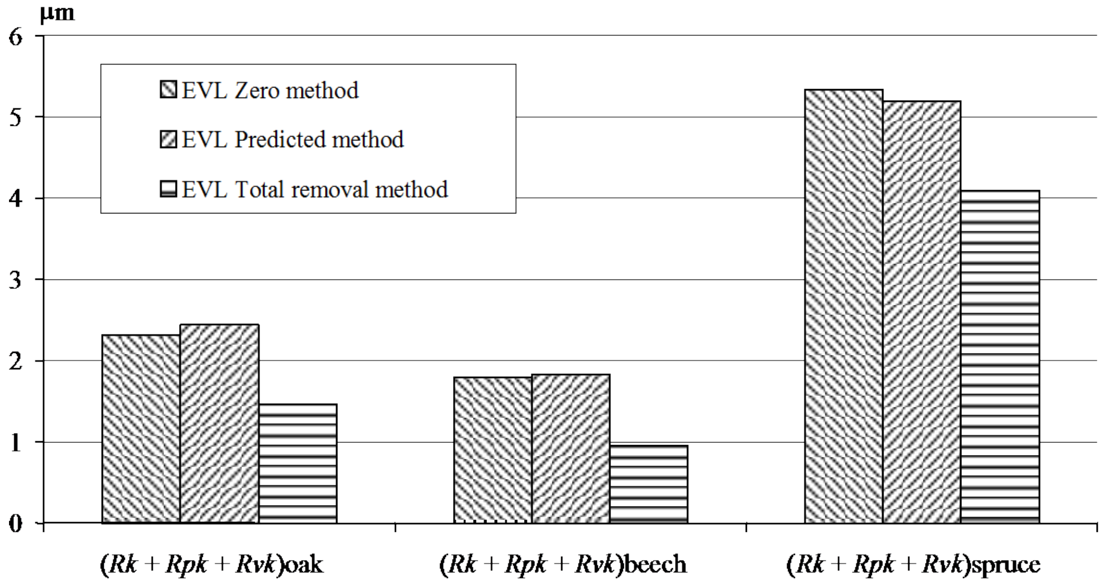

Fig. 10.
Comparison of the sum of Rk processing parameters when using three methods of replacing the anatomical data: Zero method, Predicted method and Total removal method.

In the Zero method, the number of data points left for evaluation in each sampling length will vary within the same profile and between profiles. As expected, this variation caused very different results between parameters calculated on sampling lengths as compared with those calculated on evaluation lengths (Table 1, Fig. 8 and Fig. 9). The *Ra* and *Rq* values when calculation was on sampling lengths was greater 16-36%, respectively 12-17% than the value of the same parameters calculated on evaluation length. Fewer data in the roughness profile divided by sampling lengths led also to a 33-43% lower kurtosis, *Rku*, which indicates a flattened data distribution around the mean of the density function. This is because the amount of data retained in each sampling length varied in non-zero datapoints from the neighboring sampling lengths and demonstrates that processing roughness parameters calculated with the Zero method are not reliably evaluated on sampling lengths as ISO 4287 (1998) recommends.

In contrast, parameters calculated using the Predicted method on sampling lengths, which had a constant number of data points, had very similar results to those calculated on the evaluation length: values were almost identical for *Ra* and *Rq* and differed by only 1-5% for *Rku*. This suggests that differences between parameters calculated on sampling lengths and evaluation lengths with the Zero method are caused solely by the variation in the number of data points in the sampling lengths.

The parameters calculated on the evaluation length with the Predicted method were in general close to those calculated with the Zero method differing by 1-4% for *Ra*, *Rq* and *Rk* (Table 1). This means that, although the profile length was shortened by removing the zero values, this did not affect the reliability of the parameters calculated on the evaluation length with the Zero method and therefore, a more reliable calculation of roughness parameters should refer to the evaluation length.

Exception in this comparison made the shape parameter *Rsk* and the height parameter *Rt*, which were different for predicting method compared to Zero method (Fig. 9). It appears that the artificial predicted datapoints (valleys or peaks) may introduce features outside the thresholds which are sensitive for some roughness parameters in an impredictible way (Fig. 6).

From Table 1 it can be seen that calculation of *Rk* parameters becomes unlikely for division of roughness profile into sampling lengths. Data included in a sampling length does not contain enough variation for such stratified parameters.

The method with Total removal of outliers worsened the roughness parameters results, which were influenced by the unbalanced ratio peaks-valleys reflected in very different values for the skewness, *Rsk*, kurtosis, *Rku* and shape parameters, *Rk*, *Rpk* and *Rvk* (Fig. 10).Total removal method caused little influence on *Rt*, which measures the peak to valley distance over the evaluation length, but a great impact on *Ra* and *Rq*, which were smaller by 38-50%, respectively 24-31%. The positive skewness, *Rsk*, is a clear indication of a higher peak occurrence, supported by an *Rku* greater than 3, which is an indication that the distribution has a peak around the mean. A data distribution containing more peaks than valleys, introduced errors in the calculation of *Rk* parameters, *Rk* was zero for oak and beech, which is clearly incorrect. It is clear from this, that Total removal is not a good option for replacing the outlying wood anatomy. Compared to Total removal method, the Zero method has the advantage of keeping more real datapoints in the evaluation and allows calculation of roughness parameters with no bias when the evaluation length is considered.

From the three methods tested, the Zero method proves to be a better choice if calculation of roughness parameters is made on the evaluation length.

CONCLUSIONS

Wood anatomical irregularities can be separated from processing irregularities with an Abbot-curve, whose inflexions define a lower and an upper threshold. The core data should represent the processing roughness, while the outlying data must be removed or replaced. This paper examines three methods to handle the unwanted outliers from the processing profile: replacing them with zero values disregarded at calculations, replacing with predicted values from a cubic spline interpolation or their total removal.

Compared with other methods of replacing values outside the threshold limits, the Zero method seems the most reliable because it is based on real data. Even though this method reduces the number of data points in the profile, the parameters calculated on the evaluation length appear reliable.

Replacing data with any value other than zero, such as predicted values, implies an artificial intervention that can introduce a bias in the roughness parameters.

The total removal of outlying features dramatically reduces the number of data points in the evaluation and changes the peak to valley ratio in an unpredictable way.

The calculation of processing roughness parameters was more reliable on the evaluation length than on sampling lengths.

Acknowledgements:
We hereby acknowledge the structural funds project PRO-DD (POS-CCE, O.2.2.1., ID 123, SMIS 2637, ctr. No 11/2009) for providing the infrastructure used in this work.

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