The Effect of Wood Provenance and Density on Cutting Forces While Sawing Scots Pine (*Pinus sylvestris* L.)

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Several properties of wood including the cutting power requirements can be correlated to wood density. Therefore, according to the literature, the cutting power requirements (and/or cutting forces) could be computed as a function of the wood specific gravity. This research shows that such an approach, based solely on specific gravity, may be considered a rather rough and imperfect estimate of cutting power. Samples of Scots pine (*Pinus sylvestris* L.) wood from different provinces in Poland with varying densities were machined on a sash gang saw. The average cutting force *versus* average wood density (estimated with the standard gravimetric method) was calculated, and the local cutting forces correlated to the local wood density. The average values of the cutting forces measured at selected points along the sample's length were calculated by linear regression to the X-ray absorbance (density) estimated by means of X-ray radiography.

Keywords: Cutting force; Wood density; X-ray densitometer; Wood provenance

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INTRODUCTION

Reliable estimates for the power requirements necessary to cut wood are essential for the proper design of cutting tools/machines to ensure safety of operation and to optimize production quality. A number of scientific studies, both theoretical and experimental, have been performed to understand and predict cutting forces. The resultant cutting force F_z (called often as an active force) has two main components (Grzesik 2008; Böllinghaus *et al*. 2009), the cutting force F_c, which is defined as the force in the direction of the cutting speed, and the thrust force (or back force.) F_p, which is perpendicular (normal) to F_c.

The forces acting in the cutting process have been investigated and described in several works concerning different cutting techniques. For instance, in general cutting Kivima (1950), Koch (1964), and Woodson and Koch (1970) examined the effect of the tool geometry and cutting direction on cutting forces values. Hernández *et al*. (2014) empirically evaluated effects of rake angle, cutting direction, and depth of cut on cutting forces during the canting work of a chipper-canter. A model was developed based on the assumption that there are two basic causes for energy dissipation during sawing: the creation of a new surface and the compression of material below a saw tooth (Hellström *et al*. 2013). On the other side, Naylor *et al*. (2012) created a cutting force model, which is based on wood mechanical properties.

Experimental results of cutting forces while milling were presented by Javorek *et al.* (2001), and for routing in the work by Porankiewicz and Goli (2014). In the latter work the authors analyzed surface formation mechanics. The sawing process has also been investigated: in the case of cutting with circular saw blades by Beljo-Lučić *et al*. (2004), industrial conditions (Cristóvão *et al.* 2013), wood crosscutting process (Krilek *et al.* 2014); in bandsawing processing (Moradpour *et al*. 2013) and during the process of re-sawing operations on a narrow-kerf sash gang saw (Orlowski 2010).

The empirical regression model of cutting for pine wood created firstly by Axelsson *et al*. (1993) was developed by Porankiewicz *et al*. (2011) into the more precise regression equation of cutting forces. Both of them could be applied for prediction of cutting forces while sawing. Moreover, cutting forces could also be considered from a point of view of modern fracture mechanics (Laternser *et al*. 2003; Stanzl-Tschegg and Navi 2009; Merhar and Bučar 2012; Orlowski *et al*. 2013). The issues of cutting forces from the point of view of the complex interaction between wood properties and the machining processes have been performed in review papers by Naylor and Hackney (2013), Marchal *et al*. (2009), and Orlowski and Palubicki (2009).

Several "easy to use" tools are currently available on the internet for determining cutting power consumption (Wood Products Online Expo 2014a,b). The number of variables required is small (even in the case of sawing on band- or circular saws) and, in general, all may be computed as a function of specific gravity (SG) of wood. Essentially, specific cutting resistance is directly proportional to wood SG with such software tools. It was demonstrated by Orlowski *et al.* (2012; 2013) that such an approach may be a rather rough and imperfect estimation of cutting power. Significant differences were obtained between parameters computed on the basis of SG and experimental results as well as theoretical simulations based on a modern fracture mechanics approach. Figure 1 presents predictions of cutting powers (P_c) computed on the basis of various algorithms, as described by Orlowski *et al.* (2013): (1) the classical "Manžos method" in which cutting power is predicted as a function of the specific cutting resistance k_c (Manžos 1974); (2) cutting power that was calculated as a function of specific gravity SG (Wood Products Online Expo 2014b); and (3) cutting power that was computed according to the cutting model "Fracture", which includes work of separation in addition to plasticity and friction (Orlowski *et al.* 2013).

The cutting powers shown in Fig. 1 were computed for one circular saw (kerf width 3.6 mm) with the following: Scots pine (*Pinus sylvestris*), wood density ρ = 450 kg·m^{-3}; workpiece of height H = 80 mm, circular saw HSV R200 (f. HewSaw, FI), diameter of the blade D = 350 mm, teeth number z = 30, rotational speed n = 3500 rpm. Other details for the computation algorithm are described in Orlowski *et al.* (2013).

The other variable usually underestimated in computations is the natural variability of the physical properties of wood, even within the same species (Sandak *et al.* 2011), which has a potential effect on the cutting mechanisms (Sandak *et al.* 2010). Hence, the goals of this manuscript were to investigate the effect of the density specific gravity on the reliability of cutting power estimates and to examine how the geographical variability of wood affects cutting power requirements.

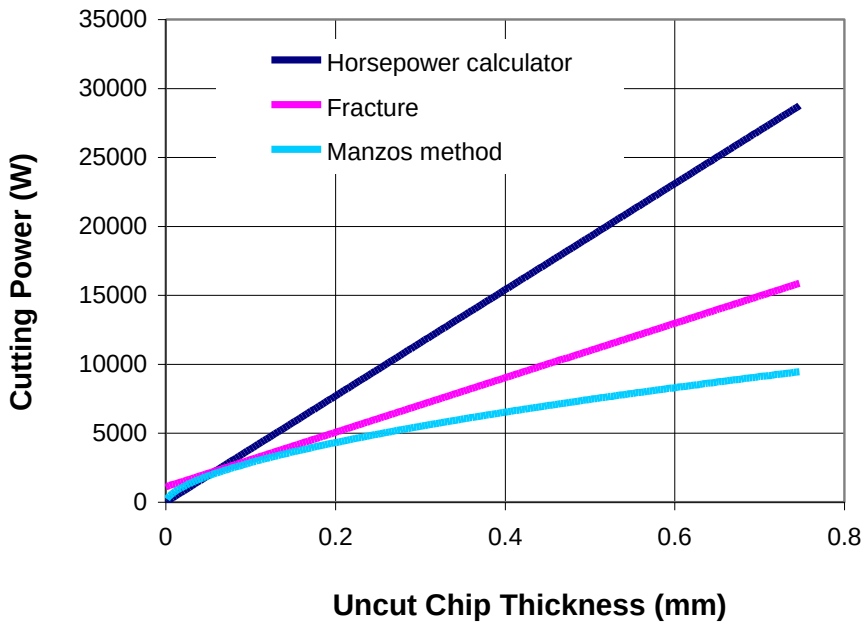


Fig. 1. Comparison of cutting power predictions. The classical Manžos method, the web source "Horsepower calculator", and the cutting model "Fracture" that includes work of separation in addition to plasticity and friction for a circular saw for dry pine sawing with one saw blade

EXPERIMENTAL

Materials

Scots pine (*Pinus sylvestris* L.) samples originating from four provinces in Poland (Fig. 2) were used as experimental samples. Samples were in the shape of rectangular blocks, with dimensions of 60 mm (H) × 45 mm (W) × 600 mm (L) and were conditioned to a moisture content (MC) of ~12%.

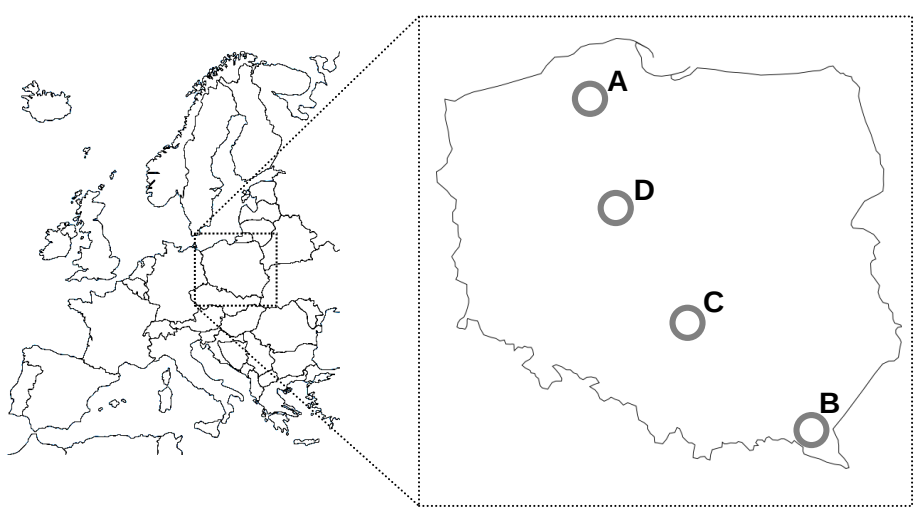


Fig. 2. Locations within Poland of natural-forest regions of Scots pine

Eight samples from each region, obtained from different representative trees, were investigated. More details on the sample selection, preparation, and characterization can be found in the related literature (Chuchala *et al.* 2011; Krzosek 2009, 2011). It should be emphasized that it was demonstrated in the monograph by Krzosek (2009), that the wood provenance significantly affects mechanical strength of wood. Part of the samples investigated by Krzosek has been explored within this research.

Table 1. Comparison of Selected Characteristics of Experimental Samples by Location (Chuchala *et al.* 2011, 2012)

Region	Name of Natural Forest Regions	Average wood density (global) ($kg \cdot m^{-3}$)	Average annual growth (ring width) (mm)	Average share of late wood (%)
A	Baltic	517	2.40	31.5
B	Carpathian	471	4.65	22.2
C	Little Poland	495	2.98	24.4
D	Great Poland-Pomeranian	636	2.38	28.3

Methods

Determination of density

Sample dimensions and weight were measured immediately before sawing. The dimensions of the sample cross-section (*i.e.*, width and height) were measured at six points equally distributed along the prism with a caliper. The length was measured with a measuring tape. The wood density was calculated using the stereometric method (Krzysik 1974), as a ratio of the sample mass and volume in the air-dry condition. This property was defined within this research as a global density in order to differentiate it from the density maps (local density) as estimated with x-rays. Measurement of mass was determined with a RADWAG balance type WPT/R 1.5/3C (f. RADWAG Wagi Elektroniczne Radom, PL) that has a measurement accuracy of 0.5 g. It is estimated that the average measurement error of the global wood density was ± 0.4 $kg \cdot m^{-3}$ (Chuchala *et al.* 2011). Table 1 compares selected characteristics of Scots pine in four different locations.

The space-resolved estimate of wood density was performed after the cutting tests using a self-designed non-destructive X-ray radiometric instrument developed at the Trees and Timber Institute, National Research Council of Italy IVALSA\CNR (IVALSA 2014). Six measurement points were selected along the sample length, as shown in Fig. 3. The X-ray absorbance radiograms were scrutinized for each wood lamella and saved as TIFF images for post-processing. The X-ray source was W bulb (ItalStructure, Rovereto, Italy) and the X-ray settings 50 kV and 40 mA, with a CSI scintillator (ACS, Hamamatsu Photonics; Iwata, Japan) and a CMOS camera (PL-A774, Pixelink; Ottawa, Canada) for image acquisition. The calibration of the x-ray instrument was performed on the basis of reference wood samples. Fourteen species of different densities (ranged from 200 to 1200 $kg\ m^{-3}$) and of varying thicknesses (from 5 to 40 mm with a step of 5 mm) were used for modeling of the x-ray attenuation. The determination of the unknown density was performed as an interpolation of experimental data in a function of the sample thickness and x-ray attenuation. The custom software in LabView 8.6 (National Instruments; Austin, TX) was developed for image processing and to estimate local density on the basis of X-ray attenuation. A sample radiogram is presented in Fig. 3.

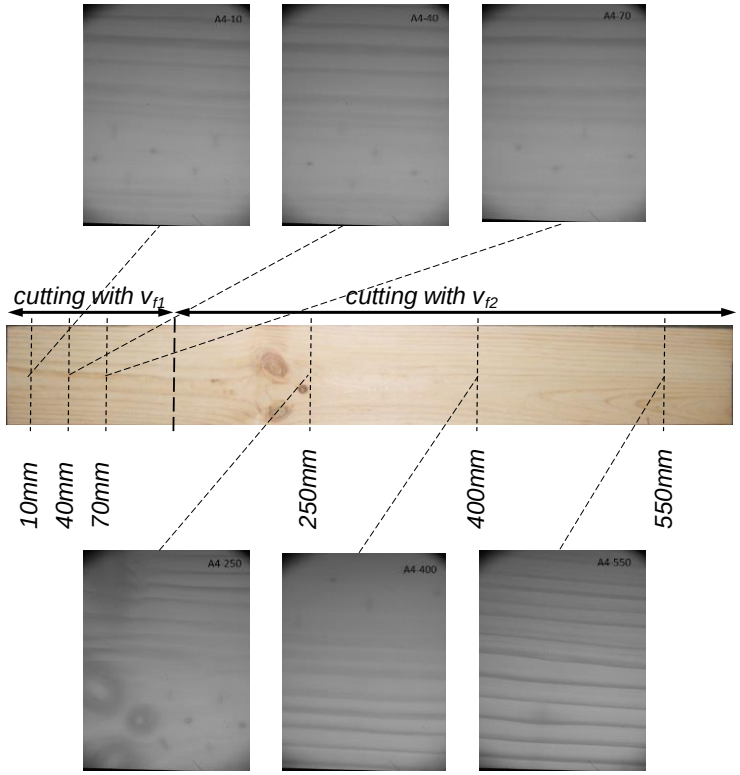


Fig. 3. An image of wood with surface lamella and X-ray radiograms from selected points in which cutting force (and local density) measurements were assessed

Determination of average ring width and latewood ratio

The average annual growth (ring width) and average share of late wood of the prepared samples were carried out according to our own methodology (Chuchala *et al.* 2011) and are shown in Table 1. The photos taken from each end cross-section of the samples were transferred to the Autocad software and scaled to the dimensions of the actual sample. In a 30 mm length segment perpendicular to the tangent, drawn to the ring, an average annual growth (ring width) was quantified. The average share of late wood was calculated as the ratio of the average width of late wood to the average annual growth.

Estimation of cutting forces (cutting power)

A series of cutting tests to empirically determine the cutting power was carried out on a PRW15M sash gang saw (a prototype designed at Gdansk University of Technology, PL; manufactured by REMA-Reszel, PL), a frame sawing system with elliptical tooth trajectory, and a hybrid dynamically balanced drive, as described by Wasielewski and Orlowski (2002). The machine settings were as follows: number of strokes of saw frame per min (n_F), 685 spm; saw frame stroke (H_F), 162 mm; number of saws in the gang (n), 5; and average cutting speed (v_c), 3.69 m·s^{-1}. The saw blades were sharp, with stellite tipped teeth: overall set (kerf width) (S_t), 2 mm; saw blade thickness (s), 0.9 mm; free length of the saw blade (L_0), 318 mm; tension stresses of saws in the gang (σ_N), 300 MPa; blade width (b), 30 mm; tooth pitch (P), 13 mm; tool side rake (γ_f), 9°; and tool side clearance (α_f), 14°. The only varying cutting parameter was feed speed, which was applied at two levels: $v_{f1} \approx 0.3$ m·min^{-1} and $v_{f2} \approx 1.1$ m·min^{-1}. This

corresponds to a feed per tooth (f_z) of ~0.04 mm and ~0.14 mm, respectively. Lamellae with thicknesses of 5 ± 0.2 mm were obtained as a result of the re-sawing process.

The corresponding cutting forces (F_c) (related to one tooth of the saw blade) were calculated according to the method of Orlowski and Palubicki (2009) and Orlowski (2010). The average idle power ($\overline{P_I}$) was measured immediately before and after cutting (Fig. 4). The total power of the main driving system ($\overline{P_{cT}}$) was recorded during all wood sawing tests, with a sampling frequency of 80 Hz (number of samples = 8192). Subsequently, the average cutting power ($\overline{P_c}$) and the mean value of the cutting force in the working stroke ($\overline{F_{cw}}$) per tooth were determined. Eventually, all the resulting cutting forces were calculated by linear regression relative to the corresponding densities estimated with the gravimetric and X-ray (global and local) approaches. The linear regressions, Pearson's *r* coefficients, and significance (*t*-test) were computed on the basis of experimental data with Statistica 8.0 (StatSoft Inc., USA) software (StatSoft 2014). Statistical analyses were performed assuming 95% confidence level (α = 0.05). The verbal interpretation/description of *r* was classified according to Evans (1996).

a

b

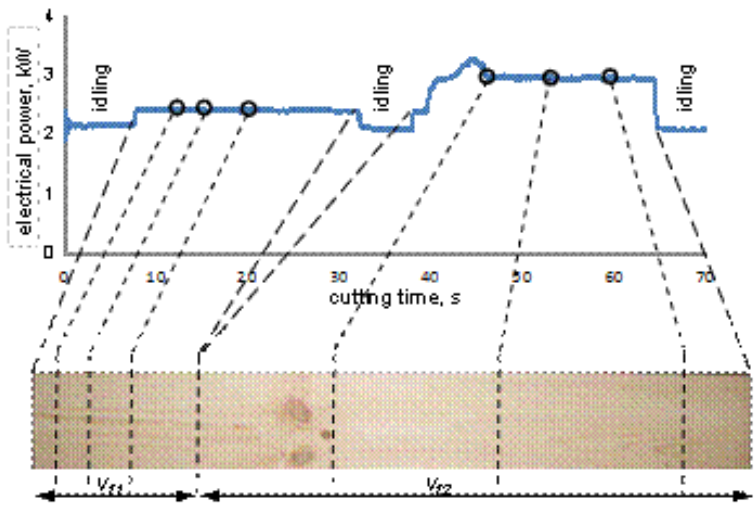


Fig. 4. Estimate of cutting power (cutting forces) while sawing wood at two feed speeds: (a) time changes of electrical power consumption and (b) location of measurement points along the sample length

RESULTS AND DISCUSSION

The relationship between cutting force (F_c) and density (ρ) for Scots pine wood was first analyzed independently for every location and for both feed speeds. Furthermore, separate regression models were developed for global and local densities. The summary of the prediction capability ($F_c = f(\rho)$) is presented in Table 2. Very diverse relationships were noted between the cutting force and the density of wood for different regions of origin. Values of correlation coefficient *r* varied from very weak correlation ($r \approx -0.02$) up to values indicating very strong correlation ($r \approx 0.92$) (Statstutor 2014). Correlation coefficients were slightly different for each level of feed per tooth. The performance of regression models computed on the basis of local density values seemed to be only slightly better than these of global density (more statistically significant

models as shown in Table 2). The regression models for region B were the most problematic, and no statistical significance of models was confirmed. A similar conclusion was derived when all experimental results (both regions and densities) were combined. As seen in Fig. 5, a trend of increasing cutting force as the density increased is evident, even if the overall accuracy of prediction was not sufficient. The results obtained from the above analysis are considered rather limited and do not properly explain the phenomenon (Fig. 5). Additional data mining analysis was therefore performed.

Table 2. Pearson's *r* Correlation Coefficients between Cutting Force and Wood Density while Sawing Pine

Region	Feed per tooth f_z (mm)	Pearson's *r*	Correlation	Significance
		Global density of sample		
A	0.04	0.75	strong	Yes
	0.14	0.54	moderate	Yes
B	0.04	-0.02	very weak (no)	No
	0.14	-0.08	very weak (no)	No
C	0.04	0.49	moderate	Yes
	0.14	0.56	moderate	Yes
D	0.04	0.83	very strong	Yes
	0.14	0.91	very strong	Yes
A+B+C+D (~Poland)	0.04	0.65	strong	Yes
	0.14	0.78	strong	Yes
		the local density of sample		
A	0.04	0.56	moderate	Yes
	0.14	0.55	moderate	Yes
B	0.04	0.15	very weak (no)	No
	0.14	0.23	week	Yes
C	0.04	0.33	week	Yes
	0.14	0.81	very strong	Yes
D	0.04	0.92	very strong	Yes
	0.14	0.89	very strong	Yes
A+B+C+D (~Poland)	0.04	0.59	moderate	Yes
	0.14	0.70	strong	Yes

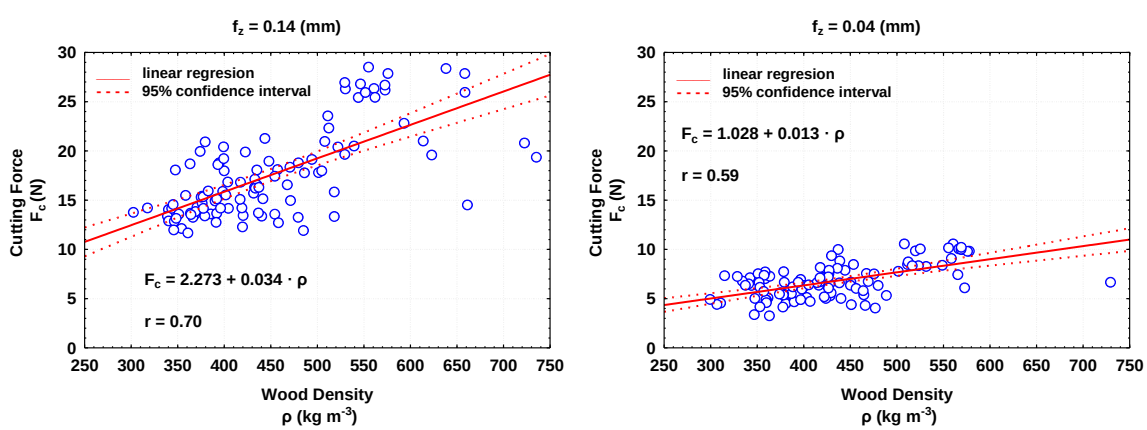


Fig. 5. The relationship between cutting force and estimated local density of wood for two feeds per tooth. (a) f_z = 0.04 mm and (b) f_z = 0.14 mm in samples from all investigated provinces

It was reported by Porankiewicz *et al*. (2011) that the cutting force prediction may be substantially improved with additional variables in the equations. Therefore, further regression models ($F_c = f(f_z,\rho)$) that consider both feed speed per tooth (f_z) and wood density (ρ) were developed.

Figure 6 presents the enhanced regression models developed separately for each wood provenance. Both global and local densities were used as variable references in the regression models. The exponential function was selected for fitting the experimental points. A relatively high quality of the regression, when compared to $F_c = f(\rho)$, was found. It was evident that the function $F_c = f(f_z,\rho)$ is also dependent on the provenance. The cutting forces had the highest values for wood samples harvested in region D, especially when cutting was performed with high values of feed per tooth (f_z). The combination of all compiled available data for the four regions is shown in Fig. 7.

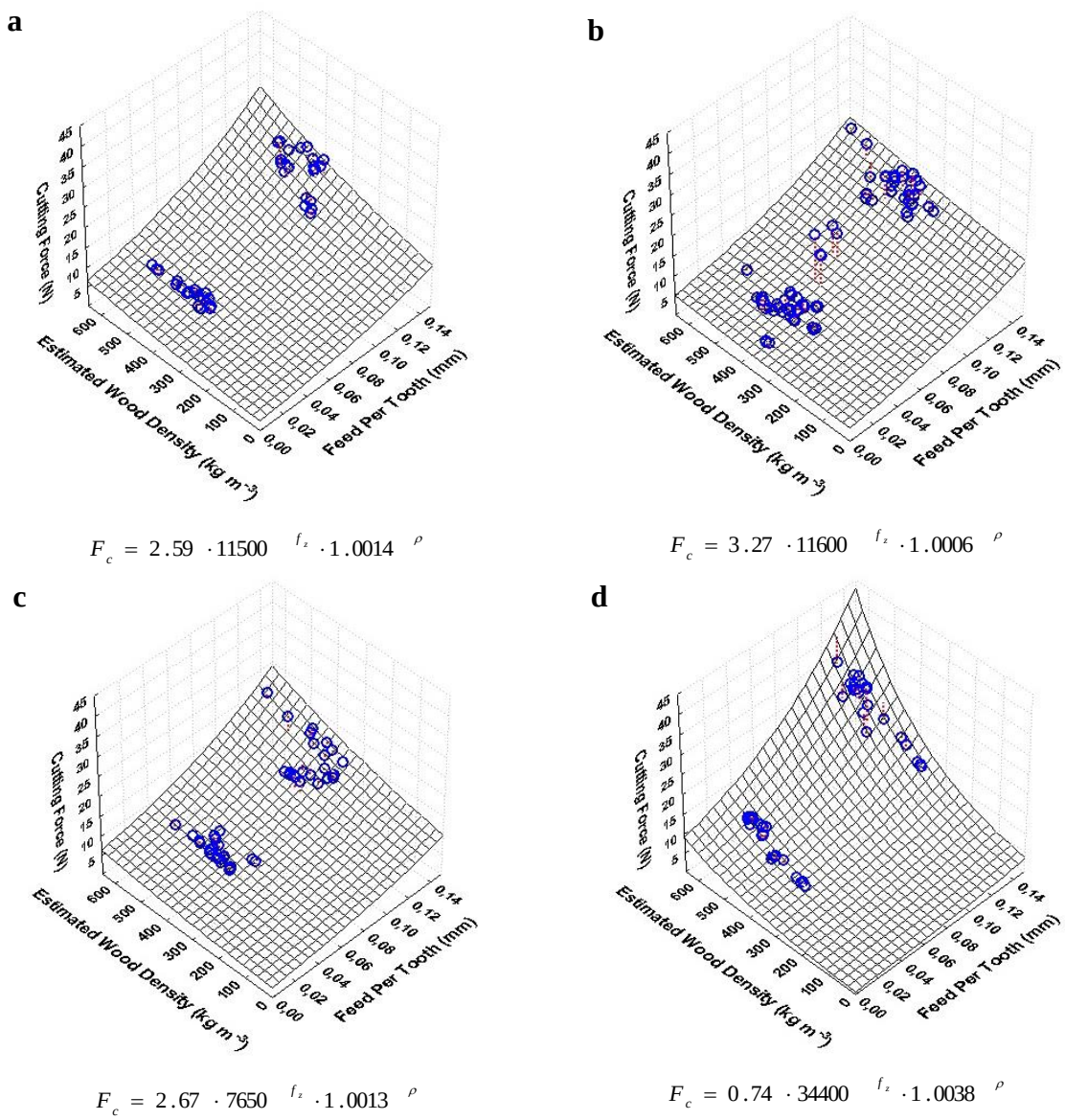
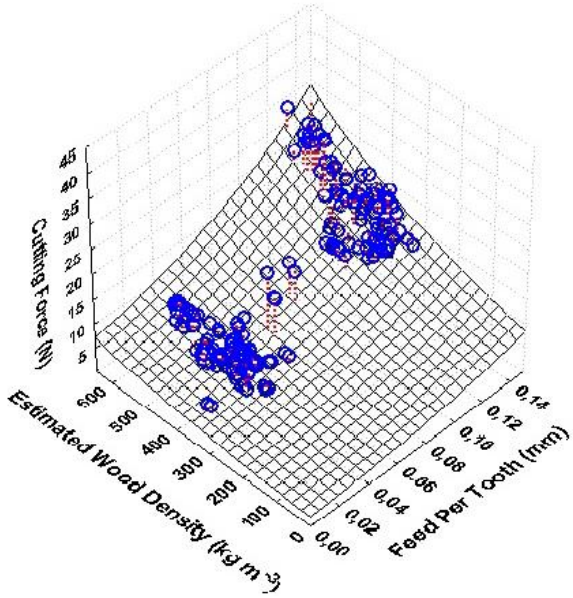


Fig. 6. Cutting force *versus* estimated local density of wood and feed per tooth as a function of wood origin: (a) region A, the Baltic natural forest, (b) region B, the Carpathian natural forest, (c) region C, the Little Poland natural forest, and (d) region D, the Great Poland-Pomeranian natural forest

The quality of the models predicting cutting force ($F_c = f(f_z,\rho)$) is summarized in Table 3. It is apparent that the $F_c = f(f_z,\rho)$ prediction capability was superior to that of the variable $F_c = f(\rho)$, as the determination coefficient (r^2) was higher in all cases. Even though the regression model for wood originating from region B was still problematic, it was substantially improved ($r^2 = 0.77$). It is expected that further model enhancement (as well as its generalization) can be obtained when testing additional samples and/or varying cutting parameters.



$$F_c = 2.01 \cdot 14000^{f_z} \cdot 1.0019^{\rho}$$

Fig. 7. Combined effect of estimated local density of wood and feed speed per tooth on the cutting force for all examined samples originating from Polish natural forest regions A, B, C, and D

Table 3. Coefficients of Determination for Regression Models Describing the Cutting Force *versus* Feed per Tooth and Wood Density

Region	Coefficients of determination r^2	
	Regression function with the global density of sample	Regression function with the estimated local density of sample
A	0.95	0.94
B	0.77	0.77
C	0.90	0.92
D	0.95	0.94
A+B+C+D	0.85	0.84

It should also be mentioned that the quality of the regression models (r^2) determined on the basis of "global" and "local" densities did not vary significantly, as confirmed by statistical calculations of confidence intervals (CI) for the difference between two independent correlations (level $\alpha = 0.05$) (Zou 2007; Baguley 2012), for each provenance independently. Therefore, additional efforts for quantification of density maps with X-ray radiography were not justified. An effect of detailed density estimation (local approach) seems to be negligible in the case of $F_c = f(f_z,\rho)$, as a relatively wide range of densities was present in the data set. The relative variation between the local

(spatially-resolved) and globally estimated (averaged) densities was minimized. It may become essential to provide detailed density assessment if more uniform (homogeneous) samples are to be evaluated or more refined process parameters input into the models. The latter can also be related to the analysis of a single cutting edge involved at a time, contrary to multiple teeth as in the case of the gang saw blades in this study.

CONCLUSIONS

1. Cutting forces estimated for samples of the same wood species but from different provenances change due to variations in morphological and physical properties as related to wood origin.
2. The cutting forces clearly correlate with density, even though the latter is not the only significant factor/variable.
3. There are no statistically significant differences ($\alpha = 0.05$) between regression models for the cutting force ($F_c = f(f_z,\rho)$) when considering "local" and "global" densities.

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