DIFFERENT APPROACHES FOR COFFEE BEAN SHAPE AND CONTOUR DETERMINATION

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ABSTRACT

Selected Arabica (*Coffea arabica L.*) coffee beans (13 different types from 13 different countries) were monitored and variability of their shape and size was analysed. The basic analysis was based on evaluation of main dimensions. Several tools were employed for performing of the objectives – determination of main dimensions ratios, determination of sphericity (parameter for the calculation of processing and handling operations), calculation of shape variability using elliptic Fourier descriptors, and calculation of curvature radius. All three approaches proven significant differences among individual coffee samples. The least variable bean parameter was bean depth with a coefficient of variation 0.05, followed by bean width with a coefficient of variation of 0.18, and bean length with a coefficient of variation of 0.85. The experiments improved previous findings concerning the relationship between length, width, and depth of Arabica beans. Sphericity also ranged and its value can be used for the design and evaluation of processing and handling operations. Reconstructed shapes (by use of Fourier descriptors) indicated that the first principal component (which represents the length-to-width ratio) is a suitable measure of the total shape variation (70.87 to 74.64 % of the total shape variation).

INTRODUCTION

The quality of coffee beans is partly determined by their size and shape (Banks et al, 1999). Shape and size of coffee berries and beans depend on many factors such as geographical zone (Freitas and Mosca, 1999), coffee variety (Ghosh and Gacanja, 1970), and planting conditions (Muschler, 2001). The first statistical review of coffee bean shape was performed by Wormer (1966). Knowledge of coffee bean is critical, e.g. for designing manipulation, handling, and processing devices. The evaluation of the coffee grain shape is relatively difficult owing to its complexity. Calculation of the bean sphericity with the use of a simple approach is one of the objectives of this work. It can be consequently used for comparison with the shape variability of different coffee types (quantified by use of Fourier descriptors) and for comparison with bean curvature radius.

MATERIAL AND METHODS

Coffee samples
Arabica coffee beans (roasted) were used for performed analyses. Coffees were produced in Brazil [B], Colombia [C], Costa Rica [CR], Ethiopia [E], Guatemala [G], Honduras [H], Indonesia [I], Kenya [K], Mexico [M], Panama [P], Papua New Guinea [P-NG], Peru [PE], and Tanzania [T]. The abbreviations in square brackets indicate the coffee type and it is used in the text hereinafter. The beans were ordered from a commercial distribution network in the Czech Republic.

Quantitative measurement of the bean weight and dimensions

Dimensions in the main axes (D1, D4, D7 – see Figure 1) were measured using a SOMET digital calliper (Germany). The remaining dimensions (D2, D3, D5, D6 – see Figure 1) were determined from digital images using Corel DRAW X3 (Corel Corporation, USA).

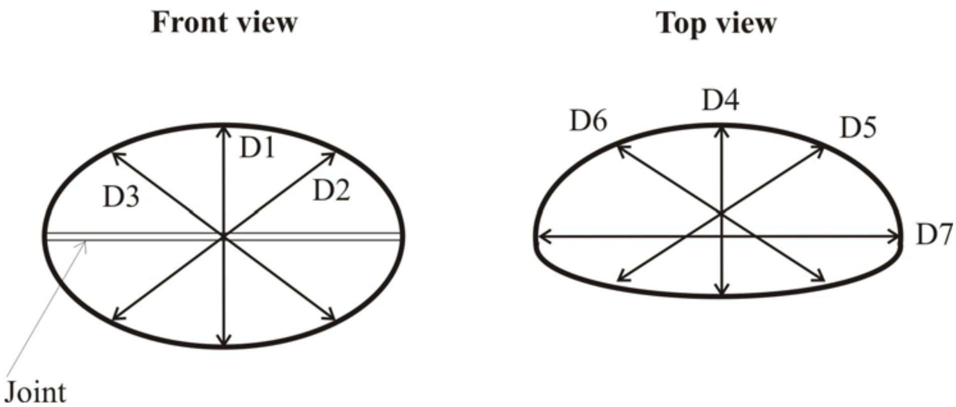

Figure 1
Illustration of measuring sides for coffee beans

Calculation of sphericity

The sphericity was calculated using Equation 1, derived by Bayram (2005).

$$\phi_s = \frac{\sum\left(D_i - \overline{D}\right)^2}{\left(\overline{D}N\right)^2} \ , \qquad (1)$$

where ϕ_s denotes sphericity, D_i is any measured dimension, $\overline{D}$ is average dimension or equivalent diameter, and N is the number of measurements. In the given model, an equivalent or nominal diameter for irregularly shaped materials is accepted as the average dimension to obtain an equivalent sphere. Differences between average diameter and actual measured dimensions are determined with the sum of square of differences. When this difference is divided by the square of the product of the average diameter and number of measurements, it gives a fraction for the approach of the slope to an equivalent sphere, i.e. sphericity. An increase in N increases the accuracy.

Coffee bean shape variation evaluated by use of elliptic Fourier analyses

The image analysis software Shape (Iwata and Ukai, 2002) was used to perform the analysis. The closed contours of the beans were obtained through binary images with appropriate thresholds and were described by a chain–code. The same or similar method was used for the chicken egg shape analysis (Havlíček et al., 2008), hazelnut shape analysis (Menesatti et al., 2008), or e.g. sperm head shape analysis (Severa et al., 2010). The coefficients of elliptic Fourier descriptors that were normalized to avoid variations related to the size, rotation, and starting point of the contour traces were then calculated from the chain–code. To summarize the information contained in the coefficients of the Fourier descriptors, the principal components analysis based on a variance–covariance matrix of the coefficients was performed. The scores of the components were used in subsequent analysis as the bean shape characteristic.

Determination of curvature radius

The contours of single projections can be accurately described in a user-defined Cartesian coordinate system. The shape of the grain counter can be described using the polar coordinates *r, φ*. The most effective function describing this dependence is given by the Fourier approach:

$$r(\varphi) = a_o + \sum_{i=0}^{\infty} a_i \cos\left(2\pi \frac{\varphi}{c_i}\right) + b_i \sin\left(2\pi \frac{\varphi}{c_i}\right) \tag{2}$$

Another approximation can be given by the polynomial fit:

$$r(\varphi) = \sum_{i=1}^{n} p_i \varphi^{n+1-i} \tag{3}$$

If we denote $x(\varphi) = f(\varphi), y(\varphi) = g(\varphi)$, the curvature radius is given by well-known relation:

$$R = \frac{\left(\dot{f}^2 + \dot{g}^2\right)^{\frac{3}{2}}}{\left(\dot{f}\ddot{g} - \ddot{f}\dot{g}\right)}, \tag{4}$$

where dot denotes the derivation with respect to *φ*.

RESULTS AND DISCUSSION

The bean width (D1) ranged from 7.56 mm (E) to 9.76 mm (M), the bean depth (D4) from 4.50 mm (CR) to 5.07 mm (K), and bean length (D7) from 10.36 mm (P-NG) to 14.90 mm (M). Generally, the least variable bean parameter was bean depth (D4) with a coefficient of variation of 0.05, followed by bean width (D1) (CV = 0.18), and bean length (D7) (CV = 0.85). The coefficient of correlation for the ratios of length/width ranged from 0.301 (C) to 0.787 (CR), length/depth from 0.376 (P) to 0.924 (P-NG), and width/depth from 0.461 (H) to 0.813 (P-NG). The values of correlation coefficients are listed in Table 1.

Table 1: Correlation (r) for length/width, length/depth and width/depth ratios

Coffee brand	r - length/width	r - length/depth	r - depth/width
B	0.621	0.744	0.690
C	0.301	0.468	0.478
CR	0.787	0.659	0.731
E	0.679	0.670	0.572
G	0.512	0.624	0.561
H	0.581	0.516	0.461
I	0.394	0.548	0.619
K	0.512	0.694	0.699
M	0.378	0.635	0.497
P	0.541	0.376	0.593
P-NG	0.864	0.924	0.813
PE	0.404	0.717	0.751
T	0.421	0.413	0.531

Sphericity

The values of Arabica bean sphericity (including standard deviation values) are listed in Table 2. The average value of sphericity ranged from 0.006536 to 0.009452 for K, M, respectively. A statistically significant difference at $\alpha = 0.05$ for average sphericity values for 100 samples was found for all coffee types. Due to important problems in available measurement and calculation methods to determine exact volume and surface area for granular materials, Equation 1 can be used easily for solid mechanics and handling operations to determine the sphericity of coffee beans.

Table 2: Mean and s.d. values of calculated sphericity. Superscript letter indicates a statistically significant difference at $\alpha = 0.05$ for average sphericity values for 100 samples.

Coffee brand	mean ϕ_s
B	$0.007510^{a} \pm 0.000842$
C	$0.007222^{a} \pm 0.001386$
CR	$0.007313^{a} \pm 0.000993$
E	$0.007182^{a} \pm 0.001413$
G	$0.006718^{a} \pm 0.000894$
H	$0.007166^{a} \pm 0.001244$
I	$0.008073^{a} \pm 0.001236$
K	$0.006536^{a} \pm 0.001087$
M	$0.009452^{a} \pm 0.001209$
P	$0.008424^{a} \pm 0.001340$
P-NG	$0.007081^{a} \pm 0.000751$
PE	$0.006782^{a} \pm 0.001001$
T	$0.007269^{a} \pm 0.001309$

Shape variability quantified by Fourier descriptors

Image analysis was used for comparative analyses of coffee bean shape variability. Principal components of elliptic Fourier descriptors were employed. The mean bean shape (for each lot) was drawn using the mean values of the standardized Fourier coefficients. The first four principal components provide a good summary of the data, accounting for almost 100 % of the total variance. The first component represents the length-to-width ratio, the second component represents the position of the centre of gravity, the third component represents curvature, and the fourth component substitutes the degree of roundness. An example (coffee B) of a complete set of principal contribution components is given in Table 3. The influence of the first and most important component (length-to-width ratio) ranges from 70.87 to 74.64 for E, I, respectively.

Table 3: Contributions of individual principal components – coffee B.

Component	**Proportion (%)**	**Cumulative (%)**	**Indicator**
1	71.23	71.23	shape index
2	21.05	92.28	position of the center of gravity
3	1.31	93.59	curvature
4	0.91	94.50	degree of roundness

Since mean values of single components of individual coffee types are known or can be determined by the above-described method, unusual detected values can show the defective state of a coffee bean and can serve as a tool for the definition of specific irregularities. This study demonstrates the potential of modern techniques using shape-based methods on digital images to achieve high efficiency performance in fruit/beans/seeds grading and classification.

Curvature Radius

The function described by Equation 3 has been used for evaluation of the grain shape, as described in the previous section. A selected "average-like" coffee bean from each coffee type was used for sample calculation.
It was found that the correlation coefficient between measured and computed grain profiles ranges from 0.9680 to 0.9987 for M and T coffee, respectively. The knowledge of the equation describing the grain contour is necessary namely for the numerical simulation of grain behaviour under different mechanical loading, for numerical simulation of different heat treatment, and also for the determination of radius of curvature R. The values of the curvature radius calculated by use of Equation 4 can be plotted (and listed) for any coffee grain as can be seen in the sample picture - Figure 2, where half of the grain C is shown.

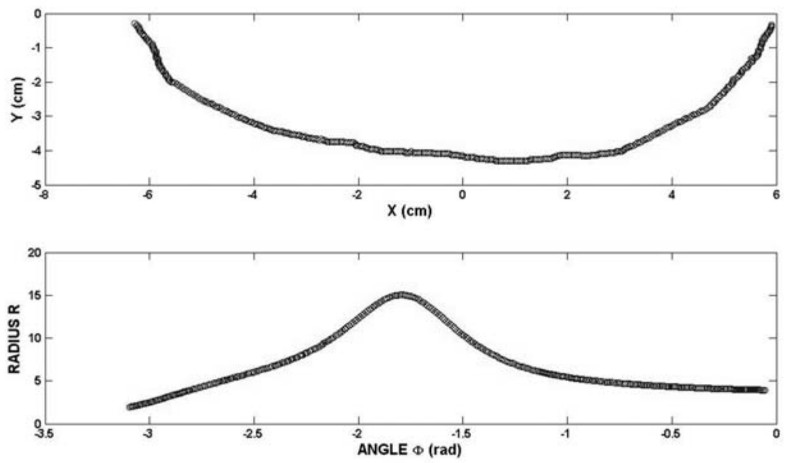

Figure 2
Example of curvature radius behaviour - C coffee grain (half-display).

CONCLUSIONS

The research revealed that all main dimensions, particularly length (D7), width (D1), and depth (D4) have changed for individual coffee types. The least variable bean parameter was bean depth (D4) with a coefficient of variation 0.05, followed by bean width (D1) with a coefficient of variation of 0.18, and bean length (D7) with a coefficient of variation of 0.85. The experiments partially confirmed partially improved previous findings concerning the relationship between length (D7), width (D1), and depth (D4) of Arabica beans. The only significant difference was revealed for the length/depth (D7/D4) ratio – presented values are higher than those in previous works. The coefficient of correlation for the length/width ratios ranged between 0.301 (C) and 0.787 (CR), for length/depth ratios between 0.376 (P) and 0.924 (P-24), and for width/depth ratios between 0.461 (H) and 0.813 (P-NG).
Another value which was monitored was sphericity. It was calculated according to procedure described by Bayram (2005) and ranged from 0.006536 to 0.009452 for K, M, respectively. The possibility of simple quantification of this parameter provides a large advantage for the design and evaluation of solid mechanics and handling operations. The highest value of sphericity was calculated for the same coffee type, where the highest values of D1 and D7 dimensions, and volume were found.
Quantification of coffee shape variability was performed by means of elliptic Fourier descriptors. Reconstructed shapes indicated that the first principal component (which represents the length-to-width ratio) is a very good measure of the total shape variation. It represents 70.87 to 74.64 % (for E and I coffee, respectively) of the total shape variation in case of the front view.
Numerical simulation of the coffee grain behaviour under different mechanical loading, heat treatment, and determination of curvature radius R can be supported by proposed mathematical formulas describing grain contour with a satisfying correlation coefficient between experimental and computed data ranging from r^2 = 0.9680 to 0.9987.

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