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Variability of cones and scale surface area of European larch (*Larix decidua* Mill.)

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Abstract. The article describes the shape of the cones of the European larch (*Larix decidua* Mill.) using the fourth degree polynomial fitting function. The material is from the seed orchard of the Barycz Forest District. The curves were used to calculate the area and volume of single cones. It was not possible to generalize the formulas to calculate the surface and volume of larch cones using the described method, due to the large variability of the empirical coefficients of the equations. Finally, to calculate the area and volume of the cones, the formula to determine the solid figure of a cone was used. A constant α_s of 0.43 was introduced to the formula. Calculated volume values were compared to actual volumes measured with a water-filled burette. The mean surface area of the larch cones was calculated from the forming function and was 780 mm^2, and the volume was 2434 mm^3. The values calculated from the cone formulas after taking into account the α_s and constants (0.68 and 0.53) were 783 mm^2 and 2415 mm^3, respectively. The outer and inner surfaces of the seed scales located in the central part of the larch cones were photographed using a Quanta 200 scanning microscope. Specific features of the scales were measured using the Multi Scan Base program. We found that the outer and inner surfaces of the larch scales, as with pine and fir, differed. On the outer side, scales are formed by thick-walled cells with visible, protruding trichomes. Thin-walled cells with jagged cell walls are visible on the inside at the location of the wings and seeds. Long stem cells, resembling threads, were observed on the surface of the scales, which are absent on pine and fir seed scales.

Keywords: morphology, surface area, volume, microscopic structure

1. Introduction

The European larch begins to produce cones around the age of 30 years when growing in dense stands, and around the age of 15 years when growing in open space. It fruits every two years on average (Załęski, edited 1995). Mature larch cones are brown, reach a length of about 40 mm and a thickness of up to 20 mm. The cones are covered with broad scales narrowing towards the top, with the upper edge usually having an oval profile.

Cones are collected after the first frosts, when they reach their lowest humidity. Only the young cones of the year are collected, along with those left from the previous season. Harvesting the seeds is labour-intensive and energy-consuming due to the construction of the cones, which open gradually. In production conditions, the seeds are extracted using a thermal, thermo-mechanical method (Załęski 2002), less often mechanically (Tyszkiewicz 1949). When using the first method, warm air with a lowered humidity should be used, and then a procedure that moistens the cones with water is applied. As a result of alternating drying and wetting, the scales of the larch cones deflect, allowing the seeds to be obtained. In the case of the second method, the cones are mechanically crushed after drying (Drachal 1958), and then the seeds are separated by a sorter from the mixture of shredded scales and stems.

The process of commercially extracting seeds from larch cones is long and lasts over 50 hours (Aniszewska 2008). Despite the introduction of modern equipment and technological solutions, it has not changed significantly in years. After reviewing the available literature on the variability and morphological structure of the European larch cones, it was found that the descriptions and analyses are insufficient to determine the conditions for effective seed extraction. The extraction procedures for this species used in cabinets and extraction kilns are

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based on changing temperature and humidity parameters (Sarnowska, Więsik 1997), and do not take into account the variability of the construction of the cones themselves, which makes the extraction process time-consuming. It may be that we need to know the surface area and volume of closed cones and the detailed characteristics of the seed scale surface before the seed extraction process (as cones contain a significant amount of water), as during this process, the evaporation of water reduces the thickness of the cell walls, which results in the scales opening and releasing the seeds. Knowledge of these elements may allow the seed extraction technology to be modified.

The aim of this study was to learn about the characteristic features of the larch cone (length, thickness, surface area and volume) in its closed state and about the variability of the surface structure of its seed scales. The description of the parameters of cones and knowledge of the construction of its external scales can help in discovering the reason for the length of time it takes for larch cones to open, what the surface of the scale looks like before they are opened, and whether there are any visible features of the cone's external structure on its surface that change before and after the extraction process. The scope of research included: measuring the length and thickness of the cones, proposing a way to describe the shape of the cones, calculating the surface area and volume of closed cones using various mathematical models, the characteristics of the external and internal surface of cone scales in a fresh state, describing and measuring visible elements on the surface of European larch seed scales.

2. Methodology

2.1. Origin, characteristic parameters, shape, surface area and volume of the cones

Closed cones of the European larch from the seed plantation of the Barycz Forest District (RDLP Radom) were used for the research; these cones were collected in the winter of 2015 and subjected to the process of seed extraction in the Grotniki Forest District (RDLP *Łódź*).

The length (*h*), thickness (*d*) and mass (*m*) of 100 randomly chosen cones were measured using an electronic caliper with an accuracy of 0.1 mm to determine the external parameters of the closed cones, as well as a WPS-600 laboratory scale with an accuracy of 0.01 g to measure mass.

Additionally, the thickness of 32 cones was measured every 2 ± 0.1 mm. The area of the cones (Gawart, Mikłaszewicz 2000) was determined, serving as the basis to calculate their surface area (S_{obl}) and volume (V_{obl}) using formulas (1) and (2):

$$S_{obl} = 2 \cdot \pi \int_0^h y \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx \quad (1)$$

$$V_{obl} = \pi \int_0^h y^2 dx \quad (2)$$

For comparison, the surface area and volume of the studied cones was calculated using a second method, treating the cones as having a conical shape S_s (3) and V_s (5) and using well-known formulas, where *d* is the diameter of a cone at its thickest point, located at distance h_l from the base, and *l* is the line creating the conical shape leading from the apex through diameter *d* to its base, and *d1* is the diameter of the base of the conical shape (Figure 1).

$$S_s = \pi \cdot r_1 \cdot \sqrt{(r_1)^2 + h^2} \quad (3)$$

From the geometric relationships, it follows that

$$r_1 = h\frac{r}{h-h_1} = \frac{r}{1-\alpha_s} \quad (4)$$

where: r_l – is the radius of the base of the cone, *r* – the radius of the conical shape, α_s – equal to $h_1 \cdot h^{-1}$

$$V_s = \frac{1}{3}\pi \cdot (r_1)^2 \cdot h \quad (5)$$

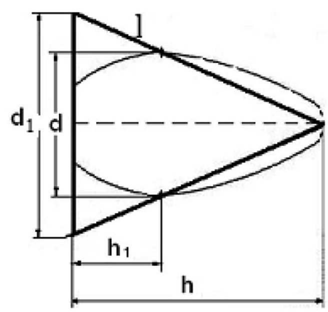


Figure 1. Geometric model mapping the shape of larch cones

In addition, the volume of the cone, V_r, was measured. A burette (beaker) filled with water was used for the measurements, assuming the volume of displaced liquid as the volume of a single cone. For cones with thickness of over 15 mm, a 25 cm^3 burette was used, with measurements having an accuracy of 0.5 cm^3. For the remaining cones, a burette with a capacity of 10 cm^3 was used, with a measuring accuracy of 0.1 cm^3.

In order to compare the calculated values from the models of surface area and volume, the indicators $k_1 = S_s/S_{obl}$, and $k_2 = V_{obl}/V_r$ or $k_3 = V_s/V_r$ were used.

A statistical description was made for the external parameters using the Statistica 10 program (StatSoft Inc. 2011). Agreement with the normal distribution was investigated using the W test (Shapiro-Wilk). The mean surface area and volume were compared using the F test. All analyses were performed at a significance level of α = 0.05.

2.2. Characteristics of the construction of the surface of seed scales from the outer and inner sides of the cone

The research was conducted at the Analytical Centre of the Warsaw University of Life Sciences, using a Quanta 200 scanning microscope, with which 40 photographs of scales taken from the middle part of the cone were made.

In order to prepare a specimen of the same size as the holder in the microscope chamber, the scales were cut into two parts. Each specimen fragment was enlarged 50 and 500 times and photographed on the outer side and inner side, on which the seeds are placed, precisely describing the location on the scale where the photograph was taken.

Visible elements of the structure of the scale on the scanning microscope photographs, such as hairs and other structures, were measured in the laboratory of the Department of Forest Mechanization, Department of Agricultural and Forestry Machines, using the Multi Scan Base program v. 18.03. Their parameters (length, diameter) were assessed with Statistica 10 (StatSoft Inc. 2011).

3. Results

3.1. Size of the cones

The length of 100 randomly selected cones ranged from 18.0 mm to 31.1 mm, on average 23.0 ± 0.56 mm (standard deviation δ = 2.83 mm), and the thickness from 10.9 mm to 21.7 mm, average 15.3 ± 0.38 mm (δ = 1.93 mm).

The mass of fresh closed cones was on average 1.50 ± 0.08g (δ = 0.43g) and ranged from 0.66 g to 2.55 g, and their humidity was on average 35%.

3.2. Determining the shape, surface area and volume of the closed cones

Table 1 shows the values of the length and thickness of 32 European larch cones chosen to establish the shape. The length of these cones was on average 23.6 ± 0.97 mm (δ = 2.8 mm), and the thickness – on average 155.2 ± 0.76 mm (δ = 2.2 mm).

Table 1. Characteristic parameters of larch cones

No. of cone	Length [mm]		α_s	Thickness [mm]
	h	h_1	h_1/h	d
1	23.4	10.0	0.43	14.7
2	18.0	9.0	0.50	11.0
3	21.1	10.0	0.48	16.5
4	21.8	8.0	0.37	18.9
5	24.4	9.0	0.37	21.7
6	26.0	10.0	0.38	13.7
7	19.6	6.0	0.31	14.2
8	18.0	8.0	0.44	12.4
9	30.1	12.0	0.40	16.0
10	25.4	10.0	0.39	16.3
11	24.4	10.0	0.41	14.6
12	27.3	12.0	0.44	15.2
13	22.3	10.0	0.45	14.2
14	23.0	10.0	0.44	15.8
15	26.1	12.0	0.46	16.0
16	23.0	10.0	0.43	16.0
17	25.2	12.0	0.48	15.7
18	27.3	11.0	0.40	15.7
19	26.6	11.0	0.41	15.0
20	23.1	10.0	0.43	14.3
21	23.4	10.0	0.43	13.7
22	27.6	10.0	0.36	19.4
23	22.5	10.0	0.44	15.4
24	23.7	11.0	0.47	14.7
25	23.3	11.0	0.47	16.6
26	20.3	10.0	0.49	11.8
27	20.3	10.0	0.49	14.1
28	24.4	9.0	0.37	15.7
29	21.7	8.0	0.37	12.4
30	22.1	10.0	0.45	15.5
31	27.5	11.0	0.40	13.5
32	23.5	11.0	0.47	17.2
Mean	23.6	10.0	0.43	15.2
Standard deviation	2.8	1.3	0.05	2.2
Minimum	18.0	6.0	0.31	11.0
Maximum	30.1	12.0	0.50	21.7
Coefficient of variation	12.0	13.0	10.7	14.1

h_1, h – as in Figure 1

The analysis shows that increasing the length of a cone by 1 mm increases its thickness by 0.31 mm. This relationship is described by a linear function (6).

$$d = 0.308h + 7.960 \quad R^2 = 0.165 \tag{6}$$

After many attempts, a fourth-degree polynomial was chosen that well reflects the shape of the cones (Aniszewska, Błuszkowska 2016). The obtained coefficients of determination R^2 ranged from 0.974 to 0.999, on average 0.990 ± 0.02 (δ = 0.007). The general equation for the shape of a cone is (7):

$$y = Ax^4 + Bx^3 + Cx^2 + Dx + E, \text{ gdzie } x \in (0, h) \tag{7}$$

The mean, standard deviation, minimum and maximum values of the coefficients from A to E are provided in Table 2, and an example of the course of changes in the curve forming the cone in Figure 2.

The designated equations forming the individual cones allowed us to calculate the surface area S_{obl} and the volume V_{obl} using formulas (1) and (2) (Table 3).

The S_{obl} surface area, calculated from formula (1) ranged from 428.1 mm^2 for a cone of 18.0 mm in length and 11.0 mm thick to 1109.7 mm^2 for a 30.1 mm long and 16.0 mm thick cone, whereas V_{obl} volume, obtained with formula (2), was from 942 mm^3 for a cone of 18.0 mm in length and 11.0 mm thick to 4835.6 mm^3 for a cone of 24.4 mm in length and 21.7 mm thick.

Volume V_r is higher by 4 mm^3 on average than volume V_{obl}, and the F test did not show any significant differences between them.

The high variability of coefficients A, B, C and E for individual cones means that despite the significant dependence of the length on the thickness of cones, it is not possible to apply the formula in practice to calculate the volume and surface area of any one larch cone when only its basic parameters are known (d and h). Therefore, formulas (3) and (5) were used to calculate the surface area S_s and volume V_s of the cones. These values differ significantly (based on the F test) from the surface area and volume calculated with formulas (1) and (2).

The values of α_s (Table 1) for individual cones were averaged and used in the calculation of the surface area S_s and volume V_s of the larch cones. The average α_s is 0.43 ± 0.02 (δ = 0.05), while h_1 is 10.0 ± 0.45 mm (δ = 1.3).

The values of S_s and V_s are provided in Table 3. However, the formulas used to calculate the values provided in Table 3, according to the cone model and including α_s, are shown in equations (8) and (9). The constants provided are the result of the conversion of recalculations of equations 3–5.

$$S_s = 2.754 \cdot d \cdot \sqrt{\frac{d^2}{1.3} + h^2} \tag{8}$$

$$V_s = 0.805 \cdot d^2 \cdot h \tag{9}$$

Table 2. Statistical values of coefficients *A÷E* form of the equation

Parameter	Values of coefficients				
	A	*B*	*C*	*D*	*E*
Mean	-0.000119	0.006092	-0.156985	1.818285	0.043564
Standard deviation	0.0001456	0.005622	0.077277	0.406385	0.168299
Minimum	-0.000688	-0.004068	-0.357911	1.008622	-0.185385
Maximum	0.000098	0.024995	-0.001631	2.457081	0.500455

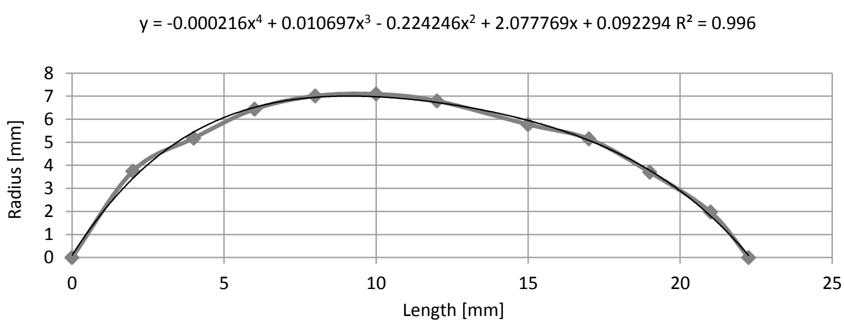


Figure 2. Cone outline data visualization

Table 3. Volume and surface for the tested larch cones

No. of cone	Volume [mm^3]				Surface area [mm^2]		
	V_{obl}	V_r	V_s	V_{sf}	S_{obl}	S_s	S_{sf}
1	2729.8	3000.0	4072.5	2158.4	832.8	1081.8	735.6
2	942.8	1000.0	1717.7	910.4	428.1	610.8	415.3
3	2675.8	2500.0	4635.7	2456.9	788.5	1164.5	791.9
4	3404.8	3500.0	6274.2	3325.3	907.0	1426.5	970.0
5	4835.6	5000.0	9210.4	4881.5	1106.7	1843.9	1253.9
6	2087.0	2000.0	3901.2	2067.7	755.7	1076.4	731.9
7	1888.2	2000.0	3177.4	1684.0	633.8	907.5	617.1
8	1363.2	1500.0	2243.8	1189.2	524.6	721.6	490.7
9	3681.1	3500.0	6232.5	3303.2	1109.7	1467.8	998.1
10	3155.8	3000.0	5410.2	2867.4	988.0	1305.2	887.5
11	2465.5	2500.0	4185.2	2218.1	815.3	1107.6	753.2
12	2743.7	2500.0	5070.0	2687.1	892.4	1270.3	863.8
13	2056.1	2000.0	3601.5	1908.8	709.0	995.4	676.9
14	2371.9	2000.0	4600.5	2438.3	771.7	1164.9	792.1
15	3044.2	3000.0	5392.7	2858.1	924.9	1307.6	889.2
16	2308.1	2000.0	4757.9	2521.7	741.0	1190.2	809.4
17	2733.3	3000.0	4975.3	2636.9	874.3	1237.6	841.6
18	2802.9	3000.0	5416.0	2870.5	901.0	1322.2	899.1
19	2452.3	2500.0	4828.1	2558.9	838.4	1227.0	834.3
20	1713.8	1500.0	3779.3	2003.0	635.0	1031.4	701.4
21	1693.4	1500.0	3535.5	1873.8	641.3	992.5	674.9
22	4118.3	4000.0	8358.5	4430.0	1099.6	1731.6	1177.5
23	2156.9	2000.0	4310.6	2284.6	716.2	1115.6	758.6
24	2013.4	2000.0	4097.2	2171.5	701.8	1087.7	739.7
25	2572.6	2500.0	5160.1	2734.9	798.0	1254.7	853.2
26	1258.8	1000.0	2286.3	1211.8	527.3	742.3	504.8
27	1628.8	2000.0	3244.1	1719.3	591.9	922.0	627.0
28	2604.4	3000.0	4820.9	2555.1	825.9	1208.3	821.7
29	1263.0	1500.0	2660.7	1410.1	529.1	824.0	560.3
30	2290.1	2500.0	4273.9	2265.2	740.7	1107.4	753.0
31	2241.7	2000.0	4016.6	2128.8	821.9	1110.3	755.0
32	2582.1	3000.0	5578.8	2956.8	802.9	1320.0	897.6

No. of cone	Volume [mm^3]				Surface area [mm^2]		
	V_{obl}	V_r	V_s	V_{sf}	S_{obl}	S_s	S_{sf}
Mean	2433.7	2437.5	4557.0	2415.2	780.4	1152.4	783.6
Standard deviation	828.2	859.0	1564.4	829.1	168.3	259.6	176.6
Minimum	942.8	1000.0	1717.7	910.4	428.1	610.8	415.3
Maximum	4835.6	5000.0	9210.4	4881.5	1109.7	1843.9	1253.9
Coefficient of variation	34.0	35.2	34.3	34.3	21.6	22.5	22.5

S_{obl}, V_{obl} – Surface area and volume of cones according to formula (1, 2)
S_s, V_s – Surface area and volume of cones according to cone model (3, 5)
S_{sf}, V_{sf} – Surface area and volume of cones calculated according to the formula for the inclusion of a fixed on a cone (10, 11)
V_r – volume of cones measured with buret

The surface area of a cone (S_s) is from 610.8 mm^2 to 1834.9 mm^2, on average 1152.4 ± 89.90 mm^2 (δ = 259.6 mm^2), and the volume (V_s) is from 1717.7 mm^3 to 9210.4 mm^3, on average 4557.0 ± 541.7 mm^3 (δ = 1564.4 mm^3) (Table 3).

The volume values calculated from the cone model were equated to V_r. The mean value of the k_2 index determining the ratio of the V_{obl} calculated volume to the V_r measurement was 1.01 ± 0.04 (δ = 0.11). The high agreement of the V_{obl} calculated volume according to the function of the fourth-degree polynomial with the value of the V_r measurement of the cone allows us to state that the S_{obl} surface area calculated with this method is a good approximation of the actual values.

The value of the k_1 index, which is the ratio of the surface area calculated with the S_s cone model to the S_{obl} surface area, according to the function of the fourth-degree polynomial, ranges from 1.30 to 1.67, on average 1.48 ± 0.03 (δ = 0.10).

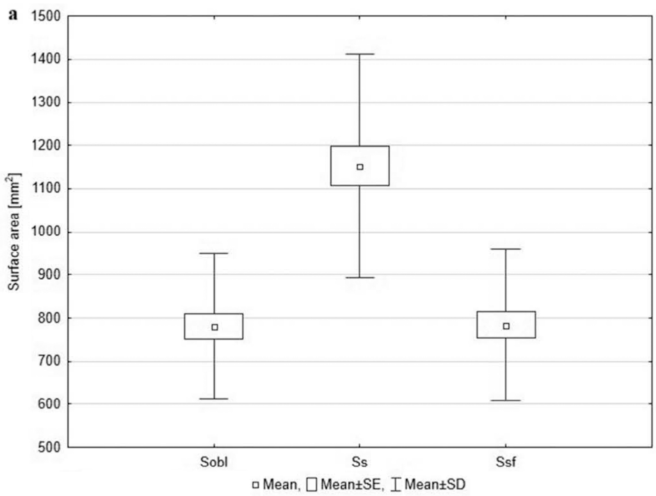
The value of the k_3 index, which is the ratio of the V_s volume calculated with the cone model to the V_r volume, ranges from 1.36 to 2.52, on average 1.9 ± 0.03 (δ = 0.10).

In order to apply the cone model to calculate the surface area (S_{sf}) and volume (V_{sf}), the obtained values should be multiplied by the constants 0.68 and 0.53 resulting from the conversion of k_1 and k_3.

$$S_{sf} = S_s \cdot 0.68 \quad (10)$$

$$V_{sf} = V_s \cdot 0.53 \quad (11)$$

The calculated values for the S_{sf} surface area and V_{sf} volume are on average 773.6 ± 61.2 mm^2 (δ = 176.6 mm^2) and 2415.2 ± 287.1 mm^3 (δ = 829.1 mm^3) (Table 3). A graphic comparison of the surface and volume fields calculated with the different methods is shown in Figure 3.



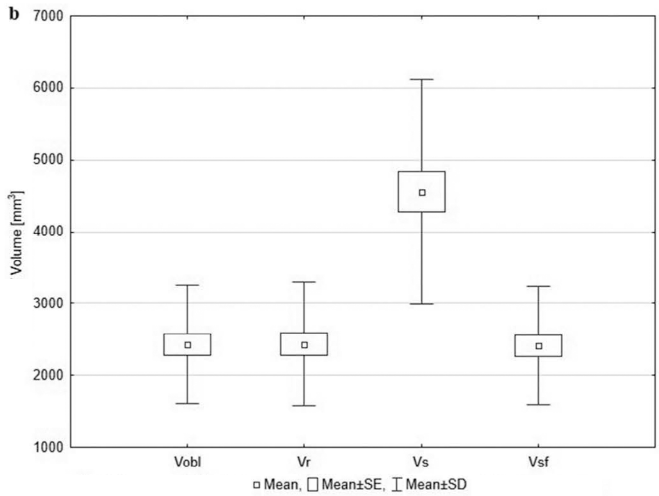


Figure 3. Comparison of mean values, standard errors and standard deviations for the test computational models: *a* – surface area, *b* – volume: S_{obl}, V_{obl} – calculated from the formula 1 and 2, S_s, V_s – calculated according to the formula on a cone (8, 9), S_{sf}, V_{sf} – calculated according to the formula for the inclusion of a fixed on a cone (10, 11), V_r – with water

The multiple comparisons test allowed us to distinguish homogeneous groups. Three homogeneous groups were determined for volume: V_{obl} and V_{sf} (p = 0.9447), V_{obl} and V_r (p = 0.9887) and V_r and V_{sf} (p = 0.9381). For the surface area, one homogeneous group was distinguished, made up of S_{obl} and S_{sf} (p = 0.9509).

3.3. Characteristics of the construction of the inner and outer surface of seed scales

Figure 4a shows the apical and middle part of the inner side of a European larch scale at ×50 magnification, and Figure 4b shows the fragment of this scale enlarged 500 times.

Figure 4a shows two areas differing in structure. The first, occupying over 80% of the surface of the scales, is where the wings rest on the scale. The surface is characterised by an uneven structure and consists of ragged cells with thin cell walls. Such a structure of this part of the scale is probably the result of the wings separating from the scale as the cone is opening. Figure 5a shows the second area of the surface of the scale between the locations of the wings.

The wing does not rest against the location shown in Figure 5b, and the surface of the scale is smooth. In this part, you can notice small protruding trichomes, called 'hairs' on the surface of the scales of silver fir by Kaniewski and Kucewicz (1978). The length of the trichomes visible in this part of the scales ranges from 23.42 μm to 51.77 μm and is on average 37.42 ± 2.86 μm (δ = 10.30 μm), while the diameter ranges from 19.27 μm to 34.03 μm with an average of 25.82 ± 1.16 μm (δ = 4.18 μm).

Figure 6 shows the basal part of the inner side of the larch scale where the seed is located. In this part, you can also distinguish two areas that differ in structure.

The first photo shows the area where the seed is placed. Thin-walled cells with irregular shapes are visible on the scale. The second is the area outside of where the seed is placed. Cells visible in this part are thick-walled, regular and close-fitting. Figure 7b shows a clear, bright line, which is the boundary of the seed's position on the seed scale.

After describing the inner side of the scale, the outer sides of the same scales were characterised. Figures 8 and 9 show

a **b**

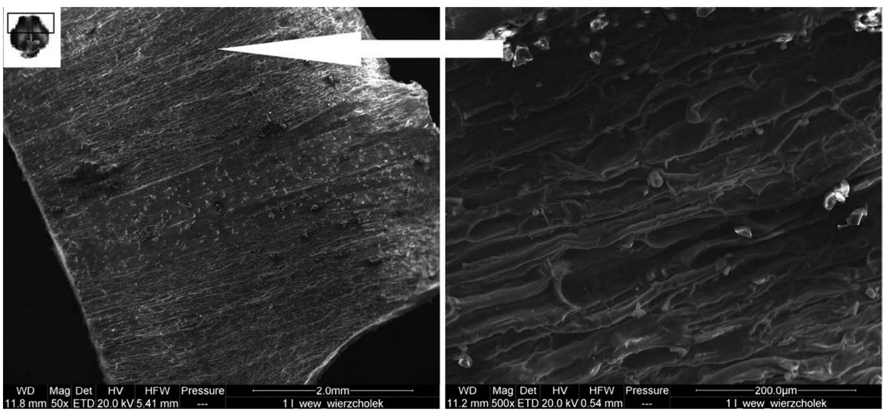


Figure 4. The upper part of the scales from the inside of the (a) ×50 and (b) ×500 (Stadnik, Śliwińska 2015)

a **b**

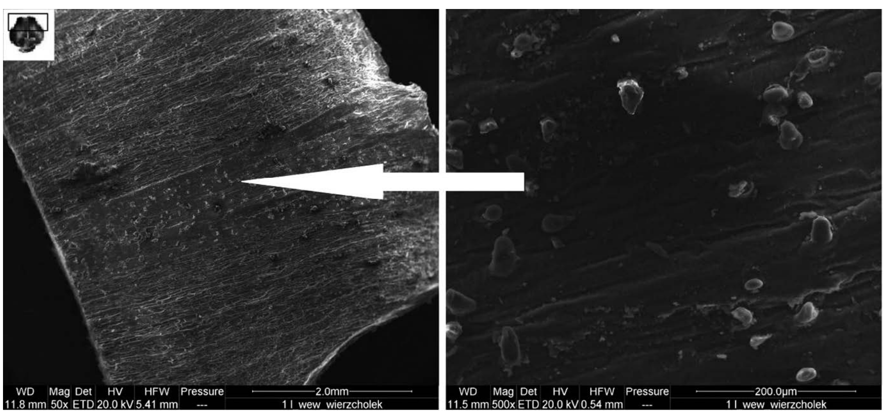


Figure 5. The upper part of the scales from the inside of the (a) ×50 and (b) ×500 (Stadnik, Śliwińska 2015)

a b

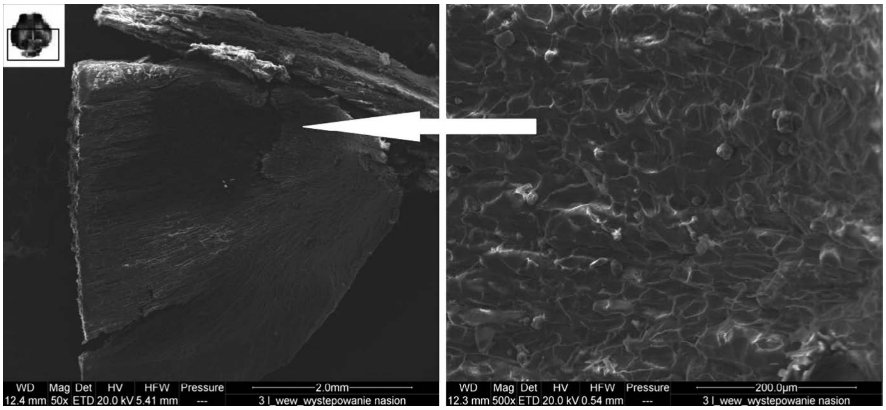


Figure 6. The basal part of the scales from the inside of the (a) ×50 and (b) ×500 – the site of the seed (Stadnik, Śliwińska 2015)

a b

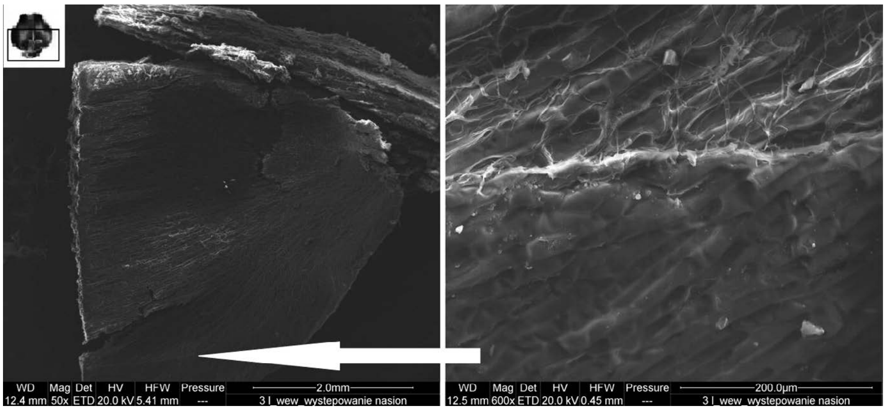


Figure 7. The basal part of the scales from the inside of the (a) ×50 and (b) ×500 – off-site seed (Stadnik, Śliwińska 2015)

a b

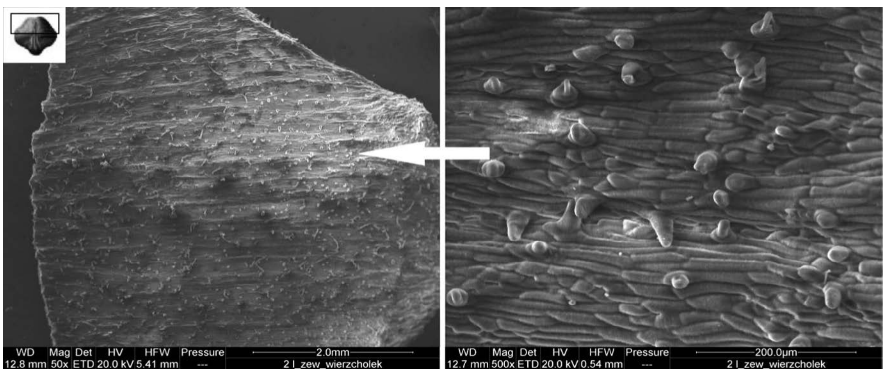


Figure 8. The upper part of the scales from the outside of the (a) ×50 and (b) ×500 (Stadnik, Śliwińska 2015)

the apex and middle part of the scale with the magnification of selected locations.

The surface of the apical portion on the outer side has regular and thick-walled cells that are tightly arranged, side by side. There are also noticeable single, short trichomes (hairs) in between the sites where the wings are found (Fig. 5) − similar to the inner part. Their average length on this part of the scale is 36.22 ± 2.21 µm (δ = 7.96 µm) with a range from 27.49 µm to 49.86 µm, while the diameter is 25.00 ± 1.07 µm (δ = 3.87 µm) with a range from 16.14 µm to 28.4 µm.

The surface of the central part of the scale differs slightly from the surface at the apex. It is characterized by a lower number of trichomes per 1 mm^2, most of which are longer by an average of 6 ± 1.07 µm (δ = 3.85 µm) compared to the a b

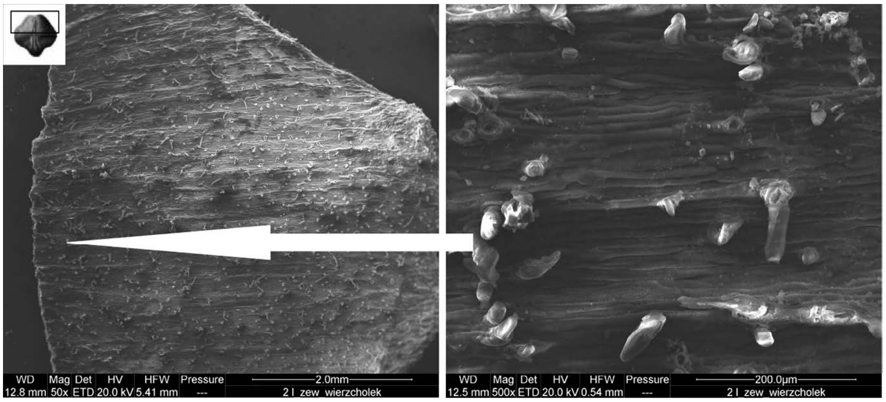


Figure 9. The central part of the scales from the outside of the (a) ×50 and (b) ×500 (Stadnik, Śliwińska 2015)

a b

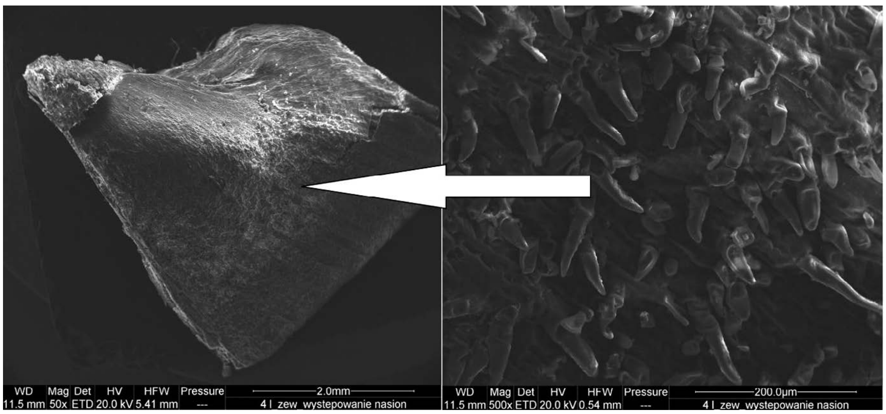


Figure 10. The basal part of the scales from the outside of the (a) ×50 and (b) ×500 – above the position of the seed (Stadnik, Śliwińska 2015)

a b

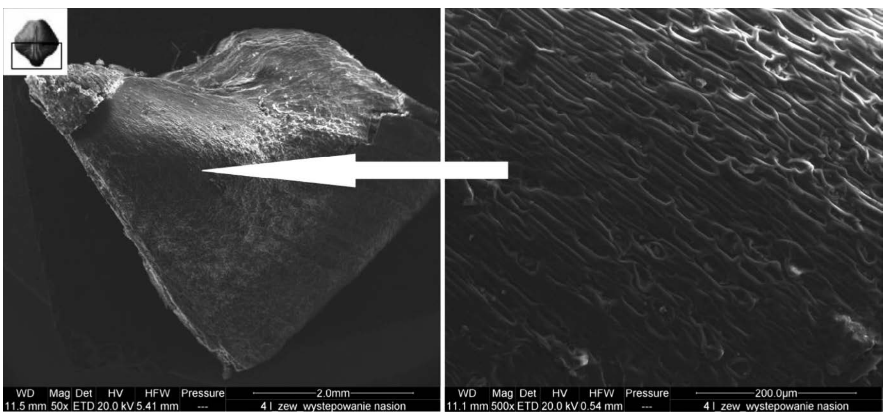


Figure 11. The basal part of the scales from the outside of the (a) ×50 and (b) ×500 – the site of the seed (Stadnik, Śliwińska 2015)

protrusions of the apical part. The cells building this part of the scale are arranged parallel to each other.

Figures 10 and 11 depict the lower part of the scales from the outer side. Figure 10 shows the site above the placement of the seed. The surface structure is strongly ruptured with noticeable bands of cells, and on the visible fragment (Fig. 10b), there are numerous trichomes through which moisture most likely passes when the scales open. The length of the trichomes on this part of the scale ranges from 47.15 µm to 126.61 µm and is on average 78.31 ± 6.86 µm (δ = 24.74 µm), while the diameter in the central area of the trichomes is on average 22.91 ± 1.13 µm (δ = 4.09 µm) and ranges from 15.95 µm to 32.05 µm.

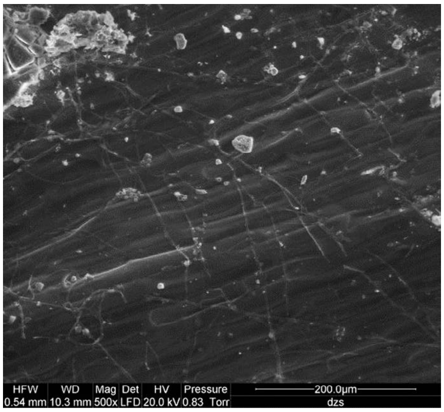


Figure 12. The threads one of the scales from the outside of the ×500

Figure 11 shows the area at the level where the seed is found. This surface is characterized by many thick-walled cells, connected to each other and resembling long chains.

When analysing the F and Duncan tests on the size of the hairs visible on the outer surface of the scale's apical, middle and lower parts, they reveal that the length of the hairs in the distinguished zones differs significantly from each other, whereas the tests did not show any significant differences for the diameter of the hairs. In turn, the hairs visible on the inner side of the scale in terms of length ($p = 0.88$) and diameter ($p = 0.62$) do not differ significantly from those visible on the outer side in the apical part of the scale, but does differ significantly from the hairs visible in its middle and lower parts.

Long strands resembling threads are visible on the outer surface of the seed scale (Figure 12). The average length of 30 measured cells with a diameter in the range of 3.04 ± 0.21 µm (δ = 0.75 µm) is 396 ± 36.00 µm (δ = 129.87 µm).

4. Discussion

The subject of the variability of the cones and seeds of certain conifer species occurring in Poland has been discussed by a number of authors. The variations of pine cones and seeds were addressed by Zajączkowski (1949), Staszkiewicz (1968), Białoboket al. (1993), and Aniszewska (2012); Norway spruce: Chmielewski (1968), Barzdajn (1996), Kulej and Skrzyszewska (1996), Tomanek (1997), Aniszewska (2001), Buraczyk (2009); and silver fir: Tracz and Barzdajn (2007), Barzdajn (2009) and Aniszewska and Błuszkowska (2016). The issues of variability, bulk density and transport properties of pine, spruce and larch cones were discussed by Aniszewska and Gendka (2016a, 2016b). There are few studies on the variability of the European larch cones, among them, one can cite the work of Bałuta (1969), Šindelář (1972) or Vîlcana et al. (2011). Vîlcana et al. (2011) compare the size of the cones and seeds of seven origins. The mass, length and thickness of European larch cones described in that study are greater than the parameters we measured here. For example, the average mass of larch cones originating from Sinaia, Romania was 4.93 g, length – 3.69 cm, and thickness – 2.09 cm. Comparing the Barycz Forest District cones of this article to those surveyed by Vîlcana et al. (2011), we can say that the former are small.

In the available literature, one can find more publications on the parameters of the larch seeds themselves, their size, weight and quality. They were examined, among others, by Tylek (2004), Skrzypczyńska and Kozioł (2001) and Kaliniewicz et al. (2012).

Optimizing extraction technologies aimed at reducing energy expenditures requires learning about the factors affecting this process. These include the thermal and humidity parameters of the process (temperature and humidity of the air supplied to the harvesting equipment and the intensity of the exchange), and the phenomena occurring in the cones − among others, changes in humidity and the opening of the scales leading to the seeds being released. In searching for these factors, mathematical models describing changes in the state of the cones during the extraction process may be helpful. The presented study mathematically describes the shape of the European larch cones depending on the dimensions of length and thickness. The designated equation for individual cones allowed us to calculate the volume and area of the cone. Using this methodology, Gawart (2000), Aniszewska (2001) and Aniszewska and Błuszkowska (2016) described the shape and calculated the volume and surface area of the cones of other species: Scots pine, Norway spruce and silver fir. The geometric structure of the cones of all three species is described exactly by the fourth-degree polynomial, whose coefficients are mostly dependent on the basic parameters of the cones. However, it is impossible to generalize these coefficients for the entire set of cones of the studied species. Therefore, we proposed that the surface area and volume of the cones be calculated using the conical (pine, spruce, larch) and cylindrical (fir) shapes. Constants were introduced into the formulas for the surface area and volume of the conical or cylindrical shapes, thanks to which the obtained results did not differ significantly from the actual values. For example, when calculating the volume of larch cones, the constant of 0.53 was introduced into the formula, and for the surface area calculation – the constant of 0.68. In the case of fir cones, the formulas for the volume and surface area of the cylinder had constants of 0.71 and 0 81, respectively.

The article also describes the construction of the surface of the seed scales. The method used was previously applied to Scots pine (Aniszewska 2012) and silver fir scales (Aniszewska et al. 2017), as well as to larch wings and seeds (Aniszewska 2014). It was noted that the surface of the scales on the outer and inner – where the seeds are located – sides differs significantly. The outer side of the scale is usually built of similarly sized thick-walled cells along the entire length. The upper part of pine and fir scales have an apophysis, which is missing in the larch. On the inner side, two parts of the scales can be distinguished: the first where the wing rests, and the second one, outside of this area. The first section is made of ragged cells, most likely formed as the result of the wings and seeds tearing away from this part of the scale. In other species, the inner surface can be distinguished by: cells arranged in a row of chains (Scots pine), small hairs and cells with thick walls (silver fir and European larch). The second part, like the outer surface of the scales, is characterized by regularly arranged cells. In addition, cells resembling long threads on the whole surface were noticed on the scales of the European larch. This element of construction is characteristic of larch scales, because it is not found on the surface of the cone scales of any other species studied.

The size parameters of the cones and their dependencies, as well as the description of the structure of the seed scales presented in the article gave no final answer to the question posed about the reasons why it takes a long time for the larch cones to open. It may be that we still need to learn about and make a detailed description of the cell structure and chemical composition of this species' cones.

5. Conclusions

The shape of larch cones is quite accurately described by a curve, which is a fourth-degree polynomial. The high variability of the empirical coefficients of the equation obtained for individual cones makes it impossible to generalize them to any one cone or use them to calculate their volume and surface area.

The general calculation model describing the surface area and volume of European larch cones can be the cone model that includes a constant of $\alpha_s = 0.43$. Additionally, the volume values should be multiplied by a constant of 0.53, and the surface area by a constant of 0.68. Analysis of the results showed that after introducing these constants, the surface area and volume of cones varied by 3.5% and 5.0%, respectively, from the actual values.

The microscope examination of the surface of the larch scales did not answer the question concerning the reasons for the long time required to extract the seeds. Further work in this area is needed.

Conflict of interest

The authors declare that there are no potential conflicts of interest.

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Authors' contributions

M.A. – concept, literature review, methodology, measurements, analysis of results, statistical analysis, conclusions, writing; S.S. – measurements, analysis of results; A.G. – analysis of results, correction.

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