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The extraction process and seed quality of silver fir cones *Abies alba* Mill.

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Abstract. Fir cones *Abies alba* Mill. are not as extensively described in the literature as cones of other species, and therefore, there is no description of the changes in water content and their dynamics during the extraction process. Developing a mathematical model describing these changes based on cone parameters and air temperature is a step forward in determining the optimal conditions for the extraction process. Here, we present such a model derived using fresh cones collected in a seed production stand in the Zwoleń Forest District (RDSF Radom). For 120 randomly chosen cones, the length and the largest diameter of the cone were measured, using the Multiscan program. In addition, for 60 randomly selected cones, the diameter was measured along the entire length of the cone at 10 mm intervals. This allowed us to generate cone models approximating rotational solids for which the outer surface area was calculated using a fourth degree polynomial function and the obtained area was then used to determine cone volume. To facilitate the generalization of surface area and volume calculations to other cones, the ks_1 and ks_2 coefficients were derived, which simplified the employed formulas without significantly affecting accuracy.

Analogous analyses were also performed for cone stems, which allowed the process of seed extraction from cones to be described by mathematical equations. The stem of the cone was found to constitute 2.6% of its volume and 4% of its dry mass. An exponential equation was used to describe the change in cone mass during the seed extraction process, in which the parameters are the initial and final water content of the cone and power factor *b*, which is a function of cone thickness. The energy content and germination rate for the extracted seeds were determined 14 and 28 days after sowing. The seeds obtained in the investigated extraction process did not reach first grade quality.

Keywords: water content, desiccation rate, cones, stem, seeds

List of symbols:

As(t),Bs(t), Cs(t), Ds(t), Es(t) – coefficients of the polynomial shape of cone (s), stem (t) *b* – cone characteristic in dicator , h^{-1}
dL– curve of shaped differential
ds.– cone thickness, cm
d_t – stem thickness, cm
exp – e(2.718) basis of natural logarithm h_s – cone length, cm
h_t – stem length, cm
$ks_1=Vs_{obl}/Vs_w$ – cone in dicator 1 (s)
$ks_2=Ss_{obl}/Ss_w$ – cone in dicator 2 (s)
$kt_1=Vt_{obl}/Vt_w$ – stem in dicator 1 (t)
$kt_2=St_{obl}/St_w$ – stem in dicator 2 (t)
l – number of scales, pcs.
m_{H_2O} – mass of water, g
m_s – mass of dry substance, g
m_{Ss} – mass of dry cone, g
N – number of seeds, pcs.
R – coefficient of determination
Ss_{obl} – area of surface calculated from the polynomial shape of a cone, cm^2
St_{obl} – area of surface calculated from the polynomial shape of a stem,cm^2
u_i – water content in cones
u_k – final water content in cones, $kg_{H_2O} \cdot kg_{s.m.}^{-1}$
u_o – initial water content in cones, $kg_{H_2O} \cdot kg_{s.m.}^{-1}$
Vs_{obl} – volume calculated from the polynomial of the cone shape, cm^3
Vt_{obl} – volume calculated from the polynomial of the stem shape, cm^3
ρ_s – cone density, $g \cdot cm^{-3}$
ρ_t – stem density, $g \cdot cm^{-3}$
τ – time, h

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Introduction

The silver fir *Abies alba* Mill. is a species growing in the southern and central part of Poland, where it reaches the northern limit of its range. It is found in the Carpathians at an altitude of 500 to 1100 m above sea level, in the Świętokrzyskie Mountains, in the Sudetes Mountains, in Roztocze and other areas of the country, as published by: Boratyński (1983), Bednarek (2002), Sugiero (2005), Barzdajn (2009), Szeligowski et al. (2011), Bis, Dobrowolska (2012). A fir tree growing in dense stands begins to produce abundant seed crops at about seventy years of age, and when it grows in open space –at about thirty years of age (Załęski 1995). This species has abundant seed crops, on an average every 3 or 4 years. According to Tyszkiewicz (1949), fir cones have a length of 10 to 17 cm, a thickness of 3 to 5 cm, while seeds with wings are acquired from cones of 10 to 25 mm. According to Gudeski (1966), fir seeds without their wings have a length of 7.5 to 12.5 mm. Cones from Slovakia examined by Kočiová (1974) had a length from 7.6 to 19.9 cm, and a thickness from 3.0 to 5.2 cm, whereas Nanu (1977) reports that there are cones in Romania of 7.0 to 19.5 cm in length and from 2.9 to 4.6 cm thick. In turn, Boratyński (1983) measured the length and thickness of fir cones, which were respectively from 10 to 15 cm and from 3 to 5 cm. Similar results regarding the thickness of cones were obtained by Suszka (1983), with the length of cones reaching 18 cm.

Gunia, Simak (1968), Czernik (1993), Ballian and Čabaravdić (2005), Tracz, Barzdajn (2007), Politiet al.(2011), andIlloul-Hachi et al. (2015) also wrote about the basic size parameters of cones, scales, wings and seeds from different regions and their interrelationships.

The influence of the environment on fir populations and hybrids was analyzed by Kobliha et al. (2014), and the healthiness of seeds by Boncaldo et al. (2010).

A. alba cones grow vertically on the branch, and after ripening, they disintegrate into scales and seeds that fall to the ground, with the stem remaining on the tree.

Collecting cones from standing trees is done manually before they are fully ripened. Extracting fir seeds from cones does not require the use of specialized extraction equipment or higher temperatures than in the case of Norway spruce *Picea abies* (L.) Karst., Scots pine *Pinus sylvestris* L. or European larch *Larix decidua* Mill. According to the "Instructions for the Collection and Storage of Genetic Resources" (LBGK2007), after collecting the fir cones, they are placed in boxes with a perforated bottom in a ventilated hall at a temperature of 20°C. During storage, the cones are raked, and as they desiccate, they partially disintegrate into scales, seeds and stems. The material is then crushed and separated in a fir seed drum sifter. This process can be mechanized. Since the 1990s, a "Tiber" device with a high degree of mechanization is used to crush cones (separate the seeds from the scales and stems), de-wing and separate the fir seeds in the Italian state forests in Dagona di Peri near Verona and in the seed extraction facility in Laufen in the Teisendorf forest district in south-eastern Bavaria (Suszka 2000). Currently in Poland, no extraction process is performed (lowering the water content of the fir cones) under controlled temperature and humidity conditions, so the process of drying each batch is not repeatable. Extracting the seeds from fir cones could be done using the cabinets or drying chambers located in almost every extraction facility. In order to obtain good quality fir seeds, one needs to know the construction of the cones (Aniszewska et al. 2017) as well as the parameters of the extraction process.

The aim of most studies on Scots pine, European spruce or European larch was to look for the methods of convection drying of cones that would be of the shortest possible duration and maintain good viability of seeds. The literature on fir cone seed extraction, however, does not sufficiently describe the process and the factors controlling it. So far, the dynamics of changes in the water content of fir cones during the extraction process has not been described. Therefore, we do not know the factors determining the course of these changes, nor the water content of cones at the moment they open. One of the ways to find the optimal conditions for the extraction process could be to develop a mathematical model describing the change in cone water content over time depending on its parameters and the temperature of the drying air. Part of such a model is to develop a description of the variability of cones.

During the research, an attempt was made to determine the variability of cones based on a determination of their shape. This allowed us to develop a detailed model of the surface area and volume of closed fir cones, which was reported by Aniszewska and Błuszkowska (2016), and to describe the process of their desiccation in a laboratory dryer with forced air circulation. The development of the model allows the change in the water content of the cones to be predicted, depending on their size, initial water content, drying temperature, and above all, allows the time to be determined when the cones will open and the seeds will separate from the scales and the stem.

Knowledge of the described parameters and the characteristics of the changes occurring during the extraction process will optimize and standardize the conditions of the process, taking into account the properties of the tested material in commercial extraction facilities.

Materials and methods

The study used fresh silver fir cones collected in a commercial seed stand in the Ciepielów township from the Zwoleń Forest Inspectorate (Regional Directorate of State Forests in Radom), from the J60 region of provenance of basic forest material.

Photographs were taken of 120 randomly selected cones (of 3888 × 2126 in size at 300 dpi) and transferred to the Multiscan v. 18 program, which was used to measure length and thickness, that is, the largest diameter of the cone, as well as the diameter of 60 cones taken sequentially in increments of 10 mm, with an accuracy of 0.5 mm. Measuring points were marked manually after scaling the images and applying a 10 mm × 10 mm grid. No additional morphological transformations of the image were used, the automatic option was chosen. On the basis of the measurement of length and diameter, the area of the outer surface and the volume of each cone were calculated. The shape of closed cones has been approximated using solids of revolution. The equation of the generating function of outer surface was determined. The distance between the position of the cross-section and the base of the cone was assumed to be the zero point of the coordinate system (Aniszewska 2001). The coordinate positions of the cross-section and the radius determined for each cone were the basis for approximating the equation describing the generating function of outer surface.

For the studied batch, the general equation calculating the shape of a cone or stem is:

$$y=As(t)\,x^4+Bs(t)\,x^3+Cs(t)x^2+Ds(t)x+Es(t) \quad (1)$$

where:
$x \epsilon (0, h)$,
$As(t), Bs(t), Cs(t), Ds(t), Es(t)$– coefficients of the polynomial shape of the cone (s) or stem (t).

The shape function $y=f(x)$ is continuous and non-negative over the entire cone length (h_s), so the surface area (Ss_{obl}) can be calculated using the equation:

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

where:
a, b – boundaries,
dL – curve of shape differential.

Because the base areas of this solid are small, it was assumed that the lateral surface area of the shape is equal to the external surface area of the cone.

Cone volume (V_{Sobl}) is determined by the equation (3):

$$V_{Sobl} = \pi \int_0^h y^2 dx \quad (3)$$

After extracting the study material using the method described above, the surface area St_{obl} and the volume Vt_{obl} of cone stems were also calculated (Aniszewska, Błuszkowska 2016).

The outer surface and the volume of the cones were also calculated by a second method, using the commonly known models for lateral surface area and volume of a cylinder (Ss_w, Vs_w). In order to compare the calculated values of volume and surface area, indicators of convergence were introduced: $ks_1=Vs_{obl}/Vs_w$, $ks_2=Ss_{obl}/Ss_w$. To apply the model of a cylinder in calculating the volume of a given cone, treating cone volume and surface area calculated from the formed curve as actual volume (Aniszewska, Błuszkowska 2016), the obtained values should be multiplied by ks_1 and ks_2 indicators. Similarly, to apply the model of a cylinder to calculate the surface area *(*St_w*)* and volume (Vt_w*)* of a stem, the obtained values should be multiplied by kt_2 and kt_1 A indicators, respstatistical ectively.description made using the Statistica 10 program (StatSoft Inc. 2011) was used for the analysis of external parameters. The mean surface area and volume were compared using the t-test and F analysis of variance, while the equality of variance (Levene test) and convergence with the normal distribution were also tested. The Shapiro-Wilk test was used to test the normality of the distribution of dependent characteristics. All analyses as sumeda significance level of 0.05.

To measure the initial weight and dry mass of cones, a WPS 600 laboratory scale with an accuracy of up to 0.01 g was used. The dry mass of the material was determined after the end of the extraction process, by drying the cone (scales and stems) without seeds using the drying-weighing method applied for wood, at a temperature of 103°±2°C, until a constant mass is established (Kubiak, Laurow 1994). The study determined the number of scales (l) on the cone, their mass and number (N) and the mass of seeds, stems and the density of closed cones ρ_s (as the ratio of initial cone mass to its volume Vs_{obl}) and stems ρ_t (as the ratio of stem mass to Vt_{obl}).

60 randomly selected cones were dried in a Heraus UT 6120 laboratory dryer with forced air circulation, ensuring the maintenance of a constant temperature. Initially, the cones were dried for 5 hours at a temperature of 25°C and then at 35°C, with air humidity decreasing from 53% to 10%. During the drying process, individual cones were on the grates inside the dryer. The decrease in mass as well as the air temperature and humidity inside the dryer were recorded at intervals of initially every 60 min (±5min), and then, every 120 min, with a break at night of about 8 hours. Air temperature was measured within an accuracy of 0.01°C, and humidity – 0.01% using an FTH 100 (Qeo FENNEL) meter.

During the extraction process, cone mass m_i was measured at given intervals, which – after determining the dry weight of the material m_s–allowed us to determine their water content u_i at that point in time (also known as cone moisture content) as the ratio of water mass m_{H_2O} to dry cone mass m_{Ss}. To describe the changes in water content of the cones during their extraction process in the dryer, an exponential equation was assumed, describing, in accordance with the first hypothesis, the second period of drying the solid matter:

$$u = (u_o - u_k) \cdot exp(-b \cdot \tau) + u_k \qquad (4)$$

where:
u_o – initial amount of water,
u_k – final amount of water, $kg_{H_2O} \cdot kg_{s.m.}^{-1}$,
τ – time, h,
b – cone characteristic indicator, $1 \cdot h^{-1}$,
exp–basis for the natural logarithm (*e*=2.718).

The value of coefficient *b* (Aniszewska 2008, 2012) was determined for each cone based on the actual course of changes in water content using the following formula:

$$b = \frac{1}{n} \sum_{i=1}^{n} \frac{ln \frac{u_i - u_k}{u_o - u_k}}{\tau_i} \qquad (5)$$

where:
n–number of readings of cone mass $m_{i,}$
τ_I–time of extraction process.

Such an averaged coefficient *b* was assumed as the characteristic parameter of the mathematical model of the process of change in cone water content. The study investigated the dependence of this coefficient on the size parameters (length and thickness) of the cone.

Characteristic parameters of the mathematical model are also the initial water content of the cone u_o and its final water content u_k recorded during the extraction process. Their values are influenced by the assumed conditions of the implemented extraction process. The u_o value can change by subjecting the cone to pre-drying, while the u_k value depends on the drying conditions.

The drying rate (decrease of cone water content relative to time) was calculated as a derivative of the time the water content u_i was measured:

$$\frac{du}{d\tau} = -b \cdot (u_o - u_k) \cdot exp(-b \cdot \tau) \qquad (6)$$

The changes in cone water content recorded during the study were described by mathematical equations, and their adequacy was verified by statistical methods. Functional dependencies were the basis for analyzing the influence of the size parameters of a cone on the course of extraction process and the time it took the cones to open.

To check the assumed conditions for seed extraction, an assessment of their viability (germination rate and energy content) was performed according to the standards of BN-76/9211-02 and Załęski et al. (2006). Fir seeds were sown on tissue paper in a Jacobsen's germinator, repeated three times with 100 pieces each and kept at a variable temperature in the range of 20−30°C, after an earlier 21-day cooling period at 3−5°C. Observations of the energy content of germination were made after 14 days, and germination viability after 28 days from sowing.

3. Results

3.1. Characteristic parameters of the cones

The length (*h*) of the 120 fir cones studied was in the range of 12.40 to 19.70 cm, with an average of 15.96 cm (standard deviation ±1.66 cm), and their thickness (*d*) was from 2.90 cm to 5.07 cm, with an average of 3.93 cm (±0.42 cm). The statistical analysis for the tested batchindicated a significant weak linear relationship between the thickness and length of the cones (7).

$$d_s = 3.048 + 0.0554 \cdot h_s \quad R = 0.218 \qquad (7)$$

Table 1 lists the values of length (h_s) and thickness (d_s) of the 60 fir cones studied in detail. The length of the cones was in the range of 12.93 to 19.25 cm, with an average of 15.97 cm (standard deviation ±1.46 cm), and the thickness from 3.75 cm to 5.07 cm, with an average of 4.34 (±0.39) cm.

The mass of closed fresh cones was an average of 109.73 g (±23.72 g) and ranged from 71.65 to 158.62 g (Table 1). The average initial water content of the cones was 112%, and their density was from 0.52 $g \cdot cm^{-3}$ to 0.73 $g \cdot cm^{-3}$, with an average of 0.63$g \cdot cm^{-3}$ (±0.06$g \cdot cm^{-3}$).

The cone stems obtained after the extraction process were on average 14.88 cm (±1.42) cm long and the thickness measured in the middle of the length was 0.64 cm (±0.06 cm), with the maximum thickness at the cone stalk– an average of 1.11 cm (±0.21 cm) (Table 2). There was no significant linear relationship between the length and thickness of the stem. Average stem density was 0.44 $g \cdot cm^{-3}$ and was 0.19 $g \cdot cm^{-3}$ lower than the density calculated for a closed cone.

3.2. Surface area and volume of closed cones and stems

A fourth degree polynomial was selected as an expression that reproduces the shape of cones well. This choice is justified by the high coefficient of determination, which ranged from 0.959 to 0.997, with an average of 0.981. The third degree polynomial showed a significantly lower coefficient, and the fifth one was comparable to the fourth degree (no significant difference).

The average (together with standard deviation), minimum and maximum values of the coefficients from *As (At)* to *Es*(*Et*) are provided in Tables 3 and 4. An example of the course of changes in the forming of the curve for cones and stems is shown in Figure 1, and below is their mathematical description (8) and (9).

Cone:

$$r_s = -0.00029 \cdot h_s^4 + 0.01031 \cdot h_s^3 - 0.12944 \cdot h_s^2 + 0.64571 \cdot h_s + 1.21638$$

$$R = 0.993 \qquad (8)$$

Table 1. Parameters characterizing fir cones

Data	Mean	Min	Max	Range	Variance	Std. deviation	Coeffi-cient of variation	Std. error	Skewness	Kurtosis
Length h_s [cm]	15.97	12.93	19.25	6.31	2.12	1.46	9.11	0.27	0.26	-0.15
Thickness max d_s [cm]	4.34	3.75	5.07	1.32	0.15	0.39	8.93	0.07	0.07	-1.17
Initial weight m_{Ss} [g]	109.73	71.65	158.62	86.97	562.80	23.72	21.62	0.58	-0.62	109.73
Density δ_s [g·cm^{-3}]	0.63	0.52	0.73	0.20	0.00	0.06	9.23	0.20	-0.91	0.63
Number of scales l	184.13	140.00	229.00	89.00	406.33	20.16	10.95	0.44	0.45	184.13
Number of seeds n	268	195	357	170	1965.95	44	16.52	8.10	0.44	-0.37

Table 2. Parameters characterizing the stem of fir cones

Data	Mean	Min	Max	Range	Variance	Std. deviation	Coeffi-cient of variation	Std. error	Skewness	Kurtosis
Length h_t [cm]	14.88	11.14	17.33	6.19	2.01	1.42	10.21	0.26	0.49	-0.11
Thickness d_t [cm]	0.64	0.48	0.72	0.24	0.004	0.06	9.84	0.01	-0.85	0.38
Thicknes [cm]	1.11	0.75	1.53	0.78	0.04	0.21	18.17	0.034	0.67	-0.18
Dry weight m_t [g]	1.94	1.19	3.27	2.08	0.20	0.44	22.71	0.08	1.33	3.35
Density δ_t [g·cm^{-3}]	0.44	0.28	0.78	0.50	0.01	0.10	21.86	0.02	1.51	4.56

Stem:

$$r_t = 0.00007 \cdot h_t^4 - 0.00288 \cdot h_t^3 + 0.03839 \cdot h_t^2 - 0.20675 \cdot h_t + 0.70108$$

$$R = 0.967 \quad (9)$$

The determined equations forming individual cones allowed us to calculate the surface area Ss_{obl} and the volume Vs_{obl} (Table 3).

The high variability of the *As, Bs, Cs* and *Es* coefficients for individual cones means that despite a significant dependence for length, it is not possible to practically apply the equation to calculate the volume and surface area of any one fir cone when only its basic size parameters are known. The *Es* coefficient did not exhibit a significant dependence on cone length, which was confirmed by Aniszewska and Błuszkowska (2016).

A statistical assessment of the coefficients of regression of the equations describing the shape of the stem *At-Et*did not show any significant dependence between stem length and thickness.

The values of cone's surface area (Ss_{obl}) calculated from equation 2 ranged from 134.18 cm^2 to 242.89 cm^2, with an average of 180.30 cm^2 (±24.01 cm^2), while the volume (Vs_{obl}) cal-

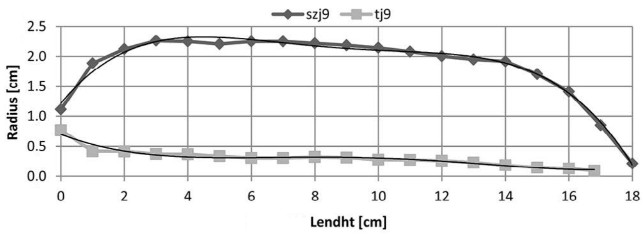

Figure 1. Graph of an exemplary generatrix of fir cone and cone stem

culated according to equation 3 was from 108.77 cm^3 to 258.99 cm^3, with an average of 175.70 cm^3(±35.98cm^3) (Table 3).

The values of cone's surface area (Ss_w) calculated according to the equations for the cylinder were from 158.86 cm^2 to 268.79 cm^2, with an average of 217.13 cm^2 (±26.56 cm^2), and the volume (Vs_w) was from 155.23 cm^3 to 311.41 cm^3, with an average of 236.67 cm^3(±45.07 cm^3) (Table 3).

The cone indicator 1 ks_1 value ranged from 0.65 to 0.89 with an average of 0.74 (±0.05), and cone indicator 2 ks_2 ranged from 0.65 to 0.93, with an average of 0.83 (±0.05). The use of averaged ks_1 and ks_2 indicators to calculate the volume and surface area of fir cones showed no significant differences between the values of Vs_{obl} and Ss_{obl}, which was confirmed by the t-test for dependent samples (p=0.817 and p=0.970) and the analysis of variance (p=0.950; F=0.0039 and p=0.989, F=0.0002).

The values of the surface area of the stem (St_{obl}) calculated from equation 2 were from 17.61 cm^2 to 36.02 cm^2, with an average of 26.46 cm^2 (± 4.66cm^2) and the volume (Vt_{obl}), according to equation 3 was from 2.40 cm^3 to 6.92 cm^3, with an average of 4.51 cm^3(± 1.11cm^3) (Table 4). Using the similarity of the stem to the form of a cylinder, the average surface area is 27.81 cm^2 and the volume is 4.48 cm^3. The t-test for dependent samples showed significant differences between St_{obl} and St_w (p = 0.043), butindicated no differences between Vt_{obl} and Vt_w (p=0.855). The stem constitutes an average of 2.59% (±0.52%) of the volume of aclosed cone, it is shorter than the cone by an average of 1.09 (±0.51) cm and constitutes 3.87% (±0.67%) of its dry mass.

Table 3. Basic statistical values of polynomial, volume, surface area and indicators of cones

Data	Mean	Min	Max	Range	Variance	Std. deviation	Coefficient of variation	Std. error	Skewness	Kurtosis
As	-0.0006	-0.0013	-0.0003	0.0010	0	0.00023	-40.26	0.000042	-0.67	0.86
Bs	0.0182	0.0092	0.0325	0.0233	0	0.00586	32.17	0.001069	0.17	-0.46
Cs	-0.2082	-0.2996	-0.1239	0.1757	0.0030	0.05124	-24.61	0.009355	0.20	-1.17
Ds	0.9728	0.6457	1.2831	0.6374	0.0310	0.17577	18.07	0.032091	-0.11	-0.96
Es	0.5998	0.3356	1.2164	0.8808	0.0290	0.17085	28.48	0.031193	1.88	5.17
Volume Vs_{obl} [cm^3]	175.70	108.77	258.99	150.22	1294.73	35.98	20.48	6.57	0.29	-0.23
Surface area Ss_{obl} [cm^2]	180.30	134.18	242.89	108.70	576.48	24.01	13.32	4.38	0.46	0.72
Volume Vs_w [cm^3]	236.67	155.23	311.41	156.18	2030.97	45.07	19.04	8.23	0.02	-0.95
Surface area Ss_w [cm^2]	217.13	158.86	268.79	109.93	705.59	26.56	12.23	4.85	-0.11	-0.11
Indicator ks_1	0.74	0.65	0.89	0.24	0.00	0.05	7.36	0.01	0.69	0.51
Indicator ks_2	0.83	0.65	0.93	0.29	0.00	0.05	6.10	0.01	-1.40	5.50

3.3. The extraction process of fir cones, extracting and evaluating the seeds

The total time of the extraction process of cones was 35 hours. The drying temperature was a maximum of 35°C, and the humidity inside the dryer decreased from 53% to 10%.

Figure 2 shows the change in water content and drying speed (dynamics) over time for a selected cone. The mathematical description of the course of the process is represented by the equations for water content (u) and drying speed ($du \cdot d\tau^{-1}$) of the cones over time, depicted in equations 4 and 6. An example of a model equation of u for a selected cone is provided below:

$$u = 1.038 \cdot e^{-0.080 \cdot \tau} + 0.084;$$
(dla $u_o = 1.122\ kg_{H_2O} \cdot kg_{s.m.}^{-1}$, $u_k = 0.084\ kg_{H_2O} \cdot kg_{s.m.}^{-1}$, $b = 0.080\ 1 \cdot h^{-1}$) (10)

$$du \cdot d\tau^{-1} = -0.083 \cdot e^{-0.080 \cdot \tau}; \quad (11)$$

and the linear form of the equation of the drying rate of the water content in a cone is:

$$du \cdot d\tau^{-1} = -0.080 \cdot (u - 0.084) \quad (12)$$

Table 5 presents the average, minimum and maximum values of specific parameters of the equations. The fir cones had an average initial water content of 1.127 $kg_{H_2O} \cdot kg_{s.m}^{-1}$ and a final content, according to the model, of 0.115 $kg_{H_2O} \cdot kg_{s.m}^{-1}$. Coefficient b was an average of 0.065 $1 \cdot h^{-1}$. A linear relationship between coefficient b and cone thickness was determined (R=0.441), but none was found between this coefficient and length. When selecting cones with similar properties of mass exchange, the thickness of cones should be used for their selection as a more reliable parameter than length, as it influences changes in coefficient b. We noticed that the higher the coefficient $b$value, the faster was the drying process (cones more intensely reduced their water content).

In most cases, the final actual water content did not equal the final model water content, the difference between them was at an average of 11% (±5.6%). The t-test showed a significant difference between these two values ($p < 0.05$).

Statistica 10 proposed another exponential equation (13) for the actual values of change in water content during drying (13). A graph describing the equation is provided in Figure 2a.

$$u = 1.187 \cdot e^{(-0.075 \cdot \tau)} \quad (13)$$

A significant linear relationship was established between the final u_k and initial u_o water content. When assessing the range of changes in cone water content for the entire process, that is, the difference between the initial and final content, we found that the highest percentage of cones (63.3%) ranged from 0.900 to 1.100 $kg_{H_2O} \cdot kg_{s.m}^{-1}$.

Figure 3 shows the change in water content during cone drying with an initial water content of 0.872 and 1.325 $kg_{H_2O} \cdot kg_{s.m}^{-1}$and a final content of 0.049 and 0.185 $kg_{H_2O} \cdot kg_{s.m}^{-1}$

Table 4. Basic statistical values of polynomial, volume, surface area and indicators of cone stems

Data	Mean	Min	Max	Range	Variance	Std. deviation	Coefficient of variation	Std. error	Skewness	Kurtosis
At	0.0001	-0.0002	0.0002	0.0004	0	0.0001	142.41	0.000014	-1.40	4.30
Bt	-0.0020	-0.0052	0.0054	0.0106	0	0.0022	-110.33	0.000395	1.22	3.28
Ct	0.0225	-0.0435	0.0535	0.0970	0	0.0206	91.78	0.003767	-0.96	2.04
Dt	-0.1102	-0.2350	0.1016	0.3367	0.006	0.0774	-70.21	0.014128	0.45	0.34
Et	0.5293	0.3708	0.7547	0.3839	0.009	0.0955	18.04	0.017436	0.67	-0.15
Vt_{obl} [cm^3]	4.51	2.40	6.92	4.53	1.23	1.11	24.62	0.20	0.13	-0.30
St_{obl} [cm^2]	26.46	17.61	36.02	18.40	21.72	4.66	17.62	0.85	0.11	-0.09
Vt_w [cm^3]	4.48	2.25	5.75	3.50	0.80	0.89	19.96	0.16	-0.79	-0.06
St_w [cm^2]	27.81	18.74	35.39	16.64	13.82	3.72	13.37	0.69	-0.53	0.42
kt_1	1.02	0.68	1.52	0.83	0.05	0.22	21.63	0.04	0.72	-0.21
kt_2	0.95	0.73	1.20	0.47	0.02	0.12	12.89	0.02	0.45	-0.26

respectively, as well as a coefficient *b* equal to 0.084 $h^{-1}$and 0.075 h^{-1}. During 35 h, enough time to obtain seeds, cone water content decreased by about 80% for the first drying curve (water content − 0.08 $kg_{H_2O} \cdot kg_{s.m}^{-1}$) and by 115% for the second curve (1.15 $kg_{H_2O} \cdot kg_{s.m}^{-1}$). Cone drying speed, or the loss of water from cones, was decreasing from the beginning, which is characteristic of the so-called second drying period of solids as described in the literature (Pabis 1982).

After the extraction process, the cones disintegrated into scales, seeds and stems. The number of scales in a cone was from 140 to 229, with an average of 184 (±20.15), and the number of seeds was an average of 268 (±44) (Table 1). A significant linear relationship was found between the number of scales and the number of seeds obtained (R = 0.750). The weight of harvested seeds from a cone was an average of 16.6 g, which shows that the weight of 1000 seeds is an average of 62 g.

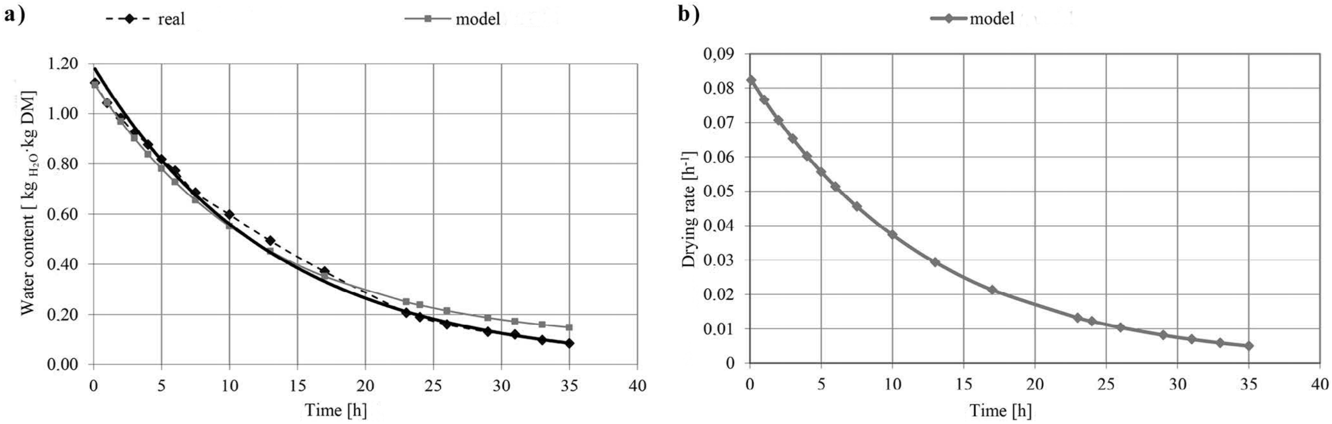

Figure 2. Graphs: a – change in water content over time for selected cones (real, model, exponential), b – speed (dynamics) of drying

Table 5. Basic statistical values of the parameters of the equation for changing of the water content and the drying rate

Data	Mean	Min	Max	Range	Variance	Std. deviation	Coefficient of variation	Std. error	Skewness	Kurtosis
u_o	1.127	0.869	1.338	0.470	0.017	0.131	11.605	0.024	-0.221	-0.319
u_k	0.115	0.036	0.248	0.232	0.003	0.053	46.178	0.097	0.327	0.019
b	0.065	0.040	0.100	0.060	0.000	0.015	22.283	0.003	0.612	-0.300

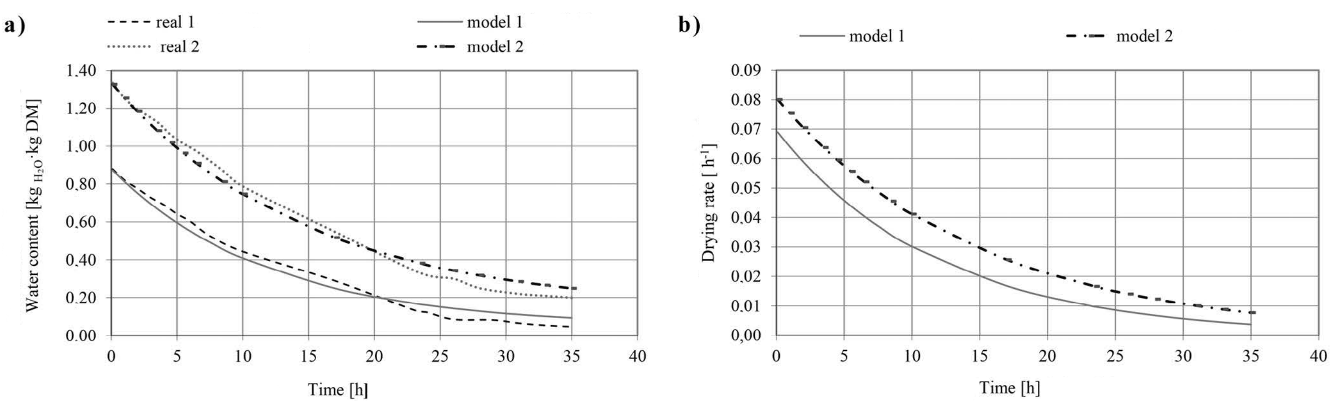

Figure 3. Graphs: a – water content in time for cones with different water content (1 – street, 2 – smaller), real and modeled, b – drying rate

The evaluation of seed quality showed that after the drying process, 32% of the fir seeds germinated after 28 days, of which 21% germinated within 14 days of sowing. According to the standards, fir seeds are categorized to the first quality class when they reach 61% to 80% germination. The obtained result indicates that the tested seeds cannot be categorized to the first quality class. Therefore, in order to check the impact of the proposed extraction process on fir cones and the seeds obtained from them, a control test was conducted to assess the viability of the seeds obtained from cones not dried in the dryer. Similar viability results were obtained, as only 35% of seeds germinated within 28 days.

4. Discussion

Whencomparing the results of the external parameters of the studied fir cones, we noted that they are within the rangesfound by other authors. They most resembled the parameters of fir cones from Romania (Nanu 1977), which had a length of 7.0 to 19.5 cm, and a thickness of 2.9 to 4.6 cm. Similar results were also reported by Kočiová (1974), describing cones from Slovakia. In turn, the results of the mass of 1000 fir seeds exceeded the values described by Antosiewicz (1970), which averaged about 12 g.

Knowing the length and thickness of cones allows you to calculate the surface area and volume of closed cones. The proposed model, in the form of a fourth degree polynomial, served only to describe the shape of the cone and to calculate the surface area and volume of specific cones. An attempt to apply this polynomial to other cones from the batch, using the average values of the equation coefficients *As, Bs, Cs, Ds, Es*, did not succeed because the results were significantly inflated. The second proposed method of calculating the surface area and volume of a fir cone based on the shape of a cylinder proved to be more useful. It is easily applied to cones from other batches by appropriately determining the coefficients (for the studied batch of cones, this was 0.74 for volume and 0.83 for surface area). In addition, it was determined that the pine cone stem constitutes approximately 2.6% of the volume of the cone, and its mass constitutes approx. 4% of the weight of a dry cone.

Similar research conducted for other provenances of silver fir or other species, that is, Scots pine and Norway spruce, determined the method of calculating surface area and volume using the shape of a cone (Gawart, Mikłaszewicz 2000; Aniszewska 2001; Aniszewska, Błuszkowska 2016); however, a cylindrical shape provides better results.

The studied values of surface area and volume as well as the described changes in water content and drying speed curves can be used to develop and program thermal extraction processes in drying cabinets for commercial purposes in order to obtain good quality seeds.

The proposed conditions inside the drying chamber, that is, an air temperature of up to 35°C and thehumidity in the last phase ofdrying of up to 10%, allow viable seeds to be obtained, as evidenced by the seed germination test. However, it is advisable to additionally check the quality of seeds using other methods, for example, cutting or dyeing the embryos in a tetryzoline solution. Fir seeds are very sensitive to changes in temperature and water content during extraction, preparation for storage and actual storage (Załęski et al. 2009). According to the information obtained from Stacja Oceny Nasion (Seed Quality Assessment Laboratory) in Sękocin, the seeds found to have high viability (up to 20%) by using the tetryzoline solution dyeing test often germinated at only a few percent in the germination test. According to Załęski (1995), the average viability of silver fir seeds in Poland, determined by the slicing test, is 43.3%. The low seed viability obtained may relate to the physical state and biochemical composition of the seeds themselves (Aniśko et al. 2001), which in turn are affected by the stage of their maturity and atmospheric conditions prevailing at the time the seeds were forming and developing.

The research presented on the size parameters, mass, drying process, including changes in water content and quality assessment, can be treated as a pilot. Its results should be confirmed by conducting experiments on cones from various provenances and harvesting years.

5. Conclusions

The shape of a silver fir cone is accurately described by a curve that is a fourth degree polynomial. However, due to the large differences in the averaged values of the polynomial and the actual values of cones, this description cannot be used to calculate the volume and surface area of any given cone, despite the significant dependence between the cone length and thickness (except for coefficient *D*).

The shape of a cylinder may be used as a general calculation model describing the surface area and volume of silver fir cones. The volume values calculated using the equation for a cylinder should be multiplied for the tested batch of cones by a constant value of 0.74, and in the case of a surface area, by 0.83. Small changes in the size of these coefficients can be expectedfor other batches of cones.

The change in cone mass during the seed extraction process as a function of time is described by an exponential equation, in which the parameters are initial cone water content –an average of 1.127 $kg_{H_2O} \cdot kg_{s.m.}^{-1}$, final water content –0.115 $kg_{H_2O} \cdot kg_{s.m.}^{-1}$and power series coefficient b equal to 0.065 $1 \cdot h^{-1}$.

The final water content depends on the initial water content of the cone, and its value increases as with increase in initial water content. Cone characteristic indicator b depends on the thickness of the cone and decreases as the thickness of the cone increases, which can be described with a linear regression equation.

The seeds obtained in the studied extraction process at a drying temperature of up to 35°C and humiditydown to 10% did not reach the first grade of seed quality. A control test for assessing the viability of seeds of the same provenance that were not subjected to the extraction process gave similar results. Therefore, the use of an automated fir cone seed extraction process at the studied temperature and humidity conditions cannot be rejected.

Conflict of interest

The authors declare no conflict of interest.

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References

Aniszewska M. 2001. Zmienność podstawowych parametrów szyszki świerka. *Sylwan* 145(6):87–93.

Aniszewska M. 2008. Charakterystyka wielofazowego procesu wyłuszczania nasion modrzewia europejskiego *Larix decidua* Mill. na przykładzie wyłuszczarni gospodarczej w Czarnej Białostockiej. *Leśne Prace Badawcze* 69(2): 155–163.

Aniszewska M. 2012. Porównanie procesu wyłuszczania nasion sosny zwyczajnej (*Pinus sylvestris* L.) z szyszek całych i pozbawionych trzpienia. *Leśne Prace Badawcze* 73(1): 65–72. DOI 10.2478/v10111-012-0007-3.

Aniszewska M., Błuszkowska U. 2016.Variability of silver fir (*Abies alba* Mill.) cones – variability of cone parameters. *Leśne Prace Badawcze* 77(3): 221–229. DOI 10.1515/frp-2016-0024.

Aniszewska M., Gendek A., Śliwińska J. 2017.Variability of silver fir (Abies alba Mill.) cones – variability of scale surface area. *Leśne Prace Badawcze* 78(1): 5–13. DOI 10.1515/frp-2017-0001.

Aniśko E., Witkowska O., Załęski A. 2001. Ustalenie wilgotności nasion przeznaczonych do przechowywania (wartości graniczne), szczególnie jodły, jaworu, brzozy, olszy czarnej, lipy, jesionu i innych. Sprawozdanie naukowe IBL, 39 s.

Antosiewicz Z. 1970. Nasiennictwo,w: Poradnik Leśnika (red. Kamiński E). SITLiD, Państwowe Wydawnictwo Rolnicze i Leśne, Warszawa, 306–330.

Ballain D. Čabaravdić A. 2005. Među populacji skavarijabilnostnekih morfoloških svojstava obične jele (*Abies alba* Mill.) izsredišnje Bosne. *Rad.* Šumar. *Inst*. 40(1): 5–18.

Barzdajn W. 2009. Adaptacja różnych pochodzeń jodły pospolitej (*Abies alba* Mill.) do warunków Sudetów. *Leśne Prace Badawcze* 70(1): 49–58. DOI 10.2478/v10111-009-0005-2.

Bednarek T. 2002. Zmienność osobnicza jodły (*Abies alba* Mill.) w lasach zarządzanych przez Regionalną Dyrekcję Lasów Państwowych we Wrocławiu. *Zeszyty Naukowe AR im. H. Kołłątaja w Krakowie* 339: 181–195.

Bis R., Dobrowolska D. 2012. Występowanie jodły pospolitej (*Abies alba* Mill.) w Puszczy Iłżeckiej. *Leśne Prace Badawcze* 73(4): 273–282. DOI 10.2478/v10111-012-0020-6.

Boratyński A. 1983. Systematyka i geograficzne rozmieszczenie jodły, w: Białobok S. (red.) Jodła pospolita (*Abies alba* Mill). PWN, Warszawa–Poznań, 41–86. ISBN 83-01-04028-9.

Boncaldo E., Bruno G., Sicoli G., Tommasi F., Mastropasqua L. 2010.Germinability and fungal occurrence in seeds of *Abies alba* Mill. populations in southern Italy. *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology* 144(3): 740–745. DOI 10.1080/11263501003755549.

Czernik Z. 1993. Badania właściwości geometrycznych nasion jodły. *Sylwan* 8: 57–64.

Gawart B. Mikłaszewicz M. 2000. Modele matematyczne kształtu szyszek sosny i świerka. *Przegląd Techniki Rolniczej i Leśnej* 2: 20–22.

Gudeski A. 1966. Morfologija na semeno i na šišarkite na elata (*Abies alba* Mill.) odnacionalniot park „Risnak". *Godišen Zbornik na Zemjodelsko-Šumarskiot Fakultetna Univerzitetot – Skopje* 19: 187–215.

Gunia S., Simak M. 1968. Effect of damaging resin vesicles in the seed coat on the germination of silver fir (*Abies alba* Mill.) seeds, in: Proceedings of the International Symposium on Seed Physiology of Woody Plants. Kórnik, Poland, Institute of Dendrology and Kórnik Arboretum, Polish Academy of Sciences,79–83.

LBGK. 2007. Instrukcja gromadzenia i przechowywania zasobów genowych. Leśny Bank Genów Kostrzyca.

Illoul-Hachi M., Derridj A., Fady B. 2015. Efficiency of seed production and cone size of *Abies numidica* De Lannoy in the plantation in Algeria. *International Journal of Research in Applied, Natural and Social Sciences* 3(7): 9–16.

Kobliha J., Škorpík P., Stejskal J., Češka P. 2014. Hybridization results using the hybrid *Abies cilicica* × *Abies cephalonica*. *Acta Scientiarum Polonorum, Hortorum Cultus* 13(4): 23–31.

Kočiová M. 1974. Dedivost'plodov jedle bielej (*Abies alba* Mill.) na Slovensku. *Acta Musei Silesiae, Series Dendrologia (Opava)* 23: 171–179.

Kubiak M, Laurow Z. 1994. Surowiec drzewny. Fundacja, Rozwój SGGW, Warszawa. ISBN 83-86241-33-0.

Nanu N. 1977. Contributii la biometriaconurilor de brad (*Abies alba* Mill.). *Revista Pădurilor* 92(3): 140–147.

Norma branżowa BN-76/9211-02, Leśnictwo, Wydawnictwa Normalizacyjne.

Pabis J. 1982. Teoria konwekcyjnego suszenia produktów. Warszawa. Państwowe Wydawnictwo Rolnicze i Leśne, 228 s. ISBN 83-09-00597-0.

Politi P. I., Georghiou K., Arianoutsou M. 2011. Reproductive biology of *Abies cephalonica* Loudon in Mount Aenos National Park, Cephalonia, Greece. *Trees* 25: 655–668. DOI 10.1007/s00468-011-0542-1.

Statistica 10. 2011. Start Soft. www.statsoft.com.

Sugiero D. 2005. Jodła pospolita (*Abies alba* Mill.) w drzewostanach zespołu żyznej buczyny karpackiej (*Dentarioglandulosae-Fagetum*). *Sylwan* 149(11): 42–49.
Suszka B. 1983. Rozmnażanie generatywne, w: Białobok S.(red). Jodła pospolita *Abies alba* Mill. PWN, Warszawa–Poznań, 566 s. ISBN 83-01-04028-9.
Suszka B. 2000. Nowe technologie i techniki w nasiennictwie leśnym. Bogucki Wydawnictwo Naukowe S.C.,Warszawa, 269 s. ISBN 83-88163-14-0.
Szeligowski H., Bolibok L., Buraczyk W., Drozdowski S. 2011. Characteristics of Silver fir (*Abies alba* Mill.) in a provenancetrial in Rogów. *Leśne Prace Badawcze* 72(3): 225–231. DOI 10.2478/v10111-011-0022-9.
Tracz M., Barzdajn W. 2007. The morphological traits of cones and seeds of *Abies alba* in Middle Sudeten. *Dendrobiology* 58: 59–65.
Tyszkiewicz S. 1949. Nasiennictwo Leśne. Instytut Badawczy Leśnictwa, Seria D. 2. 358.
Załęski A. (red) 1995. Nasiennictwo leśnych drzew i krzewów iglastych. Oficyna Edytorska Wydawnictwo Świat. Warszawa, 180 s. ISBN 83-85597-27-1.
ZałęskiA., Aniśko E, Konratowicz W. 2009. Zawartość wody w podsuszonych nasionach drzew leśnych a wilgotność względna suszonego powietrza. *Leśne Prace Badawcze* 70(2): 151–160.
Załęski A., Aniśko E., Kantorowicz W. 2006. Zasady oceny nasion w Lasach Państwowych,w: Elementy genetyki i hodowli selek-cyjnej drzew leśnych (red. J.Sabor). CILP, Warszawa, 317–326. ISBN 83-88478-21-4.

Authors' contribution

M.A.– concept, literature review, methods, measurements, developing the results, statistical analysis, conclusions, writing, correcting; J.B.– writing, measurements, correcting, W.Z. – translating, correcting.

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