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Logistics of the supplies of selected forest tree species' cones. Part 1. Cone density and substitution coefficient

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Abstract: *Logistics of the supplies of selected forest tree species' cones. Part 1. Cone density and substitution coefficient.* The article presents an analysis of specific density, bulk density and substitution coefficient of empty cones of Scots pine, Norway spruce and European larch, obtained from seed husking plants in Czarna Białostocka and Ruciane Nida. Specific density of the cones of particular species varied from 1,144 to 1,306 kg·m^{-1}, whereas bulk density was equal to 9–18% of their specific density. The highest values were recorded in the case of larch cones, whereas the lowest ones – for spruce cones. Substitution coefficients, determined pursuant to PN-EN 15103:2010 method using a helium pycnometer were, respectively, 0.26 and 0.15 for pine cones, 0.23 and 0.09 for spruce cones, 0.55 and 0.18 for larch cones. The obtained values may be used in the estimations of the load and transport weight of cones for various vehicles, as well as for evaluating transport profitability. Considering the low substitution coefficient, particularly in the case of spruce cones, its estimation ought to be performed after fragmentation of cones supplemented by the use of pressure agglomeration.

Key words: bulk density, specific density, cones, Scots pine, Norway spruce, European larch, transport

INTRODUCTION

Forest biomass, which includes medium- and small-sized wood elements not meeting applica0ble quality requirements, is being increasingly used as a renewable source of energy. Above all, the source of energy is wood from the latter category. Apart from wood, cones constituting waste of the seed husking process may also be used to produce energy.

At present, 16 seed husking plants operate in Poland. These include both old plants from before World War II, as well as upgraded and new ones using modern technologies. The applied seed husking technologies translate directly onto the manner of empty cone management. At some seed husking plants, e.g. at the one in Ruciane Nida, cones are used as fuel for boilers providing heat needed during the husking process. At state of the art seed husking plants, such as the one at Grotniki Forest Inspectorate, which are powered with electricity, cones constitute waste and are usually sold on the local market. The net price per 1 kg of empty cones falls within the range of 1.00–2.50 PLN (figures from Czarna Białostocka Forest Inspectorate, dated 27.08.2014).

Empty cones are a good fuel material, which is evidenced by their calorific value. Cones may be combusted directly in furnaces or, after fragmentation, used in the production of briquettes or pellets. Due to relatively low availability of this material, cones may only be used on the local market. According to the figures provided by Aniszewska and Kuszpit [2015], 35.8 Mg of cones were husked on average in 2009–2012 at one seed husking plant, this process leaving 27 Mg of cones without seeds to be used for energy generation purposes.

Literature contains abundant information on determination of bulk density [Waszkiewicz 1988, Keane et al. 2005, Stolarski et al. 2005, Sypuła et al. 2010, Spinelli et al. 2015], calorific value [Aniszewska and Gendek 2014, Gendek and Zychowicz 2014, Gendek 2015] and logistics of forest and agricultural biomass transported in the form of wood, chips, branches, pellets and briquettes [Pieriegud 2015]. However, available literature does not contain any information on bulk density and substitution coefficient of cones, although these values are necessary to plan their transport. Consequently, the investigation undertaken was aimed at determining those parameters for cones of three coniferous species, i.e. Scots pine, Norway spruce and European larch. The results obtained will allow determination of the actual volume and weight of empty cones, along with estimating the profitability of purchasing and transporting cones between the husking plant and a local power plant.

MATERIAL AND METHODS

"Empty" cones of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L.) and European larch (*Larix decidua* Mill.) were used in the investigations.

The investigations were carried out in February 2015 at two seed husking plants: Czarna Białostocka (GPS 53.305895, 23.273840) and Ruciane Nida (GPS 53.646460, 21.566209). Cones of Scots pine and Norway spruce were analysed at the former seed husking plant, whereas cones of European larch at the latter. Information on the place of origin and periods of obtaining the cones is specified in Table 1.

Depending on the technology and species, particular stages of the husking process were performed at the temperature from 40 to 65°C for 16–54 h, until complete opening of the cones. The shortest time was needed to husk spruce cones, whereas larch cones required the longest time. After separation of seeds, empty cones were stored loose or in chests in airy warehouses.

In order to determine the characteristics and variability of the investigated material, length, thickness (at the largest diameter) and weight of 100 randomly picked cones of each species were measured. The diameter was measured by means of an electronic slide calliper (±0.1 mm) in two perpendicular directions at the same height, followed by calculation of the average value. Weight was determined using RADWAG WPS210S (±0.001 g) moisture balance.

TABLE 1. Place of origin and periods of obtaining cones

Species	Scots pine	Norway spruce	European larch
Forest inspectorate	Płaska	Wagiły	Maskulińskie
Department	258	150 g	121
Tree stand	WDN	GDN	WDN
Seed husking plant	Czarna Białostocka	Czarna Białostocka	Ruciane Nida
Period of obtaining and husking	December 2014 – January 2015		

Relative and absolute humidity of the cones was determined with the use of the moisture balance. The applied investigation procedure was compliant with PN-EN 13183-1:2004 norm. Drying of the material in order to determine its dry weight was performed in Heraeus UT 6120 laboratory dryer at the temperature of 105 ±1°C for 24 h. For particular species, 25 repetitions of measurements for randomly picked individual cones of Scots pine (Sp) were performed, 24 for Norway spruce (Ns) and 26 for European larch (El).

For the sake of determination of bulk density and substitution coefficient, the procedure and measuring vessel with the capacity of 0.05 m^3 was used pursuant to PN-EN 15103:2010 norm for solid fuels with particles greater than 12 mm. A diagram of the measurement system is shown in Figure 1a. The measuring vessel, initially empty (1) and then filled with cones, was suspended on a tensometric sensor (2) integrated with a dynamometer with the measurement range up to 1,000 ±0.1 N. The result obtained was recalculated by the device's software into weight expressed in kilograms (3). The number of repetitions for all of the species was 15. Based on the measurement figures, volumetric density of fresh material was calculated (BD_{ar}) and was subsequently recalculated into bulk density in the dry condition (BD_d) in compliance with the relationships described in PN-EN 15103:2010 norm.

Once weighed (1), the vessel containing the cones was tightly closed using a lid (4) with a liquid inlet and vent (5). An electronic flowmeter (6) with the accuracy of 0.1 dm^3 was used to measure the flow of liquid. The time of filling the vessel with liquid was measured with a stopwatch (±1s) (Fig. 1b). The investigation did not take into account the problem of water absorption by cones, as immersion of the cones in the liquid lasted

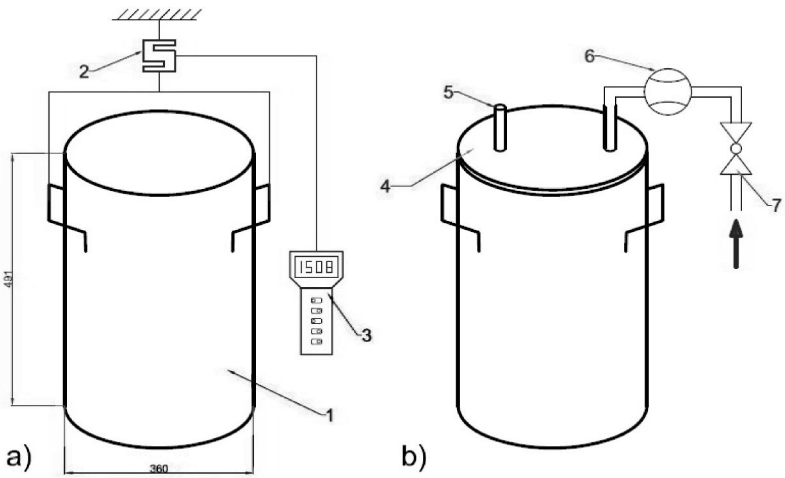

FIGURE 1. Diagram of the measurement system for: a – bulk density, b – substitution coefficient: 1 – measurement vessel, 2 – tensometric sensor, 3 – registering device, 4 – lid, 5 – vent, 6 – flow meter, 7 – valve

from 60 to 90 s, whereas – pursuant to the investigations conducted by Aniszewska [2012] as well as by Aniszewska and Bereza [2014] – water absorption rate by dry cones after 2 min is 2.54%. By way of comparison of the volume of liquid contained in the vessel and capacity of the measurement vessel itself, the volumetric substitution coefficient was calculated for empty cones of the three species, pursuant to the following formula (1):

$$K_{zu} = \frac{V_o - V_w}{V_o} \quad (1)$$

where:
K_{zu} – volumetric substitution coefficient [–];
V_o – total vessel capacity [m^3];
V_w – volume of liquid in the vessel [m^3].

Specific density of cones (±0.01 g·cm^{-3}) was determined using, Stereopycnometr helium pycnometer from Quantachrome Instruments and Pycnometersoftware computer software (version 2.7), at the Faculty of Food Sciences of Warsaw University of Life Sciences – SGGW at the laboratory of the Department of Food Engineering and Production Organisation. Pursuant to the applied measurement procedure, the analysis was repeated three times for each of the species, with three measurements performed each time. The method used for calculation of sample volume and density is presented in formulas (2) and (3) [Lisowski et al. 2011]:

$$V_p = V_c + \frac{V_a}{1 - \frac{P_1}{P_2}} \quad (2)$$

$$P_s = \frac{m}{V_p} \quad (3)$$

where:
V_p – sample volume [cm^3];
V_c – measurement chamber capacity [cm^3];
V_a – reference chamber capacity [cm^3];
P_1, P_2 – pressure read from the measurement device [Pa];
ρ_s – specific density [g·cm^{-3}];
m – weight of particles [g].

Based on the determined specific density and bulk density, the weight substitution coefficient (K_{zw}) was determined for empty cones of the three species, according to the following formula:

$$K_{zw} = \frac{BD_d}{\rho_s} \quad (4)$$

where: BD_d – bulk density, dry [kg·m^{-3}].

Statistical analyses were performed in Statistica v. 12 software, on the statistical significance level of $\alpha = 0.05$.

RESULTS AND DISCUSSION

After husking, Scots pine cones obtained for the investigation were characterised with the average length of 41.77 mm, whereas their thickness was 35.64 mm. In the case of Norway spruce, the average length was 119.42 mm and the thickness was 52.96 mm. The cones of European larch were characterised, respectively, with 37.56 and 22.44 mm (Table 2).

After the husking process, the only parameter from among the ones measured which does not change significantly is the cone length; therefore, it may be compared with the results provided by other scientists. According to the investigations carried out by Białobok et al. [1993], the length of a Scots pine cone

TABLE 2. Size and weight characteristics of cones after husking, for the three analysed species

Parameter	Scots pine			Norway spruce			European larch		
	length [mm]	thickness [mm]	weight [g]	length [mm]	thickness [mm]	weight [g]	length [mm]	thickness [mm]	weight [g]
AVG	41.77	35.64	5.89	119.42	52.96	31.49	37.56	22.47	3.78
Min	33.10	22.35	3.27	94.30	36.15	15.14	30.40	18.25	1.98
Max	49.80	48.80	10.45	151.10	64.70	48.76	46.90	27.25	6.74
SD	4.16	4.39	1.50	13.06	5.07	7.79	3.90	2.04	0.88
SE	0.42	0.44	0.15	1.31	0.51	0.78	0.39	0.20	0.09

ranges from 19 to 70 mm. Chmielewski [1968] determined variability of Norway spruce cone lengths from 60 to 175 mm, with similar results obtained by Kulej and Skrzyszewska [1996], whereas according to Bałut and Kulej [1977], the length of European larch cones falls within the range of 10–50 mm. A comparison of the obtained average values concerning length of the investigated cones led to the conclusion that they fell within the limits specified by the above mentioned authors. The material picked for analysis was homogenous and characterised with a lower scatter of results.

Knowledge of the initial and dry weight of the cones allowed calculation of absolute and relative humidity. On average, absolute humidity of the analysed cones of Scots pine and European larch was 8.63%, whereas in the case of Norway spruce it was slightly higher at 10.12%. Detailed results related to material humidity are presented in Table 3. According to the investigations of Aniszewska [2012], after the process of husking in production conditions, cones are characterised with the humidity of 7–10%. Using the variance analysis (F = 17.21; p <0.0001), significant differences in terms of cone humidity were determined among the investigated species. By way of Duncan multiple comparison test, it was stated that the humid-

TABLE 3. Absolute and relative humidity of "empty" cones of the three species

Parameter	Humidity [%]					
	absolute			relative		
	Scots pine	Norway spruce	European larch	Scots pine	Norway spruce	European larch
AVG	8.63	10.72	8.63	7.94	9.68	7.94
Min	8.36	10.17	7.58	7.72	9.23	7.05
Max	8.97	11.66	9.44	8.23	10.44	8.63
SD	0.17	0.39	0.54	0.14	0.32	0.46
CV	1.93	3.62	6.26	1.77	3.26	5.76
SE	0.03	0.09	0.11	0.03	0.07	0.09

ity of "empty" Norway spruce cones was considerably different from the humidity of Scots pine cones and European larch cones (p <0.0001), which made up a homogenous group.

Descriptive statistics concerning cone density measurements are presented in Table 4. The highest value of specific density (ρ_s) was found for "empty" Scots pine cones (1,306.48 kg·m^{-3}), whereas the lowest value was calculated for European larch cones (1,144.11 kg·m^{-3}). The difference between these species in terms of density was approximately 160 kg·m^{-3}.

By means of variance analysis, significant differences in terms of specific density were found among the cones of the investigated tree species (F = 12.05; p = 0.0002). Considerable differences among all the species were confirmed in Duncan multiple comparison test, where the highest value was p = 0.00015.

The determined specific density of empty cones was similar to the value obtained by Bergström et al. [2008] for specific density of pine pellets at 1,263–1,274 kg·m^{-3}, provided however that specific density of spruce cones was closest to this range. Yet, it was lower than the density of wood substance, as determined by Kubiak and Laurow [1994], which fell within the range from 1,460 to 1,560 kg·m^{-3}.

Bulk density of open cones depends on their outer dimensions as well as humidity, degree of cone opening and species of the tree they come from. The volumetric density (BD_{ar}) determined was greater than bulk density (BD_d) by approximately 9%, i.e. by the moisture content in the analysed material. The highest average value of bulk density with respect to dry cone weight was obtained in the case of larch cones – 206.09 kg·m^{-3} along with a very low coefficient of variation – 1.33%. A relation between bulk density and size of open cones was observed. From among the analysed species, empty larch cones were the smallest and their dimensions before opening were under 45 mm in length and under 20 mm in thickness; moreover, they were characterised with small volume changes after husking [Tyszkiewicz 1949]. According to the author, the volume of larch cones after opening increases one time, where-

TABLE 4. Specific density (ρ_s), volumetric density (BD_{ar}) and bulk density (BD_d) of cones of the investigated species

Parameter	ρ_s			BD_{ar}			BD_d		
	kg·m^{-3}								
	Scots pine	Norway spruce	European larch	Scots pine	Norway spruce	European larch	Scots pine	Norway spruce	European larch
AVG	1 306.48	1 229.83	1 144.11	213.80	118.27	223.87	196.82	106.82	206.09
Min	1 290.30	1 217.50	1 097.00	206.00	113.00	219.00	189.64	102.06	201.61
Max	1 329.10	1 246.70	1 172.90	227.00	125.00	230.00	208.97	112.90	211.74
SD	13.61	8.88	30.70	5.53	3.28	2.97	5.09	2.97	2.74
CV	1.04	0.72	2.68	2.59	2.78	1.33	2.59	2.78	1.33
SE	4.54	2.96	10.23	1.43	0.85	0.77	1.31	0.77	0.71

as the volume of spruce cones increases two times. Thanks to small dimensions, regular shape, relatively soft husks insignificantly bent away from the core, larch cones fill a given capacity more tightly than much larger cones of pine or spruce.

The lowest bulk density of dry cones was obtained for Norway spruce – 106.82 kg·m^{-3}, at 2.78% coefficient of variation. The bulk density of spruce cones was by 48.17% lower than that of larch cones. This was caused by the fact that spruce cones were the largest. According to Białobok [1977], spruce cones are characterised with the length of 150–200 mm, which evidences considerable differentiation of this parameter as described by various authors, with the thickness of 35–50 mm and approximately 100 husks each. After the husking process, their stiff but thin husks are bent away from the core by 50° [Aniszewska 2010]. During storage or transport, they do not fit well, get hooked with one another and block, thus creating considerable empty spaces.

For pine cones, the average bulk density of 196.82 kg·m^{-3} was obtained with the coefficient of variation at 2.59%. This is by 4.5% lower than the bulk density of larch cones and by 84.25% higher than the bulk density of spruce cones.

The performed statistical analyses – variance analysis ($F = 3205.06$; $p < 0.01$) and Duncan multiple comparison test (the highest $p = 0.0001$) demonstrated that there was a statistically significant difference in terms of average bulk density among the cones of the three analysed species.

The obtained value of cone bulk density may be related to the density of forest chips and chips obtained from energetic woody plants. Spinelli et al. [2015] determined the bulk density of forest chips of various origin as falling within the range of 266 to 347 kg·m^{-3}. In any case, the bulk density of cones was lower than values obtained by those authors. On the other hand, Stolarski et al. [2005] determined the bulk density of energy willow. The said density of energy willow chips from willows cultivated for one year (141.9 kg·m^{-3}) and of willows growing for four years (198.8 kg·m^{-3}) was lower than that of empty cones of Scots pine and European larch, but higher than that of Norway spruce cones. On average, the bulk density of Scots pine cones accounted for approximately 15%

TABLE 5. Substitution coefficients K_{zw} and K_{zu} calculated for cones of the analysed species

Parameter	K_{zw}			K_{zu}		
	Scots pine	Norway spruce	European larch	Scots pine	Norway spruce	European larch
AVG	0.15	0.09	0.18	0.26	0.23	0.55
Min	0.14	0.08	0.17	0.25	0.18	0.54
Max	0.16	0.09	0.19	0.29	0.27	0.56
SD	0.0045	0.0035	0.0070	0.01	0.03	0.01
CV	3.04	3.97	3.89	5.12	10.83	0.94
SE	0.001	0.001	0.002	0.003	0.01	0.001

of their specific density; in the case of Norway spruce cones, this ratio was equal to 8.7%, and in case of European larch cones – to 18.0%.

Significant from the point of view of transport, the average value of the substitution coefficient (K_{zu}) for empty cones of coniferous species was 0.55 for larch cones, 0.26 for pine cones and 0.23 for spruce cones (Table 5). Thus, loading space is filled in the tightest manner by larch cones, which leave the least free spaces. The worst fitting properties are those of spruce cones, which results from their structure. Free spaces are observed both between particular cones and between their spread husks. Significantly lower values were obtained with respect to the substitution coefficient (K_{zw}) concerning the specific density of cones. In the case of pine tree, the coefficient was by 42% lower as compared with the one determined with the use of measurement vessel and liquid, whereas in the case of spruce and larch it was lower by 65 and 67%, respectively.

Densification of the wood mass of cones by fragmentation and, additionally, by way of pressure agglomeration will increase the substitution coefficient and allow a more efficient use of loading space [Lisowski et al. 2015].

CONCLUSIONS

1. The volumetric density and specific density of the cones of Scots pine, Norway spruce and European larch was dependent on the analysed species, whereas their bulk density accounted from 9 to 18% of their specific density.
2. The values of substitution coefficient differed considerably among the cones of particular species. In the case of Scots pine cones, the coefficient was equal to 0.26, whereas in the case of Norway spruce it equalled to 0.26 and in the case of European larch – to 0.55. The same coefficient determined with respect to the specific density of cones reached the values of 0.15, 0.09 and 0.18, respectively. The obtained values of this parameter may be used to supplement the norm regarding wood raw materials, as empty cones may be used for energy generation purposes.
3. Determination of the bulk density and substitution coefficient for empty cones of Scots pine, Norway spruce and European larch will allow estimation of other parameters, such as the load size, transport weight of cones for vehicles of various size, as well as profitability of cone transportation at various distances.
4. Because of the low substitution coefficient, in particular in the case of spruce cones, it ought to be estimated for fragmented cones, with additional application of pressure agglomeration. Possible growth of the coefficient after those steps will allow more efficient use of the loading space of transport vehicles.

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Streszczenie: *Logistyka dostaw szyszek wybranych gatunków drzew leśnych. Część 1. Gęstość szyszek i współczynnik zamienny.* Szyszki drzew leśnych można wykorzystywać jako źródło ciepła powstającego podczas ich spalania. Problemem podczas transportu szyszek jest ich mała gęstość usypowa. W artykule przedstawiono analizę gęstości właściwej, usypowej i współczynnika zamiennego pustych szyszek sosny zwyczajnej, świerka pospolitego i modrzewia europejskiego pozyskanych w wyłuszczarniach nasion. Gęstość właściwa szyszek poszczególnych gatunków wahała się w zakresie 1144–1306 $kg \cdot m^{-1}$ i była mniejsza niż gęstość masy drzewnej podawana w literaturze, natomiast zbliżona do gęstości peletu sosnowego. Gęstość usypowa szyszek stanowiła od 9 do 18% ich gęstości właściwej – największa była dla szyszek modrzewia, a najmniejsza dla szyszek świerka. Współczynniki zamienne wyznaczone metodą PN-EN 15103:2010 i za pomocą piknometru helowego wyniosły odpowiednio 0,26 i 0,15 dla szyszek sosny, 0,23 i 0,09 dla świerka oraz 0,55 i 0,18 dla modrzewia. Otrzymane wartości pozwolą na oszacowanie wielkości ładunku i masy transportowej szyszek dla różnych pojazdów, jak również na ocenę opłacalności ich transportu. Ze względu na małą wartość współczynnika zamiennego, szczególnie dla szyszek świerka, należałoby wykonać jego oszacowanie dla szyszek po ich rozdrobnieniu, z zastosowaniem dodatkowo aglomeracji ciśnieniowej.

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