RESULTS OF EXPERIMENTAL STUDIES OF STEM RAW MATERIAL CHOPPER

Viacheslav Bratishko[1], Dmytro Milko[2], Volodymyr Kuzmenko[3], Oksana Achkevych[1]
[1]National University of Life and Environmental Sciences of Ukraine, Ukraine;
[2]Tavria State Agrotechnological University, Ukraine; [3]National Scientific Centre "Institute for Agricultural Engineering and Electrification" of Ukraine, Ukraine
vbratishko@gmail.com, milkodmitry@gmail.com, vfkuzmenko@ukr.net, achkevych@gmail.com

Abstract. Chopping of stem crops is one of the main operations in feed preparation technologies and biofuel production. We have proposed the design of a chopper of stem plant raw materials with a horizontal rotor, which combines in one working chamber two stages of chopping. Using the developed chopper, experimental studies of the process of chopping stem crops were carried out. The aim of the experimental studies was to establish the influence of the chopping process parameters (cutting speed, raw material supply, and the number of counter cuts) on the efficiency indicators - specific energy consumption and average particle size. The parameter of the number of counter cuts characterizes the intensity of the chopping process and is proportional to the number of crossing of the cutting pairs in one turn of the rotor. The raw material for chopping was a mixture of legumes with a predominance of alfalfa with a moisture content of 12.9%. When conducting the research, the limits of variation of factors were: the cutting speed – 36.19-54.29 $m \cdot s^{-1}$, raw material supply – 0.0167-0.0333 $kg \cdot s^{-1}$, the number of counter cuts – 21-49 pieces. As a result of processing the obtained data, the dependences of the optimization criteria on the studied factors in the form of second-order polynomials were established. The coefficient of multiple determination for the model of specific energy consumption is D = 0.796819, for the average length of the chopped particles D = 0.857278. The coefficients of the models are significant at the confidence level of at least 94%. Depending on the values of the studied parameters, the specific energy consumption for the chopping process varied from 4.00 to 15.83 $kWh \cdot t^{-1}$, the average length of the chopped particles - from 3.43 to 6.04 mm. Experimental studies have proved the possibility of establishing the optimal values of the parameters of the chopping process for a given length of particles of stem raw materials.

Keywords: stem plant bioresources, chopper, cutting speed, specific energy consumption.

Introduction

Grinding of plant materials is an integral part of technological processes of biofuel production and feed preparation [1-4]. The degree of grinding and the weighted average particle size of stem plant raw materials determine the efficiency of further technological operations [5; 6]. It is also known that choppers of plant stem materials, which work on the principle of cutting, provide significantly lower values of specific energy consumption compared to machines in which the grinding of raw materials is carried out using impact-type working bodies.

The organized supply of material to the working bodies of the chopper allows increasing the efficiency of the chopping process and the homogeneity of the product [7; 8], to ensure the most efficient sliding cutting of raw materials [9]. However, this is mainly characteristic of chopping devices of harvesting machines and does not come into practical use in fine grinding of raw materials.

Preliminary studies allow us to conclude about the effectiveness of the use for grinding plant materials the choppers that implement the movement of the working bodies in many planes. This feature allows to ensure a relatively high homogeneity and the degree of grinding of stem raw materials by single technical means. The degree of grinding and the weighted average particle size of the crushed raw material are determined by both the speed of the working bodies and their number or number of meetings of the cutting pairs per turn of the chopper shaft. The main indicators that determine the effectiveness of technical means for grinding plant raw materials in feed preparation technologies and biofuel production are the specific energy costs for the grinding process and the quality of grinding [10; 11]. The weighted average particle size of crushed plant raw materials also significantly impacts the efficiency of further technological operations, such as the production of fuel pellets [12] or fermentation [1; 3].

Materials and methods

The objective of the experimental studies was to establish the influence of the parameters of the process of crushing stem plant raw materials (cutting speed v, $m \cdot s^{-1}$; feed of raw materials q, $kg \cdot s^{-1}$ and the number of countercuts *n*, pcs.) on the efficiency of the grinding process (specific energy consumption *E*, kWh·t^{-1} and weighted average length of crushed particles *l*, mm).

A sample of a chopper of stem materials was used for experimental research. The working chamber of the chopper is presented in Fig. 1.

The experimental sample of the chopper had the following main design parameters: diameter of the working chamber – 315 mm; rotor diameter – 159 mm; working length of the rotor (distance between the outside planes of the knives) – 600 mm; distance between knives (counter cuts) – 40 (80) mm; number of knives in one plane – 2 (4) pieces; the maximum number of countersinks in one plane – 5 pieces; angle of sharpening of knives – 15 ± 5 degrees; sharpening angle of counter-cuts – 45 ± 5 degrees.

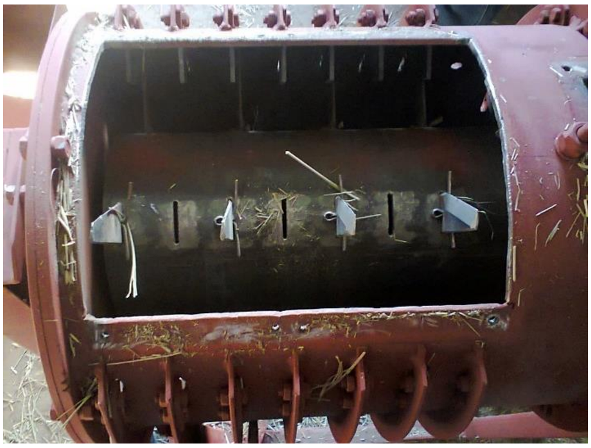

Fig. 1. **Working chamber of the chopper (with removed loading mouth)**

The intensity of grinding, namely, the number of meetings of the cutting pairs, was changed by installing a different number of countercuts.

To determine the specific energy consumption for the grinding process a pulse electricity meter NIK 2301 AP2 with a device for automatic counting of the number of pulses was used. Energy consumption was determined by counting the number of pulses during each repetition of the experiment. In this case, the energy consumption per kilowatt-hour corresponded to 8,000 pulses of the meter. The rotor shaft speed was changed using a DELTA VFD037EL43A electric current frequency converter. Idle energy consumption was determined for each rotor speed and taken into account when calculating the specific energy consumption for the grinding process.

A mixture of legumes with a predominance of alfalfa was used as a raw material for experimental studies. The initial humidity of stem plant raw materials was 12.9%, the weighted average particle size was 142 mm. The physico-mechanical properties of stem raw materials were determined in accordance with current regulations and generally accepted methods [13], using the scales RN 50SHVP-1 and scales VLK-500-M. The moisture content of the raw material was determined according to the method [14], using an Ultra X device by drying the portion until a constant mass for 1 hour. The humidity of raw materials *W* in percent was determined by the formula:

$$W = \frac{m_w - m_d}{m_w} 100, \tag{1}$$

where m_w, m_d – respectively, the mass of the sample before and after drying, g.

To determine the particle size distribution parameters of raw and crushed raw materials (Fig. 2) sieve classifiers were used with laboratory sieves metal-permeable TU U 28.7-2210200135-002:2007. Determination of the weighted average size of crushed feed particles was carried out according to the method described in DSTU 4877: 2007 [15]:

$$l_s = \frac{\frac{l_{s1}}{2} \cdot m_1 + \frac{l_{s1} + l_{s2}}{2} \cdot m_2 + \ldots + \frac{l_{si-1} + l_{si}}{2} \cdot m_i}{\sum m_i}, \tag{2}$$

where $l_{s1}, l_{s2}, \dots, l_{si}$ – average particle size of the *i*-th fraction, mm.

Fig. 2. **Crushed stem raw materials**

The studied factors and levels of their variation are presented in Table 1.

Table 1

Experimental factors and their levels of variation

Levels of variation of factors	Factors		
	Cutting speed v (x_1), m·s^{-1}	Number of countercuts n (x_2), pcs.	Feed of raw materials q (x_3), kg·s^{-1}
Top level (+1)	54.29	49	0.0333
Basic level (0)	45.24	35	0.0250
Lower level (-1)	36.19	21	0.0167
Interval of variation	9.05	14	0.0083

The data obtained as a result of the experiment were processed by the methods of mathematical statistics. The primary data processing was reduced to the calculation of arithmetic mean measurements, finding the standard error, and checking the homogeneity of variances by the Cochran test [16].

To analyse the results of experimental studies the program RegMod "Methodology for modelling normatives by regression analysis" was used, developed at NSC "IAEE"[3], which implements known methods of correlation and regression analysis [17; 18].

According to the results of the experiment, mathematical models were built - regression equations in the form of second-order polynomials [19]. In order to study the response surfaces of the obtained models, the corresponding graphs were built using the software package Wolfram Mathematica.

Results and discussion

The results of the experimental studies of the influence of the studied factors on the experimental criteria are shown in Table 2.

After processing the results of the three-factor experiment, the dependence of the optimization criterion on the studied factors was obtained - the regression equation in the form of a second-order polynomial.

For the criterion of specific energy consumption of grinding (E, kWh·t^{-1}) the obtained model had the form:

$$E = 11.819 + 2.084x_1 - 1.699x_2 + 0.834x_1x_2 - 1.173x_2^2 - 0.614x_3 - 1.993x_3^2, \quad (3)$$

and in decoded view:

$$E = -7.496 + 1.372 \cdot 10^3 q + 6.579 \cdot 10^{-3} vn - 5.985 \cdot 10^{-3} n^2 - 28.926 \cdot 10^3 q^2, \quad (4)$$

where v – cutting speed (factor x_1), m·s^{-1};
n – number of countercuts (factor x_2), pcs.;
q – feed of raw materials (factor x_3), kg·s^{-1}.

Dependence (3), (4) is adequate at the 95% confidence level. The coefficient of multiple determination is $D = 0.797$, the coefficient of multiple correlation $R = 0.893$. The value of the Fisher test $F = 9.804$; the probability of the F-criterion $P = 0.999$. All model coefficients are significant at a confidence level of at least 94%.

Table 2

Results of experimental studies

Levels of variation of factors, matrix of experiment	**Factors**			**Average value of criteria**	
	***v*, m·s^{-1}**	***n*, pcs.**	***q*, kg·s^{-1}**	**Specific energy consumption *E*, kWh·t^{-1}**	**Weighted average length of crushed particles *l*, mm**
Top level (+)	54.29	49	0.0333		
Basic level (0)	45.24	35	0.0250		
Lower level (-)	36.19	21	0.0167		
Interval of variation	9.05	14	0.0083		
Experiment	Box-Behnken design (B3)				
	x_1	x_2	x_3		
1	1	1	1	10.06	3.43
2	1	1	-1	8.25	4.84
3	1	-1	1	11.31	5.75
4	1	-1	-1	11.88	3.50
5	-1	1	1	4.75	4.30
6	-1	1	-1	4.00	5.36
7	-1	-1	1	7.75	6.04
8	-1	-1	-1	9.88	4.61
9	1	0	0	15.83	3.91
10	-1	0	0	9.83	4.96
11	0	1	0	8.92	3.61
12	0	-1	0	11.75	4.31
13	0	0	1	7.50	5.24
14	0	0	-1	13.50	5.07
15	0	0	0	10.42	5.56

For the criterion of the weighted average length of the crushed particles (l, mm) the obtained model had the form:

$$l = 4.820 - 0.384\, x_1 - 0.038\, x_1^2 - 0.267\, x_2 - 0.501\, x_2^2 + 0.149\, x_3 - 0.804\, x_2\, x_3 + 0.358\, x_3^2, \qquad (5)$$

and in decoded view:

$$l = 65.622 \cdot 10^{-3} + 0.333\, n - 4.687 \cdot 10^{-4} v^2 - 2.556 \cdot 10^{-3} n^2 - 6.916 n\, q + 5.2 \cdot 10^3 q^2. \qquad (6)$$

Dependence (5), (6) is adequate at the 95% confidence level. The coefficient of multiple determination is $D = 0.857$, the coefficient of multiple correlation $R = 0.926$. The value of the Fisher test $F = 10.812$; the probability of the F-test $P = 0.999$. All model coefficients are significant at a confidence level of at least 96%.

To analyze the obtained dependences (3-6) we received their graphical interpretations (Fig. 3, 4).

Depending on the values of the studied parameters, the specific energy consumption for the chopping process varied from 4.00 to 15.83 kWh·t^{-1}, the average length of the chopped particles – from 3.43 to 6.04 mm (average values of measurements according to (2)). Analysis of the surfaces shown in Fig. 3 and 4 show that the effect of the number of cross-sections on the performance of the grinding process is somewhat contradictory. In our opinion, the nature of these dependencies is due to the fact that the countercuts can act as local obstacles to the movement of material in the middle of the working chamber of the chopper.

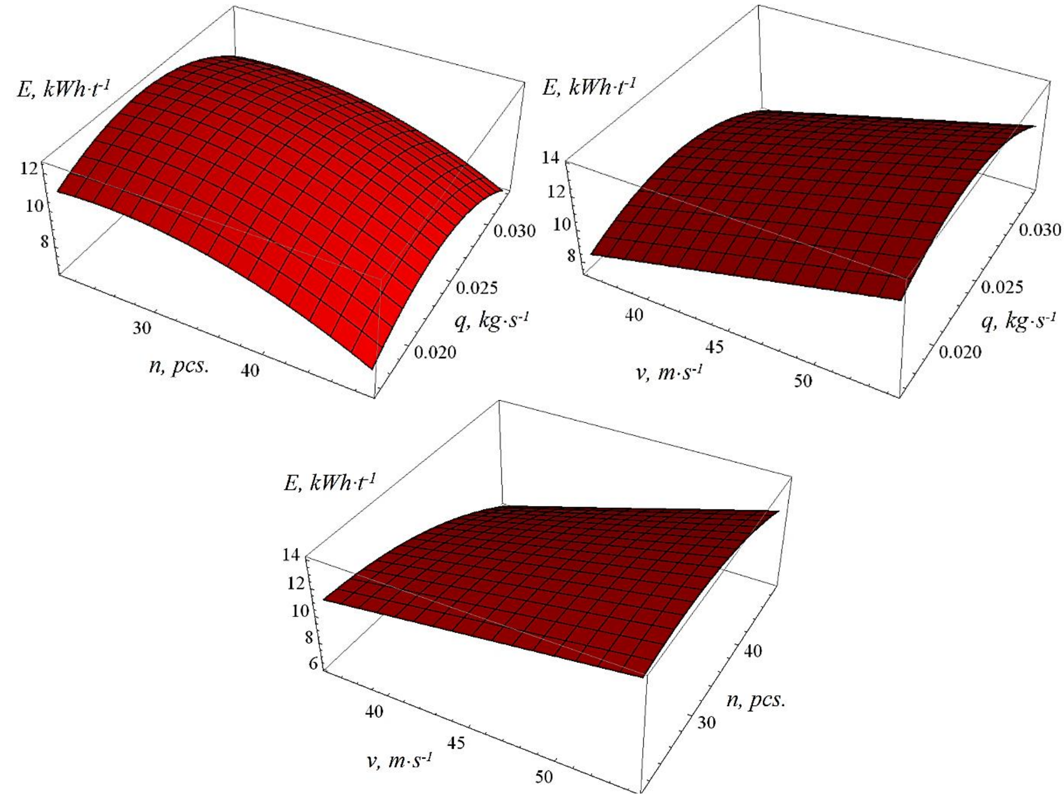

Fig. 3. **Influence of parameters of cutting speed (*v*, m·s^{-1}), number of countercuts (*n*, pcs.) and feed of raw materials (*q*, kg·s^{-1}) on specific energy consumption (*E*, kWh·t^{-1}) of grinding process (value of parameters, absent on the graph, corresponding to their zero levels)**

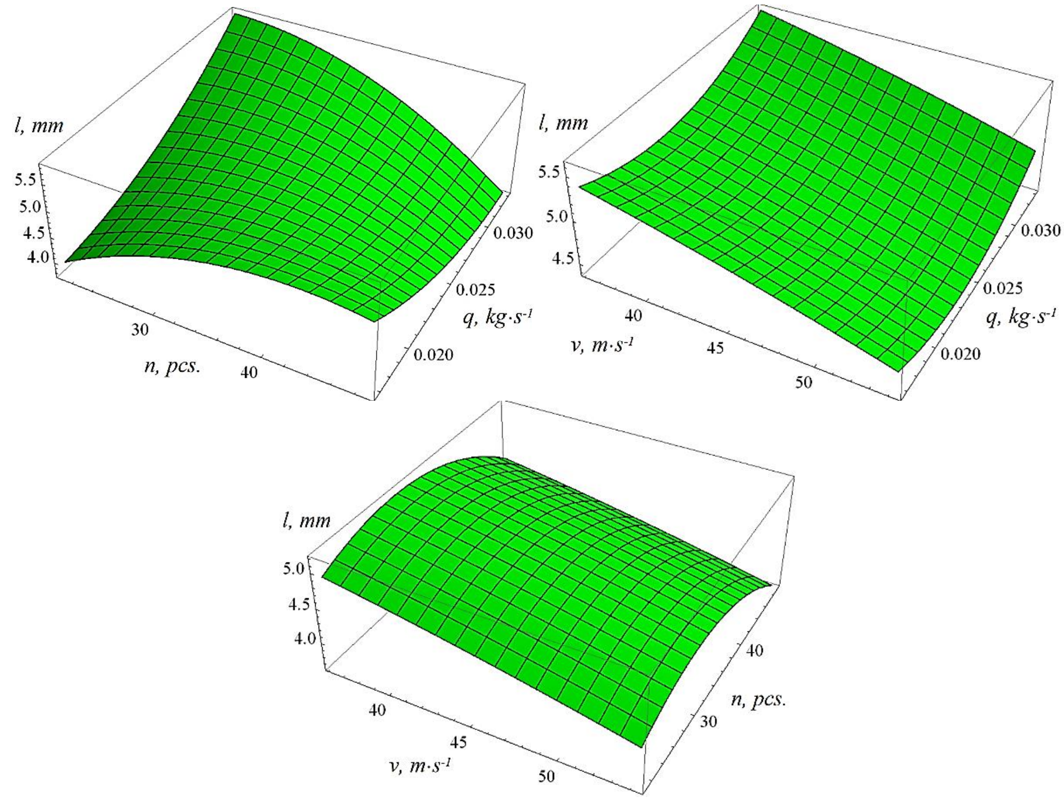

Fig. 4. **Influence of parameters of cutting speed (*v*, m·s^{-1}), number of countercuts (*n*, pcs.) and feed of raw materials (*q*, kg·s^{-1}) on weighted average length of crushed particles (*l*, mm) of grinding process (value of parameters, absent on the graph, corresponding to their zero levels)**

It is obvious that the rational values of the parameters of the chopper of plant materials should be determined, taking into account the conditions of minimizing the specific energy consumption, the weighted average length of the crushed particles of stem materials, and maximizing the productivity of the chopper. The fixation of the weighted average length of the crushed particles at a given level allows to set the optimal values of the parameters of the process of grinding stem raw materials.

Under these conditions, the rational parameters of the process of grinding stem plant raw materials by the grinder of the above design are: cutting speed $v = 36.19$ m·s^{-1} (x_1 = -1); number of countercuts $n = 49$ pcs. (x_2 = + 1); feed of raw materials $q = 0.0333$ kg·s^{-1} (x_3 = + 1).

Given the nature of the experimental dependences, it may be appropriate, in terms of reducing the specific energy of cutting, to reduce the cutting speed to the values adopted in [9]. However, the limiting parameter, in this case, is the given length of particles of crushed raw materials.

At these values, the specific energy consumption for the grinding process will be 4.75 kWh·t^{-1}, the weighted average length of the crushed particles - 4.30 mm, and the productivity of the chopper – 120 kg·h^{-1}, which corresponds to the best samples of choppers available on the market.

Conclusions

As a result of a three-factor experiment, adequate equations of the influence of the parameters of the process of grinding stem bio raw materials on the efficiency indicators – the specific energy consumption of the grinding process and the weighted average length of the crushed particles were obtained. It was found that depending on the values of the studied parameters, the specific energy consumption for the grinding process varied from 4.00 to 15.83 kWh·t^{-1}, and the weighted average length of the crushed particles – from 3.43 to 6.04 mm.

Rational parameters of the process of grinding stem plant raw materials by the chopper of the given design are established: cutting speed $v = 36.19$ m·s^{-1}; number of countercuts $n = 49$ pcs. and feed of raw materials $q = 0.0333$ kg·s^{-1}. At these values of parameters, the specific energy consumption for the grinding process will be 4.75 kWh·t^{-1}, the weighted average length of the crushed particles – 4.30 mm, and the productivity of the chopper - 120 kg·h^{-1}, which corresponds to the best samples of choppers of such purpose.

References

[1] Hassan S.S., Williams G.A., Jaiswal A.K. Emerging technologies for the pretreatment of lignocellulosic biomass. Bioresource Technology. 2018. Vol. 262. pp. 310-318.
[2] Pakhomov V., Braginets S., Bakhchevnikov O., Rudoy D. Effect of extrusion on nutritional composition of feed containing mussel meat: experimental study results. Proceedings of 19th International Scientific Conference “Engineering for Rural Development”. Volume 19, 2020, Jelgava, Latvia University of Life Sciences and Technologies, Latvia, pp. 306-312.
[3] Muthuvelu K.S., Rajarathinam R., Kanagaraj L.P., Ranganathan R.V., Dhanasekaran K., Manickam N.K. Evaluation and characterization of novel sources of sustainable lignocellulosic residues for bioethanol production using ultrasound-assisted alkaline pre-treatment. Waste Management. 2019. Vol. 87. pp. 368-374.
[4] Khmelovskyi V., Otchenashko V., Voloshyn S., Pinchevska O. Providing processes of preparation and distribution of feed for cattle on animal husbandry farms. Proceedings of 19th International Scientific Conference “Engineering for Rural Development”. Volume 19, 2020, Jelgava, Latvia University of Life Sciences and Technologies, Latvia, pp. 778-783.
[5] Milko D.O., et al. Results of the nutritional preservation research of the alfalfa laying on storage with two-phase compaction. INMATEH - Agricultural Engineering. 2020. Vol. 60. No. 1. pp. 269-274.
[6] Bratishko V., Milko D., Achkevych O., Kuzmenko V. Results of experimental studies of process of preparation of feed mixtures with their moistening. Proceedings of 19th International Scientific Conference “Engineering for Rural Development”. Volume 19, 2020, Jelgava, Latvia University of Life Sciences and Technologies, Latvia, pp. 1398-1403.
[7] Nedelcu A., Ciuperca R., Zaica A., Stefan V. Influence of forage harvester chopping equipment on characteristics of chips. Proceedings of 19th International Scientific Conference “Engineering for

Rural Development". Volume 19, 2020, Jelgava, Latvia University of Life Sciences and Technologies, Latvia, pp. 1319-1324.
[8] Nulle I., Kakitis A., Smits M., Vronskis O. Mathematical modeling of stalk biomass shredding process. Proceedings of 18th International Scientific Conference "Engineering for Rural Development". Volume 18, 2019, Jelgava, Latvia University of Life Sciences and Technologies, Latvia, pp. 1516-1522.
[9] Popa R., Popa V. Computer assisted simulation of forage chopping process. Proceedings of 18th International Scientific Conference "Engineering for Rural Development". Volume 18, 2019, Jelgava, Latvia University of Life Sciences and Technologies, Latvia, pp. 1118-1122.
[10] Khmelovskyi V., Rogach S., Tonkha O., Rosamaha Y. Quality evaluation of mixing fodder by mobile combined units. Proceedings of International Scientific Conference "Engineering for Rural Development". Volume 18, 2019, Jelgava, Latvia University of Agriculture, Latvia, pp. 299-304.
[11] Андрущак В. и др. Профессиональное кормопроизводство: сенаж, силос, сено (Professional feed production: haylage, silage, hay). Kyiv: Grain, 2012. 168 p. (In Russian).
[12] Golub G., Tsyvenkova1 N., Chuba V., Yarosh Y. Bulk density of chopped wheat straw - influence of moisture content, fine fraction content and coefficient of compaction. Proceedings of 19th International Scientific Conference "Engineering for Rural Development". Volume 19, 2020, Jelgava, Latvia University of Life Sciences and Technologies, Latvia, pp. 1892-1899.
[13] GOST 27262-87 Vegetable feeds. Sampling methods
[14] GOST 27548-87 Vegetable feeds. Methods for determination of moisture
[15] DSTU 4877:2007 Ground stem feeds. Basic indexes of fractional composition and research methods
[16] Новицкий П.В., Зограф И.А. Оценка погрешностей результатов измерений (Evaluation of measurement errors). Л.: Энергоатомиздат, 1991. 303 с. (In Russian).
[17] Chiang,C.L. Statistical methods of analysis. World Scientific. 2003. 274 p.
[18] Montgomery D. Design and Analysis of Experiments (10th ed.). New York: Wiley, 2001. 567 p.
[19] Mamchych T., Olenko A., Osypchuk M., Shportyuk V. Data statistical analysis with Statistica. Kyiv: Vidrodzhennya, 2006. 208 p.