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Studies of a Rotary–Centrifugal Grain Grinder Using a Multifactorial Experimental Design Method

Andrzej Marczuk [1], Agata Blicharz-Kania [2,*], Petr A. Savinykh [3], Alexey Y. Isupov [3], Andrey V. Palichyn [4] and Ilya I. Ivanov [4]

1 Department of Agricultural, Forestry and Transport Machines, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland; andrzej.marczuk@up.lublin.pl
2 Department of Biological Bases of Food and Feed Technologies, University of Life Sciences in Lublin, Głęboka 28, 20-612 Lublin, Poland
3 Federal Agricultural Research Centre of the North-East Named after N.V. Rudnitskiy, Kirov 610007, Russia; peter.savinykh@mail.ru (P.A.S.); isupoff.aleks@yandex.ru (A.Y.I.)
4 FSBEI HE Vologda State Dairy Farming Academy (DSFA) named after N.V. Vereshchagin, Vologda—Molochnoye 160555, Russia; zmij.hh@yandex.ru (A.V.P.); kadyichna@mail.ru (I.I.I.)
* Correspondence: agata.kania@up.lublin.pl; Tel.: +48-81-531-9646

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Abstract: A scientific and technical literature review on machines designed to grind fodder grain revealed that the existing designs of grinding machines—those based on destruction by impact, cutting, or chipping—have various drawbacks. Some disadvantages include high metal and energy intensity, an uneven particle size distribution of the ground (crushed) product, a high percentage of dust fraction, the rapid wear of work tools (units), and heating of the product. To eliminate most of the identified shortcomings, the design of a rotary–centrifugal grain grinder is proposed in this paper. The optimization of the grinder's working process was carried out using experimental design methodology. The following factors were studied: the grain material feed, rotor speed (rpm), opening of the separating surface, number of knives (blades) on the inner and outer rings, technical conditions of the knives (sharpened or unsharpened), and the presence of a special insert that is installed in the radial grooves of the distribution bowl. The optimization criteria were based on the amount of electricity consumed by and the performance of the rotary–centrifugal grain grinder. The quality of performance was quantified by the finished product, based on the percentage of particles larger than 3 mm in size. An analysis of the results of the multifactorial experiment allowed us to establish a relationship (interaction) between the factors and their influence on the optimization criteria, as well as to determine the most significant factors and to define further directions for the research of a centrifugal–rotary grain grinder. From our experimental results, we found that the grinder is underutilized in the selected range of factor variation. Furthermore, the number of knives installed at the second stage of the grinder, the gap (clearance) of the separating surface, and the technical condition of the knives are among the most important factors influencing the power consumption and the quality of the resulting product. A reduction in the number of knives at the first stage has a positive effect on all the selected optimization criteria; and by varying the factors in the selected range, it is possible to obtain a product corresponding to medium and coarse grinding.

Keywords: grain grinding; rotary–centrifugal grinder; construction optimization criteria

1. Introduction

In the cost structure of feed production, grinding represents a very labor- and energy-intensive process, constituting, according to various datasets, at least half of the total costs associated with the conservation, storage, and preparation of feed mixtures. Hence, implementing a sustainable design of tools and processes is becoming increasingly important for manufacturers [1]. There is an increasing use of concentrated feed in the composition of mixed fodder [2–4]. An important factor for improving the digestibility and ensuring the most complete extraction of the potential energy of the feed is the method of its grinding. To date, the most common method in agricultural production is grinding with hammer mills (disintegrators) [5–7]. However, modern requirements for the quality of the feed obtained in the grinding process require the minimization of metal and energy intensity.

The main approach for solving the problems discussed above is to improve existing machines and devices (units) by optimizing structural elements and the subsequent control of technological operating modes. Furthermore, one can develop and implement technical solutions based on new physical principles or by combining several previously known approaches. Thus, recently, the design of grinders has become of great practical interest in the field of grinding grain. It is possible to significantly reduce the specific energy consumption for the production of concentrated feed and obtain a product with a high uniformity of particle size by combining the grinding process with shearing and chipping [5,8–15].

Pushkarev A.S. and Fomin V.V. [3,16], in their research on the parameters of the work tools (units) of a centrifugal–rotary grain grinder, found that by modifying the curvilinear shape of the cutting pair, the specific energy intensity of the grinding process of grain is reduced; increasing the grinder's performance without changing its energy consumption. Further they found, the moisture content of the material being crushed has a significant effect on the specific energy intensity of the grinding process; an increase in the moisture content of grain, increases the energy consumption. However, the trend towards a decrease in energy intensity remains when curvilinear work tools are used. Finally, by taking into account the change in the optimal cutting angle of the material being processed as it moves in the channel of the work tool of a small-size centrifugal–rotary grinder, the grain size distribution (granulometric composition) is equalized, the dust fraction decreases, and there are no whole grains in the finished product [3,16].

Based on the analysis of Druzhynin R.A. and Ivanov V.V. [2,4] on the research of theorists and practitioners, it is recommended to use two-stage grinding for the manufacture of coarse and medium grinding products. Additionally, multi-stage crushers and grinders are more effective to obtain a fine grinding product. At the same time, the disadvantages of knife-type grinders compared to impact crushers are also noted [17]: intensive wear of the working parts (knives), a sharp decline in the quality of grinding as a result of wear of the working bodies (knives), and a higher specific energy consumption than crushers, with greater productivity.

Considering the existing industrial designs of grinders that have knives (blades) as work tools, it can be seen that they are used mainly in personal subsidiary farms, where high performance and drive power are not required, but a low price and simplicity of design are needed. Such crushers are widely represented on the market by the following manufacturers: Electromash, Greentechs, Bison, Kolos, Yarmash, Cyclone, Niva, Fermer, ZDN, etc. [17].The analysis of existing models of grinders on the market and scientific research on grinding and crushing suggests that the search continues for a method of grinding feed which improves the economic efficiency of the process, while simultaneously ensuring a high quality of the resulting product of concentrated feed.

The purpose of this study is to assess the structural elements and various operating modes of a rotary–centrifugal grinder according to key performance indicators. The task of the study is to determine the significance of factors (x_1–x_7) according to certain optimization criteria (y_1–y_3), allowing for more specific implementation in further research of rotary–centrifugal grain grinders.

2. Materials and Methods

2.1. Design of a Rotary–Centrifugal Device for Grinding Grain

Based on the analysis of the designs of crushers and grinders, we have developed and proposed the design of a rotary–centrifugal device for grinding grain [18]. The proposed device (Figure 1) consists of a stationary case or housing (1) with loading (input, 2) and output (3) nozzles. Two adjacent disks are coaxially mounted inside the housing (1): the upper (4) (Figure 2a) and the lower movable disks (5) (Figure 2b). On the work surface of the lower disk (5) there are annular protrusions (6), and on the work surface of the upper disk (4) there are installed knives (7), which are diamond-shaped with small cutting angles with respect to the large diagonals. The outer row of knives (8) forms a separating surface; thus, changing the angle of the knives makes it possible to continuously adjust the degree of grinding for the material. The lower disk (5) has grooves (9) in the radial direction which are made opposite in terms of angle to the direction of rotation of this disk. The lower disk (5) is mounted on the flange of the drive shaft (10) and is rotated by means of a pulley (11) mounted on it. The upper disk (4) is rigidly fixed to the stationary case (1). In the upper part of the stationary case, a receiving chamber (12) is installed, which is formed by vertical walls. The receiving chamber (12) communicates in its upper part with the loading nozzle (2) and is connected with the working chamber (14), which is the space between disks (4) and (5), through the radial windows (13).

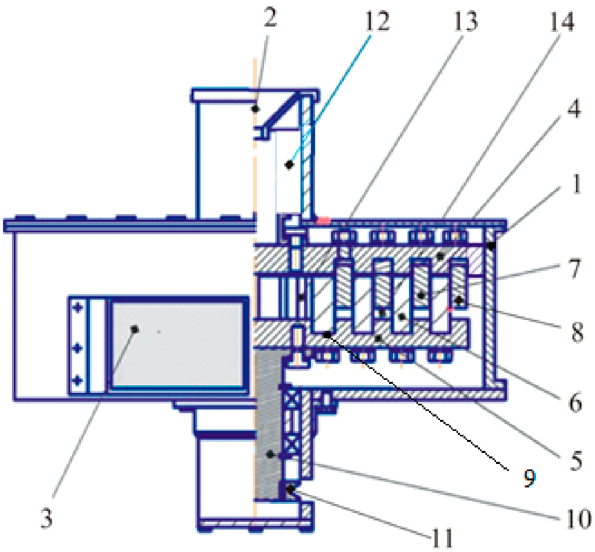

Figure 1. Design overview of a rotary–centrifugal device for grinding bulk materials. Parts include: 1—case; 2—loading (input); 3—output nozzles; 4—upper disk; 5—lower movable disk; 6—annular protrusions; 7—knives; 8—outer row of knives; 9—groove; 10—drive shaft; 11—pulley; 12—receiving chamber; 13—radial windows; and 14—working chamber.

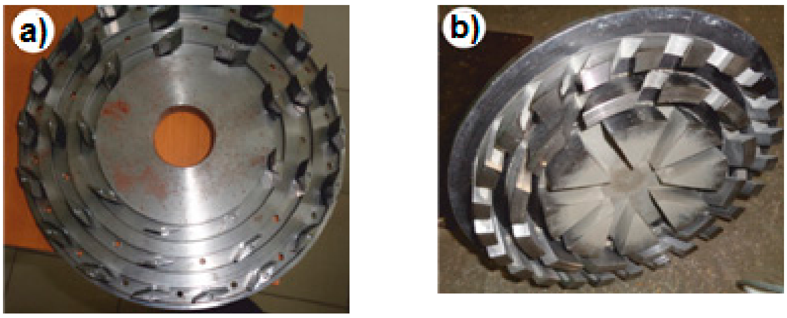

Figure 2. Photographs of the (**a**) upper disk and (**b**) lower disk.

The working process of grinding grain in the rotary–centrifugal device is carried out as follows (Figure 1). The incoming grain is subjected to the mechanical action of the first cutting pair; then, under the action of centrifugal forces, the pre-ground material moves along the grooves to the next pair. Then, the ground grains (groats or stock feed), having reached the outer row of the knives (8) which form the separating surface, pass into the gap between the knives (8) and, under the influence of the air flow created by the rotating lower disk (5), leave the housing (1) through the outlet nozzle (3).

The studies were carried out on an experimental installation of a rotary–centrifugal grinder (Figure 3) made on-site at the Federal State Budgetary Educational Institution of Higher Professional Education Vologda State Dairy Farming Academy (DSFA) named after N.V. Vereshchagin.

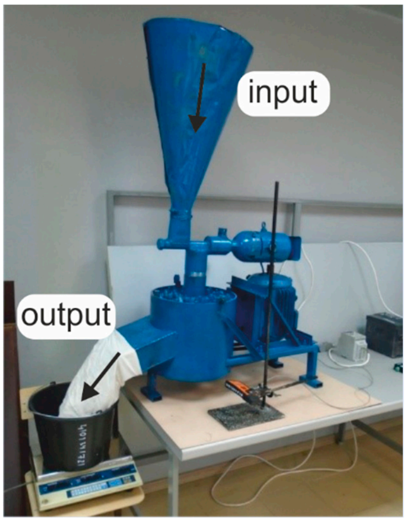

Figure 3. Overview of the experimental installation.

2.2. Description of a Multifactorial Experimental Design

To achieve the objectives of the study, the method of a multifactorial experimental design was applied. The analysis of the design of the grinder and a review of scientific and technical literature on grain grinding made it possible to identify a number of factors (Table 1) which allow us to most fully describe the process of grinding in the proposed centrifugal–rotary grinder. Below is a brief description of the selected factors (x_1–x_7) and how they vary:

- Grain was fed to the cumulative bunker of the experimental rotary–centrifugal installation with an auger conveyor and a frequency-controlled drive x_1, with a power inverter-controlled electric motor, Hyundai N700-220HF (Seul, South Korea);
- The rotation frequency of the lower disk (Figure 2b) x_2 was varied using a frequency-controlled drive with an electric motor controlled by an another Hyundai N700-220HF power inverter;
- The opening of the separating surface x_3 was adjusted by setting an appropriate size between the parallel planes of two adjacent knives, h_1 (Figure 5) on the outer row of knives (Figure 2a);
- The knives at the first x_4 and second x_5 stages of the upper disk (Figure 2a) were installed evenly, depending on the required quantity;
- To assess the impact of knife sharpening loss during operation, a factor of the technical condition of the knives x_6 was introduced as an experimental variable; i.e., "new" knives with a given angle of sharpening $\chi = 24°$ and "old" knives that have a much larger angle of sharpening (unsharpened knives); i.e., imitating their bluntness;
- The presence of inserts x_7 (Figure 4), installed in the slot of the distribution bowl of the lower disk (Figure 2b), was also considered. Eight inserts were installed in order to change the trajectory and rate of the material feed to the cutting pairs.

Table 1. Grinder experimental factors and the levels of their variations.

Factors	x_1 (kg·s^{-1})	x_2 (min^{-1})	x_3 (mm)	x_4 (pcs)	x_5 (pcs)	x_6	x_7
−1	0.023	800	2.5	9	18	"Old" ones	Present
+1	0.038	1200	3.2	3	9	"New" ones	Absent

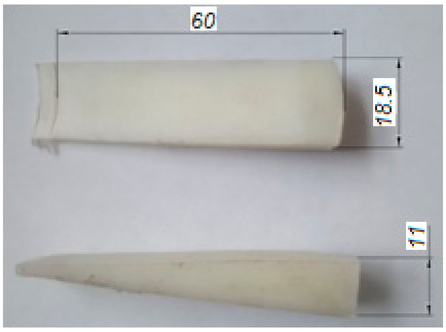

Figure 4. Geometry of the inserts with appropriate dimensions labeled.

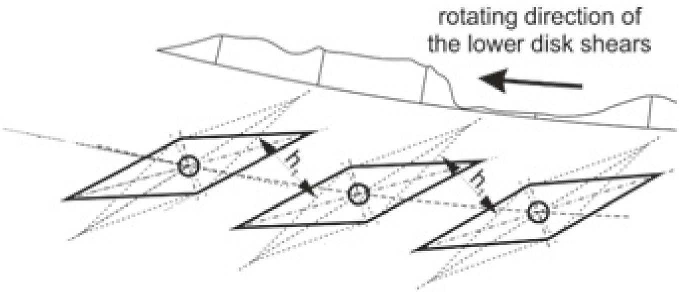

Figure 5. Geometry of the opening of the separating surface. h_1—size between the parallel planes of two adjacent knives.

Barley with 14% moisture content was used as the ground material. To reduce the amount of research, a type 2^{7-2} matrix of the fractional factor experiment was used.

The optimization criteria included the power consumption y_1 (kW) and the grinder performance (capacity) y_2 (kg/s). The measurement of power consumption was carried out using a Mercury 221 electrical energy meter connected to a PC via USB in CAN/RS-232/RS485 (Figure 6). The indicators were monitored instantly using a K-505 measurement kit.

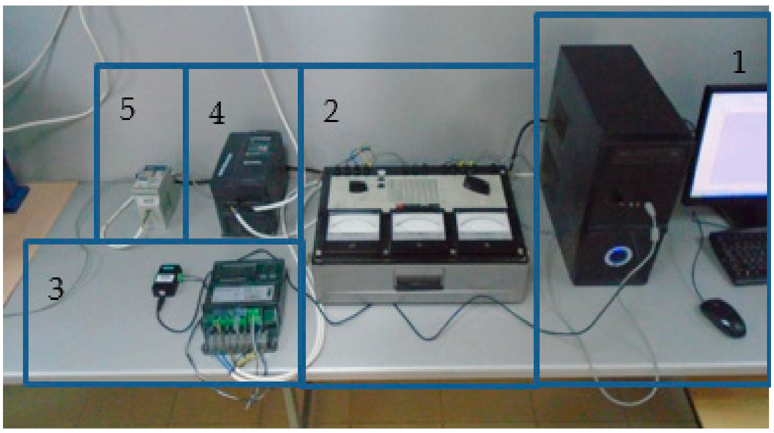

Figure 6. A set of measuring equipment used for the research. 1—personal computer; 2—K-505; 3—Mercury 221 electric energy meter with USB-CAN/RS-232/RS485 adapter; 4—frequency converter Hyundai N700-220HF; 5—circuit breaker

The performance (capacity) of the experimental installation y_2 was determined by monitoring the mass of the ground material per unit of time under a steady operating mode.

Zoo-technical requirements for mixed fodder concentrate according to GOST 9268-2015, GOST R 51550-2000, and other guidelines highlight a number of criteria for assessing the quality of the resulting product. However, the criteria directly dependent on the design and operating mode of the grain grinder. Some criteria are the percentage of particles greater than 3 mm y_3 after grinding, the grinding coarseness y_4, and the presence of whole grains in the grinding results y_5.

3. Results and Discussion

The results of the sieve analysis reveal that the most critical parameter for the compliance of the finished product with the zoo-technical requirements is the percentage of particles greater than 3 mm, y_3, which in our results is up to 60%. Screen sizing also shows the complete absence of whole grains y_5 in all samples. Calculations of the grain size (grinding coarseness) y_4 shows that grains are within the range of 1.5–3.2 mm. However, the use of this indicator as an optimization criterion at this stage is not informative, since the grain size depends largely on the percentage of particles greater than 3 mm. Thus, in this study, the most significant criterion for assessing the quality of the product is the percentage of particles greater than 3 mm, y_3. The critical particle size in different experiments depends on many factors (type of material, intended use, and subsequent processing) [19,20].

The processing of the results of the multifactorial experiment was carried out using the StatGraphics software package. A multivariate analysis of variance ANOVA (Table 2) and the regression results in Equations (1)–(3) show that the models obtained are statistically significant and describe the current processes with a reliability of at least 95%.

$$y_1 = 3.89 + 0.12x_1 + 0.2x_2 - 0.15x_3 + 0.3x_5 - 1.3x_6 + 0.28x_1x_3 + 0.12x_1x_5 - 0.28x_2x_4 + \\ +0.14x_3x_6 - 0.18x_3x_7 + 0.12x_4x_7 \quad (1)$$

$$y_2 = 0.021 + 0.004x_1 + 0.003x_2 - 0.001x_3 + 0.002x_6 + 0.002x_1x_2 - 0.001x_1x_3 + \\ +0.001x_2x_3 + 0.001x_2x_4 \quad (2)$$

$$y_3 = 13.1 + 1.71x_1 - 3.38x_2 - 5.6x_3 + 2.4x_4 + 5.75x_5 + 8.88x_6 - 2.6x_7 + 3.01x_1x_4 - \\ -1.68x_2x_6 - 8.16x_3x_6 + 3.2x_3x_7 \quad (3)$$

Table 2. Results of the model's analysis of variance (ANOVA).

	y_1	y_2	y_3
p-value	<0.0001	<0.0001	<0.0001
Error d.f.	20	18	20
Standard Error	0.464976	0.001784	4.21375
R-squared	0.9426	0.9564	0.9589

The search for a compromise solution aimed at reducing the amount of energy consumed y_1 and the percentage of particles exceeding 3 mm y_3, while increasing the performance (capacity) y_2 of the centrifugal–rotary grain grinder, was carried out using the StatGraphics software package (Table 3). The optimal values of the factors, obtained for the compromise solution in the selected range of factor variation, are presented in Table 4.

Table 3. Optimization criteria for the three factors, calculated using the StatGraphics software package.

Optimization Factor	Goal	Sensitivity	Lower Level	Upper Level	Average Predicted Value	Lower 95.0% Limit	Upper 95.0% Limit	Goal Achieved
y_1 (kW)	Minimize	Medium	-	-	2.59	2.00	3.18	0.76
y_2 (kg·s^{-1})	Maximize	Medium	-	-	0.032	0.0303	0.034	0.86
y_3 (%)	Minimize	Medium	0.0	10.0	−0.000022	−4.91	4.91	1.0

Table 4. Optimal values of the factors obtained using the StatGraphics software package.

Factor	x_1	x_2	x_3	x_4	x_5	x_6	x_7
Specified value	1	1	1	0.057	−1	1	1
Actual value	0.038 kg·s^{-1}	1200 min^{-1}	3.2 mm	6 pcs	9 pcs	"new" knives	no insert

The conducted analysis of the influence of factors on electricity consumption (1), and the performance of the centrifugal–rotary grinder (2), as well as the content of particles larger than 3 mm after grinding (3) reveals the following:

One of the most significant factors influencing the performance of the grinder y_2 is the feed of grain x_1 (Figure 7d). At the same time, an increase in the grain feed x_1 leads to an increase in all indicators y_1, y_2, and y_3. This is a consequence of an increased volume of material being transported by the lower disk of the grinder and an increased speed of transportation through the centrifugal–rotary grinder.

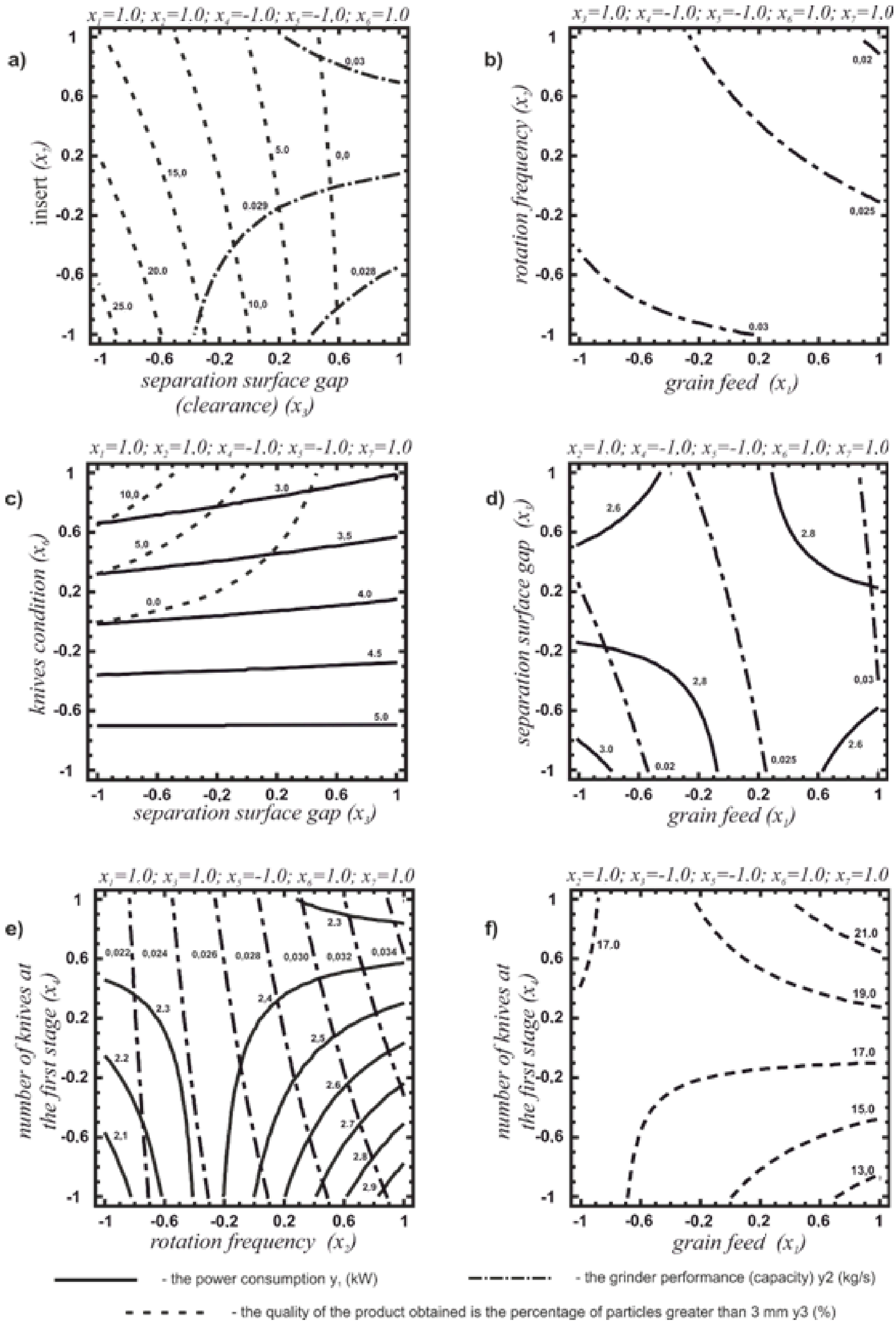

Figure 7. Two-dimensional sections of the response surface.

The increased rotation frequency of the lower disk x_2 leads to a directly proportional increase in the linear velocity of the work units, $v = 2\pi n R$ (n—rotation frequency, R—disc radius), at all stages, and an increase in the centrifugal inertial force. $F = 8m\pi^2 n^2 R$ (m—mass, n—rotation frequency, R—disc radius). As a result, the number of contacts of the grain material with the work units of the grinder is increased, while the time of its exposure in the work area is decreased. Thus, with increased values of the factor x_2, a decrease in the percentage of particles larger than 3 mm is observed with a simultaneous increase in the performance of the centrifugal–rotary grinder y_2. However, this leads to increased work for grinding and transporting the material, which is reflected in the total power consumption y_1. Bitra [21] notes that increasing speed affects the effective specific energy of hammers in different ways, depending on the type of raw material. In our experiments, the effective specific energy increases at certain rate and then decreases. Similar dependencies were shown by Moiceanu et al. [6].

Reducing the gap (clearance) of the separating surface x_3 naturally reduces the grinder performance y_2 and increases the power consumption y_1. As a result, there is an increase in the time required for the removal of the ground material from the work unit, as well as an increase in the mass of the transported ground material along the separating surface of the grinder. At the same time, reducing the gap of the separating surface x_3 does not lead to a logical decrease in the percentage of particles larger than 3 mm y_3. This phenomenon is explained by the fact that when there is a small gap of the separating surface, the particles of the material are mostly reflected from this "smooth" surface and then move along it until they pass through it. Likewise, a larger gap of the separating surface h (Figure 5) has an effect on the third grinding stage, since the knives of the separating surface have a larger approach angle and, as a result, have a lower reflectivity.

Changing the number of knives at the first grinding stage x_4 does not have a significant effect on the power consumption y_1 and grinder capacity y_2. An analysis of Equation (3), characterizing the quality of the product obtained, shows that reducing the number of knives from 9 to 3 at the first stage x_4 allows for a reduction of the percentage of particles over 3 mm in the finished product y_3 to 4.8%.

Reducing the number of knives from 18 to 9 at the second stage x_5 contributes to a reduction of particles over 3 mm y_3 in grinding by more than 11% and a reduction of the power consumption y_1 by 0.6 kW. This is understood as a result of an increase in the speed of transportation of the grain material through the grinder and a decrease in the mass accelerated by the lower disk.

Replacing the "old" knives x_6 with "new" ones is the main factor affecting energy consumption, and saves at least 2.6 kW of electricity. This can be explained by the fact that with the use of "old" knives, grinding takes place mainly by impact rather than cutting, resulting in a decrease in the number of particles larger than 3 mm y_3. At the same time, the performance (capacity) y_2 is reduced and the power consumption of the bulk grinder y_1 is increased. Kováč et al. [22] noticed that the basic factors affecting the properties of the ground material and the unit energy consumption in milling process are, among others, the knife angle and number of knives.

The presence of a special insert x_7 installed in the distribution bowls of the lower disk of the centrifugal–rotary grinder does not have any significant effect on the power consumption y_1 and the performance y_2. However, its installation increases the content of particles larger than 3 mm y_3 by 5.2%.

An analysis of the interactions of factors in the regressions, Equations (1)–(3), was carried out using (among others) two-dimensional sections (Figure 7), and shows the following results:

In general, installing a special insert x_7 into the distribution bowl of the grinder, in conjunction with the opening of the separating surface x_3, has negative effects on the percentage of particles larger than 3 mm y_3, and on the performance of the centrifugal–rotary grinder y_2. Thus, at a minimum gap (clearance) of the separating surface $x_3 = -1$, when the insert is installed, the percentage of particles larger than 3 mm is more than 25% and without the insert this value is 15%. However, when the gap is $x_3 = 0.6$ (h = 30.5 mm), particles larger than 3 mm are not observed in any case. Also, an increase in the gap (clearance) of the separating surface x_3 with the insert x_7 installed in the distribution bowl leads to a drop in the performance of the centrifugal–rotary grinder by 0.025 kg·s^{-1}, whereas without this insert the capacity increases by 0.008 kg^{-1} (Figure 7a);

The interaction of the factors x_1 and x_2 is most significant for regulating the performance of the grinder (y_2); reducing the feed and rotation frequency of the lower disk of the grinder leads to increased performance (Figure 7b);

The interaction of the factors of the condition of knives x_6 and the gap (clearance) of the separating surface x_3 is most significant for the percentage of particles larger than 3 mm (y_3). At the same time, regardless of the angle of sharpening of the knives, the number of particles larger than 3 mm y_3 decreases with an increasing gap of the separating surface. The deterioration of the sharpening of the knives leads to a twofold increase in power consumption y_1, which is more than 5 kW (Figure 7c). Branco et al. [23] suggested that knives should be replaced or sharpened periodically to ensure high efficiency in grinding.

Some of the determining parameters that affects the power consumption y_1 during grinding are the interactions of factors x_1 and x_3, as well as x_2 and x_4. When solving a compromise problem of increasing the grinder performance y_2 and reducing its power consumption y_1, it is necessary to increase the values of the factors x_3, x_2, and x_4, while decreasing the value of x_1 (Figure 7d,e).

With an increase in the feed x_1 and an increase in the number of knives at the first grinding stage x_4, the percentage of particles larger than 3 mm y_3 increases. As a result, the number of knives should be minimized (Figure 7f).

The search for a compromise solution was made using the StatGraphics software package, with equal significance of optimization criteria with the desired result shown in Table 4. The results of the optimization are shown in Table 4. These results suggest the compromised optimum is achieved by selecting the maximum values of the grain feed x_1 (in the selected range of factor variation, Table 1), the rotation frequency x_2, and opening of the separating surface x_3. Furthermore, "new" knives x_6 should be used without inserts in the distribution bowl x_7, where nine knives at the second stage x_5, and six at the first stage x_4 (Table 4) should be employed. Under these optimum conditions, it is possible to achieve a power consumption y_1 of 2.59 kW, a grinder capacity y_2 of 0.032 kg^{-1}, and the complete absence of particles larger than 3 mm y_3 after grinding. At the same time, the obtained values (Table 4) correspond in general to only 87.8% of the desired results, which indicates the insufficiency of the selected ranges for the factors to achieve the most optimal values of the power consumption y_1, performance (capacity) y_2, and quality of the resulting product, in terms of the content of particles exceeding 3 mm in size y_3.

4. Conclusions

The analysis of the results of this study (using the method of a multifactorial experimental design) into the operation of a centrifugal–rotary grinder suggests that the grinder is underutilized in the selected range of factor variation. The installation of special inserts in the distribution bowl of the lower disk (x_7) generally has a negative impact on the quality of the resulting product in terms of the content of particles larger than 3 mm. The number of knives installed at the second stage of the grinder (x_5), the gap (clearance) of the separating surface (x_3), and the technical condition of the knives (x_6) are among the most important factors influencing the power consumption and the quality of the resulting product. A reduction in the number of knives at the first stage (x_4) has a positive effect on all the selected optimization criteria. Finally, by varying the factors in the selected range, it is possible to obtain a product corresponding to medium and coarse grinding.

Summarizing the results of the study, we can conclude that, in further research the material feed (x_1) and rotor speed (x_2) should be increased, and the range of variation of the opening of the separating surface (x_3) should be extended. Further, the installation of a special insert (x_7) in the distribution bowl of the lower disk should be abandoned, or additional research related to changes in its shape and size should be carried out. Finally, the number of knives at the first stage (x_4) and at the second stage (x_5) should be reduced, and "new" knives (x_6) should be used in all cases.

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Nomenclature

h_1—size between the parallel planes of two adjacent knives (mm); x_1—grain feed (kg·s^{-1}); x_2—rotation frequency of the lower disk (min^{-1}); x_3—separation surface gap (mm); x_4—number of knives at the first stages (pcs); x_5—number of knives at the second stages (pcs); x_6—knives condition ("Old" ones/"New" ones); x_7—presence of inserts (present/absent); y_1—power consumption (kW); y_2—grinder performance (capacity) (kg·s^{-1}); y_3—particles greater than 3 mm (%); v—linear velocity (m·s^{-1}); n—rotation frequency (s^{-1}); R—disc radius (m); F—centrifugal inertial force (N); m—mass (kg).

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