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Study of the Relationships between Multi-Hole, Multi-Disc Mill Performance Parameters and Comminution Indicators

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Abstract: The knowledge of a grinder structure, its performance parameters and characteristics of biomaterials breakage are crucial for this research whose aim is to determine the dependencies between performance parameters and comminution indicators. The aim of this study is to investigate the relationships between multi-disc mill performance parameters such as discs angular speed, batch dosing speed and comminution characteristics: power consumption, specific energy consumption, throughput and size reduction ratio. To achieve these goals, an experiment was conducted on a five-disc mill with a special monitoring system. The research program was established, with disc angular speed at different configurations and different batch dosing speeds. The results show that power consumption, specific energy consumption and size reduction ratio depend on the total increase in angular speed of discs $S\Delta\omega$ in such a way that an increase in $S\Delta\omega$ causes an increase in the abovementioned comminution indicators. In turn, an increase in batch dosing speed W causes an increase in throughput. The fitting curves of comminution indicators in dependence of selected performance parameters are also presented in this study.

Keywords: comminution; biomass; specific energy consumption; size reduction ratio; efficiency

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1. Introduction

Comminution is a process that results in particle breakage caused by the impact of the mill structural elements and/or contacts between moving (often very fast) particles [1]. As was studied so far, comminution could be an effect of crushing, attrition, cutting, splitting, bending, breaking and hitting [2]. The choice of the best grinding method depends primarily on the properties of the material to be comminuted; for example, cutting is recommended for woody biomass while for brittle materials, crushing or impact comminution will be more suitable [3,4].

Due to the diversity of materials to be comminuted and their properties, many types of comminution machines are proposed; for instance, ball mills, roller mills, disc mills, rotary shears, drum mills, hammer mills and others [5]. Despite significant technological progress in the design of mills, the problem of these machines is high energy consumption and low efficiency [6,7]. To resolve this problem, the knowledge of the relations between structural features of the mills, the process parameters and the comminuted material properties is needed.

Many studies have dealt with determination of dependencies between particle size and breakage energy in static and impact crushing of single particles [8–11]. There are also studies that present the influence of multiple impacts on the breakage energy [8,12–15]. The abovementioned approaches provide data on the nature of the breakage mechanism on the particle scale and can be used in the mill designing; however, they do not provide the information on how a material will behave inside the mill. This can be obtained from experimental research on mills at the pre-implementation stage to provide results that will help to improve mill design. In many studies, the issues concerning the relations of mill design and performance parameters on the comminution indicators have been investigated so far [16–20]. Research into roller presses for mineral raw materials grinding have shown that the course of the grinding process depends on the shape of the grinding chamber and grinding elements (e.g., surface and structure of grinding rollers) [21]. An important aspect affecting the grinding energy, efficiency and size reduction ratio is also the ratio of the feed particle diameter to the inter-roll gap size (then, the charge material is compacted and the forces acting on the comminuted material and mill elements increase) [21,22]. Descriptions of forces acting on the comminuted material have found a particular application in roller presses of hard and brittle raw materials [22]. Reducing energy consumption and improving performance was achieved by creating the so-called cascade systems in multi-roller mills, where the charge material was subjected to breakage several times between a pair of rollers located one above the another [23–25]. Attempts have been made to determine reliability models of roller mills based on ARIMA (autoregressive integrated moving average) and HMM (Hidden Markov Model) models [26]. Study [27] describes, among others, the "interparticle breakage" phenomenon occurring in high pressure roller presses. The pressure distribution on a roller surface in the pressing zone has also been a subject of research [28,29]. Yang et al. [30] determined the optimal size of the inter-roll gap during milling of maize. There are several studies which also discuss the ball mill performance.

Not many studies, however, address the connection between performance parameters and comminution indicators of disc mills. Most studies of this aspect have been undertaken in Poland. A specific structure of multi-hole, multi-disc mill has been proposed and it has been found that this type of mill is characterized by higher performance and lower energy consumption than other types of mills intended for cereals comminution. The so far conducted research concerns, among others, the impact of the multi-disc mill design on the quality of the product, charge properties, comminution efficiency, relations between the material properties and comminution energy [31–35]. Understanding the relationships between the disc movement and the mass flow is necessary to understand the essence of the multi-disc comminution process and its phenomena, as they have a significant impact on the efficiency of comminution.

The energy relations of multi-disc comminution have already been described in the works of J. Flizikowski [36–39]. The relationship between the mass flow and the angle of the charge repose on the comminution efficiency in a five-disc mills have been discussed in [40–42]. Study [43] includes results of research on multi-disc comminution concerning determination of the dependencies and effects of the mill structural features and physical–mechanical features of the charge on the comminution indicators, i.e., energy consumption and quality. In [41,44–46], the phenomenon of operation irregularity of multi-disc mills is described. Dudziak analyzed the comminution process efficiency in a supersonic disc mill [47]. Yildirim et al. [48] investigated the effect of the disc gap size on the quality of the product, energy consumption and efficiency. Study [49] describes energy losses in the form of heat during comminution and the possibility of its recovery. Zuñiga and Mantari conducted research on dynamics of forces acting on the comminuted material and the working disc [11]. Study [18] shows the machine and the process factors influencing the efficiency and the size reduction ratio indicated on the basis of research on a five-disc mill. These factors include [18]: disc setting in relation to the horizontal plane, the method of feeding the batch material to the comminution chamber, the number of fixed and rotating discs, geometry of the discs and holes in the discs, the order of the discs with different geometry, the size of the inter-disc gap. The energy indicators and environmental assessment of the comminution process of a multi-disc mill were also provided. The influence of angular velocities on the changes of these indicators was analyzed in studies [50–52].

The literature provides examples of several comminution indicators [1,16], which can be classified in many ways, for example, as technical, technological and economic ones [53] or indicators of quality, efficiency and harmlessness [54]. In general, comminution indicators are used to assess the performance and efficiency of the comminution process in different areas. The most frequently used comminution indicators are power consumption, specific energy consumption, throughput and size reduction ratio. From the point of view of the comminution product application, the most important are indicators connected with the material particle size after comminution and size reduction ratio.

The particle size after comminution is usually described by statistical dependencies determined based on the particle size analysis by means of a sieve analysis or a dynamic imaging analysis. In these methods, the material is divided into size classes and the percentage of each size class is generated in the whole sample. Based on these results, the cumulative size distribution and frequency distribution of the particle size are determined. To describe the empirical size distributions, several functions have been proposed, for instance Gates–Gaudin–Shuman (G.G.S) power distribution, Rosin–Rammler distribution, log-normal distribution, beta distribution or Kolmogorow distribution [2]. They are also frequently used to find dependencies between distributions parameters of the particle size and the comminution process performance parameters. These distributions can also be used to find the characteristic particle size, for example, the average or median particle size which can be used to determine the size reduction ratio [55,56]. The studies conducted so far [32,40] have proven that a higher size reduction ratio can be obtained by increasing the number of impacts of the comminution elements with the material particles; this, however, results in an energy consumption increase [57–59].

An analysis of the state-of-art of the subject leads to a conclusion that there is still no systematic knowledge of the development of multi-disc comminution and the relations between structural features, process parameters and particle breakage. No precise mathematical models describing relations between performance parameters and comminution indicators have been developed yet. Gaining new knowledge of the grinders design and their operational characteristics and biomaterials breakage characteristics is the foundation of the research aimed at determination of the dependencies between performance parameters and comminution indicators. Similar dependencies and models have not yet been described for the analyzed multi-hole, multi-disc mills.

A review regarding the issues and models of comminution engineering confirms the relevance and importance of the undertaken research. This includes both the product quality (e.g., obtaining the desired particles size after comminution) and determination of indicators for assessing the performance of granular biomass comminution systems. Research into these issues directed in this way can stimulate the development of techniques and methods for granular and fibrous biomaterials grinding.

Bearing in mind the gaps in this kind of research, this study is supposed to investigate the relationships between multi-disc mill performance parameters such as discs angular speed, batch dosing speed and comminution characteristics: power consumption, specific energy consumption, throughput and size reduction ratio. This study will provide answers to the following research questions: (1) How will the intentionally changed angular speed of discs in multi-disc mill and speed of batch dosing affect the power consumption, specific energy consumption, throughput and size reduction ratio? (2) What values of operational parameters will ensure the occurrence of the possibly lowest power consumption and specific energy consumption and possibly highest throughput and size reduction ratio?

To achieve the goals, an experiment was conducted on a five-disc mill with a special monitoring system. The research program was established for different disc angular speed configurations and different batch dosing speeds. The comminution indicators were determined for each configuration, and then an analysis of the influence of performance parameters on these indicators was carried out

2. Materials and Methods

2.1. Comminution Indicators

In this study, the most commonly used indicators including power consumption, specific energy consumption, throughput and size reduction ratio have been determined.

Power consumption is an indicator that could be easily monitored based on direct measurement and it consists of the power for the machine power unit idle run and the power for effective comminution, according to equation [60,61]:

$$P_{tot} = P_i + P_u \tag{1}$$

where: P_u—power consumption for the material comminution in a given moment t, kW, P_i—power consumption of the idle run in a given moment t, kW.

In many cases, the average total power consumption is calculated for a certain time interval [52]:

$$\overline{P}_{tot} = \frac{\sum_{i=1}^{n} P_{toti}}{n} \tag{2}$$

The next important parameter, indicator of the comminution process, which can be measured directly and is necessary in the assessment of the process and machine efficiency, is throughput (sometimes called production yield or simply efficiency). This indicator informs about the mill performance; it is about the amount of material that is comminuted in the specific time frame, and it is expressed as [62]:

$$Q_r = \Delta m / \Delta t \tag{3}$$

where: Δm—the change in comminuted material mass in time interval Δt, Δt—comminution time interval from t_1 to t_2.

Equation (3) can take the continuous form and then the throughput is described by relationship [52]:

$$Q_r = \int_0^t m \, dt. \tag{4}$$

Generally, the power consumption and throughput are connected. Usually, an increase in throughput causes an increase in power consumption.

The indicator of specific energy consumption (called also specific energy demand) is commonly used for comparison of comminution machines. It gives information about the amount of energy consumed for comminution of a specified unit of material (mass or volume) [45,60,61,63,64]. It could be expressed in two ways:

1. as a ratio of energy consumption for the comminution and the mass (or volume) of material comminuted:

$$E_u = E_{tot} / m \tag{5}$$

2. as a ratio of average power consumption $\overline{P}_{tot}$ to throughput Q_r [62,64,65]:

$$Eu = \overline{P}_{tot} / Q_r \tag{6}$$

where: E_u—specific energy consumption, kWh·kg^{-1}, E_{tot}—total energy consumption used for comminution of a specified portion of material m, kWh.

The size reduction ratio is considered as one of the comminution product quality indicators [63,66]. It describes the relation between the characteristic sizes of the material before and after comminution [67,68]. Depending on which characteristic particle dimensions will be adopted, the following expression for size reduction ratio can be provided:

- overall size reduction ratio [2]:

$$\lambda = D/d \tag{7}$$

- limit size reduction ratio [2]:

$$\lambda_l = D_{max}/d_{max} \tag{8}$$

- average size reduction ratio [2]:

$$\lambda_a = D_a/d_a \tag{9}$$

- 80% size reduction ratio [62]:

$$\lambda_{80} = D_{80}/d_{80} \tag{10}$$

where: D—equivalent diameter of the particles before comminution, mm, d—equivalent diameter of the particles after comminution, mm, D_{max}—average value of the diameters of the largest particles of the crusher's batch, mm, d_{max}—average value of the grinding product largest particle diameter, mm, D_a—average dimension determined based on the weighted average for the feed average grain, mm, d_a—average dimension determined on the basis of the weighted average for the product average grain, mm, D_{80}—dimension of the sieve hole, through which 80% of the feed material passes, d_{80}—dimension of the sieve hole, through which 80% of the grinding product passes.

In this study, an 80% size reduction ratio was accepted for the comminution assessment.

2.2. Test Stand

The research was carried out on the test stand presented in the Figure 1.

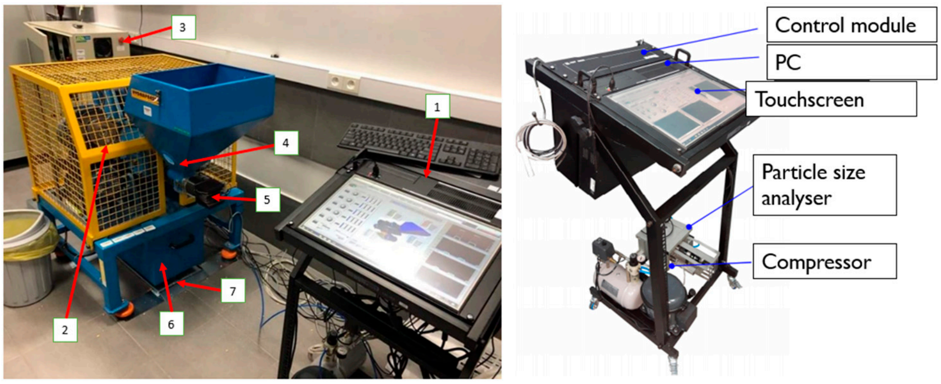
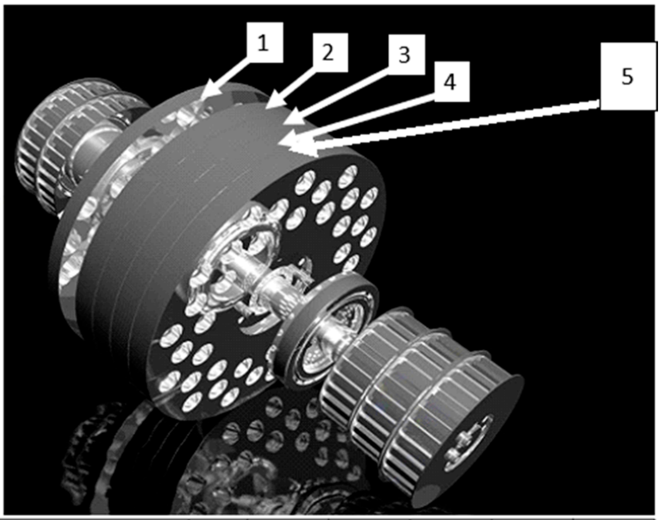


Figure 1. *t* Test stand of a multi-disc grinder: 1—control unit, 2—multi-disc grinder, 3—control cabinet, 4—screw feeder, 5—step motor, 6—receiving basket, 7—scale. Adapted from Kruszelnicka, W. (2021).

The stand consists of the five-disc mill RWT_KZ_5 (University of Science and Technology in Bydgoszcz, Bydgoszcz, Poland) and a control unit ADP 8080 (ADP, Brzoza, Poland). The mill is equipped with a hopper with a screw feeder driven by a stepper motor, which enables one to control the speed of batch dosing. The comminution unit consists of five discs with holes (see Figure 2) driven by five electric motors (each disc has its own drive motor) which allows for independent control of angular speed for each disc. The scale (ADP, Brzoza, Poland) was installed below the receiving basket for measuring the weight of the comminuted material. The integrated part of the research stand is the system for particle size analysis consisting of a high speed camera CMOS UI-1480SE-C-HQ (uEyeSE USB2.0 Camera, 1/2" CMOS Color Sensor, 2560 × 1920 Pixel, Rolling/Global Start Shutter, C-Mount, HQ-IR-Filter, IDS Imaging Development Systems Inc, Obersulm, Germany) with telecentric lens TEC-55 (COMPUTAR, CBC Group, Warszawa Poland) and a vibrating feeder PL-2 (Wibramet, Koszalin, Poland) for material dosing into the measuring chamber. This system along with dedicated software for particle size and shape analysis ADP 8080 v.2019.1 (ADP, Brzoza, Poland) allows one to conduct the particle size analysis during comminution of a batch. Additionally, the stand was equipped with moisture sensor SHT71 (Sensirion AG, Staefa ZH, Switzerland) in the hopper (for batch moisture content measurement) and temperature sensors LM135 (National Semiconductor, Santa Clara, USA) for measuring the air temperature in the lab and the temperature of the motors.

The control of the mill performance parameters such as disc angular speed and batch dosing speed is possible through the application Młyn 2019 developed in LABView 2012 (National Instruments, Austin, TX, USA). The control panel of this application is presented in Figure 3. The control system enables one to record and archive the changes in time of mills performance parameters such as torques, power consumption, angular speed for each disc, moisture content of a batch, product weight and particle size.



Parameter	Unit	Disc 1	Disc 2	Disc 3	Disc 4	Disc 5
Disc diameter D_n	mm	274	274	274	274	274
Number of holes l_n	pcs.	14	22	27	33	39
Holes diameter d_n	mm	30	23	21	17,5	17,5

Figure 2. A scheme of the comminution unit structural features.

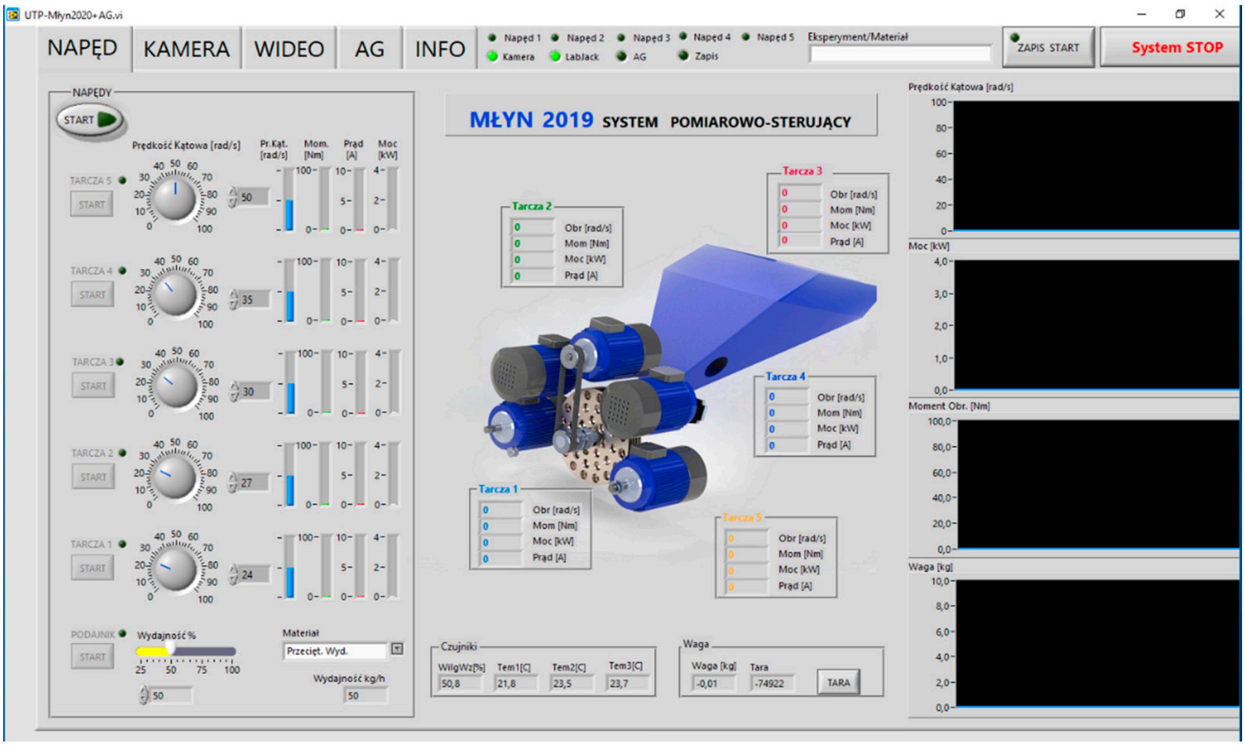


Figure 3. The control panel of the five-disc mill.

2.3. Test Conditions

The influence of the performance parameter changes on comminution characteristics was investigated during comminution of rice and corn grains. Table 1 presents the data for grain cumulative particle size distribution before comminution obtained in a granulometric analysis carried out on a Camsizer device (Retsch Technology GmbH, Haan, Germany) according to ISO standard 13322-2:2006 [69]. Volume based cumulative particle size is described as [70]:

$$Q_3(xc\_min, m) = \sum_{i=1}^{m} \overline{q}_3(xc\_min, i)\Delta xc\_min, i \tag{11}$$

where: Q_3—the cumulative size distribution, $\overline{q}_3$—the area beneath the histogram, *xc_min*—the particle diameter, which is the shortest chord of the measured set of the particle projection maximum chords. The same method was used for the material after comminution.

Table 1. The particle size distribution of rice and corn grains before comminution.

Rice			Corn		
Size Class (mm)		**Q_3 (%)**	**Size Class (mm)**		**Q_3 (%)**
0.000	1.000	0.0	0.000	3.350	0.0
1.000	1.180	0.0	3.350	4.000	0.1
1.180	1.400	0.1	4.000	4.750	1.8
1.400	1.700	8.4	4.750	5.600	9.0
1.700	2.000	56.5	5.600	6.700	2.7
2.000	2.360	97.0	6.700	8.000	72.1
2.360	2.800	98.8	8.000	9.500	10.0
2.800	3.350	99.6			
3.350	4.000	100.0			

The moisture of grains was determined using moisture content analyzer MAC 210/NP (RADWAG, Radom, Poland), which operates under a thermogravimetric principle. The moisture is determined based on the measurement of the material weight loss, by heating by halogen light. Samples weighing 5 g of material were used. The analyzer continuously measures the weights loss and calculates the moisture. The accuracy of the results in this case is 0.001%. The moisture content for corn grains was 12.234% and for rice grains 11.342%.

Next, 1 kg samples of rice and corn grains were prepared and comminuted in the mill. The experimental procedure is programmable; that is, the parameters were chosen in such a way that some dependencies can be observed. Independent variables were not randomly selected. Each experiment differed in batch dosing speed and disc angular speed configuration as presented in Table 2. The total increase of the disc angular speed $S\Delta\omega$, defined as a sum of the angular speed increase on each disc from the lowest speed level equal to 20 rad·s^{-1} at which material is comminuted, was accepted as a variable, like in papers [51,52], to investigate the influence of the disc angular speed changes on the comminution indicators such as power consumption, specific energy consumption, throughput and size reduction ratio. During comminution, the torques, power consumption, angular speed for each disc, moisture content of batch, product weight and particle size were recorded with sampling frequency of 0.5 s and archived. Based on the recorded parameters, the comminution indicators—power consumption, specific energy consumption, throughput and size reduction ratio—were determined.

Table 2. Tested configurations of batch dosing speed and comminution disc velocities.

W	$S\Delta\omega$	$\Delta\omega$	ω_1	ω_2	ω_3	ω_4	ω_5
kg·h^{-1}	**rad·s^{-1}**	**rad·s^{-1}**	**rad·s^{-1}**	**rad·s^{-1}**	**rad·s^{-1}**	**rad·s^{-1}**	**rad·s^{-1}**
100	200	20	100	80	60	40	20
	150	15	80	65	50	35	20
	100	10	60	50	40	30	20
	50	5	40	35	30	25	20
80	200	20	100	80	60	40	20
	150	15	80	65	50	35	20
	100	10	60	50	40	30	20
	50	5	40	35	30	25	20
60	200	20	100	80	60	40	20
	150	15	80	65	50	35	20
	100	10	60	50	40	30	20
	50	5	40	35	30	25	20
40	200	20	100	80	60	40	20
	150	15	80	65	50	35	20
	100	10	60	50	40	30	20
	50	5	40	35	30	25	20

ω_1, ω_2, ω_3, ω_4, ω_5—angular speeds of discs, $\Delta\omega$—increase in angular speeds, $S\Delta\omega$—total increase in angular speeds.

2.4. Statistical Analysis

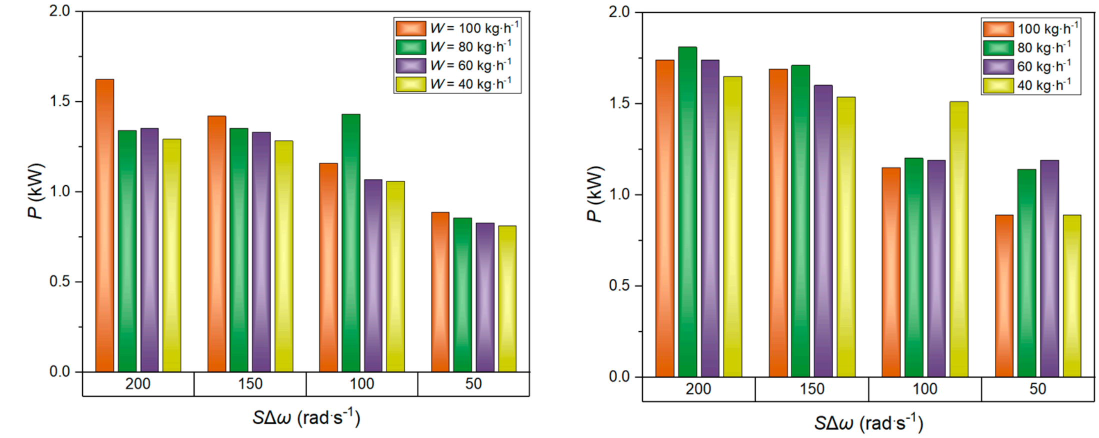
A statistical analysis of the results involved the correlation analysis, multiple linear regression analysis and polynomial fitting. For the statistical analysis, the Origin Pro 2021b (OriginLab Corporation, Northampton, MA, USA) software was used. First, the correlation of the independent and dependent variables was performed using the Pearson correlation analysis and next, the partial correlation analysis, first choosing the batch dosing speed and secondly the total increase in disc angular speeds as a control variable. The correlation analysis was done to investigate the influence of the independent variable on the dependent variables, and partial correlation analysis to check the influence of a single variable, excluding the effect of the second variable on the dependent variables. The significance level was accepted to be $p < 0.1$ for both analyses.

After correlation analysis, a multiple linear regression was performed to build and check the accuracy of the dependent variable prediction models. The models and the model coefficients were found to be significant for $p < 0.05$. Next, the polynomial fitting functions was built, to check the accuracy of models other than linear, which can be used for descriptions of the relations between the mill performance parameters and comminution indicators. Different polynomial models were tested and the maximum degree of independent variables was set to three. The fitting of the models was ranked based on the BIC criterion and determination coefficient R^2. The best fitted model was the one for which R^2 was greater than 0.5 and BIC assumed the lowest value.

3. Results

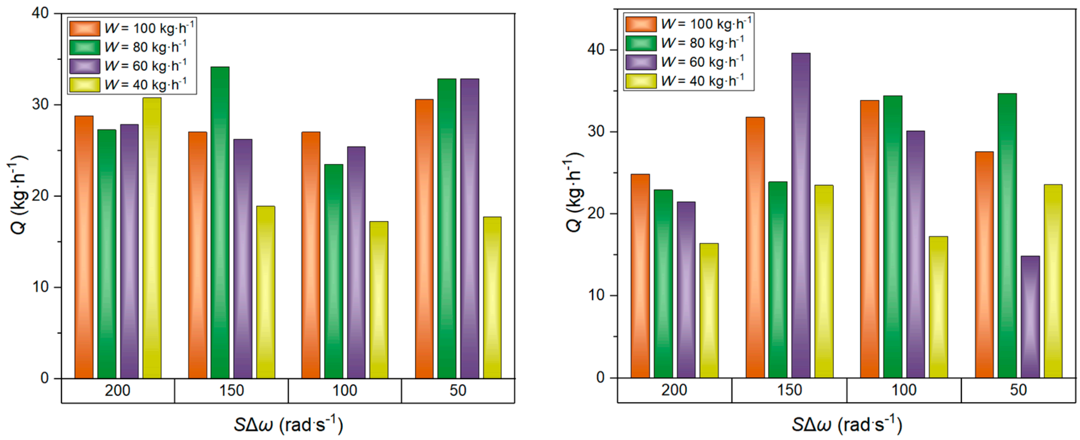
3.1. Values of Comminution Indicators

Figures 4–7 shows the values of comminution indicators: power consumption, throughput, specific energy consumption and size reduction ratio for the tested configuration of disc speed and batch dosing speed, according to Table 2.



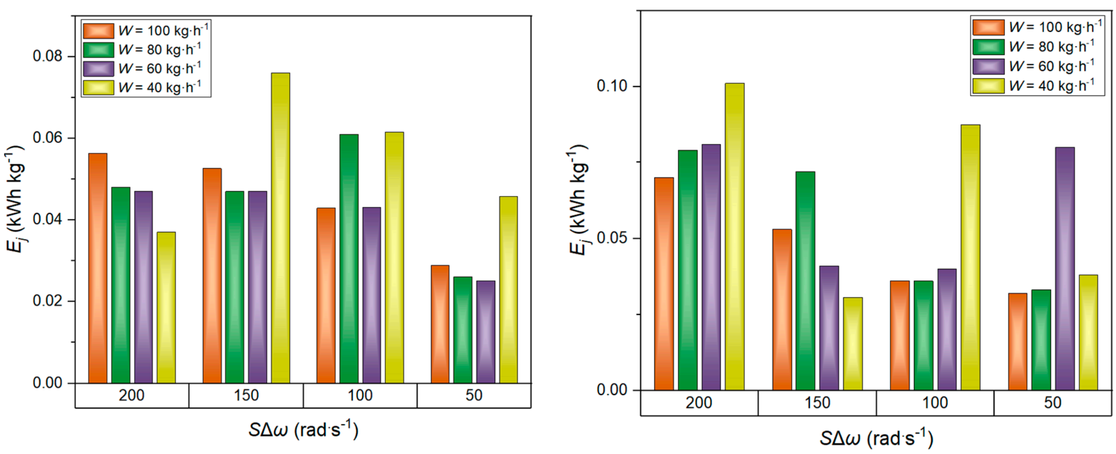
(**a**) (**b**)

Figure 4. Power consumption during comminution on five-disc mill: (**a**) rice; (**b**) corn.



(**a**) (**b**)

Figure 5. Throughput during comminution on five-disc mill: (**a**) rice; (**b**) corn.



(**a**) (**b**)

Figure 6. Specific energy consumption during comminution on five-disc mill: (**a**) rice; (**b**) corn.

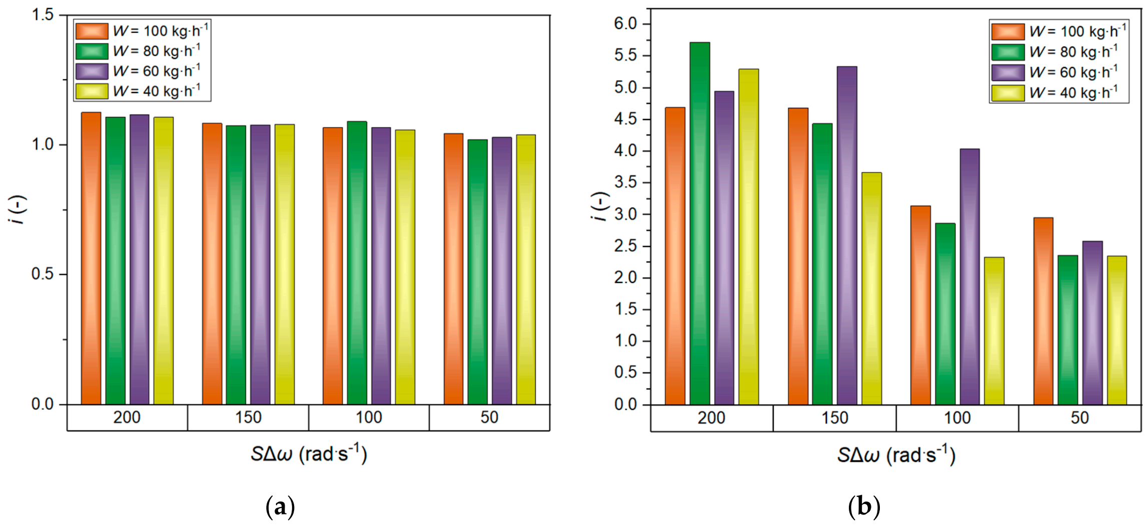


Figure 7. Size reduction ratio of 80% during comminution on five-disc mill: (**a**) rice; (**b**) corn.

The highest power consumption (Figure 4) was measured when $S\Delta\omega$ = 200 rad·s^{-1} and the batch dosing speed was 100 kg·h^{-1} for rice comminution and 80 kg·h^{-1} for corn processing; the lowest was for $S\Delta\omega$ = 50 rad·s^{-1} and W equal to 40 kg·h^{-1} for both grains size reduction. Generally, the power consumption was higher for corn processing than rice. It can be observed that during comminution of rice and corn gains, the power consumption is increasing along with a disc speed increase and, in effect, the total increase in disc angular speed. Power consumption decreases along with a decrease of batch dosing speed during comminution of rice. This statement is only partially true for corn comminution. Based on the results presented in Figure 4b, power consumption was decreasing along with the batch dosing speed decrease only for $S\Delta\omega$ = 200 rad·s^{-1} and $S\Delta\omega$ = 150 rad·s^{-1}. For other levels of $S\Delta\omega$ the dependence between power consumption and batch dosing speed is not clear.

The second determined indicator was throughput, calculated according to Equation (3) on the basis of mass measurement in the receiving basket. The highest throughput for rice comminution appears when $S\Delta\omega$ = 150 rad·s^{-1} and W = 100 kg·h^{-1}; the lowest, for $S\Delta\omega$ = 100 rad·s^{-1} and W = 40 kg·h^{-1}. During the experiment with corn, the highest throughput was noted for $S\Delta\omega$ = 150 rad·s^{-1} and W = 60 kg·h^{-1}, while the lowest was for $S\Delta\omega$ = 50 rad·s^{-1} and W = 40 kg·h^{-1}. Based on the results presented in Figure 5, it is hard to find any regularities in throughput changes with changes of performance parameters. However, it can be seen that throughput was decreasing with the batch dosing speed decrease for the disc speed setting for which $S\Delta\omega$ was equal to 150 rad·s^{-1} and 100 rad·s^{-1} for rice comminution and 200 rad·s^{-1} and 100 rad·s^{-1} for corn processing. In experiments with rice, it was found that decreasing the disc speed ($S\Delta\omega$ getting smaller values) when W = 40 kg·h^{-1} causes a decrease in throughput, while in the experiment with corn, decreasing the disc speed results in throughput increase when W = 80 kg·h^{-1}.

Specific energy consumption was calculated according to Equation (5) for each tested configuration of performance parameters and the results are presented in Figure 6. The lowest value of specific energy consumption occurred for $S\Delta\omega$ = 50 rad·s^{-1}, W = 60 kg·h^{-1} and $S\Delta\omega$ = 150 rad·s^{-1}, W = 40 kg·h^{-1}, respectively, for rice and corn comminution. In turn, the highest value of specific energy consumption was found for $S\Delta\omega$ = 150 rad·s^{-1}, W = 40 kg·h^{-1} and $S\Delta\omega$ = 200 rad·s^{-1}, W = 40 kg·h^{-1} for rice and corn comminution, respectively. Based on the presented results, some regularities can be stated. Generally, in the case of rice and corn comminution increase along with the disc speed, which is equivalent to total increase in angular speeds $S\Delta\omega$ results in specific energy consumption increase.

The last analyzed comminution indicator was 80% size reduction ratio calculated according to Equation (10) based on the dimensions of particle size dimensions measured before and after comminution. The size reduction ratio was higher in the case of corn comminution than for rice (Figure 7). The highest value of size reduction ratio occurred for $S\Delta\omega$ = 220 rad·s^{-1}, W = 100 kg·h^{-1} and $S\Delta\omega$ = 200 rad·s^{-1}, W = 80 kg·h^{-1} for rice and corn comminution, respectively. The lowest values were recorded for $S\Delta\omega$ = 50 rad·s^{-1}, W = 80 kg·h^{-1} and $S\Delta\omega$ = 100 rad·s^{-1}, W = 40 kg·h^{-1}. It can be observed that the size reduction ratio decreases with a decrease in total gradient of angular speed of discs $S\Delta\omega$.

3.2. Dependencies between Mill Performance Parameters and Comminution Indicators

To investigate the relationships between mills performance parameters and comminution indicators and to check their statistical significance, the Pearson correlation was used. Table 3 presents the results of the analysis. It was found that there is high correlation between batch dosing speed and throughput ($0.5 < r < 0.7$, according to the Guilford scale [71]) for rice comminution and average correlation ($0.3 < r < 0.5$) between the above mentioned variables for corn comminution. Statistically significant correlations ($p < 0.1$) appear also between $S\Delta\omega$ and power consumption, specific energy consumption and size reduction ratio. Almost complete correlation (r > 0.9) was obtained between $S\Delta\omega$ and size reduction ratio during rice comminution as well as between $S\Delta\omega$ and power consumption during corn comminution. Very high correlation ($0.7 < r < 0.9$) was found between $S\Delta\omega$ and power consumption for rice comminution and between $S\Delta\omega$ and size reduction ratio while corn processing. The correlation between disc angular speed total increase and specific energy consumption was high for corn comminution and average for rice size reduction.

Table 3. Results of Pearson correlation analysis between mill operational parameters and selected comminution indicators.

			P	Q_r	E_j	i
Rice grains	W	Pearson Corr.	0.271	0.505 *	−0.211	0.108
		p-value	0.310	<0.1	0.433	0.690
	$S\Delta\omega$	Pearson Corr.	0.854 *	0.083	0.430 *	0.935 *
		p-value	<0.1	0.760	<0.1	<0.1
Corn grains	W	Pearson Corr.	−0.018	0.486 *	−0.266	0.094
		p-value	0.947	0.057	0.319	0.728
	$S\Delta\omega$	Pearson Corr.	0.915 *	−0.167	0.534 *	0.892 *
		p-value	<0.1	0.535	<0.1	<0.1

Two-tailed test of significance is used; (*) Correlation is significant at the 0.1 level, P—power, kW, Q_r—throughput, kg·h^{-1}, E_j—specific energy consumption, kWh·kg^{-1}, i—80% size reduction ratio.

Pearson analysis of correlation showed the relation between independent and dependent variables, but the real effect of one independent variable changes on a dependent variable cannot be measured by this coefficient because another independent variable is confounding and affects the values of the dependent variable at the same time. To avoid the impact of the confounding (control) independent variable on the accepted comminution indicators, a partial correlation analysis was performed. The partial correlation coefficients between the mill performance parameters and selected comminution indicators, for batch dosing speed selected as a controlling variable, is presented in Table 4. The results of the partial correlation analysis for the total increase in disc angular speeds as a controlling variable are presented in Table 5.

Table 4. Partial correlation coefficients between mill performance parameters and selected comminution indicators when batch dosing speed is selected as a controlling variable.

			P	Q_r	E_j	i
Rice grains	$S\Delta\omega$	Partial Corr.	0.888 *	0.096	0.440	0.941 *
		p-value	<0.1	0.734	0.101	<0.1
Corn grains	$S\Delta\omega$	Partial Corr.	0.915 *	−0.192	0.554 *	0.896 *
		p-value	<0.1	0.494	<0.1	<0.1

Two-tailed test of significance is used; (*) the partial correlation is significantly different from zero at the 0.1 level, P—power, kW, Q_r—throughput, kg·h^{-1}, E_j—specific energy consumption, kWh·kg^{-1}, i—80% size reduction ratio.

Table 5. Partial correlation coefficients between mill performance parameters and selected comminution indicators when total increase in disc angular speeds is selected as a controlling variable.

			P	Q_r	E_j	i
Rice grains	W	Partial Corr.	0.522 *	0.506 *	−0.234	0.305
		p-value	<0.1	<0.1	0.402	0.269
Corn grains	W	Partial Corr.	−0.045	0.492 *	−0.315	0.208
		p-value	0.875	<0.1	0.254	0.457

Two-tailed test of significance is used; (*) the partial correlation is significantly different from zero at the 0.1 level, P—power, kW, Q_r—throughput, kg·h^{-1}, E_j—specific energy consumption, kWh·kg^{-1}, i—80% size reduction ratio.

When batch dosing speed was selected as a controlling variable, significant correlations were obtained for rice comminution between $S\Delta\omega$ and power consumption (very high correlation) and size reduction ratio (almost complete correlation), whereas for corn comminution, between $S\Delta\omega$ and power consumption (almost complete correlation), specific energy consumption (high correlation) and size reduction ratio (very high correlation). When the total increase in angular speeds of discs was selected as a controlling variable, a significant correlation appeared between batch dosing speed and throughput for both size reduced grains. A high partial correlation for rice comminution was also found between batch dosing speed and power consumption.

3.3. Models of Comminution Indicators

After the correlation analysis, a prediction model of comminution indicators was built. On the basis of correlation analysis, it can be supposed that the comminution indicators could be described by the models of one variable; for instance, batch dosing speed W or total increase in angular speed of discs $S\Delta\omega$. To check if the model of two variables would be accurate to predict the values of comminution indicators, a multiple linear regression was done. The results of the analysis are presented in Tables 6 and 7.

The results show that models of two variables have the form

$$V_D = AW + BS\Delta\omega + C \quad (12)$$

where: V_D—dependent variable (in this study power consumption, throughput, specific energy consumption, 80% size reduction ratio), A, B, C—regression coefficients, are statistically significant ($p < 0.05$) for power consumption and size reduction ratio for both rice and corn comminution (Tables 6 and 7). The model of two variables $S\Delta\omega$ and W explained 77.3% and 81.3% of power consumption variability for rice and corn comminution, respectively. The variability of 80% size reduction ratio was explained in 86.8% in the case of rice comminution and 77.4% in the case of corn comminution. The models of two variables better explained variability of power consumption and 80% size reduction ratio than the models of single variable—batch dosing speed or total increase in angular speed of discs (see values of R^2 in Tables S1, S2, S7 and S8 in Supplementary Materials). The models of throughput and specific energy consumption in dependance on the selected two independent variables were not statistically significant.

Table 6. Results of a multiple linear regression for modeling the comminution indicators by two variables: batch dosing speed and total increase in angular speeds of discs during rice processing.

		Parameters						ANOVA		Statistics	
		Value	Standard Error	95% LCL	95% UCL	t-Value	Prob > |t|	F Value	Prob > F	R^2	Adj. R^2
	C	0.529 #	0.118	0.274	0.783	4.492	6.060×10^{-4}				
P	A (W)	0.003 #	0.001	5.784×10^{-5}	0.006	2.204	0.046	26.535 *	2.574×10^{-5}	0.803	0.773
	B ($S\Delta\omega$)	0.004 #	5.296×10^{-4}	0.003	0.005	6.944	1.017×10^{-5}				
	C	17.790 #	4.816	7.386	28.194	3.694	0.003				
Q_r	A (W)	0.115	0.054	−0.002	0.232	2.117	0.054	2.301	0.140	0.262	0.148
	B ($S\Delta\omega$)	0.008	0.022	−0.039	0.054	0.348	0.734				
	C	0.043 #	0.013	0.015	0.070	3.364	0.005				
E_j	A (W)	-1.234×10^{-4}	1.425×10^{-4}	-4.313×10^{-4}	1.845×10^{-4}	−0.866	0.402	1.938	0.183	0.230	0.111
	B ($S\Delta\omega$)	$1.008 \cdot 10^{-4}$	5.701×10^{-5}	-2.236×10^{-5}	2.240×10^{-4}	1.768	0.101				
	C	1.001 #	0.011	0.977	1.026	89.276	1.635×10^{-19}				
i	A (W)	1.456×10^{-4}	1.262×10^{-4}	-1.270×10^{-4}	4.182×10^{-4}	1.154	0.269	50.451 *	7.468×10^{-7}	0.886	0.868
	B ($S\Delta\omega$)	5.036×10^{-4} #	5.047×10^{-5}	3.946×10^{-4}	6.127×10^{-4}	9.979	1.845×10^{-7}				

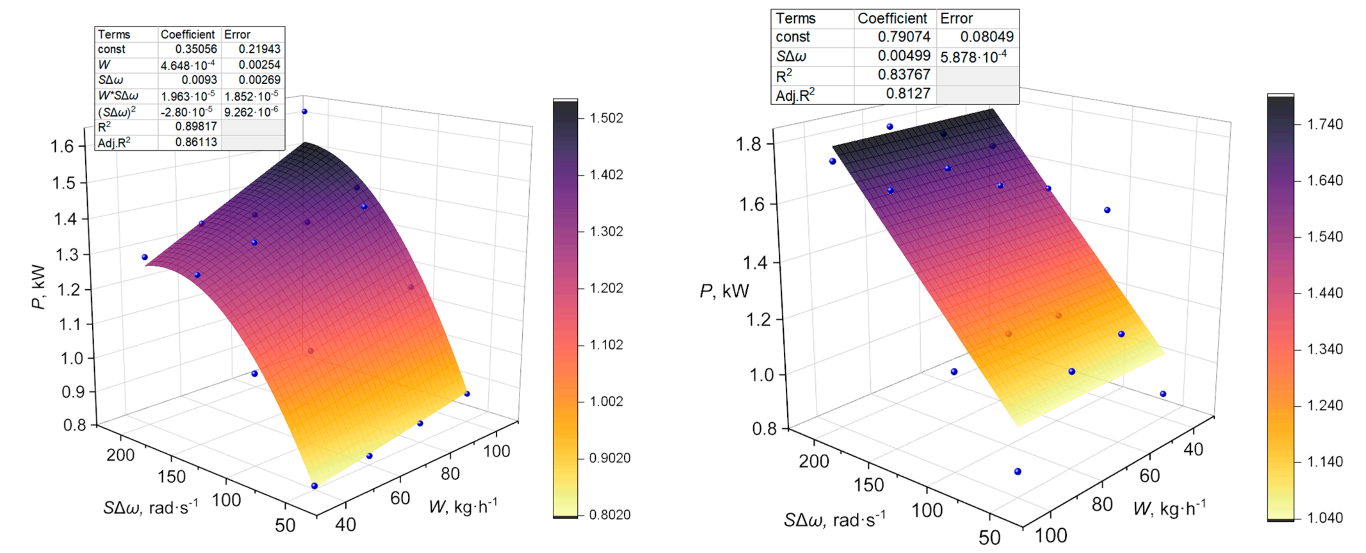
Standard error was scaled with square root of reduced Chi-Square; (#)—the value is statistically significant at the level of 0.05, (*)—at the 0.05 level, the fitting function is significantly better than the function y = constant, P—power, kW, Q_r—throughput, kg·h^{-1}, E_j—specific energy consumption, kWh·kg^{-1}, i—80% size reduction ratio.

Table 7. Results of multiple linear regression for modeling the comminution indicators by two variables: batch dosing speed and total increase in angular speeds of discs during corn processing.

		Parameters						ANOVA		Statistics	
		Value	Standard Error	95% LCL	95% UCL	t-Value	Prob > |t|	F Value	Prob > F	R^2	Adj. R^2
	C	0.808 #	0.135	0.515	1.100	5.966	4.696×10^{-5}				
P	A (W)	-2.448×10^{-4}	0.002	−0.004	0.003	−0.161	0.875	33.542 *	7.372×10^{-6}	0.838	0.813
	B ($S\Delta\omega$)	0.005 #	6.094×10^{-4}	0.004	0.006	8.189	1.730×10^{-6}				
	C	18.279 #	6.632	3.951	32.606	2.756	0.016				
Q_r	A (W)	0.152	0.075	−0.009	0.313	2.040	0.062	2.328	0.137	0.264	0.150
	B ($S\Delta\omega$)	−0.021	0.030	−0.085	0.043	−0.703	0.494				
	C	0.049 #	0.021	0.004	0.093	2.373	0.034				
E_j	A (W)	-2.749×10^{-4}	2.301×10^{-4}	-7.721×10^{-4}	2.222×10^{-4}	−1.195	0.254	3.585	0.058	0.356	0.256
	B ($S\Delta\omega$)	2.206×10^{-4} #	9.205×10^{-5}	2.174×10^{-5}	4.195×10^{-4}	2.397	0.032				
	C	1.186	0.566	−0.037	2.408	2.096	0.056				
i	A (W)	0.005	0.006	−0.009	0.019	0.767	0.457	26.618 *	2.533×10^{-5}	0.804	0.774
	B ($S\Delta\omega$)	0.019#	0.003	0.013	0.024	7.256	6.403×10^{-6}				

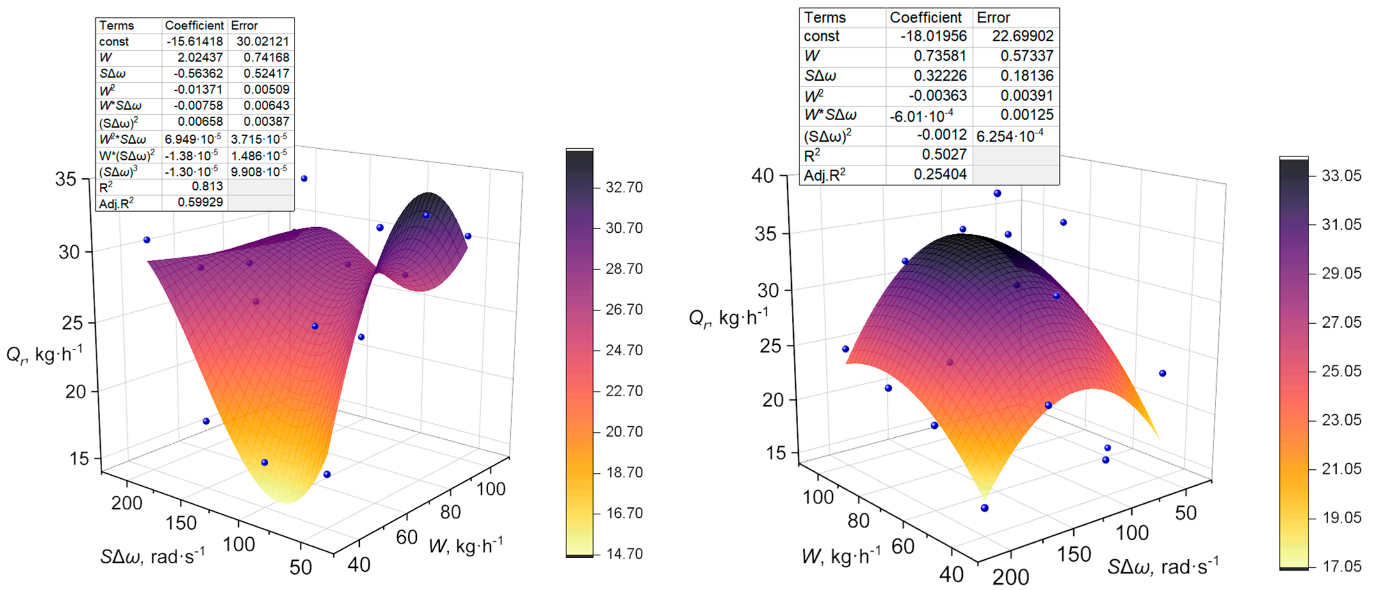
Standard error was scaled with square root of reduced Chi-Square; (#)—the value is statistically significant at the level of 0.05, (*)—at the 0.05 level, the fitting function is significantly better than the function y = constant, P—power, kW, Q_r—throughput, kg·h^{-1}, E_j—specific energy consumption, kWh·kg^{-1}, i—80% size reduction ratio.

To check the adequacy of models different than linear, the polynomial fitting was performed. The models of variables to the third degree were tested and then ranked. The models that best describe the variability of dependent variables were selected from models for which R^2 was greater than 0.5 and BIC assumed the lowest value. The values of BIC and R^2 for the ranked models are presented in Tables S1–S8 in Supplementary Materials. Figures 8–11 present the surface plots of power consumption, throughput, specific energy consumption and 80% size reduction ratio for selected best-fit models from among the tested ones. In the case of power consumption during rice comminution, the most suitable model was a polynomial model presented on Figure 8a (R^2 = 89817, adj. R^2 = 0.86113, BIC = −65.49439). The linear dependance of $S\Delta\omega$ best describes the variability of power consumption during corn comminution (R^2 = 0.83767, adj. R^2 = 0.8127, BIC = −58.75516, Figure 8b).



(**a**) (**b**)

Figure 8. Fitting surface of power consumption in dependence on batch dosing speed *W* and total increase in angular speed *S*Δ*ω* during comminution: (**a**) rice; (**b**) corn.

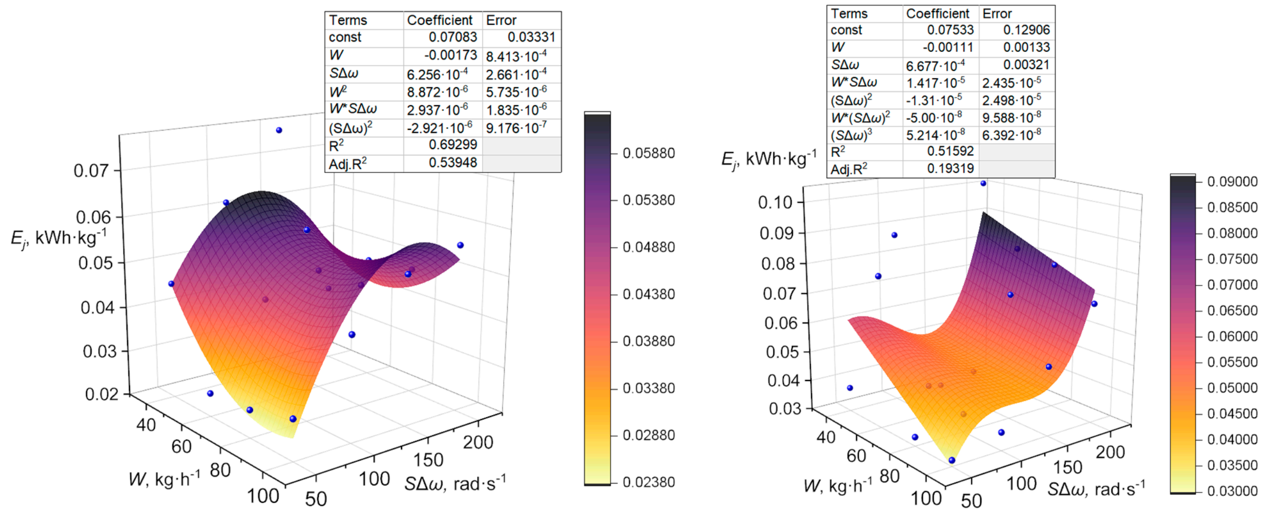


(**a**) (**b**)

Figure 9. Fitting surface of throughput in dependence on batch dosing speed *W* and total increase in angular speed *S*Δ*ω* during comminution: (**a**) rice; (**b**) corn.

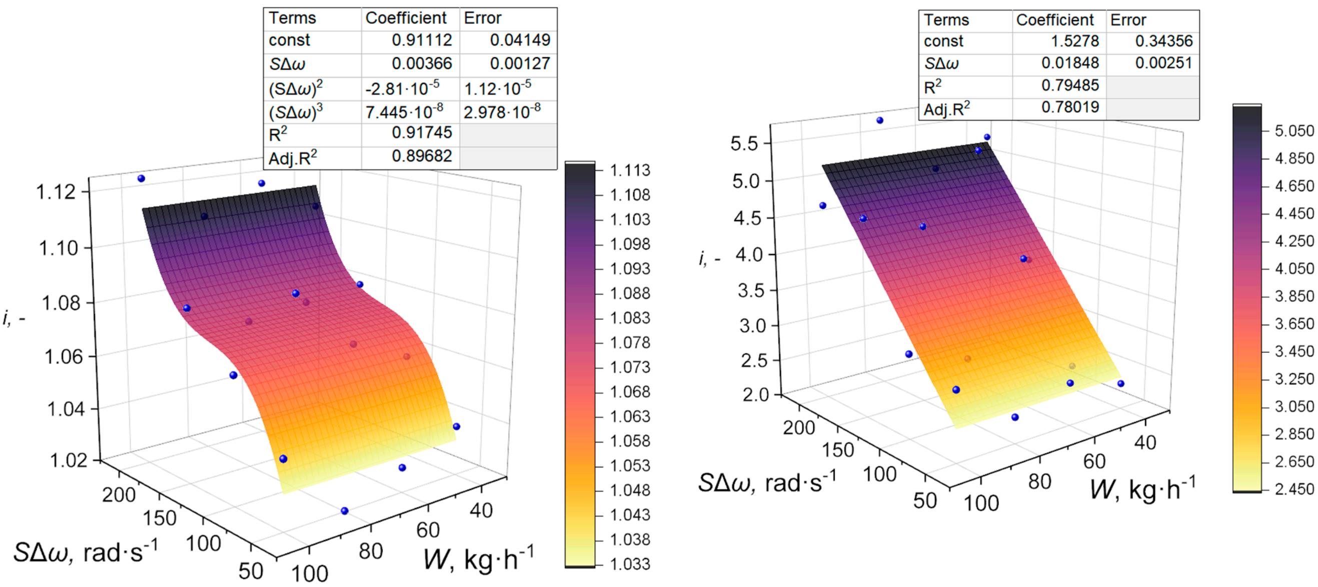
The changes in throughput for rice comminution were best described by the model where the maximum degree of *W* was two and *S*Δ*ω* three (R^2 = 0.813, adj. R^2 = 0.59929, BIC = 52.92825, Figure 9a), while for corn, the throughput was best described by the model where the maximum degree of *W* and *S*Δ*ω* was two (R^2 = 0.507, adj. R^2 = 0.25404, BIC = 70.54922, Figure 9b); however, it explained only a little bit more than 25% of the throughput variability.

The specific energy consumption in experiments with rice was best fitted by the function where the maximum degree of *W* and *S*Δ*ω* is two (R^2 = 0.693, adj. R^2 = 0.53948, BIC = 70.54922, Figure 10a), while for corn size reduction, by the model where the degree of *W* was two and *S*Δ*ω*—three (R^2 = 0.516, adj. R^2 = 0.19319, BIC = −109.98685, Figure 10b).



(**a**) (**b**)

Figure 10. Fitting surface of specific energy consumption in dependence on batch dosing speed *W* and total increase in angular speed *S*Δ*ω* during comminution: (**a**) rice; (**b**) corn.



(**a**) (**b**)

Figure 11. Fitting surface of size reduction ratio in dependance on batch dosing speed *W* and total increase in angular speed *S*Δ*ω* during comminution: (**a**) rice; (**b**) corn.

The best-fitted model describing the changes in the size reduction ratio during rice comminution was the third-degree model as a function of total increase in the angular speed of discs (R^2 = 0.917, adj. R^2 = 0.89682, BIC = −138.13822, Figure 11a). The linear dependance of $S\Delta\omega$ best describes the variability of the size reduction ratio during corn comminution (R^2 = 0.794, adj. R^2 = 0.78019, BIC = −12.31371, Figure 11b).

4. Discussion

In this study, the influence of batch dosing speed and total increase in disc angular speed on comminution indicators during multi-hole, multi-disc comminution of rice and corn gains was assessed. The results presented in Figures 4–7 and results of correlation analyses (Tables 3–5) show that power consumption, specific energy consumption and size reduction ratio depend on the total increase in disc angular speed $S\Delta\omega$ in such a way that the increase in $S\Delta\omega$ causes an increase in the considered comminution indicators. In turn, an increase in batch dosing speed W causes an increase in throughput, as the obtained average and high positive correlations suggest (Tables 3–5).

In the partial correlation analysis, when batch dosing speed was selected as a controlling variable, the values of correlation coefficients between variables (Tables 4 and 5) were slightly higher than those obtained from Pearson analysis (Table 3), which suggests that the values of power consumption, specific energy consumption and size reduction ratio depend mostly on total increase in disc angular speeds and subsequently on the disc speed. When total increase in disc angular speeds was selected as a controlling variable, positive correlations appeared between batch dosing speed and throughput for both comminuted gains and between batch dosing speed and power consumption in the case of rice comminution.

The above relations are in line with the results for other mills presented in studies [16,56,62,72–76]. The relation between power consumption and total increase in disc angular speed is a result of a simple dependence that power is the product of torque and angular speed multiplication, which for idle run of the multi-disc mill (without batch) is a linear dependance and is more than half of the total power requirement, even for a batch loaded mill as was presented in [77]. Many studies show that power consumption is irregular during comminution, which is caused by irregular flow of the material in the comminution chamber and movement irregularity of milling elements [40,41,46]. It appears as a periodical increase and decrease in power consumption in time. The variability of power for batch dosed comminution chamber is an effect of disc movement irregularities, irregularities of the feeder movement and irregularities of the material flow inside the chamber described in [41,45,46]. This causes that during each observation, a different amount of material is comminuted (different cutting and crushing resistance appears). Higher power consumption for corn comminution than for rice grinding results from the differences in the grain size, structure and mechanical properties. As described earlier [78,79], higher forces and energy are needed to break the corn grains than rice grains. In the case of rice comminution, the power consumption depends also on the batch dosing speed W. Generally, this dependance is quite obvious; the more material between the discs, the larger force (power) is needed to break the grains. However, for corn comminution, this dependence has not been confirmed. It should be noted that the amount of material that undergoes comminution is not only the effect of the batch dosing speed but also the volume of material that could be inserted into the disc mill holes. This amount is dependent on the total volume of holes and angular speed, which determine the hole filling time. This type of material dosing involves periodical dosing, that is, different material amounts are between the discs in a given time interval. The presence of a positive correlation between batch dosing and power consumption in the case of rice comminution and the absence of such a relation in the case of corn comminution can be a result of physical–mechanical properties of grains. The rice grains are smaller and can be easier pressed into the disc holes (more grans will fall into the holes) than corn grains. In this case, also the flowability of gains is important. In practice, to decrease the power consumption, a lower angular speed of disc should be applied.

The throughput was found to be dependent only on batch dosing speed (Figure 5, Tables 3–5). This relation can be easily justified; the more material is dosed, the more is comminuted. However, the obtained results (Figure 5) and the values of correlation coefficients (Tables 3–5) suggesting only average and high correlations lead to a conclusion that there are some cofounders that disrupt the flow of material inside the mill. The variability of throughput can be caused by the material structure, its moisture content and the adhesive abilities of particles. Wet particles with the adhesive properties will cause problems with the material flow [80–83], because agglomerates will be created and some material will stick to the discs and walls of the comminution chamber. This makes some part of the material remain in the grinding chamber, and there may also be moments when the residual material peels off, causing abrupt increases in efficiency, which was further described in [41,45,46]. When analyzing the throughput values (Figure 5), it should be stated that they did not exceed 40 $kg \cdot h^{-1}$, which leads to the conclusion that with the number and size of holes used and the range of angular velocities of the first disc, despite using feeder capacities higher than 40 $kg \cdot h^{-1}$, the mill will not be able to achieve higher capacities. Thus, in order to improve the performance, the disc design should be modified, i.e., the total volume of holes in the discs should be increased. The lack of dependance of the throughput on the total increase in disc angular speed could be the effect of a small range of disc angular speed total increases and the existence of different pairs of angular velocity –batch dosing speed, which will ensure the maximum throughput for a given level of batch dosing.

The specific energy consumption was positively correlated with the total increase of the angular speed of the disc (Tables 3–5). By definition (Equation (6)), the specific energy consumption depends on the power consumption and throughput. Power consumption was strongly correlated with $S\Delta\omega$, while the throughput was moderately correlated with the batch dosing speed; hence, a moderate and high correlation with $S\Delta\omega$ and a lack of correlation with the batch dosing speed result.

The 80% size reduction ratio was found to be dependent only on the total increase of disc angular speed (see Figure 7, Tables 3–5). A strong positive correlation occurred ($R^2 > 0.89$). The obtained relation is similar to that presented in [52,84–86]. The increase in the size reduction ratio with the increase of $S\Delta\omega$ results from a higher number of contacts between the material and comminution elements occurring for higher angular velocities. There were no statistically significant correlations between size reduction ratio and batch dosing speed, so the relation obtained for a stirred mill, that is, the grain fineness increase with the feed rate decrease presented in [86], was not confirmed. The lack of statistical dependence may be due to the fact that only four rates of batch dosing were tested in this study. Due to the fact that the size reduction ratio did not correlate with the batch dosing speed, the fitted curves describing changes in size reduction ratio were functions of one variable, namely, $S\Delta\omega$.

Further research should be focused on identification of the flow inside the multi-hole, multi-disc mill with the use of the discrete element modeling, which will help one to look inside the comminution chamber and identify any material blockage. Another study that should be conducted is to determine the best ratio between the comminuted particle size and the dosed material volume and the number and diameter of holes in the subsequent discs so as to ensure the highest possible throughput and eliminate the problems with the material flow through the holes.

5. Conclusions

Based on the research results, the following conclusions can be drawn:

- Power consumption, specific energy consumption and size reduction ratio of multi-hole, multi-disc comminution depend on the total increase in angular speed of discs $S\Delta\omega$ in such a way that the increase of $S\Delta\omega$ causes an increase in the analyzed comminution indicators;
- An increase in batch dosing speed W causes an increase in throughput;
- The variability of throughput can be caused by the material structure of the material, its moisture content and the adhesive abilities of particles;
- In order to improve the performance, the design of the disc should be modified, i.e., the total volume of holes in the discs should be increased,
- Further research should focus on identification of the flow inside the multi-hole, multi-disc mill with the use of discrete element modeling;
- It is necessary to determine the best ratio between the comminuted particle size, the dosed material volume and the number and diameter of holes in the subsequent discs to improve the mill performance;

- The size reduction ratio for rice and corn comminution and power consumption during corn size reduction can be predicted using the models of one variable—total increase of discs speed, while other indicators can be predicted by models of two variables—total increase of discs speed and batch dosing speed.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13158260/su13158260/s1, Table S1: Ranks of tested polynomial fitting curves for power consumption during rice comminution as a function of batch dosing speed W and total increase in angular speeds SΔω, Table S2: Ranks of tested polynomial fitting curves for power consumption during corn comminution as a function of batch dosing speed W and total increase in angular speeds SΔω, Table S3: Ranks of tested polynomial fitting curves for throughput during rice comminution as a function of batch dosing speed W and total increase in angular speeds SΔω, Table S4: Ranks of tested polynomial fitting curves for throughput during corn comminution as a function of batch dosing speed W and total increase in angular speeds SΔω, Table S5: Ranks of tested polynomial fitting curves for specific energy consumption during rice comminution as a function of batch dosing speed W and total increase in angular speeds SΔω, Table S6: Ranks of tested polynomial fitting curves for specific energy consumption during corn comminution as a function of batch dosing speed W and total increase in angular speeds SΔω, Table S7: Ranks of tested polynomial fitting curves for size reduction ratio during rice comminution as a function of batch dosing speed W and total increase in angular speeds SΔω, Table S8: Ranks of tested polynomial fitting curves for size reduction ratio during corn comminution as a function of batch dosing speed *W* and total increase in angular speeds *S*Δω.

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