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THE POSSIBILITIES OF WHEAT ROLLER MILLING OPTIMIZATION USING THE RESPONSE SURFACE METHODOLOGY

MOGUĆNOST OPTIMIZACIJE MLEVENJA PŠENICE MLINSKIM VALJCIMA PRIMENOM METODE ODZIVNE POVRŠINE

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ABSTRACT

Roller mills are one of the most frequently used grinding machines especially for cereal milling. Magnitude and type of the forces acting on particle depend on the set of roll parameters. Particle size distribution (PSD) resulting from milling a particular feed size critically depends on the ratio of roll-gap to input particle size. Box-Behnken experimental design was applied in order to optimize roll-gap adjustments and desired PSD of the milling output obtained by subsequent grinding of wheat on three pair of rollers. Adequate models, which allow the optimization of the milling process, were obtained by regression analysis. Values that define the PSD of the output, i.e. weight fractions of the milling output size fractions, were set to minimum, maximum or values within a certain interval. The examples of optimization which set the roll-gap values to ensure the desired PSD of the output, were obtained with a high level of desirability.

Key words: *wheat, milling, response surface methodology, optimization.*

REZIME

Mlinski valjci predstavljaju jedan od najčešće korišćenih uređaja za mlevenje žitarica. Najpoznatiji primer primene mlinskih valjaka predstavlja tehnološki postupak mlevenja pšenice. Takođe, njihova primena za mlevenje žitarica i drugih komponenti za potrebe proizvodnje hrane za životinje dobija sve više na značaju. Mlevni prostor formira par valjaka koji se, pri relativnom malom razmaku, obrću jedan prema drugom različitim obimnim brzinama. Na efekte usitnjavanja mlinskim valjcima utiču strukturno-mehanička svojstva usitnjavanog materijala i parametri usitnjavanja (razmak između valjaka, obimne brzine valjaka, prenosni odnos, karateristike radne površine i dr.) koji određuju intenzitet i karakter sila deformacije koje deluju na čestice. Geometrijski i kinematički parametri usitnjavanja nisu operativni u pogonskim uslovima. U toku rada može se menjati razmak između valjaka, a u užem opsegu i specifično opterećenje valjaka. Promenom razmaka između valjaka povećavaju se sile sabijanja materijala u mlevnom prostoru i odnos sila smicanja i sabijanja. Odnos između dimenzije čestice koja se usitnjava i razmaka između valjaka presudno utiče na stepen usitnjenosti mliva. U radu je primenjen Box-Behnken eksperimentalni dizajn pri optimizaciji mlevenja pšenice višestrukim usitnjavanjem na mlinskim valjcima (tri para valjaka) i to u smislu usklađivanja razmaka između valjaka i željene raspodele veličina čestica mliva. Primenom metode regresione analize dobijeni su adekvatni modeli koji omogućavaju optimizaciju. U radu su navedeni primeri optimizacije koji sa visokim nivoom zadovoljenja daju vrednosti za razmake između parova valjaka pri kojima se ostvaruje željena raspodela veličina čestica izražena preko prinosa pojedinih frakcija mliva, koji su, u zavisnosti od primera, postavljeni na minimalnu, maksimalnu ili vrednost u okviru nekog intervala.

Ključne reči: *pšenica, mlevenje, metoda odzivne površine, optimizacija.*

INTRODUCTION

Size reduction is a unit operation included in many industrial processes. Different types of comminution equipment are distinguished by the design and working principle or the maximum size of the product (*Haque, 1991*). Roller mills are one of the most frequently used grinding machines especially for milling of cereals. The best example of roller mills application is probably the wheat flour milling process. Nowadays the grinding of cereals or other diet ingredients by roller mills, for the purpose of animal feed production, is getting more attention (*Vukmirović et al., 2016a; Vukmirović et al., 2016b*).

In roller milling the material is passed between two counter-rotating rolls separated by a small gap. The rolls are with either a corrugated or smooth finish and for most grain grinding operations the two rolls run at different speeds. Degree of particle size reduction depend on the interaction between its structural characteristics and set of roll parameters (roll gap, roll velocities, differential, roll surface etc.). They influence the magnitude and the relative contributions of compressive and shearing forces acting on the particle (*Haque, 1991*). During the milling process in industrial conditions, only the roll gap and feed rate (to a limited degree) can be adjusted, while the other roll parameters remain the same (*Fistes et al., 2008*). As roll gap decreases, greater stresses are imposed, increasing the number of fractures and the degree of particle size reduction (*Scanlon et al., 1988; Fang and Campbell, 2002*). In addition, by decreasing the gap the grinding zone size increases and grinding action is prolonged (*Haque, 1991*). *Campbell and Webb (2001) and Campbell et al. (2001)* stated that PSD of the milling output critically depends on the ratio of roll gap to input particle size. So, in order to achieve successful roller milling operation it is imperative to find an optimum gap setting for a particular feed stock and product.

Particle size distribution (PSD) of solids is often an important quality factor (*Fistes et al., 2013*). For example, each break passage in the flour milling flow has a predetermined target break release in order to keep the mill in balance (*Wilson, 2001*). Break releases determine the distribution and PSD of intermediate stocks throughout the rest of the milling process and in this way it is assured that subsequent equipment in the process is being feed by the appropriate amount of stock (*Bojanić et al., 2016*). PSD of wheat flour is also of interest since the flour particles of different sizes have different characteristics *(Tarjan et al., 2009)*. In recent years there is a growing interest in PSD of animal feed since it is closely related with the utilization of nutrients and production efficiency (*Amerah et al., 2008; Svihus, 2011; Vukmirović et al., 2016b*).

Control of any milling process is based on ability to relate the PSDs of input and output material in a milling operation. Different approaches were used for modeling particle size reduction such as population balance models, breakage matrix approach, etc. (for details refer to *Bilgili and Capece, 2012*). Population balance type of modeling requires continual intra-process sampling (difficult or impossible) in order to monitor the evolution of PSDs over time. In breakage matrix approach the relationship between the input and output PSDs is described by the matrix equation $B \cdot f = o,$ where *f* and *o* are column vectors of the PSD in the input and output material from a milling operation, and *B* is the breakage matrix. By determing the B for any PSD of input material, PSD of output can be predicted. Reverse problem in the breakage matrix context (*Fistes et al., 2013, 2014*) aims to calculate the input PSD in a milling operation, in order to obtain the desired output PSD.

The most efficient way to influence the outlet PSD is by changing the process parameters, such as gap considering the roller milling. Experimental design method, and response surface method (RSM) within it, simultaneously monitors the changes of input factors and analyzes the significance of their influence to the output. In that sense, Box-Behnken experimental design was applied in order to optimize the milling of wheat by subsequent grinding on three pair of rolls. The goal was to investigate the possibilities of using the RSM to optimize the roll-gap adjustments and the desired PSD of the milling output. More precisely, the major objective was to find the optimal combination of roll gap settings (input factors) such that desired PSD of the stock (output factors) is obtained. Values that define the PSD of the output, that are the weight fractions of the milling output size fractions, were set to minimum, maximum or values within a certain interval.

MATERIAL AND METHOD

Material

Wheat sample (27 kg) was characterized (moisture content 11.4 %, bulk density 80.7 kg/hl, vitreousness 42.5 %, thousand kernel weight 31.5 g), and then separated using the automatic sampler divider (Gompper-Maschinen KG) into 1 kg batches.

Methods

Wheat samples were milled using a roller mill equipped with three pairs of rolls (ROSKAMP TP650-9, California pellet mill, USA). Fluted rolls are 165 mm in diameter and 230 mm long with 1.77, 4.33 and 5.51 corrugations per cm from the first (upper) to the third (lower) pair of rolls, respectively. A differential of 1.5 was employed relative to a fast roll speed of 750 rpm for the 1st roll and 850 rpm for the 2nd and 3rd rolls. The roller mill is equipped with dosing system and samples were feed at the rate of 26 kg/cm h. The roll gaps were set to: 1st (upper) rolls: 1.2, 1.4 and 1.6 mm; 2nd (middle) rolls: 0.8, 1.0 and 1.2 mm and 3rd (lower) rolls: 0.4, 0.6 and 0.8 mm. Roll gap combinations were set according to Box-Behnken experimental design (Table 1). Sieve analysis was performed on the Bühler laboratory sifter operating at 220 rpm (MLU-300, Switzerland) using the entire milled stock. Samples were sieved for 3 min and separated into five fractions using square aperture sieves of size 1500, 1000, 450 and 150 μm, along with a bottom collecting pan. Rubber balls were used as sieve cleaners. The stock held on each sieve and pan was weighed to 0.1 g using a Sartorius Precision balance (Sartorius AG, Germany) and PSD is given as weight fractions of the milling output size fractions.

Experimental design, statistical analysis and optimization

The Box-Behnken experimental design with 3 input factors arranged at 3 levels and three central points (which is 15 runs in total) (*Myers et al., 2009*) was used to reduce number of experimental runs and to evaluate the influence of roll gap settings and their interactions on PSD of the stock following the grinding on three pairs of rolls. The regression analysis is performed and model is described by the polynomial of second order:

$$R = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_{12} AB + \beta_{13} AC + \beta_{23} BC + \beta_{11} A^2 + \beta_{22} B^2 + \beta_{33} C^2 \qquad (1)$$

where, R is a measured response (weight fractions of the milling output size fractions); β_0 is an intercept; β_1 to β_{33} are regression coefficients; A, B and C are the coded levels of input factors. The terms AB, AC and BC represent interactions of input factors, while A^2, B^2 and C^2 represent quadratic terms. Model adequacy checking is done by calculating the R^2 value and graphically by predicted versus actual plot. In addition, within the residual analysis a normal probability plot of the residuals and residual versus predicted plot are checked. Optimization is carried out using constrained optimization problem where numerical calculation is performed by nonlinear programming methods (*Myers et al., 2009*). This procedure maximizes desirability function:

$$\mathrm{D} = (\mathrm{d_1 d_2 \cdots d_n})^{\frac{1}{n}}, \qquad (2)$$

where $\mathrm{d_i}, \mathrm{i} \in \{1,2,\dots,\mathrm{n}\}$ are individual desirability functions associated to constrains on responses $\mathrm{R_i}$. The analyses were carried out using Statistica 12 (Stratosoft, USA) and Design-Expert 10 (trial version) (*Anderson and Whitcomb, 2007*).

RESULTS AND DISCUSSION

A total of 15 experimental runs were determined by the Box-Behnken design. Recommended order of roll gap combinations and the obtained responses, i.e. PSD of the milling output given as weight fraction of the milling output size fractions are presented in Table 1.

Mean values, standard deviation, range of results for the analyzed responses and the ratio between maximum and minimum values are shown in Table 2. Regresion equation coeficients for responses together with R^2 values are shown in Table 3.

Positive or negative sign of the obtained regression equation coefficients for the depended responses indicates that the response increases or decreases with the corresponding input factor. As it was mentioned earlier in the text model adequacy checking is done by plotting a normal probability plot of the residuals and residual versus predicted plot (not shown in the paper), as well as, actual versus predicted plot (Fig. 1).

Table 1. The Box-Behnken experimental design and obtained responses

Grin. run	Roll gap (mm)			Weight fraction (%) of the milling output size fraction (μm)				
	A 1st roll	B 2nd roll	C 3rd roll	>1500 μm	1500/1000 μm	1000/450 μm	450/150 μm	<150 μm
1	1.6	1.0	0.4	9.9	32.0	39.7	12.4	6.0
2	1.6	1.2	0.6	25.2	40.5	22.8	7.6	3.9
3	1.4	0.8	0.8	46.3	33.5	12.4	5.1	2.7
4	1.2	1.0	0.8	55.1	28.4	9.8	4.4	2.3
5	1.4	1.0	0.6	29.6	40.3	19.9	6.9	3.4
6	1.6	1.0	0.8	52.3	30.3	10.4	4.5	2.4
7	1.4	1.0	0.6	25.7	40.4	22.5	7.5	3.8
8	1.4	1.0	0.6	25.7	40.3	22.7	7.6	3.7
9	1.4	0.8	0.4	6.7	27.6	44.6	14.8	6.4
10	1.6	0.8	0.6	22.6	41.2	24.0	8.2	4.1
11	1.2	1.0	0.4	6.8	27.0	44.2	15.3	6.7
12	1.4	1.2	0.4	7.6	28.0	39.5	16.6	8.2
13	1.2	0.8	0.6	25.3	41.2	22.4	7.5	3.6
14	1.2	1.2	0.6	26.9	39.7	22.0	7.6	3.8
15	1.4	1.2	0.8	52.9	29.4	10.3	4.5	2.9

Table 2. Descriptive statistics for responses

Response – weight fraction		Min. (%)	Max. (%)	Mean (%)	Standard deviation (%)	Ratio (max/min)
Milling output size fraction	>1500 μm	6.7	55.1	28	16	8.29
	1500/1000 μm	27	41	35	5.7	1.53
	1000/450 μm	9.8	44.6	24	12	4.57
	450/150 μm	4.4	16.6	8.7	3.9	3.8
	<150 μm	2.3	8.2	4.3	1.7	3.51

Table 3. Regression equation coefficients for responses

Regression coefficient	Response - weight fraction (%) of the milling output size fraction				
	>1500 μm	1500/1000 μm	1000/450 μm	450/150 μm	<150 μm
β_0	0.2700	0.4000	0.2200	0.0730	0.0370
β_1	-0.0052	0.0096	-0.0018	-0.0025	0.0000
β_2	0.0150	-0.0072	-0.0110	0.0008	0.0025
β_3	0.2200	0.0088	-0.1600	-0.0510	-0.0210
β_{12}	0.0028	0.0019	-0.0021	-0.0019	-0.0007
β_{13}	-0.0150	-0.0076	0.0130	0.0075	0.0018
β_{23}	0.0140	-0.0110	0.0076	-0.0063	-0.0041
β_{11}	0.0035	0.0006	0.0022	-0.0037	-0.0027
β_{22}	-0.0230	0.0026	0.0089	0.0074	0.0044
β_{33}	0.0370	-0.1100	0.0410	0.0220	0.0093
R^2	0.9954	0.9747	0.9929	0.9861	0.9786

Since the points on normal probability plot of the residuals and actual versus predicted plot are distributed close to the straight lines the normality assumption and adequacy of obtained model are confirmed (*Montgomery, 2001*). In a real manufacturing process it is usually necessary to coordinate few responses in order to achieve the best solution.

Optimization of controllable parameters determines the levels at which the system achieve optimal conditions. In this method, each of identified responses is transformed to the value called the single function of satisfaction which can range from 0 to 1. The closer the value to 1, the response is closer to the desired value. Combination of individual satisfaction functions produces the total satisfaction function which should also be close to 1. In this way, a compromise solution for the harmonization of the conditions given for responses, which often conflict with each other, is obtained. Model determined by regression analyses is used to perform the optimization of roll-gap adjustments in order to find the optimal combination of gap settings (input factors) such that desired PSD of the stock is obtained. The responses, that is the weight fractions of the milling output size fractions, were set to minimum or maximum value (Example 1), within certain (narrow) interval (Example 2) or combination of extreme and interval values (Example 3) (Table 4).

The recommended roll gap settings and obtained weight fractions of the milling output size fractions together with the obtained desirability functions (D) are given in the Tables 5, 6 and 7 for examples 1, 2 and 3 respectively.

As can be seen from tables 5-7 the obtained desirability ranges from almost 90 % (example 3) to even 100 % (example 2) proving that the approach of using RSM can be successfully used for this purpose. Complete solution of the problem (desirability 100 %) was obtained in example 2 where the weight fractions were set out in intervals, although these intervals were set to a relatively narrow range. For example, the weight fraction of the size fraction >1500 μm range in interval of almost 50 % (from 6.7 % to 55.1 %) while the weight fraction of fraction <150 μm range between only 2-8 %. For both size fractions the targeted weight fraction was set within only 2 % (20-22 %). On the other hand, it needs to be pointed out that practically there is no difference in the proposed solutions, i.e. there is no difference in combinations of roll gap settings as well as obtained weight fractions in five recommended solutions. In example 1 the weight fractions were set to either a minimum or maximum value while desirability ranged from 90 % to almost 97 %. Considering the proposed roll gap settings it can be noticed that all solutions propose the same roll gap at 3rd roll while differences exist in roll gap settings on first two rolls. The lowest desirability was obtained in example 3, which combines min/max and interval target for weight fractions. However, with almost 90 % this desirability can also be classified as high. In this example the variability of suggested roll gap settings is highest, but again for the upper and middle pair of rolls, while the gap setting for the lower pair of rolls varies to a relatively small extent. It needs to be emphasized that this approach was evaluated as general principle and the results would be different if the range for the roll gap settings or the output size classes were different. Nevertheless, the possibility of obtaining such high desirability values indicates usefulness of this approach in optimization of the milling process.

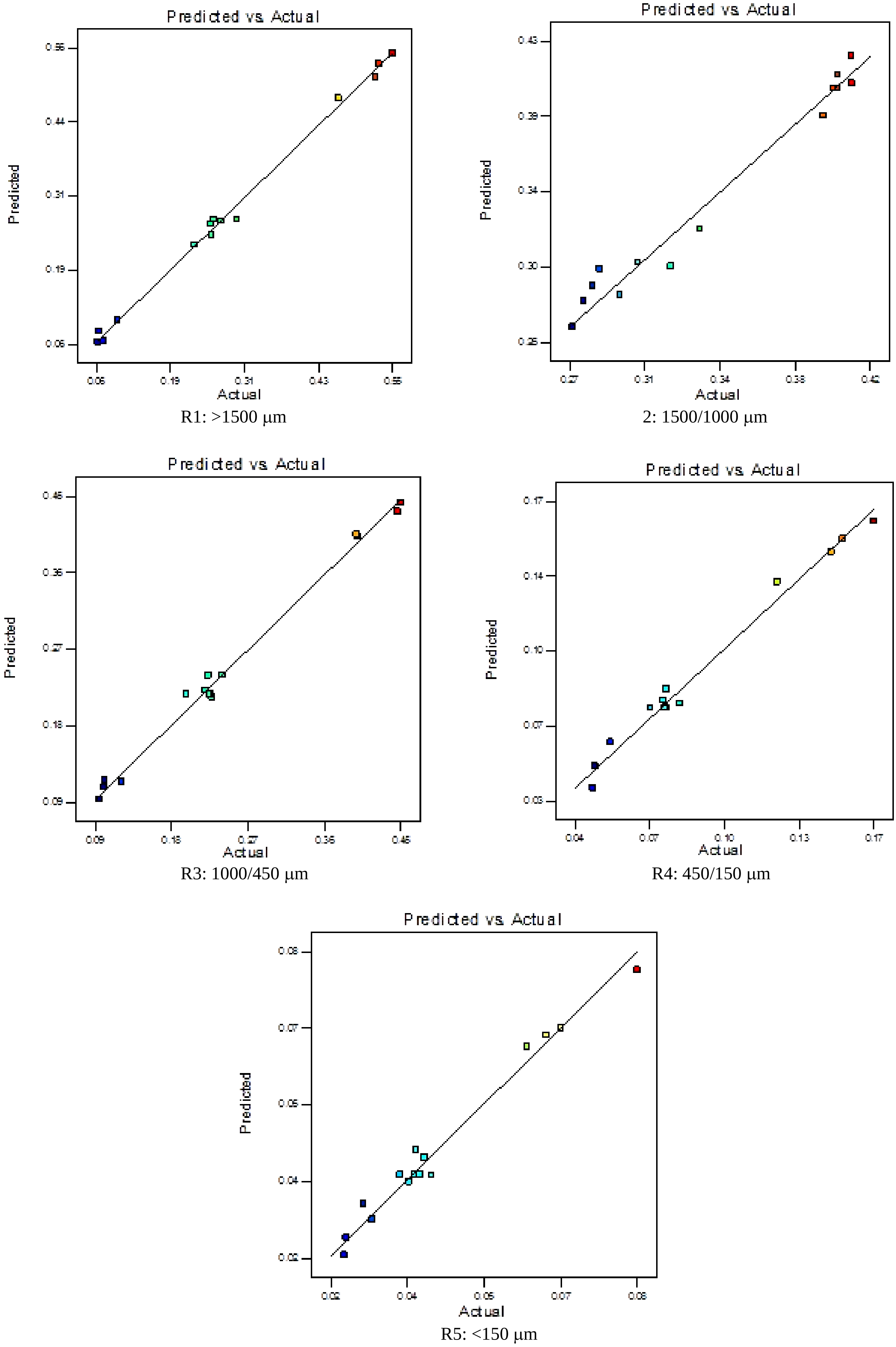

Fig. 1. Actual versus predicted plot

Table 4. Targets and limits for input factors and responses

Input factors		Roll gap (mm)		
		Target	Limit value	
			Lower	Upper
A – 1st roll		in range	1.2	1.6
B – 2nd roll		in range	0.8	1.2
C - 3rd roll		in range	0.4	0.8
Responses		Weight fraction (%)		
Example	Milling output size fraction (μm)	Target	Limit value	
			Lower	Upper
1	R1: >1500	minimum	6.65	55.14
	R2: 1500/1000	minimum	27.00	41.20
	R3: 1000/450	maximum	9.76	44.61
	R4: 450/150	maximum	4.38	16.63
	R5: <150	maximum	2.34	8.19
2	R1: >1500	in range	20	22
	R2: 1500/1000	in range	36	39
	R3: 1000/450	in range	23	25
	R4: 450/150	in range	8	11
	R5: <150	in range	3	5
3	R1: >1500	minimum	6.65	55.14
	R2: 1500/1000	in range	30	32
	R3: 1000/450	maximum	9.76	44.61
	R4: 450/150	maximum	4.38	16.64
	R5: <150	in range	5	7

Table 5. Roll gap settings, weight fractions of the milling output size fractions and desirability (Example 1)

Roll gap (mm)			Weight fraction (%) of the milling output size fraction					Desirability (%)
1st roll	2nd roll	3rd roll	>1500 μm	1500/1000 μm	1000/450 μm	450/150 μm	<150 μm	
1.2	1.2	0.4	5.59	27.32	42.42	16.87	7.80	96.91
1.31	1.2	0.4	5.95	28.28	41.36	16.53	7.88	95.00
1.2	1.13	0.4	7.04	27.08	42.49	16.11	7.28	94.35
1.36	1.2	0.4	6.25	28.83	40.81	16.25	7.86	93.32
1.22	0.8	0.4	6.02	27.00	45.54	15.05	6.38	90.34

Table 6. Roll gap settings, weight fractions of the milling output size fractions and desirability (Example 2)

Roll gap (mm)			Weight fraction (%) of the milling output size fraction					Desirability (%)
1st roll	2nd roll	3rd roll	>1500 μm	1500/1000 μm	1000/450 μm	450/150 μm	<150 μm	
1.32	1.18	0.56	22.00	39.00	24.82	9.38	4.80	100
1.29	1.19	0.56	21.99	38.81	24.91	9.47	4.82	100
1.29	1.2	0.56	21.94	38.80	24.90	9.51	4.85	100
1.31	1.2	0.56	21.68	38.93	24.97	9.54	4.89	100
1.33	1.16	0.56	21.97	39.00	25.00	9.31	4.73	100

Table 7. Roll gap settings, weight fractions of the milling output size fractions and desirability (Example 3)

Roll gap (mm)			Weight fraction (%) of output size class (μm)					Desirability (%)
1st roll	2nd roll	3rd roll	>1500 μm	1500/1000 μm	1000/450 μm	450/150 μm	<150 μm	
1.4	0.8	0.41	7.32	30.00	42.44	13.99	6.25	89.86
1.34	0.8	0.42	7.46	30.00	42.34	14.02	6.18	89.75
1.49	0.8	0.41	7.25	30.00	42.68	13.81	6.25	89.56
1.2	1.17	0.43	8.59	30.00	39.26	15.15	7.00	89.40
1.56	0.8	0.4	7.33	30.00	42.93	13.56	6.17	88.93

CONCLUSION

Control of the milling process essentially involves finding the optimal combination of grinding parameters which would, relative to the characteristics of the input material, result in desired PSD of the milling output. Characteristics of input material are often not under control so the control of the grinding parameters is most efficient way to influence the output PSD. The RSM proved to be applicable for the optimization of wheat roller milling. By defining the range of variation for roll gap settings, through the model obtained by regression analysis, it is possible, with a high level of desirability, to find the optimal combination of roll-gap settings which would lead to the targeted PSD of the milling output.

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