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Mathematical modeling of a linear load of felt

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Abstract

While modelling slitting machines, special attention should be paid to the manufacturing with the help of an immovable knife blade mainly its geometry. The obtained regression equations describe the total costs during the slitting cutting and the loss amount on the fabric friction on the immovable part of the grooved knife with the one-sided sharpening and the grooved knife with the cross section and prove the goodness of analytical fit. The comparison of total losses during the slitting cutting with one-side sharpening knife and the grooved knife with one sided sharpening highlights the practicability of the usage of the knife with an arcuate shape of the cross section.

Key words: linear load, total costs, fabric friction loss, rollers, knife blade.

The relevance of the topic. The slitting cutting of materials is divided into 2 ways: with the help of a movable or immovable knife blade. Manufacturing with the immovable part of the knife should be paid special attention to as such equipment has simple design (absence of movable parts during slitting cutting, absence of drive unit), low cost, easy maintenance in comparison with the equipment which uses movable method of the slitting cutting (movable knife blade), ability to process different materials, to obtain necessary amount of processed fabric under low energy costs spent on the slitting cutting. Therefore, the perspective direction of slitting cutting machines upgrading is a decrease of energetic costs of technological process of cutting due to the geometry of knife edge.

Setting the task. The slitting cutting machines are used to align or double materials in thickness suitable for using in different branches of productions. The main part of technological process of the slitting cutting - is the cooperation of workable parts of the machine (transport rollers and knife edge with a fabric which impacts on the energy costs) [1-11, 14].

Recent publications and researches analysis. In works [2-8, 10] the regression equations which describe total costs during the slitting cutting and the amount loss of fabric friction on the knife edge have been obtained, the linear load of different fabrics (microporous and solid rubber, felt) has been distinguished using different shapes of knife: one-sided and two-sided sharpening, namely one-sided sharpening (with different shapes of the cross section and configuration) [3, 5, 7-8, 10], two-sided knife sharpening [2, 4, 6].

Identifying unexplored parts of the general problem. The authors of works [8, 11] conducted analytical researches which highlight the practicability of using knife with one-sided sharpening of the arc cross section which decreases the separating force during the slitting cutting due to the decrease of fabric tension between transport roller and knife surface therefore cut losses on fabric friction which happens during the sltting cutting. However, there is still an unexplored issue of the total costs allocation during the slitting cutting and the number of losses on the fabric friction at the immovable part of the grooved knife with one-sided shape of the cross section.

Setting the task. The main task of the research is to verify a mathematical and experimental model of authors works [1, 10], namely to define the resistance force of split parts promotion, to develop an effective way of defining the gap size between the transport roller and the distance from the vertical axis of transport rollers to the edge of the grooved knife blade with one-sided cross section.

Fabric layout. An experimental research is a final stage of this type machine modelling, namely the geometry of the cutting instrument, is done until the specification of the linear load of felt cutting and costs comparison while using the grooved knife with one-sided shape of the cross section.
In order to calculate the total costs during the slitting cutting of felt and the number of losses of felt friction at the edge of the grooved knife with a one sided shape and also the linear load of the cutting, the two factor experiment has been conducted for the research model [2-8, 10, 12-14]:

$$y = F(x_1,\ x_2)$$

where y – optimization criteria which measures q_p ; x_1 i x_2 – controllable factors, which describe the gap size between transport rollers; h and the distance from the vertical axis of the rollers rotation to the knife edge a.

By measuring q_p, it is necessary to conduct double fabric processing which measures the total costs of its processing while being cut P, and then after cutting the fabric is put together and passed through the knife with the connection plane and the loss amount on the friction F is calculated. Therefore, only the difference of these values related to the dimension of the width of the part indicates the real dimension of linear load of cutting fabric (felt) [2-8, 10, 12-14]:

$$q_p = \frac{P-F}{B}. \tag{1}$$

Planning of the experiment was done with the help of rotatable plan of Boks for two factor experiment ($k_{1.2} = 2$), which is recommended at $k_{1.2} \leq 5$ [13].

The total number of experiments is measured with the formula [13]:

$$N_{1,2} = 2^2 + 2 \cdot 2 + 5 = 13$$

Codes, factors dimensions and intervals of variation are given in the table 1, where dimensions have been calculated with the help of correlations:

$$x_1 = \frac{x_{\mathrm{i}} - 4.35}{1};\ x_2 = \frac{x_j - 5}{0{,}5} \tag{2}$$

Table 1: Table of levels and intervals of variations of operative factors which are to be researched

Factors	Variations levels					Factor of variability intreval
	-1,414	-1	0	+1	+1,414	
h – distance between transport rollers, мм (x_1)	2,95	3,35	4,35	5,35	5,75	1
a – distance between vertical axis of transport rollers rotation and the edge of the knife, мм (x_2)	4,3	4,5	5	5,5	5,7	0,5

The experiment data is to be processed by measuring the total costs during the slitting cutting of the felt. The matrix of two factor experiment planning is given in the table 2. Measuring the number of dimensions for each research, five repeated measurements on the zero level have been conducted (researches 9 – 13) and approximate dimension of rms error of equation has been defined [13]: $S_p = 1{,}118$

The calculated criterion value of Student in this case: $t_{\text{расч(Р)}} = 4{,}0001$

The table name of Student criterion $a_B = 0{,}95$ i $n_1 = 5$ [13]. Under the condition: $t_{\text{расч(Р)}} \geq t_{\text{табл}}$

So, the number of calculations $n_1 = 5$ for each research is sufficient. After conducting the experiment and decoding the notes with the help of tare schedule the average of 5 repeated measurements of optimization criterion for each research has been calculated and the data was put into working matrix of planning (table. 2.).

In this case it is necessary to indicate the K value of the regression equation [13]:

$$y_u = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{11} x_1^2 + b_{22} x_2^2 \tag{3}$$

In order to calculate these coefficients, the equations for 2 factor experiment suggested by the author has been used [13]:

$$a_1 = 0{,}2; a_2 = 0{,}1;\ a_3 = 0{,}125;\ a_4 = 0{,}25;\ \ a_5 = 0{,}125;\ \ a_6 = 0{,}187;\ a_7 = 0{,}1.$$

Hence: $b_0 = 259{,}66;\ b_1 = -19{,}37;\ b_2 = -26{,}6;\ b_{12} = -3{,}5;\ \ b_{11} = -0{,}43;\ b_{22} = 0{,}06.$

So, the equation (3) is:

$$y_u = 259{,}66 - 19{,}37x_1 - 26{,}6x_2 - 3{,}5x_1x_2 - 0{,}43x_1^2 + 0{,}06x_2^2 \qquad (4)$$

The hypothesis about the adequacy of the equation (4) is checked in the following order.

As the experiments were duplicated only in zero point, the dispersion of the adequacy is according to the equation [13]:

$$S^2_{\text{ад}} = \frac{13{,}56 - 5{,}22}{3} = 2{,}78$$

Reproducibility variance in this case is calculated based on formula [13]:

$$S^2_{\{y\}} = \frac{5{,}22}{4} = 1{,}3$$

Table 2: Matrix of planning 2 factor experiment of total costs calculation during slitting cutting by grooved knife with one sided cross-section

Research number	**Matrix planning**		**Working matrix**			**Data for calculation**	
№	x_1	x_2	h	a	y_u	y_u	$(y_u\text{-}y_u)^2$
1	1	1	5,35	5,5	210	209,82	0,0332
2	-1	1	3,35	5,5	257	255,55	2,0932
3	1	-1	5,35	4,5	269	270,04	1,0758
4	-1	-1	3,35	4,5	302	301,77	0,0517
5	-1,414	0	2,95	5	286	286,18	0,0330
6	1,414	0	5,75	5	233	231,41	2,5293
7	0	-1,414	4,35	4,3	299	297,42	2,4926
8	0	1,414	4,35	5,7	222	222,17	0,0285
9	0	0	4,35	5	261	259,66	1,7881
10	0	0	4,35	5	260	259,66	0,1137
11	0	0	4,35	5	260	259,66	0,1137
12	0	0	4,35	5	259	259,66	0,4393
13	0	0	4,35	5	258	259,66	2,7650
					$\sum_1^{13} = 3376$	$\sum_1^{13} (y_u - y_u)^2 = 13{,}56$	

Knowing the number of degrees of freedom for higher dispersion ($f_{ад} = 3$) and lower ($f_e = 4$) dispersion [13], the criterion value in the table of Fisher for 95%- confidence interval:

$$F_{табл} = 6{,}59$$

Calculated value of Fisher criterion according to the formula [13]:

$$F_{расч(P)} = \frac{2{,}78}{1{,}3} = 2{,}13$$

Comparison of able and calculated value of Fisher criterion showed that the equation (4) can be considered as an adequate with the confidence interval $a_B = 0{,}95$, as the condition is followed: $F_{табл} \geq F_{расч(P)}$

The value of regression coefficients in the equation (4) is verified taking into account equations in case when $k_1 = 2$ [13]. In this case: $a_8 = 0{,}2$; $a_9 = 0{,}125$; $a_{10} = 0{,}1438$; $a_{11} = 0{,}25$;
Hence: $S^2_{\{b_0\}} = 0{,}2 \cdot 1{,}3 = 0{,}26$ i $S_{\{b_0\}} = 0{,}51$; $S^2_{\{b_\mathrm{i}\}} = 0{,}125 \cdot 1{,}3 = 0{,}1625$ i $S_{\{b_\mathrm{i}\}} = 0{,}4$; $S^2_{\{b_\mathrm{ii}\}} = 0{,}1428 \cdot 1{,}3 = 1{,}87$ i $S_{\{b_\mathrm{ii}\}} = 0{,}43$; $S^2_{\{ij\}} = 0{,}25 \cdot 1{,}3 = 0{,}325$ i $S_{\{b_{ij}\}} = 0{,}57$.
From this ratio [13]: $\Delta b_0 = \pm 2 \cdot 0{,}51 = \pm 1{,}02$; $\Delta b_i = \pm 2 \cdot 0{,}4 = \pm 0{,}8$; $\Delta b_{ii} = \pm 2 \cdot 0{,}43 = \pm 1{,}86$; $\Delta b_{ij} = \pm 2 \cdot 0{,}57 = \pm 1{,}14$.

Comparison of absolute value of coefficients of regression equation (4) and corresponding errors in their evaluation show that with the confidence interval 0,95 all coefficients can be considered as significant, except b_{11} and b_{22}, it can be obtained:

$$y_u = 259{,}66 - 19{,}37x_1 - 26{,}6x_2 - 3{,}5x_1x_2 \tag{5}$$

Equation (5) is the regression equation, which describes the total costs during the slitting cutting of fabric with the grooved knife with one-sided cross-section depending on the distance from transport rollers (x_1), and the distance between a vertical axis of rotation of transport rollers and the knife edge (x_2).

Taking into account expressions (2), consider the concrete numbers:

$$y_u = 259{,}66 - 19{,}37(h - 4{,}35) - 26{,}6\left(\frac{a-5}{0{,}5}\right) - 3{,}5(h - 4{,}35)\left(\frac{a-5}{0{,}5}\right)$$

After simplification, the equation is:

$$P = 458 + 15{,}6h - 7ah - 22{,}8a \tag{6}$$

An obtained expression (6) – is an experimental mathematical model of total costs value dependence during slitting cutting on the gap size between transport rollers and the distance from the vertical axis of rollers rotation to the grooved knife edge with one-sided shape of cross-section.

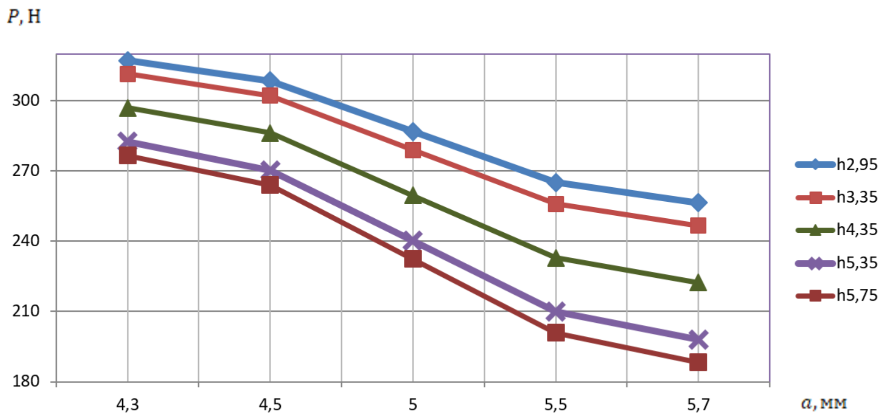

Figure 1: Graph of dependence of total costs P during felt cutting with the grooved knife with one-sided cross-section on the distance value h, between transport rollers:
while $a = const$, in the range $a_{min} = 4{,}3 - a_{max} = 5{,}7$

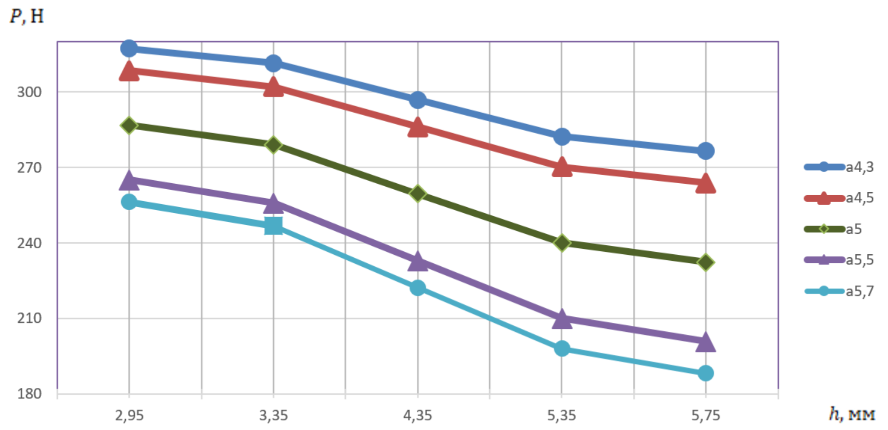

Figure 2: Graph of dependence of total costs P during cutting of felt with the grooved knife with one-sided cross-section,on the distance a from vertical axis of transport rollers to the knife edge:
while $h = const$, in the range $h_{min} = 2{,}95 - h_{max} = 5{,}75$

To process the experiment data of calculation of total costs of fabric friction at the edge of the grooved knife with one-sided cross-section. Planning matrix of two factor experiment is given in the table 3.

After conducting the experiment and decoding the notes with the help of tare schedule, the average value of 5 repeated measurement optimization criterion of each experiment has been calculated and data has been put into working matrix of planning (table 3.).

Table 3: Planning matrix of two factor experiment with calculation of total costs with fabric friction at the edge of the grooved knife with one-sided cross section

Research number	Planning matrix		Working matrix			Calculation data	
	x_1	x_2	h	a	y_u	y_u	$(y_u-y_u)^2$
1	1	1	5,35	5,5	168	168,00	0,0000
2	-1	1	3,35	5,5	208	206,35	2,7242
3	1	-1	5,35	4,5	216	217,42	2,0150
4	-1	-1	3,35	4,5	242	241,77	0,0545
5	-1,414	0	2,95	5	230	230,55	0,2990
6	1,414	0	5,75	5	188	186,22	3,1606
7	0	-1,414	4,35	4,3	240	238,37	2,6461
8	0	1,414	4,35	5,7	178	178,40	0,1566
9	0	0	4,35	5	210	208,45	2,4010
10	0	0	4,35	5	208	208,45	0,2029
11	0	0	4,35	5	208	208,45	0,2029
12	0	0	4,35	5	210	208,45	2,4010
13	0	0	4,35	5	206	208,45	6,0049
					$\sum_1^{13} = 2712$	$\sum_1^{13}(y_u - y_u)^2 = 22{,}2687$	

In this case, it is necessary to calculate the coefficient value of regression equation for two factor experiment suggested by the author [13]: $b_0 = 208{,}45$; $b_1 = -15{,}67$; $b_2 = -21{,}21$; $b_{12} = -3{,}5$; $b_{11} = -0{,}033$; $b_{22} = -0{,}033$

Hence, the equation (3) looks like:

$$y_u = 208{,}45 - 15{,}67x_1 - 21{,}21x_2 - 3{,}5x_1x_2 - 0{,}033x_1^2 - 0{,}033x_2^2 \tag{7}$$

The hypothesis of equation adequacy (7) is checked in above mentioned way.

Variance of adequacy:

$$S_{\text{ад}}^2 = \frac{22{,}2687 - 11{,}2127}{3} = 3{,}69$$

Reproducibility variance in this case:

$$S_{\{y\}}^2 = \frac{11{,}2127}{4} = 2{,}8$$

Calculated Fisher value:

Comparison of table and calculated Fisher criteria showed that the equation (7) can be considered as adequate with confidence interval $a_B = 0{,}95$, as the condition is followed: $F_{\text{табл}} \geq F_{\text{расч}(P)}$.

The value of regression coefficients in the equation (7) was checked in the same way as it is explained in the methodology above.

Hence: $S_{\{b_0\}}^2 = 0{,}2 \cdot 2{,}8 = 0{,}56$ i $S_{\{b_0\}} = 0{,}74$; $S_{\{b_i\}}^2 = 0{,}125 \cdot 2{,}8 = 0{,}35$ i $S_{\{b_i\}} = 0{,}61$; $S_{\{b_{ii}\}}^2 = 0{,}1438 \cdot 2{,}8 = 0{,}4$ i $S_{\{b_{ii}\}} = 0{,}63$; $S_{\{b_{ij}\}}^2 = 0{,}25 \cdot 2{,}8 = 0{,}7$ i $S_{\{b_{ij}\}} = 0{,}84$

From this the correlation [13]: $\Delta b_0 = \pm 2 \cdot 0{,}74 = \pm 1{,}48$; $\Delta b_i = \pm 2 \cdot 0{,}6 = \pm 1{,}2$; $\Delta b_{ii} = \pm 2 \cdot 0{,}63 = \pm 1{,}26$; $\Delta b_{ij} = \pm 2 \cdot 0{,}84 = \pm 1{,}68$.

Comparison of absolute values of regression coefficients of equation (7) and corresponding errors in their value indicate that with confidence interval 0,95 all coefficients can be considered significant, ex cept b_{11} and b_{22}, then it is obtained:

$$y_u = 208{,}45 - 15{,}67x_1 - 21{,}21x_2 - 3{,}5x_1x_2 \tag{8}$$

Equation (8) is an regression equation which describes total costs during slitting cutting of fabric with an immovable knife depending on the distance between transport rollers(x_1), and the distance between vertical axis of transport rollers rotation and the knife edge (x_2).
Taking into account expressions (2), pass to named values:

$$y_u = 208{,}45 - 15{,}67(h - 4{,}35) - 21{,}21\left(\frac{a-5}{0{,}5}\right) - 3{,}5(h - 4{,}35)\left(\frac{a-5}{0{,}5}\right).$$

After simplification, the equation looks like:

$$F = 336 + 19{,}3h - 12a - 7ha \tag{9}$$

Obtained expression (9) – is an experimental mathematical model of total costs value dependence of the fabric friction at the edge of the grooved knife with one-sided cross-section during slitting cutting on the gap size between rollers and distance between vertical axis od rollers rotation and the knife edge.

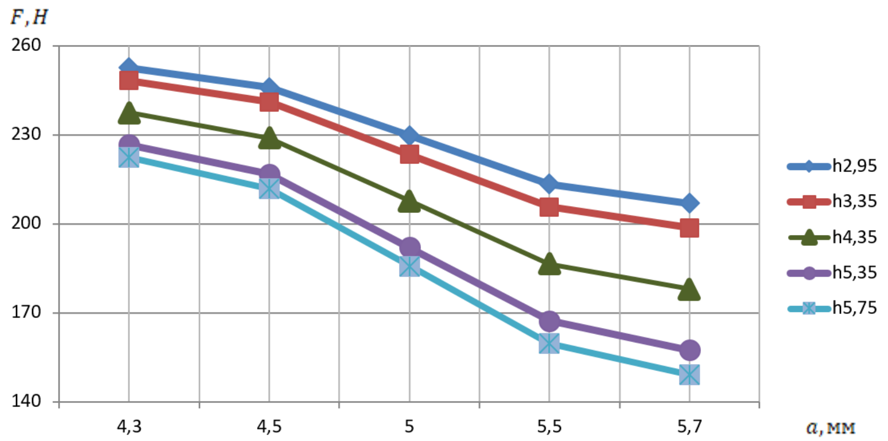

Figure 3: Dependency graph of total costs F during cutting the felt with the grooved knife with one-sided cross-section on the gap size $h = const$, between transport rollers: while $a = const$, in the range $a_{min} = 4{,}3 - a_{max} = 5{,}7$.

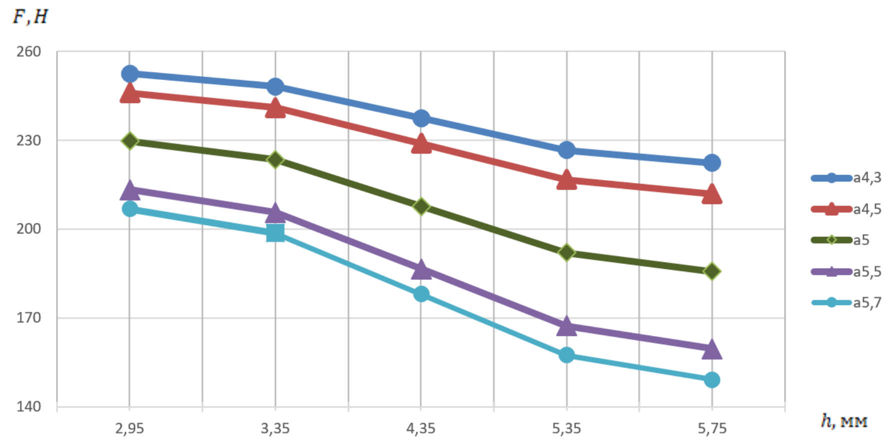

Figure 4: Dependency graph of total costs F during slitting cutting with the grooved knife with one-sided cross-section on the gap size a from the vertical axis of transport rollers to the knife edge: while $h = const$, in the range $h_{min} = 2{,}95 - h_{max} = 5{,}75$

Obtained experimental models, namely calculation of total costs (6) and the amount of losses from fabric friction (9) allow to measure the linear load of felt cutting. Placing numeric expressions in an equation (1) we obtain an average expression of the linear load of felt: $q_P = \frac{1}{B}(122 - 10,8a - 3,7h)$ $q_P = 1,483\ \frac{\text{Н}}{\text{мм}}$.

Any deviation from obtained prior results [6] and [7] are respectively $\Delta = 7,82\%$ and $\Delta = 12,88\%$, which indicates the adequacy of conducted experiment.

By comparing total costs during the slitting cutting of felt with the grooved knife with one-sided sharpening (obtained by the author in work [7]), and using the grooved knife with one sided cross-section, we obtain:

$$\Delta P = \frac{314,88 - 259,66}{314,88} \cdot 100\% = 17,5\%$$

Indicated deviation of total costs during slitting cutting of fabric proves the mathematical model developed by the author in work [7] and shows that it is efficient to use the blade of the grooved knife with one-sided cross-section which allows to decrease total costs in comparison with one-sided sharpening which in its turn decreases energy costs.

Conclusions. Obtained regression equations describe total costs during slitting cutting of fabric and the number of losses for fabric friction at the edge of immovable grooved knife with one-sided cross-section prove the adequacy of analytical model. Comparison of total costs during slitting cutting of fabric with the knife with one-sided sharpening of cross-section proves the efficiency of the grooved knife usage with one-sided cross-section.

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