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OPTIMAL SELECTION OF COTTON WARP SIZING PARAMETERS UNDER SYSTEM RESEARCH LIMITATION

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Abstract. Warp sizing is the process of applying the sizing agents to the warp yarn to improve its weavability along with improving the economic performance of weaving. We consider a finite set of sizing agents or parameters mapped into a finite set of sizing quality indicators. Due to various limitations of material and time resources, exhaustive system research and constructing an information technology to interpret and optimize sizing data is impossible. Therefore, we suggest an algorithm for controlling warp sizing quality under system research limitation, where optimal selection of cotton warp sizing parameters is exemplified. The algorithm utilizes a set of basis vectors of sizing parameters corresponding to a set of respective vectors of quality indicators. The method of radial basis functions is used to determine the probabilistically appropriate vector of quality indicators for any given vector of sizing parameters. The uncountably infinite space of sizing vectors is uniformly sampled into a finite space. The finite space may be refined by excluding sizing vectors corresponding to inadmissible values of one or more quality indicators. A set of Pareto-efficient sizing vectors is determined within the finite (refined) space, and an optimal, efficient sizing vector is determined as one being the closest to the unachievable sizing vector. The suggested algorithm serves as a method of optimal selection of warp sizing parameters, resulting in improved performance of warp yarns that can withstand repeated friction, stretching, and bending on the loom without causing a lot of fluffing or breaking. The algorithm is not limited to cotton, and it can be applied to any yarn material by an experimentally adjusted radial basis function spread.

Keywords: warp sizing, sizing agents, colloidal systems, inorganic compounds, sizing quality indicators, radial basis function, Pareto efficiency.

INTRODUCTION

Manufacture of high-quality fabric is a very important industrial branch whose impact cannot be overestimated. The basis of high-quality fabric is high-quality thread. Spinning high-quality thread is not that much complicated process, but it relies on technologically correct and efficient sizing applied to thread [1; 2]. The purpose of the sizing is to improve the breakage characteristics of the yarn and increase its resistance to friction and multi-cycle loads on the loom during fabric production. Efficient sizing is required for efficient textile manufacturing. The latter is a major industry largely based on the conversion of fiber into yarn, then yarn into fabric which is subsequently dyed and fabricated into cloth [3; 4].

The sizing is applied to single-threaded yarn. An adhesive substance is applied to the surface of the threads, which covers the threads after drying with a smooth elastic film. This reduces the breakage of the threads, protects them from rubbing against the parts of the loom, improves abrasion resistance of the yarn, and decreases hairiness of the yarn. In the process of sizing, the warp threads must be glued evenly along their entire length and the width of the fill [1; 2; 5].

The protective film of the sizing should have approximately the same elongation indicators as the warp threads, and also provide the threads with great uniformity, wear resistance, and durability under repeated loads [5; 6]. The sizing film should not fall off, and the thread impregnated with it should not be brittle. The sizing should have a good affinity for the fibrous material, not spoil the yarn and weaving equipment, be easy to get desized (washed), and be relatively cheap [7; 8].

The sizing recipe and its parameters are determined by the type of yarn material (e. g., cotton, polyester, linen), the thickness of the yarn, the type of weaving machinery, and conditions under which the fabric weaved from the yarn is assumed to be used [2; 9; 10]. For sizing of cotton yarn (warp), starches are used as the main component of the sizing compositions [11; 12]. Starches are relatively cheap, are characterized by a reliable raw material base, and are completely biodegradable without harming the environment. Nevertheless, the films formed by starch have an unsatisfactory set of physical and mechanical indicators [4; 5; 13]. Another issue is the cost of the sizing [2; 8]. Depending on the type of adhesive, the sizing material can be from 23% to 78% of the sizing process cost. Moreover, the cost of energy consumption accounts for from 9% to 24% of the sizing process cost. Therefore, developing new sizing technologies is aimed at improving the economic performance of weaving [8; 14]. Thus, a physico-chemical rationale is provided in [15] for the technology of cotton warp sizing by using starches with hygroscopic additions of kaolin or potassium alum. However, the parameters of the cotton warp sizing are basically taken from rule of thumb, rather than from an exhaustive system research and constructing an information technology to interpret and optimize sizing data [5; 7; 9; 16]. This is so due to the physico-chemical research of colloidal systems with inorganic compounds is resource-intensive in both time and materials [1; 4; 5; 9; 15].

PROBLEM STATEMENT

Conducting an exhaustive system research would give a sufficient amount of sizing data which subsequently could be optimized to further improve sizing quality. However, it is impossible due to various limitations of material and time resources. Therefore, the goal of our research is to suggest an algorithm of optimally selecting cotton warp sizing parameters under system research limitation, i.e. when a limited amount of data is available. In general terms, this is about to control sizing quality. To achieve the goal, we have to accomplish the following four tasks:

1. To report and describe main characteristics of materials and sizing agents used for cotton warp sizing during real experiments. This is done for repeatability of the sizing research.
2. To suggest a consistent algorithm to control sizing quality. Apart from the verifiability, the algorithm consistency implies also its independence on the number of sizing parameters and the number of quality-controlled factors.
3. To apply the suggested algorithm to the results of the factually conducted experiments.
4. To discuss and conclude on the significance, practical applicability, and contribution of the suggested algorithm as a method of optimal selection of cotton warp sizing parameters under system research limitation.

CHARACTERISTICS OF MATERIALS AND SIZING AGENTS

The quality of sizing is assessed through experimenting with various parameters of the cotton thread sizing and measuring characteristics of the sized thread. The following sizing agents and chemical materials are used for the experiments [14; 15]:

1. Water H_2O for household and drinking purposes.
2. Kaolin $Al_2Si_2O_5(OH)_4$ or, in oxide notation, $Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O$ — a white mass (a shade of another color is possible), soft to the touch, insoluble in water.
3. Potassium alum $Al_2(SO_4)_3{\cdot}K_2SO_4{\cdot}24H_2O$ — colorless cubic crystals soluble in water.
4. Soft paraffins — mixtures of hydrocarbons of the methane series with a normal structure in the range $C_{19}H_{40}$ — $C_{35}H_{72}$. They are derived from petroleum, their molecular mass is 300 to 400, melting point is between 50 and 54 ºC, and the oil content does not exceed 2.3%.
5. Corn starch of a general composition $(C_6H_{10}O_5)_n$.
6. Polyvinyl alcohol $[CH_2CH(OH)]_n$ — a colorless, odorless, weakly hygroscopic, water-soluble powder. For sizing, it is used in the form of granules with a size of 0.3 — 1.7 mm.
7. Syntanol DS-10 — a mixture of polyethylene glycol ethers of synthetic fatty alcohols $C_nH_{2n+1}O(C_2H_4O)_mH$, where $n \in \{\overline{10, 18}\}$, $m \in \{\overline{8, 10}\}$. It is a non-ionic material in the form of a soft white or light yellow paste, biodegradable, well soluble in water at 30 — 40 ºC.
8. Caustic sodium NaOH — white rhombic blurring crystals, a caustic substance.
9. Hydrogen peroxide H_2O_2 — colorless liquid.
10. Iodine I_2 — purple-black rhombic crystals with a metallic luster with a density of 4.933 g/cm^3.
11. Potassium iodide KI — colorless cubic crystals, soluble in water.
12. Phenolphthalein — is a polyfunctional polynuclear aromatic compound whose crystals are soluble in alcohol. It is an acid-base indicator with a pH range 8.3 — 10.
13. Sodium bromide dihydrate $NaBr{\cdot}2H_2O$ — colorless monoclinic crystals, well soluble in water.
14. Zinc sulfate heptahydrate $ZnSO_4{\cdot}7H_2O$ — colorless crystals soluble in water.
15. Copper sulfate $CuSO_4{\cdot}5H_2O$ — blue triclinic crystals, well soluble in water, losing water of crystallization at 110 ºC.
16. Ammonium chloride NH_4Cl — colorless cubic crystals, well soluble in water.
17. Potassium dichromate $K_2Cr_2O_7$ — orange monoclinic or triclinic crystals, well soluble in water.

The research of the technological parameters of the sizing process and quality indicators of the sized warp is carried out with the use of the cotton yarn of class 1, number 34. It is characterized by the following indicators:

1. Nominal linear density is 29 Tex.
2. Specific breaking load (tenacity) is 12.1 cN/Tex.
3. Coefficient of variation by breaking load is 10.4%.
4. Quality indicator is 0.859.

The above-mentioned characteristics and properties are intentionally reported for repeatability of the sizing research. More specificities about the sizing experiments can be found in [15].

CONTROL OF SIZING QUALITY

Consider a warp with F sizing parameters or features compiled into a numerical vector $\mathbf{U} = [u_i]_{1\times F}$ of positive values $\{u_i\}_{i=1}^{F}$. Denote a space of all feasible combinations of F sizing parameters by U, where $\mathbf{U} \in U$. During practical experiments with a definite set of F sizing parameters

$$\mathbf{U}_c = [u_i^{(c)}]_{1\times F} \in U \tag{1}$$

numbered by c, we measure a quality-controlled factor (numbered by j) and denote the average of its measured values by $\tilde{y}_c^{(j)}$, $c = \overline{1, C}$, $j = \overline{1, J}$, where C is the number of distinct sets of sizing parameters, and J is the number of distinct quality-controlled factors. Vector (1) should be standardized to provide comparability:

$$v_i^{(c)} = \frac{u_i^{(c)}}{\max\limits_{k=\overline{1, C}} u_i^{(k)}}, \quad c = \overline{1, C}, \quad i = \overline{1, F}. \tag{2}$$

Thus, values (2) are compiled into a vector

$$\mathbf{V}_c = [v_i^{(c)}]_{1\times F} \in V, \tag{3}$$

where every $v_i^{(c)} \in (0; 1]$ and V is a standardized space U.

For a set of F sizing parameters $\mathbf{V} = [v_i]_{1\times F} \in V$, we can use the method of radial basis functions [17] to ascertain the topological location of vector $\mathbf{V}$ within set $\{\mathbf{V}_c\}_{c=1}^{C} \subset V$. A value proportional to the probability of a similarity between vectors $\mathbf{V}$ and $\mathbf{V}_c$ is [18]

$$p_c(\mathbf{V}) = e^{-d_c}, \quad c = \overline{1, C}, \tag{4}$$

by

$$d_c = \frac{\sum_{i=1}^{F} [v_i - v_i^{(c)}]^2}{2\sigma^2}, \tag{5}$$

where σ is a radial basis function spread [17; 18]. Then the probability of a similarity between vectors $\mathbf{V}$ and $\mathbf{V}_c$ is

$$p_c^*(\mathbf{V}) = \frac{p_c(\mathbf{V})}{\sum_{k=1}^{C} p_k(\mathbf{V})}, \quad c = \overline{1, C}. \tag{6}$$

Therefore, a weighted value of the j-th quality-controlled factor is

$$\tilde{y}^{(j)}(\mathbf{V}) = \sum_{c=1}^{C} \tilde{y}_c^{(j)} p_c^*(\mathbf{V}), \quad j = \overline{1, J}. \tag{7}$$

The sizing quality is commonly based on quality-controlled factors (quality indicators) which should be maximized. Thus, we have to solve J maximization problems

$$\mathbf{V}^{*(j)} \in \arg\max_{\mathbf{V}\in V} \widetilde{y}^{(j)}(\mathbf{V}) \subset V, \; j = \overline{1, J}. \tag{8}$$

However, it is highly probable that solutions $\{\mathbf{V}^{*(j)}\}_{j=1}^{J}$ to J maximization problems (8) are different. This means that a J-criterion problem

$$V^{*(j)} = \arg\max_{\mathbf{V}\in V} \widetilde{y}^{(j)}(\mathbf{V}) \subset V, \; j = \overline{1, J}, \tag{9}$$

does not have an exact solution, i.e.

$$\bigcap_{j=1}^{J} V^{*(j)} = \varnothing.$$

An approximate solution to this problem can be found as follows [19; 20]. First, we have to find a set of Pareto-efficient points. So, we have to find every Pareto-efficient point $\mathbf{V}^{**}$, at which inequalities

$$\widetilde{y}^{(j)}(\mathbf{V}) \geqslant \widetilde{y}^{(j)}(\mathbf{V}^{**}) \quad \forall j = \overline{1, J} \tag{10}$$

are impossible for any $\mathbf{V} \in V$ unless $\exists \mathbf{V}_0 \in V$ such that

$$\widetilde{y}^{(j)}(\mathbf{V}_0) = \widetilde{y}^{(j)}(\mathbf{V}^{**}) \quad \forall j = \overline{1, J}. \tag{11}$$

Suppose that set U is sampled (uniformly or close to that) into M sample vectors

$$\{\mathbf{U}^{(m)}\}_{m=1}^{M} \subset U,$$

which are subsequently standardized to a set V_M of M sample vectors

$$\{\mathbf{V}^{(m)}\}_{m=1}^{M} = V_M \subset V, \tag{12}$$

whose entries are within half-interval $(0; 1]$. A set V of H Pareto-efficient points is then determined for vectors (12) by using (10), (11), where

$$\mathsf{V} = \{\mathbf{V}^{**(h)}\}_{h=1}^{H} \subset V_M \tag{13}$$

and $\mathbf{V}^{**(h)}$ is an h-th Pareto-efficient point, $h = \overline{1, H}$ and H is a number of efficient sizing configurations. Weighted values

$$\{\{\widetilde{y}^{(j)}(\mathbf{V}^{**(h)})\}_{h=1}^{H}\}_{j=1}^{J} \tag{14}$$

of the quality-controlled factors calculated by (7) are further standardized as

$$\widetilde{y}_1^{(j)}(\mathbf{V}^{**(h)}) = \frac{\widetilde{y}^{(j)}(\mathbf{V}^{**(h)})}{\max\limits_{l=\overline{1, H}} \widetilde{y}^{(j)}(\mathbf{V}^{**(l)})}, \; h = \overline{1, H}, \; j = \overline{1, J}. \tag{15}$$

Then the distance to the (most likely, unachievable) unit point in R^J is calculated for every Pareto-efficient point:

$$\rho_h = \sum_{j=1}^{J} [1 - \widetilde{y}_1^{(j)}(\mathbf{V}^{**(h)})]^2, \; h = \overline{1, H}. \tag{16}$$

Finally, the best Pareto-efficient point is the closest to the unit point, and thus

$$\mathbf{V}^{***} = [v_i^{***}]_{1\times F} \in \arg \min_{\{\mathbf{V}^{**(h)}\}_{h=1}^{H}} \rho_h =$$

$$= \arg \min_{\{\mathbf{V}^{**(h)}\}_{h=1}^{H}} \sum_{j=1}^{J} [1 - \tilde{y}_1^{(j)}(\mathbf{V}^{**(h)})]^2 . \quad (17)$$

Hence, $\mathbf{V}^{***}$ by (17) is the optimal configuration of the sizing parameters standardized according to ratio (2).

To get back to real values of sizing parameters, we unstandardize entries of vector $\mathbf{V}^{***}$ by using ratio (2):

$$u_i^{***} = v_i^{***} \max_{k=\overline{1, C}} u_i^{(k)} , \quad i = \overline{1, F}. \quad (18)$$

Thus, vector $\mathbf{U}^{***} = [u_i^{***}]_{1\times F}$ contains the optimal values of the sizing parameters. Real values of the quality-controlled factors are calculated similarly by unstandardizing entries of vector

$$\tilde{\mathbf{Y}}_1(\mathbf{V}^{***}) = [\tilde{y}_1^{(j)}(\mathbf{V}^{***})]_{1\times J} \quad (19)$$

by using ratio (15):

$$\tilde{y}^{(j)}(\mathbf{V}^{***}) = \tilde{y}_1^{(j)}(\mathbf{V}^{***}) \cdot \max_{l=\overline{1, H}} \tilde{y}^{(j)}(\mathbf{V}^{**(l)}), \quad j = \overline{1, J} , \quad (20)$$

where upon vector

$$\tilde{\mathbf{Y}}(\mathbf{V}^{***}) = [\tilde{y}^{(j)}(\mathbf{V}^{***})]_{1\times J} \quad (21)$$

contains the best values of the quality-controlled factors.

COTTON WARP SIZING

During the real-time experimental research of the cotton yarn of class 1, three sizing parameters were studied:

1. The amount of starch, g/liter ($i = 1$).
2. The amount of hydrophilic component of kaolin or potassium alum as a percentage of the starch mass ($i = 2$).
3. The amount of soft paraffin plasticizer as a percentage of the starch mass ($i = 3$).

An exhaustive experimental research is impossible due to the research of every feasible combination of these three sizing agents spans up to 36 hours, let alone spending other material resources. Thus, only marginal values of the sizing agents were used to control the sizing quality (Table 1).

Table 1. Combinations of the three sizing agents for the cotton yarn of class 1

Number of the distinct combination, c	1	2	3	4	5	6	7	8
Amount of starch $u_1^{(c)}$, g/liter	40	40	40	40	60	60	60	60
Amount of hydrophilic component of kaolin or potassium alum $u_2^{(c)}$, %	0.1	0.1	1	1	0.1	0.1	1	1
Amount of soft paraffin plasticizer $u_3^{(c)}$, %	0.8	1.5	0.8	1.5	0.8	1.5	0.8	1.5

In fact, Table 1 shows up a matrix of eight vectors (1) for this study case. The sizing quality here is studied for three quality indicators:

4. The tenacity or relative breaking strength ($j = 1$), cN/Tex.
5. The percentage of breaking elongation ($j = 2$).
6. The percentage of adhesion strength ($j = 3$).

The averages of the quality indicators are presented in Table 2.

Table 2. The averaged values of quality indicators for combinations in Table 1

Number of the distinct combination, c	**Averages of quality indicators**		
	Relative breaking strength $\tilde{y}_c^{(1)}$	Percentage of breaking elongation $\tilde{y}_c^{(2)}$	Percentage of adhesion strength $\tilde{y}_c^{(3)}$
1	13.675	5.05	4.425
2	13.25	5.15	4.125
3	13.275	5.175	4.4
4	13.25	5.225	4.4
5	16.825	4.8	7.1
6	16.1	4.85	6.625
7	16.65	4	7.25
8	16.75	4.775	6.85

Consequently, by the method of controlling the sizing quality in accordance with formulae (1)–(21) with an experimentally adjusted spread of $\sigma = 0.1$, we have eight sets of sizing parameters

$$\{\mathbf{U}_c\}_{c=1}^{8} = \{[u_i^{(c)}]_{1\times 3}\}_{c=1}^{8} \in U \tag{22}$$

which are standardized into eight sets

$$\{\mathbf{V}_c\}_{c=1}^{8} = \{[v_i^{(c)}]_{1\times 3}\}_{c=1}^{8} \in V$$

by (2) as

$$v_i^{(c)} = \frac{u_i^{(c)}}{\max\limits_{k=\overline{1,8}} u_i^{(k)}}, \quad c = \overline{1,8}, \quad i = \overline{1,3}.$$

We sample set (22) uniformly into 1000 to 343000 sample vectors and determine the number of Pareto-efficient points according to (10), (11). In order to prevent an excessive adhesion strength of over 6%, we exclude from set (13) all Pareto-efficient points such, for which

$$\tilde{y}_1^{(3)}(\mathbf{V}^{**(h)}) > 6, \quad h = \overline{1, H}. \tag{23}$$

Thus, set (13) is refined with a fewer number H of Pareto-efficient points. Formulae (14)–(17) are subsequently applied and the optimal values of the three sizing parameters by (18) are

$$u_i^{***} = v_i^{***} \max\limits_{k=\overline{1,8}} u_i^{(k)}, \quad i = \overline{1,3}. \tag{24}$$

The best values of the relative breaking strength, breaking elongation percentage, and adhesion strength percentage are

$$\widetilde{y}^{(j)}(\mathbf{V}^{***}) = \widetilde{y}_1^{(j)}(\mathbf{V}^{***}) \cdot \max_{l=\overline{1,H}} \widetilde{y}^{(j)}(\mathbf{V}^{**(l)}), \quad j = \overline{1,3}, \tag{25}$$

respectively. The best values (25) are obtained by the optimal amounts of starch, hydrophilic component of kaolin or potassium alum, and soft paraffin plasticizer by (24) or, in standardized units, by (17). The results of solving the problem are presented in Table 3, where $M^{(6)}$ is a number of sample vectors after refinement by (23) prior to determining set $\mathbf{V}$ of H Pareto-efficient points. It is clearly seen that the optimal values of the three sizing parameters (24) and the best values of the quality indicators (25) depend on the sampling. In particular, the amount of hydrophilic component of kaolin or potassium alum badly depends on the sampling, ranging from it minimum to maximum possible percentages. The amount of soft paraffin plasticizer varies much less, but its efficient value is mostly at the upper bound (i.e., $u_3^{***} = 1.5$). Meanwhile, the amount of starch varies the least, and its relative deviation is just a bit greater than 1 g/liter. The quality indicators obtained by the optimal values of the three sizing parameters vary also, but their variation decreases as the sampling becomes denser.

Starting from $M = 15625$ up to $M = 343000$, the variation of the best Pareto-efficient point entries (24) significantly decreases. The minimum, maximum, and average for $M \geqslant 15625$ are presented in Table 3 also. The variation of the starch amount does not exceed 0.66 g/liter, the amount of hydrophilic component of kaolin or potassium alum ranges from 0.55 to 1, whereas the amount of soft paraffin plasticizer remains constantly at the upper bound. Fig. 1 showing the variation of u_1^{***} confirms its trend to decreasing (here and in the plots below the average value is shown with a horizontal line). To the contrary, Fig. 2 shows that the amount of hydrophilic component of kaolin or potassium alum varies at denser sampling as mush as it varies at sparser sampling down to at $M = 15625$.

Table 3. Solutions (24), (25) of the three-criterion problem for the cotton yarn of class 1

M	$M^{(6)}$	H	u_1^{***}	u_2^{***}	u_3^{***}	$\widetilde{y}^{(1)}(\mathbf{V}^{***})$	$\widetilde{y}^{(2)}(\mathbf{V}^{***})$	$\widetilde{y}^{(3)}(\mathbf{V}^{***})$
1000	545	112	51.1111	0.6	1.5	15.519	4.9329	5.9889
1331	726	120	50	1	1.5	15	5	5.625
1728	942	139	50.9091	0.9182	1.5	15.4328	4.9444	5.9279
2197	1219	134	51.6667	0.1	1.2667	15.3078	4.9335	5.9266
2744	1477	183	50.7692	0.9308	1.5	15.3683	4.9526	5.8828
3375	1855	167	51.4286	0.55	1.5	15.4364	4.9293	5.9668
4096	2199	204	50.6667	1	1.5	15.3204	4.9588	5.8493
4913	2673	219	51.25	0.55	1.5	15.3676	4.9374	5.9132
5832	3239	337	51.7647	0.5235	1.5	15.3624	4.929	5.9631
6859	3772	322	51.1111	0.6	1.5	15.519	4.9329	5.9889
8000	4410	410	51.5789	0.1	1.2053	15.3596	4.9283	5.955
9261	5061	374	51	0.595	1.5	15.4669	4.9394	5.9526
10648	5831	495	51.4286	0.1	1.2	15.3226	4.932	5.9198
12167	6723	539	50.9091	0.9182	1.5	15.4328	4.9444	5.9279
13824	7632	538	51.3043	0.1391	1.1652	15.4105	4.9225	5.9695
15625	8582	640	50.8333	0.925	1.5	15.398	4.9488	5.9036
17576	9643	534	51.2	0.568	1.5	15.4917	4.9316	5.9789

Continued Tabl. 3

M	$M^{(6)}$	H	u_1^{***}	u_2^{***}	u_3^{***}	$\tilde{y}^{(1)}(\mathbf{V}^{***})$	$\tilde{y}^{(2)}(\mathbf{V}^{***})$	$\tilde{y}^{(3)}(\mathbf{V}^{***})$
19683	10762	571	50.7692	0.9654	1.5	15.3683	4.9526	5.8828
21952	12254	629	51.1111	0.6	1.5	15.519	4.9329	5.9889
24389	13301	608	51.4286	0.55	1.5	15.4364	4.9293	5.9668
27000	15016	678	51.0345	0.6276	1.5	15.4891	4.9371	5.9674
29791	16186	693	51.3333	0.55	1.5	15.4	4.9336	5.9385
32768	18128	757	50.9677	0.9129	1.5	15.4594	4.9409	5.9466
35937	19825	1019	51.25	0.55	1.5	15.3676	4.9374	5.9132
39304	21674	870	50.9091	0.9182	1.5	15.4328	4.9444	5.9279
42875	23579	895	51.1765	0.5765	1.5	15.5162	4.931	5.9912
46656	25596	920	50.8571	1	1.5	15.409	4.9474	5.9113
50653	27964	1101	51.1111	0.575	1.5	15.4833	4.9348	5.9684
54872	30236	1198	50.8108	1	1.5	15.3876	4.9502	5.8963
59319	32700	1139	51.0526	0.5974	1.5	15.4918	4.9363	5.9699
64000	35198	1284	50.7692	0.9308	1.5	15.3683	4.9526	5.8828
68921	37878	1276	51	0.9775	1.5	15.474	4.939	5.9568
74088	40625	1332	51.2195	0.561	1.5	15.4542	4.9332	5.9592
79507	43855	1723	50.9524	0.9357	1.5	15.4525	4.9418	5.9417
85184	46622	1332	51.1628	0.5814	1.5	15.5225	4.9311	5.9939
91125	50238	1820	50.9091	0.9795	1.5	15.4328	4.9444	5.9279
97336	53455	1495	51.1111	0.58	1.5	15.497	4.9341	5.9763
103823	57382	1954	50.8696	0.9413	1.5	15.4147	4.9467	5.9153
110592	61306	2236	51.0638	0.5979	1.5	15.497	4.9357	5.9736
117649	64815	2062	50.8333	0.9063	1.5	15.398	4.9488	5.9036
125000	69187	2315	51.0204	0.9449	1.5	15.4832	4.9379	5.9632
132651	72897	1972	50.8	0.91	1.5	15.3826	4.9508	5.8928
140608	77641	2206	50.9804	1	1.5	15.4651	4.9402	5.9506
148877	82037	2037	51.1538	0.5673	1.5	15.4684	4.9343	5.9626
157464	86698	2372	50.9434	0.983	1.5	15.4484	4.9423	5.9389
166375	91996	2412	51.1111	0.5833	1.5	15.5036	4.9337	5.98
175616	96508	2555	50.9091	0.9182	1.5	15.4328	4.9444	5.9279
185193	102226	2618	51.0714	0.5982	1.5	15.5006	4.9352	5.9761
195112	107485	2807	50.8772	0.9526	1.5	15.4182	4.9462	5.9177
205379	113130	2768	51.0345	0.8914	1.5	15.4895	4.9371	5.9676
216000	118864	2557	50.8475	0.9847	1.5	15.4045	4.948	5.9082
226981	124826	3006	51	0.925	1.5	15.474	4.939	5.9568
238328	130884	2625	50.8197	0.9852	1.5	15.3917	4.9496	5.8992
250047	138396	3358	50.9677	0.9129	1.5	15.4594	4.9409	5.9466
262144	144298	3222	51.1111	0.5857	1.5	15.5073	4.9335	5.9822
274625	151787	3814	50.9375	0.9438	1.5	15.4457	4.9427	5.937
287496	158087	3464	51.0769	0.5846	1.5	15.4906	4.9355	5.9706
300763	165932	4032	50.9091	0.9182	1.5	15.4328	4.9444	5.9279
314432	173480	4270	51.0448	0.6239	1.5	15.4935	4.9365	5.9705
328509	180889	3533	50.8824	0.9338	1.5	15.4205	4.9459	5.9194
343000	189565	4689	51.0145	0.987	1.5	15.4805	4.9382	5.9614
Minimum			50	0.1	1.1652	15	4.9225	5.625
Maximum			51.7647	1	1.5	15.5225	5	5.9939
Average			51.0352	0.7421	1.4809	15.4325	4.9405	5.9377
Minimum for $M \geqslant 15625$			50.7692	0.55	1.5	15.3676	4.9293	5.8828
Maximum for $M \geqslant 15625$			51.4286	1	1.5	15.5225	4.9526	5.9939
Average for $M \geqslant 15625$			**51.0054**	**0.7965**	**1.5**	**15.4512**	**4.9403**	**5.9444**

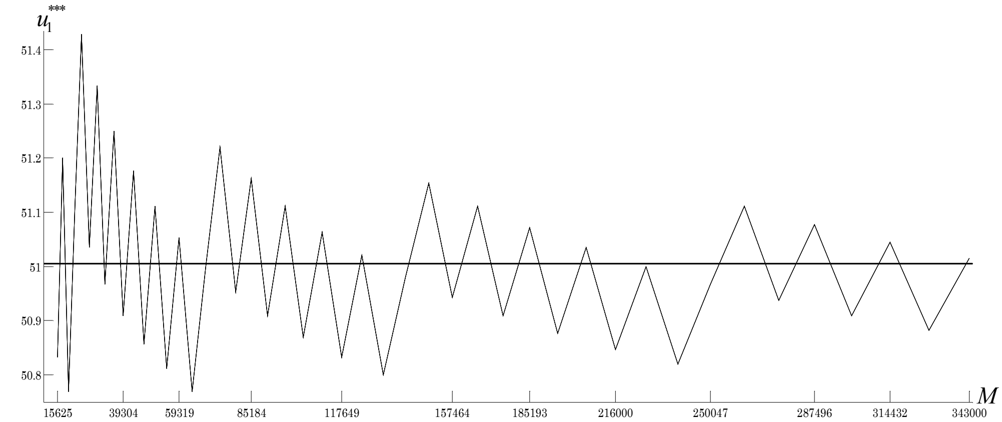

Fig. 1. The variation of the starch amount in the best efficient sizing

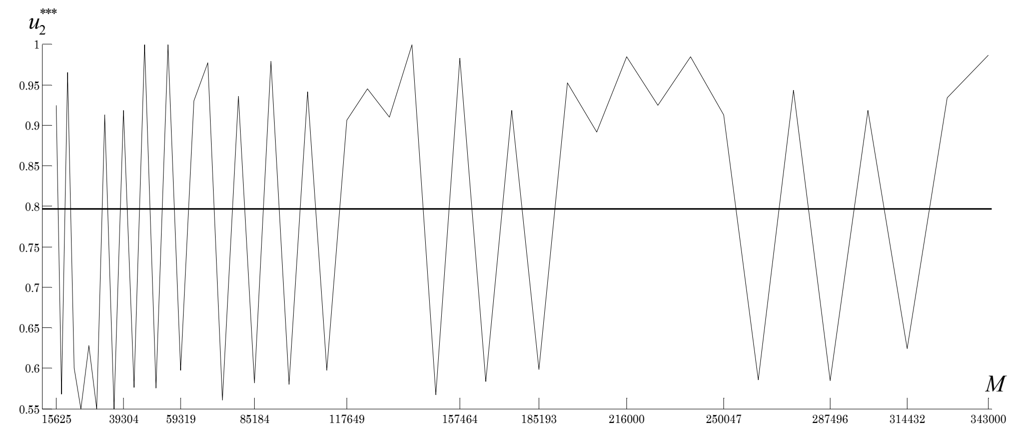

Fig. 2. The variation of the amount of hydrophilic component of kaolin or potassium alum

The relative breaking strength obtained at the optimal selection of cotton warp sizing parameters varies by 1% at most (Fig. 3). The percentage of breaking elongation varies by about 0.473% at most (Fig. 4). The variation of the percentage of adhesion strength is a little bit more significant — it varies by 1.889% at most (Fig. 5). Nevertheless, the above-mentioned decreasing trends of the variations are quite apparent in Figs. 3–5.

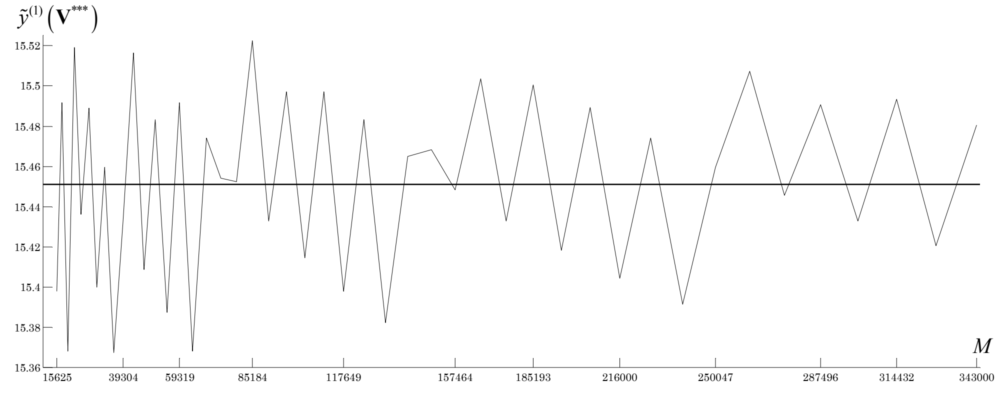

Fig. 3. The variation of the relative breaking strength

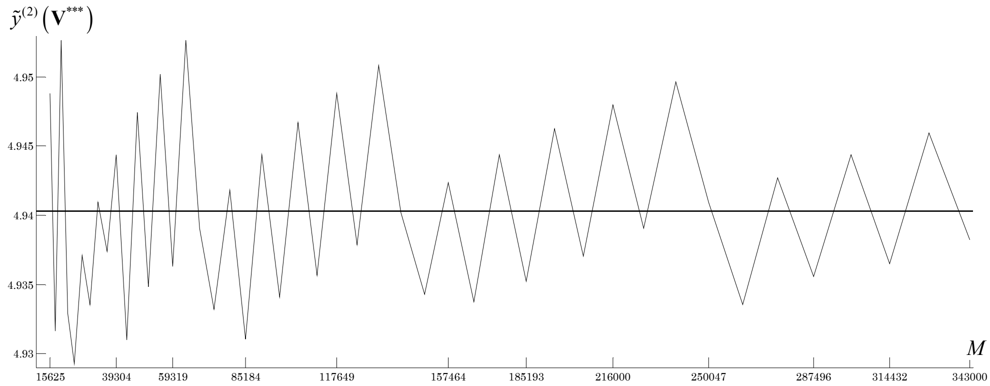

Fig. 4. The variation of the percentage of breaking elongation

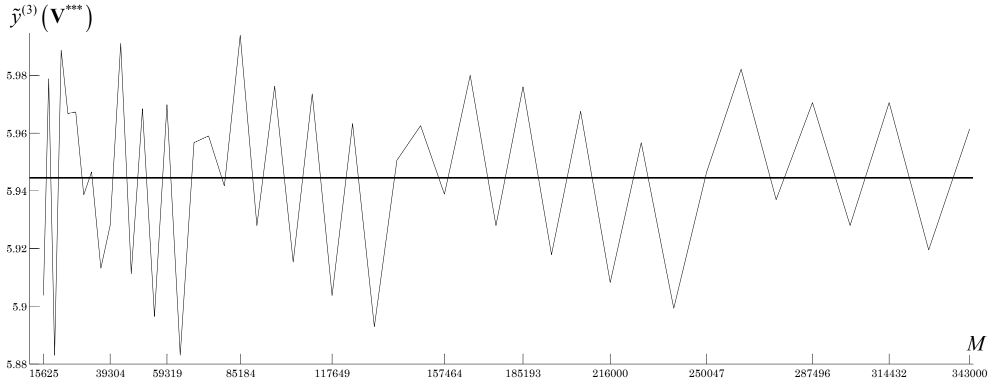

Fig. 5. The variation of the percentage of adhesion strength

It is worth mentioning that the variations of the optimal values for sizing agents and of the best quality indicators are explained with the probabilistic nature of the quality-controlled factors calculated by (7). The variations are further decreased by increasing the radial basis function spread σ, but then accuracy of the respective probabilistic classifier significantly drops [21; 22] and values of the quality-controlled factors calculated by (7) become irrelevant.

Therefore, the averages highlighted bold in Table 3 are considered as the final solutions (24), (25) of the three-criterion problem for the cotton yarn of class 1, where some rounding is still admissible, though. Thus, the optimal amount of starch is 51.0054 g/liter (however, by weighing it accurately to milligrams, it becomes 51.005 g/liter). The optimal amount of hydrophilic component of kaolin or potassium alum is 0.7965% (depending on weighing accuracy and technology, it can be rounded to 0.8%). The optimal amount of soft paraffin plasticizer is 1.5%. The obtained relative breaking strength is 15.4512 cN/Tex, which is 1.0828 times better than that obtained in [14; 15] by conducting a factorial experiment based on data in Tables 1 and 2. The breaking elongation percentage is less optimistic — it is 4.9403% versus the range from 5.12% to 5.4% reported in [15]. On average, $\tilde{y}^{(2)}(\mathbf{V}^{***})$ is 1.0647 times worse, but Table 3 shows that a 5% breaking elongation is hardly achievable for the given characteristics of materials and sizing agents. The percentage of adhesion strength is quite satisfactory — it is 5.9444% versus the range from 4.9% to 5.8% reported in [15].

DISCUSSION OF THE CONTRIBUTION

The method of radial basis functions renders ascertaining a topological location of any vector $\mathbf{V}$ within set $\{\mathbf{V}_c\}_{c=1}^{C} \subset V \subset \mathrm{R}^C$ into an approximation problem [23; 24]. This approximation problem can be considered as an interpolation approach [23; 25]. Thus, given a basis of C vectors $\{\mathbf{V}_c\}_{c=1}^{C} \subset V$, each of which corresponds to a distinct vector of quality indicators, the task is to determine a vector of quality indicators $\mathbf{Y} \in Y \subset \mathrm{R}^J$ for any vector $\mathbf{V} \in \mathrm{R}^C$. This task is solved by (4)–(7).

It is impossible to ascertain an analytical bond between uncountably infinite vector spaces $V \subset \mathrm{R}^C$ and $Y \subset \mathrm{R}^J$, but space V is sampled so that each element of the finite sampled space (12) can be mapped into a vector in R^J by using (4)–(7). The single variable of the mapping is the radial basis function spread σ. This parameter could be optimized during training the respective probabilistic neural network whose pattern matrix [22] would consist of vectors $\{\mathbf{V}_c\}_{c=1}^{C}$ concatenated into an $F \times C$ matrix of these vectors transposed into columns.

Upon the mapping, a set of Pareto-efficient vectors within subset (12) is determined. This relieves from considering useless vectors of quality-controlled factors whose values are below the already achievable quality level. More specifically, the efficiency selection saves memory and computational resources. It is seen from Table 3 that, in the case of the experimental research of the cotton yarn of class 1, the percentage of the number of Pareto-efficient vectors H with respect to the number of sampled vectors M does not exceed 11.2%.

Formally, optimization problem (17) is always solvable, but its practically consistent solvability depends on selecting a reasonably dense sampling of space U and spread σ. The approximation error has an upper bound [25; 26], which is exemplarily seen in Figs. 1–5, but its estimates would heavily depend on M and σ, as well as on the experimental sizing itself. Figs. 1–5 also show that practical convergence is possible by a moderate number of sample vectors.

Refining set (13), where vectors with inadmissible values of one or more quality indicators are excluded, is optional. In the particularly conducted experiments, overly adhered cotton warp leads to brittleness of the cotton yarn, and so Pareto-efficient vectors of sizing parameters producing an excessive adhesion strength of over 6% are not considered further. Constraints similar to (23) can be imposed on any other sizing quality indicators [27; 28].

The suggested algorithm of controlling sizing quality is consistent, verifiable, and scalable. It does not depend on the number of sizing parameters, nor depends it on the number of quality-controlled factors. Applied to the results of the factually conducted experiments, the algorithm has allowed to increase two of three sizing quality indicators, by acceptably decreasing the third one. Thus, this is a method to improve warp yarn weavability along with improving the economic performance of weaving. This is a practically significant and easy applicable contribution to the theory and real-time practicing of optimal selection of cotton warp sizing parameters, when the number of factual experiments is limited due to material and time resources limitations. Moreover, the algorithm is not limited to cotton, and it can be applied to any yarn material by following formulae (1)–(21) with an experimentally adjusted spread.

CONCLUSION

An algorithm has been suggested to control warp sizing quality under system research limitation, where optimal selection of cotton warp sizing parameters is exemplified. The algorithm has been successfully applied to the results of the factually conducted experiments with the cotton yarn of class 1, yielding the improved quality indicators of the sized warp. The algorithm utilizes a set of basis vectors of sizing parameters that corresponds to a set of respective vectors of quality indicators. Next, the method of radial basis functions is used to determine the probabilistically appropriate vector of quality indicators for any given vector of sizing parameters. Having sampled the uncountably infinite space of sizing vectors, it may then be refined by excluding sizing vectors corresponding to inadmissible values of one or more quality indicators. A set of Pareto-efficient sizing vectors is determined within the finite (refined) space of sizing vectors, and an optimal efficient sizing vector is determined as one being the closest to the best-ever sizing vector, which is usually unachievable.

The suggested algorithm serving as a method of optimal selection of warp sizing parameters under system research limitation depends on both the radial basis function spread and the number of basis vectors of sizing parameters. The latter, however, may have little significance due to only marginal values of the sizing parameters are commonly used. The research is possible to supplement with studying an impact of optimizing the radial basis function spread. While the relationship between the variation of sizing parameter optimum and the radial basis function spread is known to be inverse, an optimized spread may not change much the variation by insignificantly increasing one or a few quality indicators.

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ОПТИМАЛЬНИЙ ВИБІР ПАРАМЕТРІВ ШЛІХТУВАННЯ БАВОВНЯНОЇ ПРЯЖІ ЗА ОБМЕЖЕНОСТІ СИСТЕМНИХ ДОСЛІДЖЕНЬ / Г.С. Ткачук, В.В. Романюк, А.В. Ткачук

Анотація. Шліхтування основи тканини полягає у нанесенні матеріалів шліхтування на основу пряжі для покращення її властивостей при ткацтві разом з підвищенням економічної ефективності технологічного процесу ткацтва. Розглянуто скінченну множину агентів або параметрів шліхтування, котра відображається у скінченну множину показників якості шліхтування. Оскільки існують різні обмеження на матеріальні та часові ресурси, вичерпне системне дослідження і побудова інформаційної технології для інтерпретації та оптимізації даних шліхтування неможливі. Тому запропоновано алгоритм контролю якості шліхтування основи тканини за обмежень системного дослідження, наведено приклад оптимального вибору параметрів шліхтування бавовняної основи. Алгоритм використовує множину базисних векторів параметрів шліхтування, яку зіставлено з множиною відповідних векторів показників якості. Використано метод радіальних базисних функцій для визначення ймовірнісно прийнятного вектора показників якості для довільного вектора параметрів шліхти. Незліченно нескінченний простір векторів шліхти рівномірно дискретизується у скінченний простір. Цей скінченний простір можна також поліпшити вилученням векторів шліхти, котрі відповідають недопустимим значенням одного або декількох показників якості. У межах даного скінченного (поліпшеного) простору визначається множина Парето-ефективних векторів шліхти, й оптимальний ефективний вектор шліхти визначається як той, який є найближчим до недосяжного вектора шліхти. Запропонований алгоритм слугує методом оптимального відбору параметрів шліхтування основи тканини, результатом застосування якого є покращені властивості основ пряж, що можуть витримувати циклічні тертя, розтягування та згинання на ткацькому верстаті без наслідків ворсування чи іншого псування. Розроблений алгоритм не обмежується використанням бавовни і може бути застосований до довільного матеріалу пряжі за експериментально допасованого значення розтягу радіальної базисної функції.

Ключові слова: шліхтування основи тканини, агенти шліхтування, колоїдні системи, неорганічні складники, показники якості шліхтування, радіальна базисна функція, ефективність за Парето.