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U.J. Eshbaeva

Tashkent institute textile and light industry, Guli-67@mail.ru

I.G. Shin

Tashkent institute textile and light industry, shin-i-g@mail.ru

A.A. Djalilov

Tashkent institute textile and light industry, anvar-matbaa@mail.ru

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OPTIMIZATION OF COLOR PERCEPTION PROCESS IN THE PRINT PRODUCT BY THE STEEP CLIMBING METHOD BY BOX-WILSON

U.J.Eshbaeva, I.G.Shin, A.A.Djalilov (TITLI)

Annotation. In the article is discussed the optimization of color perception process of printed products by the method of steep climbing in Box-Wilson. There are presented results of experiment planning and statistical modeling of the process of color perception with the offset printing method on paper, including synthetic polymers. It is presented a mathematical model of the color perception by the Box-Wilson steep ascent method, it is achieved the optimum range for the response function in the form of the paint layer thickness depending on the pressing force (pressure), the pressing process speed and paper smoothness. As a result, on the basis of the obtained color perception model, optimal parameters were established, which allow to hold objective assessment and prediction of the color perception of the printed materials. The results of the study are the basis for the rational determination of the compositional composition of the experimental paper in its design and development of both paper and printing products.

Key words: ink layer, print, ink transfer coefficient, rheological properties, absorbency (sorption), print quality, ink perception.

Introduction. Scientific work on optimizing the process of paint perception by modeling was carried out by many scientists from all over the world. The work [1] is devoted to the analysis of print quality by offset printing on an uncoated surface of the paper to determine the conformity of quality to ISO 12647 standards.

The quality of the printed product, *ceteris paribus*, is determined by the nature of the interaction between paper and ink, which depends on number of properties and conditions of the ink: the rheological properties of the ink suspension, the ability to distribute a thin layer on the colorful rollers and the printing form, ensuring uniform prints of intensity and the ability to securely fix them on.

The pressure during the printing contact has a decisive influence on the condition of the interaction of ink and paper, since under its influence the printing process is carried out by introducing ink through the surface pores into the thickness of the paper [2, 3]. Impressions are the result of complex physicochemical phenomena associated with the transfer and division of ink layers, the movement of suspension of ink in wet material, the interaction of ink and the transfer of ink to paper.

Paper is the main material of the printing process, whose properties determine the quality of prints [4]. In the process of printing, the paper is wetted with a binder (carrier) pigment, and then bonded. A feature of the interaction of ink with paper is the penetration of ink or its components into the porous structure of the paper. Depending on the porosity of the paper, its interaction with the ink proceeds differently.

Cotton cellulose is widely used in the paper industry. From cotton cellulose, is obtained soft and dense paper that retains its properties for a long time. Paper obtained from cotton raw materials is used for the production of banknotes, checks and other high-strength bank papers [5, 6]. However, the technology of manufacturing paper on an industrial scale from cotton pulp is not economically feasible. The addition of textile and chemical industries to the paper cellulose will solve the problem of efficient and rational use of raw materials, save expensive cotton pulp, reduce the cost of paper and significantly reduce the need to import paper from the outside [7, 8].

Experimental part. In order to use rationally the waste of synthetic fiber resources and to create new assortments of paper material based on local raw materials in the manufacture of composite paper, we used lint of cotton pulp, untreated and hydrolyzed wastes of polyacrylonitrile (PAN) fibers of nitron, dyed natural silk (DNS) and modified nitron fiber [8]. Hydrolysis of nitron waste was carried out in a 5% alkali solution at a temperature of $(90 \pm 2) \text{ }^{\circ}\text{C}$.

Together with the specialists of the testing center for pulp, paper, cardboard and products made from them - UzRITS PPM at the Joint Stock Company “Toshkent Qog’ozi”, prototypes of paper were made and their quality was evaluated according to the approved technological regulations [4].

For research and statistical analysis of the distribution of the ink layer on the surface of the print, we selected eight optimal paper options (Table 1).

Table 1

Paper prototypes and their fibrous composition

Sample №	Fiber Composition
№1	100% cotton pulp, glued in bulk with gum rosin
№2	85% cotton cellulose and 15% nitron waste, sizing in bulk with acrylic emulsion
№3	85% cotton cellulose and 15% nitron waste, sizing in bulk with mylar emulsion
№4	85% cotton cellulose and 15% nitron waste, sizing with rosin glue
№5	85% cotton cellulose and 15% modified nitron waste, sizing with rosin glue
№6	85% cotton cellulose and 15% waste hydrolyzed nitron, sizing in bulk with rosin glue
№7	85% cotton cellulose, 7.5% nitron waste and 7.5% natural silk waste, sizing in bulk with gum rosin
№8	85% cotton cellulose and 15% natural silk waste, sizing with rosin glue

In this work, the transfer coefficient of ink on the printed material was determined by comparing the mass of printed material before and after printing. Below are given the results of the calculation of statistical analysis of ink layer distribution on experimental papers.

The main input factors were: pressure, speed and paper smoothness. The temperature of the ink was not taken into account in order to simplify the description of transition process of the ink to the printed paper.

By planning the full factorial experiment [9], the number of output parameters (optimization parameters) were investigated and obtained: the ink layer thickness, the optical density and the transfer coefficient of the paint.

The first plan was drawn up of two-level ($k = 2$) three-factor experiment, where the first factor is pressure with encoding, the second is speed, with encoding, and the third is paper smoothness, with encoding, with two parallel experiments. From the analysis of priori information, the main factors were determined and a table 2 was compiled.

Table 2

**Input parameters for full three-factor experiment
1-experience ($p = 1$)**

Factors	X_{\max}	X_{\min}	Δ	X_0
Clamping Force (N)	650	450	100	550

Speed (print/hour)	9000	5000	2000	7000
Paper smoothness (s)	60	20	20	40

2-experience ($p = 2$)

Factors	X_{\max}	X_{\min}	Δ	X_0
Clamping Force (N)	750	450	150	600
Speed (print/hour)	11000	5000	3000	8000
Paper smoothness (s)	70	20	25	45

Before conducting the regression analysis, It was checked homogeneity of the dispersion of experimental errors and was established distribution law. Checking the homogeneity of the variance of the experimental errors hold due to the method described in [10, 11] work.

To determine the regression equation, a matrix was compiled at two levels ($k = 2$) for optical density (\bar{y}_{ui}), ink layer thickness, (\bar{z}_{ui}) and ink transfer coefficient (\bar{r}_{ui}) obtained in parallel experiments, each of which is determined from the tests. Thus, we have

$$\bar{y}_{ui} = \frac{1}{n} \sum_{l=1}^n y_{ul}, \bar{z}_{ui} = \frac{1}{n} \sum_{l=1}^n z_{ul}, \bar{r}_{ui} = \frac{1}{n} \sum_{l=1}^n r_{ul} \quad (l = 1.2...m) \quad (1)$$

For the experiment there were built the planning matrix and the working matrix. Let's Consider the case of two experiments in each variant with a set number $N_2 = N = 8$, we assume $m = 2$ and make their values in table 3.

At the first stage of the research It was held a complete factorial experiment. To eliminate the systematic errors of the experiment provided by the matrix, the experiments were carried out in random order. Statistical processing of the experimental data was first carried out for the thickness of the ink layer \bar{z}_{ui} . In order to determine the indicator of ink perception of paper on a sheet printing machine Ryobi 780-4 (in the publishing and printing creative house named by "G. Gulyam" in Tashkent), under the given conditions, prints (CMYK) were printed [4]. The printing was carried out with Flint Group K + E Novavit F 700 ink. The parameters of the surrounding air were constant and correspondingly equal: relative air humidity $\Psi = 50-55\%$ and temperature $t = 20-21$ °C. The optical density of the resulting prints was measured by using a Gretag Makbet densitometer.

In the table № 3 is presented the matrix of the experimental design and measurements results of optimization parameter (the ink layer thickness) with some statistical characteristics.

Table 3

Thickness value results of the paint layer

№ Experience	Levels of variability			Test Results						
				Feedback						
	x_1	x_2	x_3	\bar{z}_{i1}	\bar{z}_{i2}	\bar{z}_u	S_u^2	\hat{z}_u	\bar{z}_u	$R_0(\%)$
1	-	-	-	0.60	0.60	0.60	0	0.476	0.60	20.62
2	+	-	-	1.30	1.35	1.32	0.00125	1.372	1.32	3.585
3	-	+	-	0.65	0.70	0.67	0.00125	0.740	0.67	9.629

4	+	+	-	1.60	1.65	1.62	0.00125	1.636	1.62	0.692
5	-	-	+	0.75	0.86	0.80	0.00605	0.862	0.80	7.142
6	+	-	+	1.70	1.78	1.74	0.00320	1.759	1.74	1.077
7	-	+	+	0.93	1.32	1.12	0.07605	1.126	1.12	0.111
8	+	+	+	1.90	2.30	2.10	0.08000	2.022	2.10	3.690

Before carrying out the regression analysis, was checked the homogeneity of the variance of the experimental errors and was established the distribution law:

We calculate the values by the formula:

$$S_u^2 = (\bar{z}_{u1} - \bar{z}_u)^2 + (\bar{z}_{u2} - \bar{z}_u)^2, (u = 1, 2, 3, 4, 5, 6, 7, 8).$$

$$S_1^2 = 0., S_2^2 = 0.00125, S_3^2 = 0.00125, S_4^2 = 0.00125, S_5^2 = 0.00605, S_6^2 = 0.0032,$$

$$S_7^2 = 0.076, S_8^2 = 0.08,$$

Assuming, $S_{u(\max)}^2 = S_8^2 = 0.08$, $\sum_{u=1}^8 S_u^2 = 0.169$ we calculate the calculated value of the

$$\text{Cochren criterion } G = \frac{S_{u(\max)}^2}{\sum_{u=1}^N S_u^2} = 0.437$$

Cochren's criterion is verified with tabular data G_{α, k_1, k_2} , where $\alpha = 0.05$, $k_1 = N = 8$. Moreover, we have $G_{0.05, 8, 1} = 0.68$. Since $G < G_{0.05, 8, 1}$, the homogeneity of the variance of the input parameters for the ink layer thickness is not refuted. Thus, in this case, the variance S_y^2 averaged over the variants can be used to assess the adequacy of the mathematical model for the paint layer thickness according to the formula:

$$S_y^2 = \frac{1}{N} \sum_{u=1}^N S_u^2 = 0.02113$$

The regression coefficients with numerical values are:

$$b_0 = 1,249375, b_1 = 0,448125, b_2 = 0,131875, b_3 = 0,193125;$$

$$b_{12} = 0,033125, b_{13} = 0,029375, b_{23} = 0,038125, b_{123} = 0,023125;$$

The regression equation in coded variables, and for the paint layer thickness:

$$\begin{aligned} \hat{z} = & 1,249375 + 0,448125x_1 + 0,131875x_2 + 0,193125x_3 + 0,033125x_1x_2 + 0,029375x_1x_3 + \\ & + 0,038125x_2x_3 - 0,023125x_1x_2x_3, \end{aligned} \quad (2)$$

We estimate the regression coefficients according to the student criterion. First, we calculate the confidence interval Δb for $\alpha = 0.05$, $N = 8$, $m = 2$, $k = N(m-1) = 8$. Using the table data ($t_{0.05, 8} = 2.31$), we have

$$\Delta b = t_{\alpha, k} \frac{S_y}{\sqrt{N}} = 2.31 \frac{\sqrt{0.02113}}{\sqrt{8}} = 0.1187$$

Comparing with the coefficients and, we have

$$b_0 > \Delta b, b_1 > \Delta b, b_2 > \Delta b, b_3 > \Delta b, |b_{12}| < \Delta b, |b_{13}| < \Delta b, |b_{23}| < \Delta b, |b_{123}| < \Delta b$$

Thus, in the regression equation for the ink layer thickness, the coefficients, b_1 , b_2 and b_3 are also significant. If other coefficients are not taken into account in the regression equation, then we

have the following linear dependence, where the output parameter is the ink layer thickness linearly depends on three factors, and

$$\hat{z} = 1,249375 + 0,448125x_1 + 0,131875x_2 + 0,193125x_3 \quad (3)$$

To verify the adequacy of the linear model of the paint layer thickness of the according to the Fisher criterion, we find the residual dispersion \hat{y}_u, \hat{z}_u и \hat{r}_u . To assess the adequacy of the models, we calculate the values and determine the relative discrepancy R_0 between the actual \bar{y}_u and calculated data. The largest discrepancy between the calculated and actual data is observed for the thickness of the ink layer, where factors X_1 (pressure), X_2 (speed) and X_3 (paper smoothness) take the minimum values. In other options, the discrepancy is negligible. To verify the adequacy of the linear model of the paint layer thickness of the according to Fisher criterion, we find the residual dispersion:

$$S_{oc}^2 = \frac{\sum_{u=1}^8 (\bar{z}_u - \bar{z}_u)^2}{N - k - 1} = \frac{1}{4} \sum_{u=1}^8 (\bar{z}_u - \bar{z}_u)^2 = 0.008$$

We calculate the calculated value of the Fisher criterion $F = S_{oc}^2 / S_y^2 = 0,008 / 0,02113 = 0,3737$ and compare it with Fisher criterion for $\alpha = 0.05$, $k_1 = N - k - 1 = 4$, $k_2 = N(m - 1) = 8$, $F_{0.05,4,8} = 3.84$. Since $F < F_{0.05,4,8}$ the hypothesis of the adequacy of the linear model of the regression equation for paint layer thickness according to Fisher criterion is not refuted.

Thus, confirmation of the adequacy hypothesis of the developed mathematical model in the form of regression equations (2) allows us to switch to the Box-Wilson steep ascent method [10] to achieve the optimum region of the considered response functions. A steep climb is effective when all the factors under the factors are significant.

It should be noted that this method is a special case of planning an experiment and relates to an extreme experiment, when the minimum number of additional experiments and the conditions are selected for their implementation. Steep ascent is the process of moving towards the optimum along the steepest path, provided that the factors change in proportion to their coefficients. The movement along the gradient provides the direction of the steepest slope leading from this point to the top.

As you know, the gradient is the vector of the fastest change in a certain quantity in space during the transition from one point to another, i.e. the gradient ($\Delta\varphi$) of the continuous single-valued function φ is a vector:

$$\Delta\varphi = \frac{\partial\varphi}{\partial x_1} \bar{i} + \frac{\partial\varphi}{\partial x_2} \bar{j} + \dots + \frac{\partial\varphi}{\partial x_k} \bar{k}$$

where $\frac{\partial\varphi}{\partial x_1}$ is the partial derivative of the function with respect to the i -th factor; $\bar{i}, \bar{j}, \dots, \bar{k}$ - unit vectors in the direction of the axes of the vectors.

In accordance with Taylor theorem on the expansion of an analytic function in series, the partial derivatives of the function with respect to the factors are equal in magnitude and sign to the corresponding coefficients of the regression equation. Therefore, the gradient Δy of the response function (y) is a vector:

$$\Delta y = \epsilon_1 \bar{i} + \epsilon_2 \bar{j} + \dots + \epsilon_k \bar{k}$$

The gradient motion step is chosen so that its minimum value is greater than the error with which the factor is fixed. The maximum step size is limited by the factor definition area. It is necessary to take into account that, when moving towards the optimum, a small step will require

significant number of experiments, and the larger step may lead to a slip of the optimum region. The movement step is chosen for one factor, and for the rest it is calculated by the expression:

$$\Delta i = \Delta e \frac{b_i \varepsilon_i}{b_e \varepsilon_e} \quad (4)$$

where Δe is the selected movement step for the factor L; Δi is the movement step for the i-th factor; b_i, b_e - regression coefficients of the i-th and L-th factors; $\varepsilon_i, \varepsilon_e$ are the intervals of variation of the ith and Lth factors.

The movement along the gradient starts from the zero point (the ground level of each factor), since the regression coefficients are calculated for the response function expanded in Taylor series in the vicinity of the zero point. Having calculated the movement step for each factor, the conditions of “mental” experiments are found, the conditions for which at the stage of steep ascent are established taking into account the movement step for each factor. Part of the mental experiments are carried out to check the results of a steep ascent.

A steep climb stops if optimization conditions are found, or if restrictions on factors make further movement along the gradient is unreasonable.

Consider Box-Wilson method on the example of studying the ink perception when printing on experimental paper. The optimization parameter is the ink layer thickness z , microns. We start the steep ascent from the center of the plan, i.e. from a point with coordinates $x_1 = x_2 = x_3 = 0$, which corresponds to pressure $p = 550$ N, a speed of $v = 7000$ print / hour and paper smoothness of $q = 30$ s (Table 5). The movement step for the factor x_3 is taken $\Delta_3 = 10$ s. By the formula (8) we calculate the step of movement for factors x_1 and x_2 ;

$$\Delta_2 = \Delta_3 \frac{b_2 \varepsilon_2}{b_3 \varepsilon_3} = 10 \frac{0,132 \cdot 2000}{0,193 \cdot 20} = 689,94; \quad \Delta_1 = \Delta_3 \frac{b_1 \varepsilon_1}{b_3 \varepsilon_3} = 10 \frac{0,448 \cdot 100}{0,193 \cdot 20} = 116,06;$$

The best result was obtained in the 10th experiment. The value of the optimization parameter - the ink layer thickness (z , micron) is satisfactory, and therefore the experimental work was completed. Thus, it took 10 experiments to determine the optimal printing conditions: $p = 780$ N, speed $v = 8380$ ott / hour and paper smoothness $q = 40$ s. It should be noted that the conditions that are optimal for the thickness of the ink layer (z) are very close for the formation of the best optical density ($D_{op.pl.} = 1.45$) and ink transfer ($K_p = 47.5$) (Table 5).

Table 5

Step climb calculation

№	Name	P,H	V, print/hour	q, s	z, micron	$D_{op.den.}$	K_{π}
1	Main level	550	7000	30	–	–	–
2	Coefficient b_i	0,448	0,132	0,193	–	–	–
3	The range of variation ε_i	100	2000	20	–	–	–
4	$b_i \times \varepsilon_i$,	44,8	264	3,86	–	–	–
5	Gradient Step	116,06	689,94	10	–	–	–
6	Rounded step	116	690	10	–	–	–
7	Experience 9 implemented	666	7690	30	2,1	1,35	47
8	Experience 10 implemented	780	8380	40	2,17	1,45	47,5

9	Experience 11 implemented	898	9070	50	2,05	1,47	49,1
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The optimal value of clamping force $p = 780\text{N}$ can be easily converted to pressure (MPa) if we use the well-known Hertz formula for contact stresses, obtained by compressing of two cylinders with uniformly distributed force along their generatrix. For this effort, a pressure value of 0.76 MPa was obtained with the following parameters: diameter of the printing cylinder $\varnothing 65$ mm and reduced radius of curvature $\rho_{pr} = 16.25$ mm; the elastic modulus and Poisson's ratio for rubber are 2.67 MPa and $\mu = 0.5$, respectively; tensile strength (in rubber, it is almost equal to the elastic limit) $\sigma_B = 80$ kg / cm²; elongation of at least 300%.

Conclusions. Thus, according to the results of the studies, the following results were obtained:

1. It is developed a mathematical model of paint perception according to Box-Wilson steep climb method, It was achieved the optimum region for the response function in the form of the thickness of the paint layer, depending on the pressing force p (pressure), speed (v) and paper smoothness (q).

2. The optimal conditions for the interaction of ink and experimental paper are, the average pore radius is 35 nm, the paper smoothness is 40 s, the brightness is 84%, $K_p = 47.5$, $Dop.pl. = 1.45$. The following printing mode is recommended: printing speed: $v = 8380$ print / hour, pressure $p = 0.76$ MPa (Ryobi 780-4).

3. The results of the research are the basis for rational determination of composition of experimental paper in its design and development of both paper and printing products. Data from experimental studies of paper ink perception can be used to develop methods for automatic controlling the printing process.

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AUTHOR INFORMATION:

- **last name, first name, patronymic:** Eshbaeva Ulbosin Jamalovna
- **place and address of work:** Tashkent institute textile and light industry.
Address: 100100, Republic of Uzbekistan, Tashkent, st. Shohjahon, 5.
- **position:** professor
- **phone:** +99890 805-99-55
- **education:** higher
- **academic degree:** Doctor of Technical Sciences
- **e-mail:** Guli-67@mail.ru

- **last name, first name, patronymic:** Shin Illarion Georgevich
- **place and address of work:** Tashkent institute textile and light industry.
Address: 100100, Republic of Uzbekistan, Tashkent, st. Shohjahon, 5.
- **position:** professor
- **phone:** +99890 347-60-03
- **education:** higher
- **academic degree:** Doctor of Technical Sciences
- **e-mail:** shin-i-g@mail.ru

- **last name, first name, patronymic:** Djalilov Anvar Abdugafarovich
- **place and address of work:** Tashkent institute textile and light industry.
Address: 100100, Republic of Uzbekistan, Tashkent, st. Shohjahon, 5.
- **position:** senior teacher
- **phone:** +99897 703-33-96
- **education:** higher
- **academic degree:** -
- **e-mail:** anvar-matbaa@mail.ru