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Optimization and forecasting models of the sublimation printing process on textile materials

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Abstract

The paper presents the results of the analysis of the sublimation printing process on fabrics by the Taguchi method and forecasting the process quality using the fuzzy logic principles. Imprints obtained in different technological modes and on textiles with different absorbency. Based on the results of the analysis, it was established that the temperature and the material absorption capacity have the greatest influence on the optical density of imprints. Using the Taguchi method it was determined that the optimal parameters of the printing process to achieve high optical density are the material moving speed of 18 m/h, the temperature of the printing process of 215 °C and the textile absorption of 19 mm. Taking into account that the influence of the material moving speed in the range of 18–32 m/h showed to be insignificant, two factors were selected to forecast the process quality: the temperature and the material absorption capacity. The formed fuzzy knowledge base made it possible to construct forecasting models of the influence of these two factors on CMYK ink printing process quality. The comparison of the simulated values of optical density with the values that were obtained experimentally shows the adequacy of the models for CMK colours. Significantly higher optical density deviations are observed for the yellow colour (Y), which indicates a less controlled thermal transfer process. This is also indicated by the value of the signal-to-noise ratio, which is minimal for yellow.

Keywords: sublimation printing, process factors, optimization, Taguchi method, fuzzy logic, forecasting model

1. Introduction

The development of the digital inkjet printing method has created new possibilities for producing images on fabric materials by sublimation. This process is an indirect printing method: the image is first printed by inkjet onto special paper and then transferred to the textile under high pressure and temperature. A high-quality thermal transfer is possible on fabrics containing more than 60 % polyester, which allows the inks to diffuse into the fibers in vapor form (Leber, 2016).

According to market research by Global Information Company, the sublimation printing market was estimated at USD 15.97 billion in 2024 and projected to reach USD 26.23 billion by 2029, growing at a compound annual growth rate (CAGR) of 10.44 % during the forecast period (Mordor Intelligence, 2024). Sublimation printing on textiles continues to dominate the European individual printing-services segment because the printed image is extremely durable compared to other textile-printing methods, thanks to ink penetration into the material rather than layer formation on the surface (Allied Market Research, 2021). The sublimation-paper market also confirms these trends, with an average annual growth rate of 8.9 % forecast for 2024–2032 (Business Research Insights, 2024).

The growth trends are driven by technology improvements, improved energy efficiency, the creation of sublimation paper recycling capabilities, and the minimization of environmental impact compared to traditional fabric printing methods. The world market of sublimation paper is provided by companies Guangdong Guanhao High-Tech, Hansol, Sappi Group, Neenah Coldenhove, Ahlstrom-Munksjö, McCoulin Jasper Inc., Felix Schoeller, Beaver Paper, Jiangyin Allnice Digital Technology.

Publication analysis indicates two main research directions in textile printing: studying imprint quality under various process factors and evaluating operational performance of imprints on fabric materials. Several studies focus on wash resistance of images produced by direct, sublimation, or screen printing methods. The article of Toshikj and Prangoski (2022) reports a slight color difference (>1 ΔE) between imprints on sublimation transfer paper printed at 270 % and 100 % total ink limitation levels, which could reduce unnecessary costs in the sublimation printing process. Toshikj and Prangoski (2023) describe the effect of transfer temperature and dwell time of the ink-black layer on textile image quality, achieving low print mottle, high color strength, and optimal cost–performance balance. Other studies examine wash resistance of imprints obtained by direct, sublimation, or screen printing methods (Stancic and Kasikovic, 2014; Prybeha, et al., 2021).

Özdemir, et al. (2021) highlight optimization of the printing process using Taguchi methods. Vujčić (2019) applied a Taguchi design to assess how printing parameters affect wash resistance. Jung, Kim and Park (2016) used the Taguchi method to optimize screen printing, maximizing color intensity to reduce color difference of imprints while minimizing ink consumption.

Fuzzy logic methods have yielded positive results in forecasting process quality. Repeta, et al. (2023) constructed prognostic models predicting flexographic printing quality based on printing plate parameters, anilox roller characteristics, ink viscosity, and surface energy. Repeta, Kukura and Kukura (2018) described forecasting models for factors influencing solventless lamination of flexographic imprints. Tymchenko (2022) used fuzzy logic calculations to define a forecast-level indicator and visualized process quality through infographics.

Given the diversity of inkjet printing modes, substrate materials, and thermal transfer regimes, further research using the Taguchi method is reasonable, as it has proven effective for forecasting technological process quality.

2. Research methods

2.1 Methods of experimental research

The sublimation printing process comprises two stages. In the first stage, a test chart was printed on an Epson SC-F7100 printer using Epson UltraChrome DS ink on 65 g/m^2 Kaspar Dye Sub Lite (Kaspar Papir) sublimation paper. Print settings were Quality Mode: 720 × 1440 dpi, six-pass, ink limit 250 %. In the second stage, the printed image was thermally transferred onto the textile using a Termon KP-1728 calender thermopress at material speeds of 18, 24, and 32 m/h and temperatures of 200 °C, 215 °C, and 240 °C.

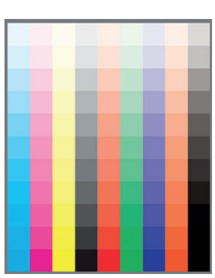

Figure 1: Fragment of the test scale

The optical density of CMYK color imprints was measured with an X-Rite SpectroEye spectrodensitometer on a fragment of the test chart shown in Figure 1, where CMYK vector patches were printed in 10 % increments. These patches show how accurately single- and multi-color areas are reproduced under the selected printing conditions. Fabric absorption capacity was determined by the height of ink capillary rise using the Klemm capillary-rise method, measured 60 seconds after immersion of the fabric strip (Figure 2). Accounting for the fabric's anisotropic properties, strips were cut along the direction of greatest ink spread, onto which a known ink weight had been previously applied. The characteristics of the textile materials are presented in Table 1.

Using the Klemm method, fabric absorption capacities were determined as follows: K190 – 19 mm, S013 – 24 mm, and F02 – 29 mm.

Table 1: Studied textile samples from Janmar Sport (Poland), showing brand, composition and weight (PES = polyethylene terephthalate; EL = elastane)

Brand	Composition	Weight
K190	82 % PES, 18 % EL	0.20 g/m^2
S013	82 % PES, 18 % EL	21.24 g/m^2
F02	100 % PES	2.294 g/m^2

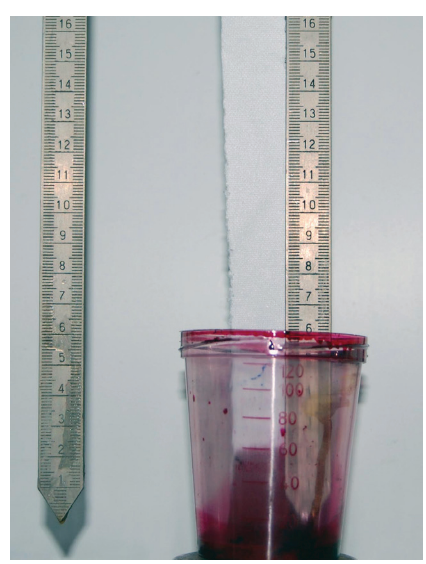

Figure 2: Klemm-type-capillary-rise method

2.2 Analysis of the sublimation process using the Taguchi method

Multi-factor analysis typically requires numerous experiments, making it time-consuming. The Taguchi method enables reducing the number of samples by employing an orthogonal matrix, thereby decreasing the required experiments (Taguchi, 2005). Data were processed with Minitab 21 software.

A larger-the-better objective function was employed to evaluate the optical density response. The larger-the-better signal-to-noise *(S/N)* ratio, based on a base-10 logarithm, was calculated as:

$$S/N = -10 \times \log\left(\frac{\Sigma(1/Y^2)}{n}\right) \qquad [1]$$

where Y is the response for a given factor-level combination, and n is the number of responses in that combination (Methods and Formulas for Analyze Taguchi Design, 2024). Each sublimation process factor was studied at three levels, as shown in Table 2.

The orthogonal matrix was selected to minimize the number of experiments required for process-parameter optimization. Minitab offers standard orthogonal matrices based on the number of factors; here, an L9 matrix was used.

2.3 Construction of a forecasting model using fuzzy logic tools

Fuzzy logic was introduced in 1960s by Lotfi Zadeh to mathematically represent uncertainty and vagueness in human reasoning (Zadeh, 2008). Fuzzy logic has found wide application across diverse technological fields. It can handle uncertainty and imprecision, making it particularly valuable for AI applications.

Table 2: Factors and levels of the sublimation process

№	Factors	Levels		
		1	2	3
1	Speed of the material movement (S), 10^{-1} m/h	1.8	2.4	3.2
2	Temperature (T), °C	200	215	240
3	Absorption (A), mm	19	24	29

Table 3: Linguistic variables of factors influence on the sublimation printing quality

Variable	Universal set	Assessment terms
Temperature, °C	200–240	low, medium, high
Absorption, mm	19–29	low, medium, high

To implement fuzzy logic, follow these steps:

1. Define linguistic variables and terms corresponding to process factors.

2. Construct membership functions.

3. Create a fuzzy knowledge base with “If–Then” rules.

4. Obtain a fuzzy output.

5. Perform defuzzification.

Table 3 lists the universal sets and terms for the linguistic variables. Therefore, we divided each input variable into three levels for our membership functions. Symmetric Gaussian membership functions were used to describe the fuzzy set terms. The “Centroid” principle (TutorialsPoint, n.d.; Rotshtein and Shtovba, 2002) was used for defuzzification.

3. Results and Discussions

The factor-distribution matrix for image sublimation on textile materials is presented in Table 4. Table 5 presents CMYK optical densities measured across test-scale areas under the orthogonal factor combinations. Table 6 presents the calculated S/N ratios.

Taguchi analysis yields the following interpretation. A larger difference (Δ) in average S/N ratio indicates a greater influence of that control factor on the process. Based on S/N ratio calculations, factors are ranked by influence in the sublimation process: temperature (Rank 1), material absorption (Rank 2). Material moving speed has a negligible influence (Rank 3).

Figure 3 depicts the main effect of each factor on optical density. Factor levels corresponding to maximum S/N values indicate the system’s optimal conditions. Therefore, optimal process parameters for high optical density are: a material transfer rate of 1.8 m/min, a process temperature of 215 °C, and textile absorption of 19 mm.

Pareto analysis of the results that are presented in Table 6 indicates that temperature and absorption capacity account for 93 % of heat-transfer process variation, with the remaining influence attributable to the speed parameter. Data processing enabled the construction of models predicting how temperature and absorption affect CMYK ink optical density presented in Figure 4 a–d. The plots illustrate that increasing temperature enhances ink-layer formation up to 215 °C – yielding peak optical density for all colors – after which density decreases gradually, with the rate dependent on absorp-

Table 4: Orthogonal array L9 and distribution of the process factors

№	Orthogonal array			Value of factors by levels		
	S	*T*	*A*	*S*	*T*	*A*
1	1	1	1	1.8	200	19
2	1	2	2	1.8	215	24
3	1	3	3	1.8	240	29
4	2	1	2	2.4	200	24
5	2	2	3	2.4	215	29
6	2	3	1	2.4	240	19
7	3	1	3	3.2	200	29
8	3	2	1	3.2	215	19
9	3	3	2	3.2	240	24

Table 5: Values of the optical density according to the experiment options

№	Optical density			
	C	M	Y	K
1	0.92	1.04	0.65	1.57
2	1.22	1.35	0.85	1.78
3	0.98	1.13	0.79	1.58
4	0.85	0.95	0.58	1.47
5	1.16	1.21	0.76	1.57
6	1.16	1.29	0.84	1.83
7	0.83	0.94	0.56	1.37
8	1.3	1.36	0.77	1.78
9	1.2	1.32	0.84	1.85

tion capacity. Although the general factor effects are similar across colors, they vary slightly due to differences in inkjet pigment chemistry and corresponding physical and chemical properties.

As optical density represents a “larger-is-better” objective, it was used to calculate the *S/N* ratio. *S/N* ratios for all experimental conditions are given in Table 7. Comparison of maximum S/N values shows that yellow

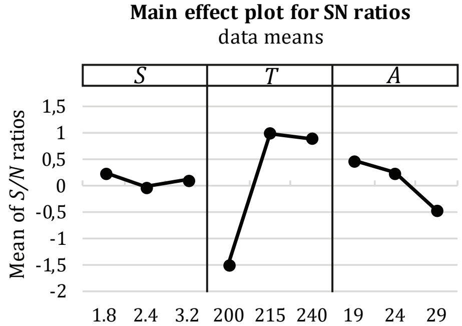

Figure 3: Graph of the average values of S/N ratio for the sublimation process factors

Table 6: Ranks of the process factors according to the analysis

Level	Factors		
	S	*T*	*A*
1	0.23192	-1.51555	0.45330
2	-0.01414	0.97579	0.31330
3	0.12142	0.87896	-0.42741
Δ	0.24606	2.49135	0.88071
Rank	3	1	2

ink exhibits the lowest *S/N* ratio, indicating reduced process controllability and suggesting additional influencing factors – particularly the unique physical and chemical properties of yellow ink.

Regression analysis yielded the following predictive equations for the optical density of each CMYK inkjet ink:

$$D_{\mathrm{C}} = 0.536 + 0.0403\,S + 0.0049\,T - 0.0247\,A \quad [2]$$

$$D_{\mathrm{M}} = 0.151 + 0.0279\,S + 0.0064\,T - 0.0176\,A$$

$$D_{\mathrm{Y}} = 0.312 - 0.0399\,S + 0.00327\,T - 0.0067\,A$$

$$D_{\mathrm{K}} = 1.555 + 0.0372\,S + 0.0023\,T - 0.0183\,A$$

where D_c to D_K is optical density of CMYK inkjet inks; *S* is speed of the material movement; *T* is temperature; *A* is absorption.

In general, the results of the analysis of the sublimation image transfer process show that 200 °C and 215 °C is not enough for the complete transfer of the ink layer to the fabric, while reducing the moving speed and, accordingly, increasing the thermal contact time slightly improves this process. At a higher temperature, 240 °C,

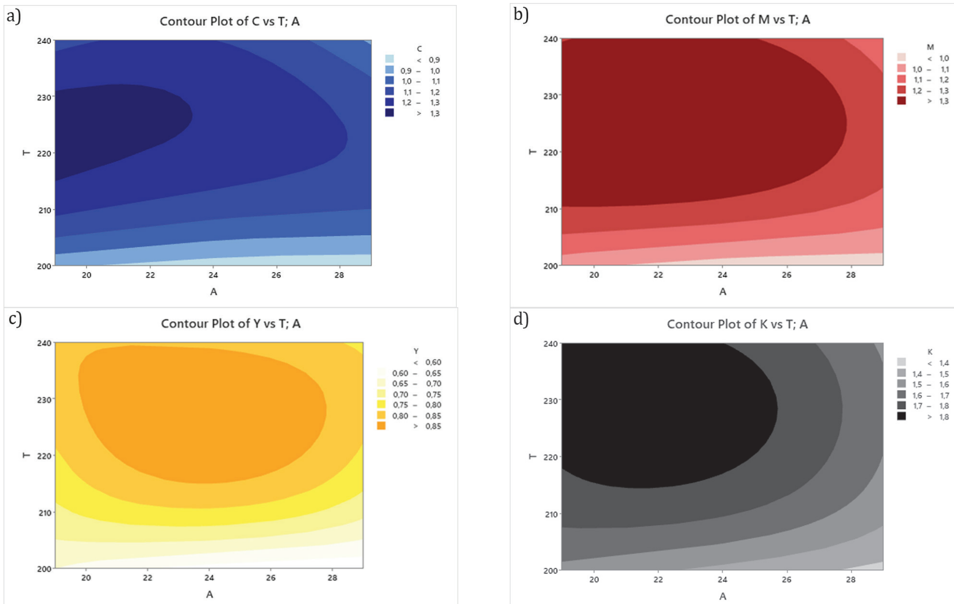

Figure 4: Contour plots of influence of transfer temperature and material absorption on the optical density of the image: a – cyan ink; b – magenta ink; c – yellow ink; d – black ink

and a low material moving speed, the ink layer begins to diffuse into the material thickness and, as a result, the optical density begins to decrease.

In the following, the factors with the highest priority will be used, which will be presented in the form of the following linguistic variables: the temperature (*T*) and the material absorption (*A*). The scheme of logical formation of the overall quality of the image sublimation formation process on textile material is presented in Figure 5.

When constructing the membership function for "Temperature" variable, its value is determined on the universal set: u_1 = 200 °C; u_2 = 210 °C; u_3 = 220 °C; u_4 = 230 °C; u_5 = 240 °C. For the linguistic assessment of this indicator, a set of fuzzy terms is used:

T(x) = <low, medium, high>.

The value for the variable "Absorption" for the construction of membership functions is determined on the universal set: u_1 = 19 mm; u_2 = 21,5 mm; u_3 = 24 mm; u_4 = 26,5 mm; u_5 = 29 mm. For the linguistic assessment of this indicator, a set of fuzzy terms is used:

T(y) = <low, medium, high>

For the initial indicator – optical density, the distribution of membership functions by terms is applied:

T(z) = <very low, low, medium, high, very high>

Table 7: Analysis results of S/N Ratio

Factors			**S/N Ratio**			
S	*T*	*A*	**C**	**M**	**Y**	**K**
1.8	200	19	-0.724	0.341	-3.741	3.917
1.8	215	24	1.727	2.607	-1.412	5.008
1.8	240	29	-0.175	1.062	-2.047	3.973
2.4	200	24	-1.411	-0.445	-4.731	3.346
2.4	215	29	1.289	1.656	-2.383	3.917
2.4	240	19	1.289	2.212	-1.514	5.153
3.2	200	29	-1.618	-0.537	-5.036	2.734
3.2	215	19	2.278	2.671	-2.270	5.008
3.2	240	24	1.583	2.411	-1.514	5.106
		Max	2.278	2.671	-1.412	5.153

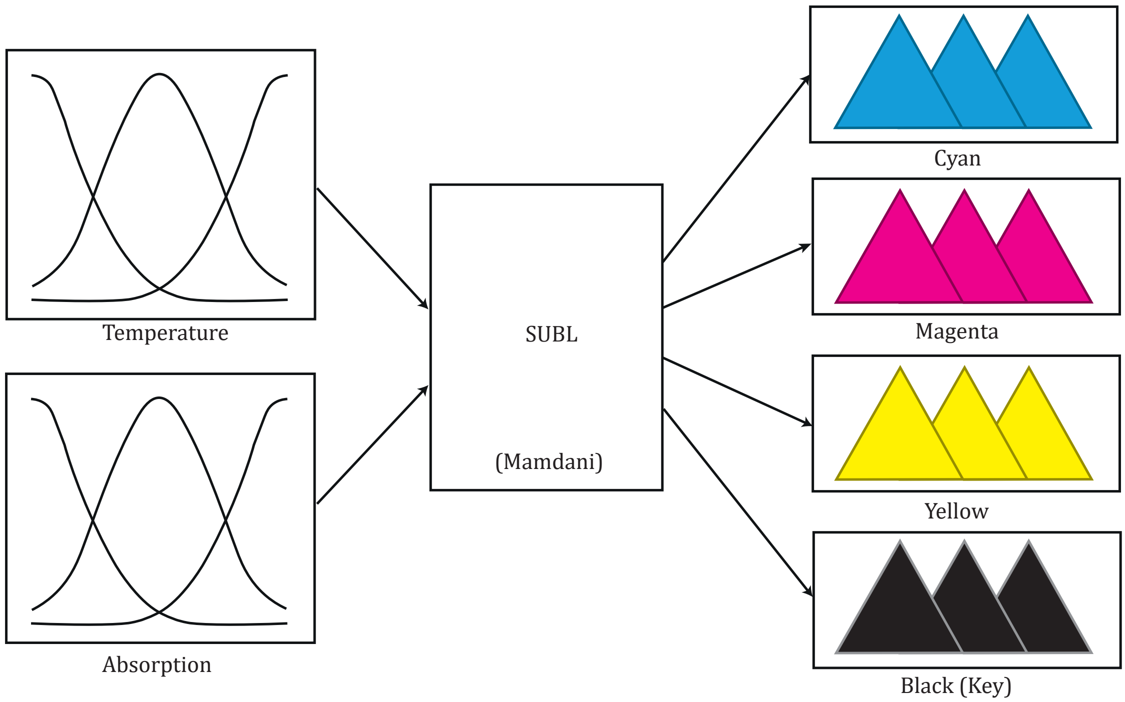

Figure 5: Scheme of the logical formation of the quality of the image formation process on textiles

Let one form a fuzzy knowledge base for determining the optical density using a set of fuzzy rules "if – then":

– if (T is "low") and (A is "low") then (D is "low");

– if (T is "low") and (A is "medium") then (D is "very low");

– if (T is "low") and (A is "high") then (D is "very low");

– if (T is "medium") and (A is "low") then (D is "very high");

– if (T is "medium").and (A is "medium") then (D is "high");

– if (T is "medium") and (A is "high") then (D is "medium");

– if (T is "high") and (A is "low") then (D is "high");

– if (T is "high") and (A is "medium") then (D is "medium");

– if (T is "high") and (A is "high") then (D is "low").

To check the formed knowledge base and construct a forecasting model of the influence of priority factors, a package for developing fuzzy control systems was used – the Fuzzy Logic Toolbox system of the Matlab technological calculation environment and the Mamdani principle (Mamdani and Assilian, 1975). The result of modeling by fuzzy logic tools is shown in Figure 6. In this case, the influence of the temperature and the fabric absorption capacity on the optical density of black ink is demonstrated. To forecast the influence of these factors for CMK colors, when forming the membership functions for the initial value D (optical density), its maximum and minimum values, which were previously obtained experimentally, are indicated. In this way, D range is formed on the graphic models of each colour separately.

After obtaining models of the influence of temperature and absorption, a comparison of the results obtained experimentally and the results obtained on the basis of the formed fuzzy knowledge base is carried out using the Matlab capabilities in the graphical representation of logical equations.

Figure 7 (a–d) demonstrates the adequacy of the simulated results, in comparison with the results of measuring the optical density of experimentally obtained imprints, except for the yellow colour. For it, a slightly larger difference in optical density values is observed in the experiment and the model, which indicates a lower controllability of the thermal transfer process in this case. This is also indicated by the value of the S/N ratio according to the Taguchi method, which is presented in Table 7 and is minimal for yellow. One possible explanation for this result could be significant changes in the properties of the yellow pigment system in a narrow temperature range, which in turn depends on the speed of the material movement.

4. Conclusions

In this work, the imprints were obtained on inkjet paper and at the stage of the image thermal transfer, the influence of temperature, the material moving speed (as the time of the contact point in the thermal press) and the textile material absorption capacity were studied. Various options, the value of the optical density of CMYK colours were determined. Using the Taguchi method, it is established that the temperature and the material absorption capacity have the greatest influence on the optical density of imprints. In general, the use of the method made it possible to establish the optimal parameters of the sublimation process, namely, to achieve a high value of optical density: the material moving speed of 18 m/h, the process temperature of 215 °C, and the textile absorption capacity of 19 mm (Klemm method). Taking into account that the influence of the material moving speed in the range of 18–32 m/h is insignificant, two factors were selected to forecast the process quality: the temperature and the material absorption capacity. Accordingly, a fuzzy knowledge base was formed and forecasting models of the influence of these two factors on the quality of the CMYK ink sublimation process were constructed. The comparison of the simulated values of optical density with the experimentally obtained values showed the adequacy of the models for CMK colours. For the yellow colour, a slightly larger difference in optical density values was observed in the experiment and the model, which indicates a lower controllability of the thermal

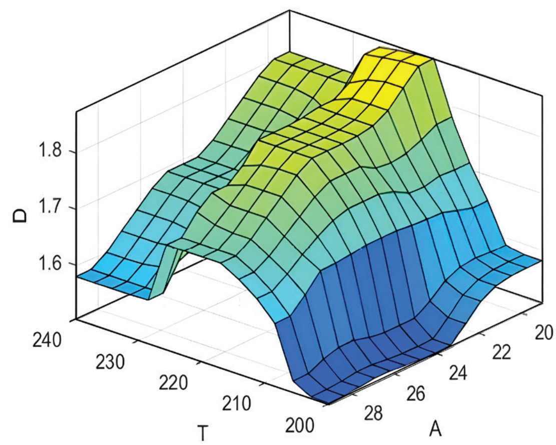

Figure 6: A model for forecasting the influence of the temperature and the absorption capacity on the optical density of a black ink layer

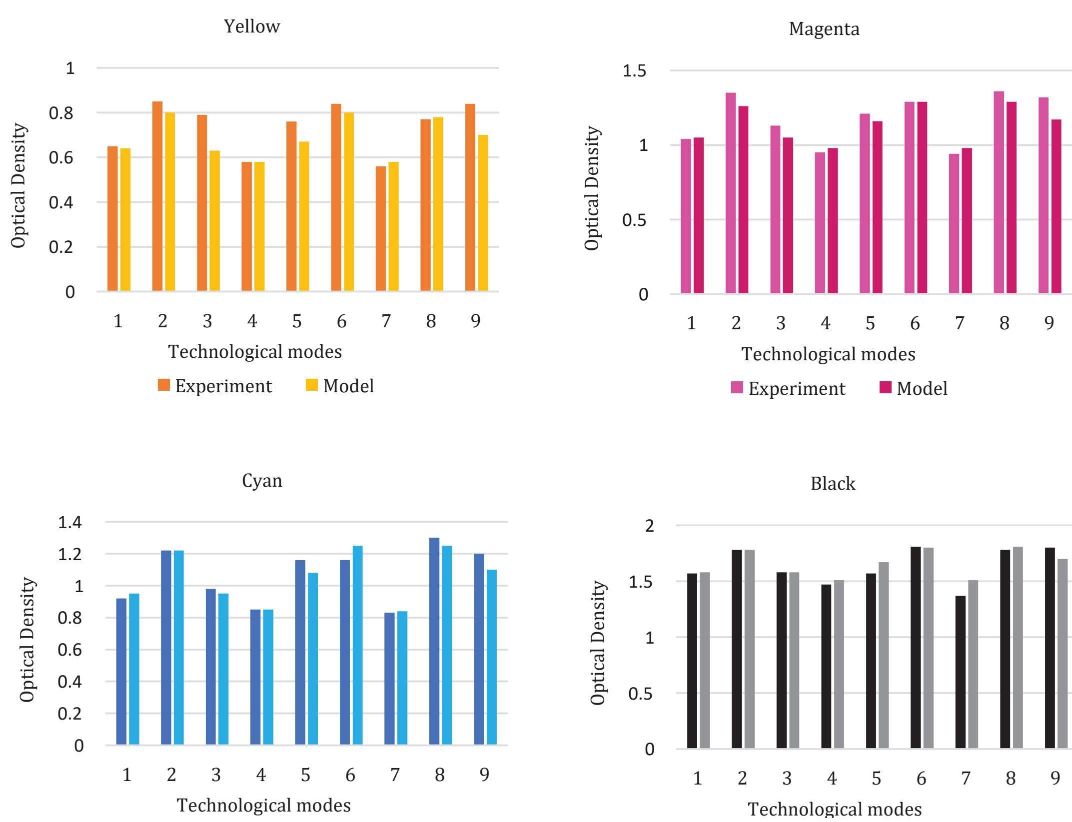

Figure 7: Experimental and simulated values of the optical density of the ink layer for nine technological modes (see Table 4): a – cyan ink: b – magenta ink; c – yellow ink; d –black ink.

transfer process in this case. This is also indicated by the value of *S/N* ratio according to the Taguchi method, which was minimal for yellow. In this case, the material movement speed will also affect, which determines the contact duration during thermal image transfered. All this requires further additional research and the construction of a separate model of the factors, influence specifically for a yellow ink. In general, the use of fuzzy logic and the construction of graphic models will allow developing a simulation model for a priori forecasting the quality of the thermal transfer stage of a sublimation image.

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