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Multivariate Model for Characterising Physical Dot Gain, Chroma and Lightness in Offset Lithography

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ABSTRACT

Bright print images help any product on the shelf stand out, attract the consumer, and add a unique value to the product. This research work is to empirically identify significant factors and optimize printing press parameters like press speed (x1: 5000, 7000, and 9000 sheets per hour), ink viscosity (x2: 15, 25, 35 Pa·s), and blanket rubber hardness (x3: 65, 70 and 75 shore A) to achieve prints with rich chroma yet with low dot gain in the lithography process, the most economical and widely used process today in the field of label and packaging industry. The parameters used during the printing process can affect the physical dot gain and the color of printed images. To study this, measurements were taken of the dot gain (y1) and color (measured in terms of lightness (y2) and chroma (y3)) at three different dot areas - highlight (25 %), middle tone (50 %), and shadow (75 %). Box-Behnken Design was used to test fifteen different print conditions. The second-order polynomial model's fit quality was good concerning the responses. The optimum printing machine conditions determined to minimize dot gain and lightness and maximize chroma were a press speed of 5000 sheets per hour, 30 Pa·s ink viscosity, and blanket rubber having 70 A shore hardness. The optimized values agreed with the predicted responses were acceptable, considering the right balance of minimum dot gain, higher chroma, and lower lightness to give the vibrant yet controlled halftone dot area in print production. Prog. Color Colorants Coat. 17 (2024), 365-380© Institute for Color Science and Technology.

1. Introduction

The offset lithography print process is a high-speed process used to print on various paper substrates for different packaging and commercial printing applications. The offset printing process is currently the most important technology that prints a lower ink film thickness but can still print sharp, close to original reproduction. Offset technology utilizes the halftoning technique. The ink gets transferred from the roller surface to the dots on the image areas of a lithographic plate using the computer-to-plate (CTP) technology widely used today. Halftone dots must be printed accurately, and their dot gain can be controlled through several parameters. Achieving a print quality acceptable to the customer is essential in print production. Print quality is defined by its print density, dot values, and the color of solids and halftones. An important condition in printing is that the solid patch must be entirely covered by ink, the dot area percentages in the highlight regions such as 10, 20, 25,

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and 30 shall print correctly, and dot area percentages in the shadow regions like 70, 80, and 90 must not fill-in and look like solids [1]. The dot gain generated during the printing process is considered a total dot gain, a sum of two independent effects: physical and optical dot gain. Dot gain or tone value increase, as it is now called in recent times, occurs when there is an increase in the screened element (dots) compared to the actual size of the dot to be printed. Physical dot gain is a phenomenon in the transfer of ink to the dots, affecting the size of the dot due to spreading or penetration [2]. Optical dot gain results from light scattering inside the substrate, and the dot printed on such substrate gathers light, giving an additional optical effect [3]. An increase in dot gain results in a variation in the lightness and chroma of the dots, thus providing a sheet-to-sheet variation.

The print quality of the solids and tones is a result of many prepress parameters like type of paper substrate, screen frequency, dot shape, and machine parameters such as press speed, ink viscosity, ink water balance rising due to the chemistry of fountain solution, pressure settings of plate cylinder, blanket cylinder, and impression cylinder, the type of CTP plates, blanket rubber hardness. The optimized setting of press parameters will yield precise color and density and increase productivity due to lower variation in color as sheets get printed. As an effective statistical and mathematical tool for developing, improving, and optimizing processes, Response Surface Methodology is applied in situations where several input parameters influence a quality characteristic of the product or process. Our study uses the Box-Behnken Design (BBD) optimization approach in Response Surface Methodology (RSM) [4]. For this, version 18 of Minitab software was used. With the help of BBD, the press speed, ink viscosity, and blanket rubber hardness could be optimized with a minimum number of experiments to achieve lower dot gain, higher chroma, and lower lightness, resulting in an overall sharp yet vibrant print with faster and cost-effective production.

Our research aimed to evaluate the impact of multivariate machine parameters, including speed, rubber hardness of blankets, and ink viscosity, on the optical properties of dot gain, lightness (L*), and chroma (C*), based on experimental data related to press parameters. We conducted fifteen press trials. The 3D surface plots helped explain the trend of achievable dot gain and color values under specific machine parameter combinations. Previous research has focused on understanding the effect of independent parameters on dot gain, analyzing only one factor at a time, and studying the rheological properties, such as thixotropy and viscosity, on dot gain and gloss. Our study has helped optimize press parameters, resulting in faster production and less wastage while maintaining print quality. Figure 1 provides a brief illustration of the work carried out.

During printing, ink is transferred from the ink rollers to the plate, then from the plate to the blanket, and finally from the blanket to the substrate. However, at each point of transfer, there is a nip area where the ink film applied to the dots can get squashed under pressure, causing the dots to increase in size. This ink transfer ultimately leads to increased ink coverage, contributing to dots' growth [5].

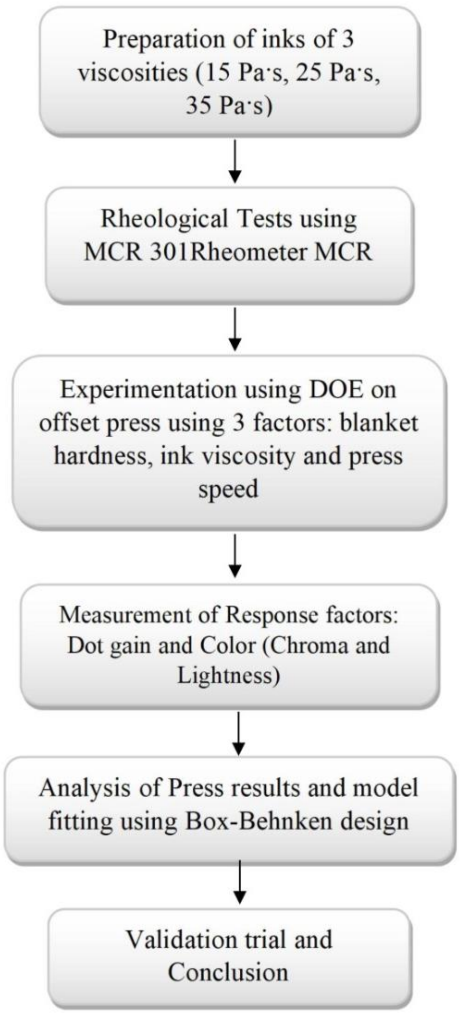


Figure 1: Brief workflow of the work done in this experimental research.

The total dot gain is a combination of dot gain originating from three sources:

- The exposure of the plate
- The pressure in the printing nip
- The optical response due to paper

For a high-quality print, it is necessary to have as good control as possible of all three sources separately and be able to achieve the different steps in the prepress and printing processes [6]. Inks with higher thixotropy lower dot gain [7]. The physical dot gain results from the surface forces acting upon the ink particles and on the substrate during the transfer [8]. The blanket mounted on the cylinder is categorized as soft, medium, and hard. The type A Shore hardness tester is an effective instrument for measuring the hardness of the rubber blanket in printing to study its impact on print [9]. The ink film thickness printed on the substrate is measured with equipment called a densitometer, which measures the ink film thickness in terms of its optical density. Ink density has an impact on color quality. CIE LAB is a color model recommended by CIE for the measurement of color. This color space resembles the human eye's red, green, blue, and yellow signals [10]. L* value determines the brightness from 0 to 100, '0' indicating black and '100' indicating white. a* indicates red/green coordinates,and b* indicates the blue/yellow coordinates. Its lightness describes the appearance of an object [11]. C* is the radial distance from the neutral axis, where C* equals the square root of a* squared plus b* squared. We should use a color system based on our sensations' hue, value, and chroma* rather than attempting to describe them using the indefinite and varying colors of natural objects. Chroma refers to the quality distinguishing a strong color from a weak one [12]. Changes in the ink film thickness or density affect the appearance or lightness value of the print.

2. Experimental

2.1. Ink

We conducted experiments using cyan inks as the base. Huber Group India provided us with the base ink; its composition is in Table 1. We prepared three types of ink with varying viscosities by adding the raw materials calculated by weight described in Table 2. We then analyzed and compared the flow behavior and print performance of the inks.

Table 1: Composition of base ink.

Base Ink	
Pigment	16.50
Wetting Resin	6.00
Wetting Varnish	11.00
Structure Varnish	44.00
Vegetable Oil	3.00
Mineral Oil	8.50
Anti-Skinning Agent	1.50
Rub Improver	6.00
Drier	2.50
Litho Improver	1.00
Total	**100.00**

Table 2: Modified inks with their inks.

Raw Material	Ink sample 1 (low viscosity)	Ink sample 2 (medium viscosity)	Ink Sample 3 (high viscosity)
Base Ink	100.00	100.00	100.00
Fumed Silica	0.00	0.00	4.00
Clay Thickener	0.00	3.00	2.00
Mineral Oil	0.75	1.00	1.50
Flow Improver	0.00	0.50	0.70
Viscosity of ink	15 Pa·s	25 Pa·s	Pa·s

Ink comprises four primary raw materials: pigment, resin, solvent, and additives. These materials work together to give the ink its specific rheological properties. After adding rheology modifiers, we examined the rheology tests and the print characteristics of three ink types. The viscosity of these inks was measured in the lab using a Larray viscometer. The rheology was measured using a control-shear stress (CSS) rheometer PHYSICA MCR 301 made by Anton Paar with cone and plate (CP50) geometry that had a cone radius of 25 mm and a cone angle of 10 degrees, using Rheoplus software. Other properties of the ink, such as tack and flow, were measured using a Thwing Albert inkometer and a glass slab, respectively. The results are presented in Table 3.

In Table 3, we can find a comparison of the properties of three different inks. The high-viscosity ink has a low flow but a high tack due to the rheology modifiers added to the ink, which increase its tackiness.

2.2. Substrate

A coated paper substrate was used to print with the three inks developed. The grammage of the coated paper was 150 grams per square meter and was measured with a grammage tester. A coated paper can give excellent performance in printing and conversion. It can hold out the ink and is suitable for offset and gravure printing. The substrate is one of the parameters that can influence color reproduction characteristics [13]. Our study is about optimizing machine parameters, so we have used a single substrate. The TAPPI test methods have been followed to measure the properties of paper. The PPS technique is an indirect method of measuring surface smoothness by air leakage. This test detects minor imperfections in the coated surface. A lower PPS value indicates higher smoothness. The surface roughness of the coated art paper is around 0.73 microns. The details of both sides-coated art paper (2/S) and its test results are given in Table 4.

Table 3: Comparative properties of the 3 inks.

Properties	Low viscosity ink sample 1	Medium viscosity ink sample 2	High viscosity ink Sample 3
Tack/800 RPM (GM)/32°c Thwing Albert Inkometer	11.1	11.4	11.6
Flow in cm @ 60°A, 10 min.	5.0	3.0	2.0

Table 4: Paper test results.

Size	Test Method Reference				Both sides (2/S) Coated Art Paper (Gloss) 150 gsm 45.72 × 58.42 cm
Particulars/Grade	Side	TAPPI Standard	Unit	Specifications	Results
Grammage	-	T-410 om-23	gsm	150 ± 2.5%	147-153
Bulk	-	T-411 om-89	Cc/gm	0.80 ± 0.03	0.77-0.79
ISO Brightness	-	T-452 om-92	%	87 ± 1	86.24-86.99
ISO Opacity		T-425 om-89	%	98 ± 2	97-99
Gloss	*TS/BS	T-480 om-92	%	70 ± 5	67-73
Parker Print Surf (PPS)	*TS/BS	T-555 pm-94	Microns	Max 1.00	0.73-0.96

*TS-Top side, BS-Bottom side

2.3. Rubber blanket

The blanket mounted on the cylinder is vital in ink transfer to the substrate. It is the final point of ink transfer in the offset lithography print process. The surface of the rubber comprises micropores [14]. A blanket's parameters include surface roughness, compressibility, ink acceptance, swelling, and hardness, which can affect the ink transfer. Compressible blankets come in a variety of hardness. Blanket rubber hardness is an important parameter that helps the blanket conform to the paper surface and ensure a transfer of a thin, uniform ink layer. Increasing blanket rubber hardness will decrease print quality due to blanket ink holdout and ghosting.

2.4. Sheetfed offset press

The Komori L 226 is a medium-sized sheetfed offset press that can print up to 19" × 26" on paper sizes. Press speed is a crucial factor in production, as a faster press speed will result in quicker production times. However, it is important to note that press speed can also affect print parameters, specifically dot reproduction and color. Therefore, it is essential to analyze the impact of press speed on dot gain to ensure optimal results.

2.5. Computer-to-plate and pressroom parameters

The plates were imaged using a computer-to-plate (CTP) process using a Violet CTP plate of 560 mm x 670 mm. The selected screen frequency was Amplitude Modulation with 150 lines per inch (lpi) screen ruling and a round dot shape. The ambient temperature in the press room was 24 degrees Celsius, and the humidity was RH 52 %. All the conditions in the press and press room were kept constant. A fount concentrate of 2 % and an alcohol substitute of 1.5 % were added to the water to prepare a fountain solution with a pH of around 5.4.

2.6. Layout of the test chart and measurement of dot gain and chroma and lightness

A print layout design (Figure 2) was prepared to measure the parameters on the press, such as ink film density and dot gain (tone value increase). The layout comprised standard test elements such as an image with skin tone, a step wedge starting from 10 % with an increment of 10 up to 100 % solid patches, and images from roman16 bvdm reference images [15, 16]. The response parametersdot gain and L* and C* were measured using aspectro-densitometer Techkon SpectroDens Spectro-Densitometer. The tone value increase was measured at all areas of the halftone values; however, for ease of presentation, data of only 25, 50, and 75 % is presented in this paper. The dot's tonal value increase is calculated using the Murray Davies equation, which includes the mechanical and optical dot gain by equation 1.

$$\text{Dot Area} = \frac{1-10^{-Dt}}{1-10^{-Ds}}\ x\ 100 \quad (1)$$

Dt is the density of the halftone value, also known as tint, and Ds is the density of the solid patch in print [17]. The Murray–Davies equation is computed directly by the spectro-densitometer that measures density and dot area, so it is unnecessary to calculate it manually. Dot area is a density functionthat measures the dot's size printed in the halftone areas.The increase in the size of the dot is known as dot gain or tone value increase (TVI) and is calculated in percent value. The dot gain response in each tonal range from 0-100 % is measured to understand the dot behavior of the print.An optical density value of 1.45 throughout the press run was kept constant. In this work, the paper substrate is kept constant. The resulting dot gain is due to the changes in the press parameters or the physical conditions resulting in a physical dot gain influenced by ink viscosity, press speed, and any other variable related to the offset press.

The color values of 25, 50 and 75 % of the halftone areas were also measured using Techkon SpectroDens. The lightness (L*) was measured with the instrument, and Chroma C* was calculated using equation 2.

$$\text{Chroma } C^* = \sqrt{a^2 + b^2} \quad (2)$$

2.7. Experimental design

Table 5 lists parameters, levels, and their respective variation range. Offset presses can produce approximately 10000 copies per hour. The chosen press speeds aim to observe the behavior of the printing press at low and high speeds and study its impact on various halftone areas, such as 25 % (highlight), 50 % (middle tone), and 75 % (shadow) areas.

Table 5: Experiment parameters, their levels, and variation range.

Parameter	Unit	Levels	Variation range
Press speed	Impressions per hour	5000, 7000, 9000	-1,0,1
Ink viscosity	Pa·s	15, 25, 35	-1,0,1
Blanket rubber hardness	shore A	65, 70, 75	-1,0,1

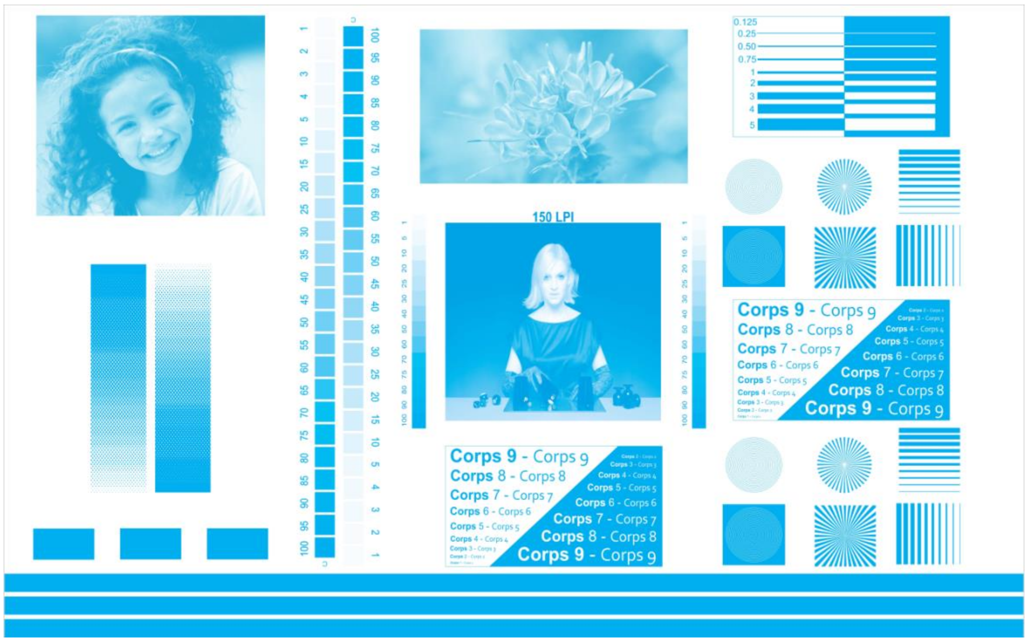


Figure 2: Layout of test chart.

The selection of ink viscosities (15 Pa·s, 25 Pa·s, 35 Pa·s) was based on observations of ink viscosities used in different presses. The ink viscosity levels were chosen to consider the lower and higher viscosities that could affect dot gain and color characteristics. Low or high viscosities can cause dot gain, color variation, and poor transfer during printing in image areas. Hence, it was necessary to assess the viscosity range.

The blanket rubber hardness levels were selected based on the availability of blankets and the issues related to dot transfer and ink film transfer that could be resolved with this hardness. The choice of press speed levels would directly impact the nip area (between plate-blanket and blanket substrate) and the dot gain during ink transfer on dots.

2.8. Experimentation

Fifteen trials were conducted on the Komori L 226 sheetfed press using the test chart shown in Figure 1. The press was operated at three speeds and with each ink and blanket. Coated stock was used in all trials. Sample sheets were selected to measure dot gain and color, and the responses were recorded. Once the data was collected, predicted responses were analyzed and calculated using Minitab software's Response Optimizer. The results are summarized in Table 6. Response Surface Methodology (RSM) is a statistical method to analyze the relationships between multiple variables and responses. It involves fitting mathematical models, often second-order or higher-order polynomials, to experimental data to understand the response surface. The Box-Behnken design is the commonly used experimental design model for three-level, three-factor experiments [17, 18].

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 \qquad (3)$$

In equation 3, y is the response variable. β represents the coefficients, and x represents the predictor variables. Regarding β parameters: β0 is a constant; β1 and β2 are the linear terms; β11 and β22 are the quadratic terms; and β12 is the interaction terms between variables 1 and 2.

Table 6: The Box-Behnken design for the dot gain and color as responses.

Run	Independent variables			Observed (y)								
	Variables - Coded			Dot gain			Lightness (L*)			Chroma (C*)		
	Press speed in copies per hour (x_1)	Ink viscosity Pa·s (x_2)	Blanket rubber hardness in degrees shore (x_3)	25 % patch (y1)	50 % patch (y2)	75 % patch (y3)	25 % patch (y4)	50 % patch (y5)	75 % patch (y6)	25 % patch (y7)	50 % patch (y8)	75 % patch (y9)
1	0	0	0	38.42	65.70	90.26	89.75	80.51	66.76	14.29	30.29	44.24
2	1	0	-1	33.25	62.04	88.12	91.80	83.83	69.18	11.48	27.38	41.87
3	-1	0	1	41.10	69.16	94.36	87.76	76.72	61.22	17.71	32.06	49.08
4	0	1	-1	36.20	63.44	88.48	91.07	82.04	68.17	12.28	28.38	42.85
5	0	0	0	38.80	65.16	90.76	88.72	80.26	67.09	14.62	30.82	44.71
6	-1	-1	0	42.32	70.94	93.80	87.65	75.68	58.78	17.15	32.68	48.64
7	0	-1	-1	38.25	65.14	90.76	90.25	80.00	66.09	13.52	29.15	44.72
8	1	0	1	35.60	64.54	90.18	90.24	82.02	67.76	13.22	28.89	43.77
9	0	-1	1	42.15	67.44	93.74	88.83	78.90	63.93	15.87	32.09	47.63
10	0	1	1	39.65	65.56	90.50	89.53	80.23	66.11	14.50	29.11	44.67
11	1	-1	0	37.62	64.40	89.44	90.07	81.71	67.26	13.20	28.76	43.48
12	0	0	0	38.68	65.00	90.68	89.04	80.69	66.91	14.44	31.15	45.47
13	-1	0	-1	39.00	67.86	91.58	89.10	78.04	64.06	14.58	30.19	44.35
14	1	1	0	34.07	63.06	87.22	91.54	82.49	69.06	12.62	27.37	42.19
15	-1	1	0	39.62	66.44	92.98	88.84	78.81	64.31	15.26	32.03	45.89

3. Results and Discussion

This section includes the results from rheology measurements done on the rheometer for low-, medium-, and high-viscosity ink samples. A model fitting from the data obtained has been done to characterize the relation between the multiple variables and dot gain, chroma, and lightness.

3.1. Rheological results

The apparent viscosity of inks decreases with the increase in shear rate. The rheology data measured from the PHYSICA MCR 301 rheometer is given in Figure 3. All inks exhibit shear thinning behavior. The shear rate was increased from 0.11/s to 501/s for all three inks.

The degrees of shear thinning are different for all three inks. At lower shear rates, the three inks' viscosity is seen differently. As the shear rate increases, the viscosity tends to be the same. At higher shear rates, ink flocculants break down quickly compared to the ink flocculated at low shear rates. Ink sample 1 exhibits a lower yield value than the other two inks. The flow curves and the yield values indicate sample 1 has a lower viscosity. While samples 2 and 3 have higher viscosity values. Adding rheology modifiers to the inks has increased the concentration of samples 2 and 3, thus giving them a higher yield value. Values of yield stress are calculated using the Carreau model by Rheoplus software, where the viscosity values are extrapolated to 0 and infinity to calculate $\eta 0$ and $\eta\infty$ in Table 7.

The higher the yield stress of an ink, the shorter the length of the ink during the splitting of the ink from one roller to another. At the same time, ink with a longer ink filament length has a low yield stress. Sample 1 indicates long ink, while sample 3 indicates short ink. During the ink transfer process, the longer ink does not snap back faster on the surface of the substrate, breaking into smaller fragments, thus rendering a higher dot gain on the print due to excess deposition [19].

Table 7: Yield stress of the three ink samples.

Ink sample	Sample 1	Sample 2	Sample 3
Yield value (Pa)	166.7	454.0	815.9

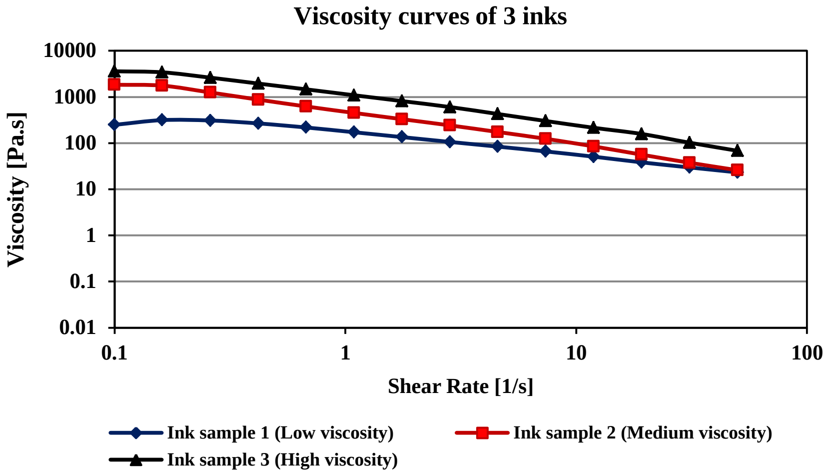


Figure 3: Viscosity curves of the three ink samples.

3.2. Model fitting for press trials

The second-order RSM representing the relationship between each of the output parameters, viz. dot gain, lightness, and chroma, and the input process parameters, viz. press speed, ink viscosity, and blanket rubber hardness, was generated using the values of the experimental data is given in Table 4. Table 8 describes the regression coefficients of the model and theirp-values, R^2, and F values of the models. The fitness of the models was studied with the help of coefficients of correlation R^2, probability values, and lack of fit values (Table 7). The fitness of the second-order polynomial models was in the acceptable range since the R^2 ranged from 0.982 (lightness) to 0.953 (dot gain). Moreover, p-values were less than 0.05 ($p < 0.05$), thus indicating they are significant. F-values ranged from 3.99 (dot gain) to 16.73 (chroma). The best results for the lack-of-fit test were obtained for all responses, including dot gain, lightness, and chroma ($p > 0.05$).

Table 8: Regression coefficients, p-value, R^2, and F values of the quadratic models determined for dot gain, chroma, and lightness at 25, 50, and 75 %.

Parameter	Dotgainat 25 % (y1)	P value	Dotgainat 50 % (y2)	P value	Dotgainat 75 % (y3)	P value	L* at 25 % (y4)	P value	L* at 50 % (y5)	P value	L* at 75 % (y6)	P value	Cat 25 % (y7)	P value	Cat 50 % (y8)	P value	Cat 75 % (y9)	P value
β0	23.53		78.38	0.000	84.08		182.0		66.50		38.46		-79.7		-147.0		0.6	
β1	0.002139	0.000	-0.004733	0.000	-0.001110	0.000	0.000643	0.000	0.003734	0.000	0.007232	0.000	0.001125	0.000	-0.000910	0.000	0.00389	0.000
β11	-0.00000	0.005	0.00000	0.010					-0.00000	0.010	-0.00000	0.001						
β2	-0.550	0.000	-0.3942	0.000	-0.1070	0.000	0.0520	0.001	0.4712	0.000	0.857	0.000	0.1781	0.000	0.702	0.003	-0.1108	0.000
β22	0.00830	0.012							-0.00348	0.044	-0.00770	0.019	-0.01458	0.006	-0.0314	0.015		
β3	0.2950	0.000	0.2055	0.000	0.2460	0.000	2.665	0.000	-0.1510	0.000	-0.2122	0.000	2.519	0.000	4.85	0.001	0.777	0.000
β33							0.01799	0.023										
β12			0.000039	0.004					-0.000029	0.003	-0.000047	0.006	0.000016	0.009	-0.01106	0.056	-0.000070	0.018
β13													-0.000035	0.007				
β23																		
R^2	97.60%		97.97%		95.36%		95.12%		99.08%		98.22%		99.28%		94.66%		96.20%	
F	73.16	0.000	86.82	0.000	75.34	0.000	48.78	0.000	143.52	0.000	73.72	0.000	184.91	0.000	31.92	0.000	63.24	0.000

Table 9: ANOVA for the response surface quadratic models determined between responsevariables (y1, y2, y3, y4, y5, y6, y7, y8 and y9) and independent variables (x1, x2 and x3).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Lightness (L*) at 50 % dot area					
Model	6	67.824	11.304	143.52	0.000
Linear	3	65.195	21.731	275.92	0.000
Square	2	1.241	0.620	7.88	0.013
Interaction	1	1.387	1.387	17.62	0.003
Error	8	0.630	0.078		
Lack-of-Fit	6	0.538	0.089	1.97	0.375
Pure Error	2	0.091	0.045		
Total	14	68.454			
Chroma (C*) at 50 % dot area					
Model	5	40.378	8.075	31.92	0.000
Linear	3	36.852	12.284	48.55	0.000
Square	1	2.304	2.304	9.11	0.015
Interaction	1	1.222	1.222	4.83	0.056
Error	9	2.277	0.253		
Lack-of-Fit	7	1.899	0.271	1.44	0.470
Pure Error	2	0.377	0.188		
Total	14	42.655			
Dot gain (&) at 50 % dot area					
Model	5	75.713	15.142	86.82	0.000
Linear	3	71.354	23.784	136.36	0.000
Square	1	1.863	1.863	10.68	0.010
Interaction	1	2.496	2.496	14.31	0.004
Error	9	1.569	0.174		
Lack-of-Fit	7	1.300	0.185	1.38	0.482
Pure Error	2	0.269	0.134		
Total	14	77.283			

3.3. Lightness (L*) at 25, 50 and 75 % dot values

From the variables in Table 9, all the variables had a significant effect ($p < 0.05$) on the lightness values at different dot areas. The quadratic term of blanket rubber hardness (β 33) is seen as significant on the lightness values in the middle tone and shadow areas. On the other hand, the quadratic term of ink viscosity (β 22) and press speed (β 11) is seen as significant in the middle tone and shadow areas. The coefficient of correlation, R^2, is high, and the model is significant at $p < 0.05$. Higher press speed and blanket rubber hardness decrease the lightness value in these halftone areas. However, higher ink viscosity increased the lightness values.

3.4. Chroma (C*) at 25, 50 and 75 % dot values

The interaction terms and main factors are also significant for chroma at 25 and 75 %. The R^2 value is also good: 99.28, 94.66 and 96.20 %, respectively, for the halftone areas. The lack of fit was higher than 0.5. Higher press speeds and higher blanket rubber hardness values indicated increased chroma values, making the halftone dots in the image look more saturated.

3.5. Dot gain at 25, 50 and 75 % dot values

The variables with the most significant effect were linear and quadratic terms (β11 and β22) for the highlight and middle tone areas. The R^2 value was 97.60 % for the predicted model for 25, 50 and 75 % dot areas with a p-value less than 0.05, and the lack of fit equal to the mathematical modelis given in equations 4, 5, and 6.

Dot gain 25 % = 23.53 + 0.002139 Press Speed - 0.550 Ink Viscosity + 0.2950 Blanket rubber hardness - 0.000000 Press Speed*Press Speed + 0.00830 Ink Viscosity*Ink Viscosity (4)

Dot gain 50 % = 78.38 - 0.004733 Press Speed - 0.3942 Ink Viscosity + 0.2055 Blanket rubber hardness +0.000000 Press Speed*Press Speed + 0.000039 Press Speed*Ink Viscosity (5)

Dot gain 75 % = 84.08 - 0.001110 Press Speed - 0.1070 Ink Viscosity + 0.2460 Blanket rubber hardness (6)

3.6. Effect of press speed, ink viscosity, and blanket rubber hardness on the dot gain and color of the halftone dots

For ease of understanding, a representation of surface plots of only 50 % of halftone areas is shown in the graphs. The 3D surface plots in Figure 4 a, b and c showed that lower ink viscosity and lower press speed resulted in higher dot gain, whereas lower press speed and higher blanket rubber hardness resulted in higher dot gain. Similarly, lower viscosity and higher blanket hardness resulted in higher dot gain.

The chroma values in Figure 5 a, b and c were higher at lower speeds, lower viscosity, and harder blanket hardness. In contrast to C* and dot gain, lightness values in Figure 6 a, b and c were lower at low viscosity and low press speed but increased at lower blanket thickness and higher press speeds. Dot gain is caused by an increase in the size of the dot, which occurs due to ink penetration or spread on the paper. However, the coated paper substrate used in this study did not allow for much ink penetration, so the ink spread around the dot due to pressure exerted in the printing nip. The results indicate that ink spread is less at higher viscosity, especially 35 Pa·s, and chroma is also lower. Higher press speeds result in lower dot gain and lower chroma. The transfer of ink during printing is affected by the blanket rubber hardness and press speed, which exerts stress at that point.

3.7. Optimal conditions and validation of the models

This work used the Response Optimizer option in Minitab software to determine the press and physical conditions that optimized the dot gain, lightness, and chroma. This option helps to identify a combination of input parameters that will optimize a single response or a combination of responses. "Composite Desirability" is evaluated with the help of the combined optimization that must satisfy all the goals defined for the responses, as shown in Figure 7. A value equal to 1 corresponds to the ideal case, while 0 indicates that one or more responses are outside the acceptable limits. A print production expects lower dot gain, higher chroma value, and a lower lightness value to get the desired print quality regarding dot reproduction and color reproduction. We selected the optimization targets accordingly.

The best solution satisfying the above criteria was obtained using the Minitab software, which is given below in Table 10 a and Table 10 b, and it has an overall desirability of 0.5315.The results indicated that the multiple responses predicted were satisfied in part.

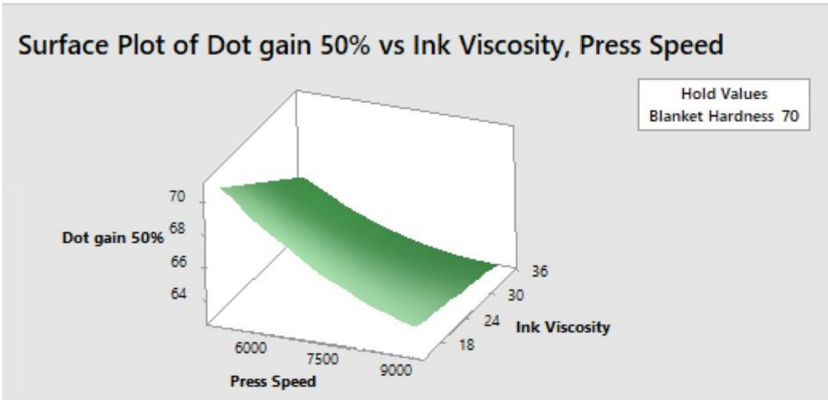
The models were validated by a new experiment with ink viscosity at 30 Pa·s and blanket rubber hardness at 70 degrees shore at a press speed of 5000 copies per hour, and the dot gain, lightness, and chroma were measured and compared to the calculated values from the equations.

Table 10: a) Optimal conditions and response to Dot gain.

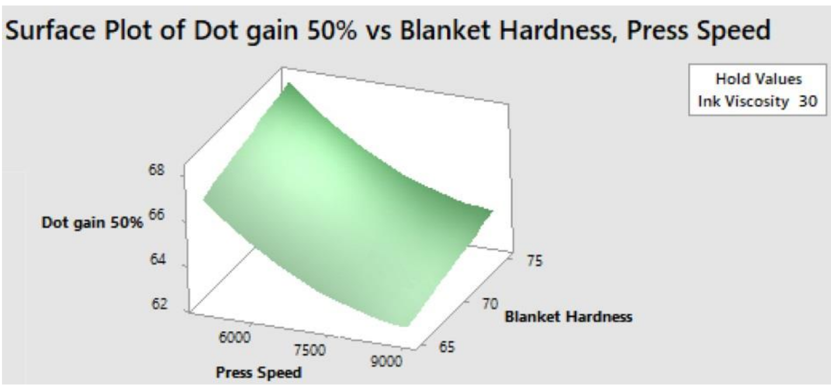
Press speed (copies per hour)	Ink Viscosity (Pa·s)	Blanket rubber hardness (degrees shore)	Dot gain at 75%	Dot gain at 50%	Dot gain at 25%
5000	30	70	92.45	67.43	39.60

Table 10: b) Optimal press conditions and their response to Lightness and Chroma.

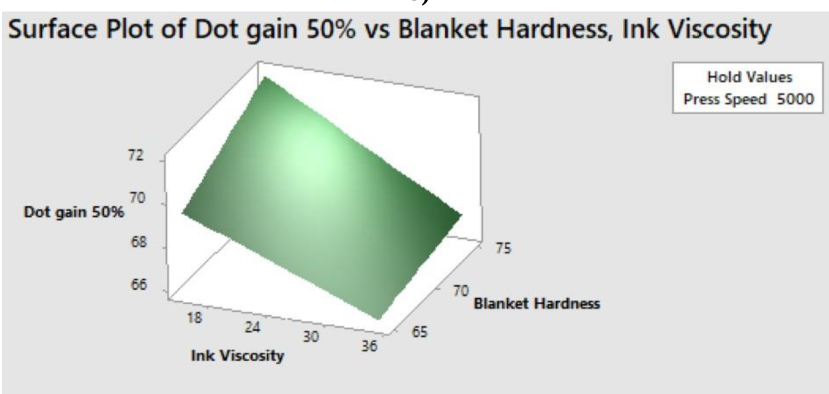
Press speed (copies per hour)	Ink Viscosity (Pa·s)	Blanket rubber hardness (degrees shore)	C* at 75 %:	C* at 50 %:	C* at 25 %:	L* at 75 %	L* at 50 %	L* at 50 %
5000	30	70	46.34	31.83	15.72	63.61	78.25	88.39



a)

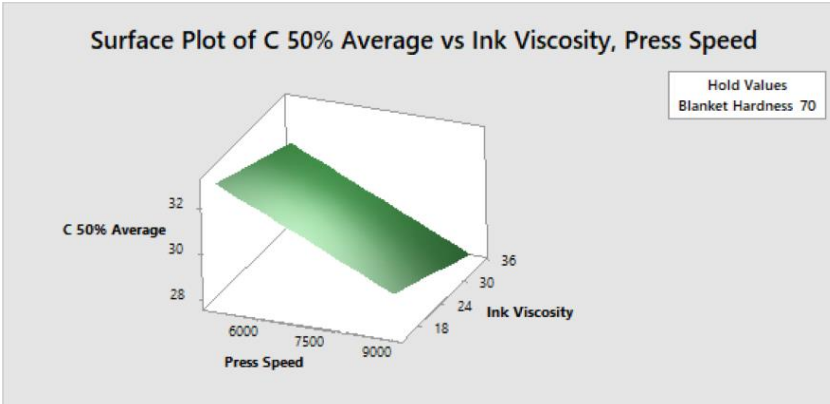


b)

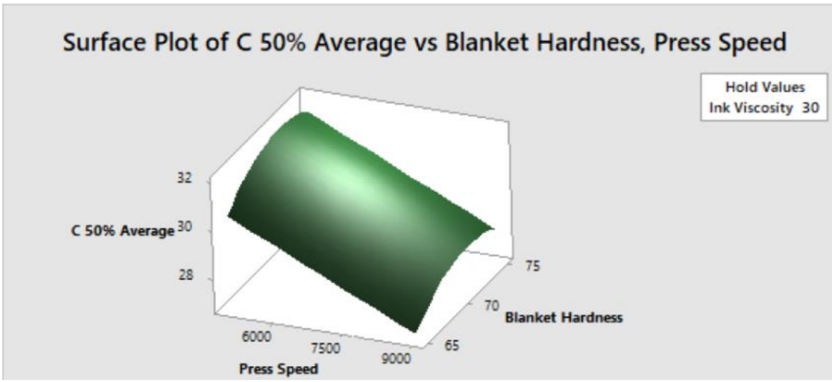


c)

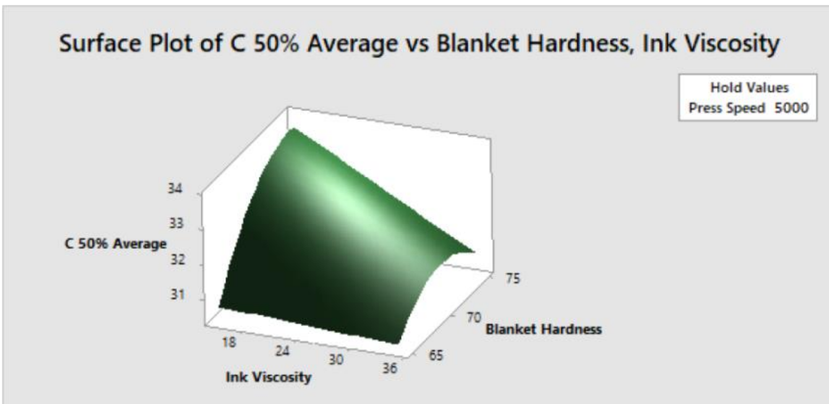
Figure 4: a, b and c: 3D Surface plots for dot gain at 50 % tone values.



a)

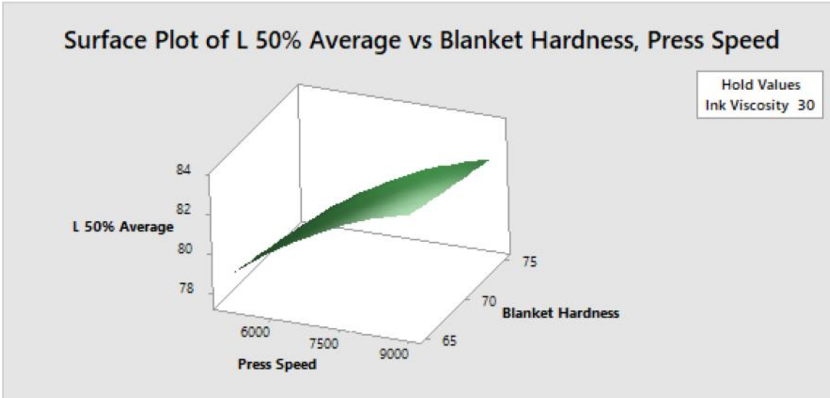


b)

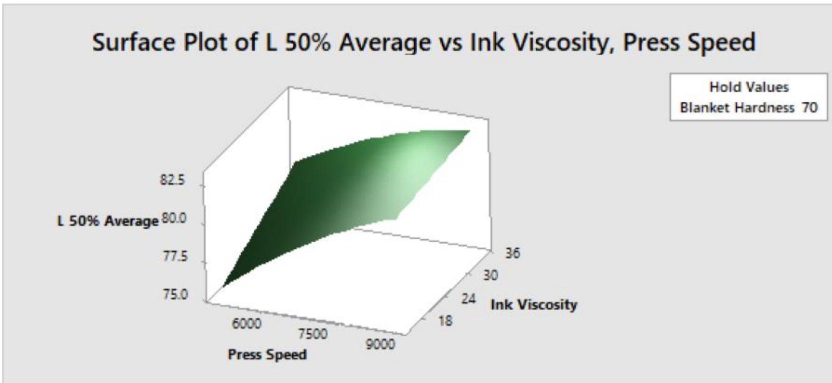


c)

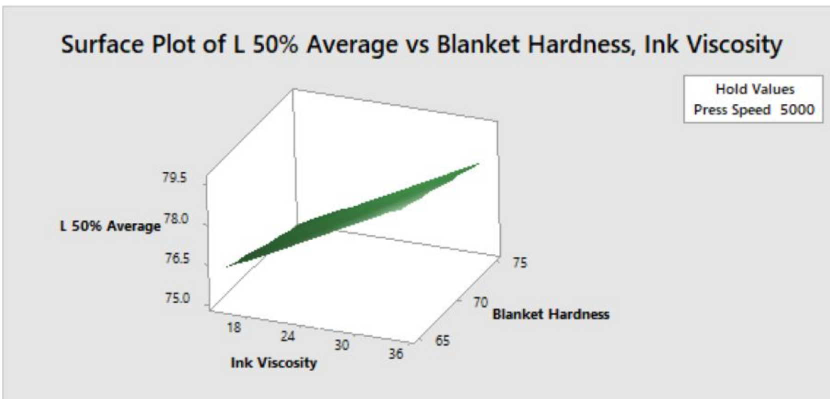
Figure 5: a, b and c: 3D Surface plots for chroma at 50 % tone values.



a)



b)



c)

Figure 6: a, b and c:3D Surface plots for lightness at 50 % tone values.

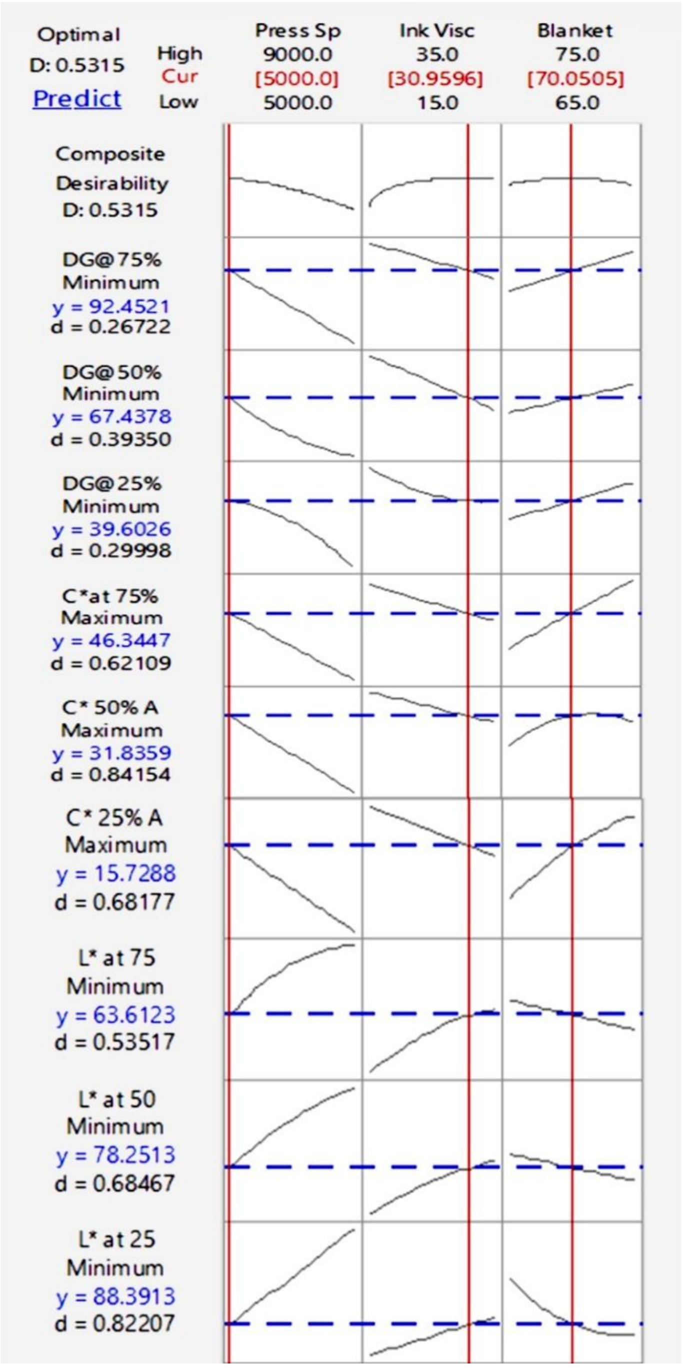


Figure 7: Optimization plot.

4. Conclusion

This research evaluated multiple parameters and characterized the physical dot gain, chroma, and lightness, important response parameters for quality print. In this designed experiment, we successfully adopted the Box-Behnken design. Press speed, blanket hardness, and viscosity significantly influenced the print characteristics. Higher dot gain results in darker images. It results in higher chroma and lower lightness. However, higher chroma may be higher, but a higher dot gain is not suitable for printing. The optimization helps in giving the right combination of factors and characterizes the response factors.The validation run gave the following resultsin dot gain for halftones 75, 50 and 25 %: 93.2, 68.1, and 38.2, respectively. The results of lightness obtained in the validation run were 64.02, 77.2, and 87.5, respectively. The results from the validation trial for chroma were 46.7, 32.5, and 15.2, respectively. Thus, our results showed that the predicted and experimental values were similar, and the models can be used to produce prints.We can thus conclude that with the help of this statistical tool, we can create a multivariate model to understand the relationship between the printing machine parameters and the multi-response parameters with minimum experiments, thus saving resources and time. Ink viscosity and press speed are significant factors influencing the quality of print. Choosing the right ink viscosity for a given press speed and blanket hardness produces vibrant yet sharp print results. It is, therefore important to decide the accurate combination of factors for quality and consistent press results.

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