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SCIENTIFIC PAPER

Application of box behnken design to optimize some parameters for flexographic printing process

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ABSTRACT:

The flexographic printing process parameters are crucial elements in ensuring the appropriate print quality and efficient use of resources associated with the printing process. For this, an effective study on establishing the relationship between the multiple input factors and the key output responses are necessary. This study investigates the print quality assessment and optimization of process parameters associated with the flexographic printing process based on Design of Experiment (DoE) carried out by one of the most efficient quadratic models in Response Surface Methodology called Box Behnken Design. The experimental approach designates three factor inputs such as three kinds of anilox roller screen rulings, three grades of paper substrates with different smoothness and three levels of halftone dot percentages. The dot gain and print contrast are taken as the output responses that denote the degree of accomplishment of print quality. The flexographic print trials are executed with the printing of a grey scale image on three grades of paper substrate with three anilox roller screen rulings conditions. The halftone image is created with AM square dots for study. The Box Behnken Design (BBD) is implemented here for the optimization of process parameters with proper employment of analytical approach such as ANOVA and regression analysis. The results found the suitability of BBD model and regression analysis in selecting the parameters to get the better print in flexography. The value of Variance Inflation Factor (VIF) in regression analysis is found below 1.5 that indicates the less occurrence of multi-collinearity in the regression model. The ANOVA result for the dot gain gives R-sq value 97.37% which implies the suitability of the regression model in defining the relation between input variables with the output (dot gain). The ANOVA result for the print contrast shows R-sq value 99.77% which suggests that independent variables are capable of explaining the variance of the dependent variable (print contrast). It is also found that the roughness of paper surface, anilox roller screen rulings and dot percentage influence the dot gain and print contrast.

KEYWORDS:

Flexography, LPI, Dot Gain, Print Contrast, Box Behnken Design

1. INTRODUCTION

1.1. The Flexographic Printing

The flexographic printing is an impact printing technique with a rotary relief image carrier which is flexible enough to deliver printing ink onto a wide variety of substrates like paper, paperboards, plastic films, foils etc. [1]. The plates that mounted on the plate cylinder get ink from the anilox roller, which is a key element of flexographic printing system and is crucial to transfer the ink from the ink chamber to the printing plate. An anilox roller is a cylinder with tiny engraved cells on its surface in order to facilitate a controlled transfer of ink. The amount of ink that is transferred to the anilox roller is adjusted with a doctor blade. Through this procedure, the ink is transmitted from the anilox roller to the raised regions of the plate during printing. The image area then pushes against the impression roller to make contact with the substrate and thus the image will be transferred. In flexography, a slight pressure is well enough to transfer ink from the plate to the substrate at the printing nip [2]. Figure 1 represents the schematic diagram of flexographic printing unit.

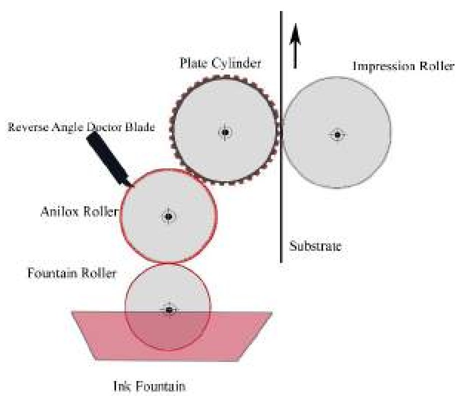

Figure 1 *Schematic diagram of a flexographic printing unit*

The flexography may create halftone dot sizes with percentage coefficients of variation (%CV) of 19.64 in highlight picture areas [3]. Conversely, in the shadow and midtone image regions, the %CV of halftone dot size changes tends to decrease as the dot size increases. Human senses detect non-uniform halftone picture dot patterns when the percentage CV is more than 6.72 [3].

The dot gain increases in flexographic halftone printing in proportion to drops in anilox roll line frequency and increases in plate image screen frequency. It is evident that both the lower and higher screen rules of plate image are reacted to the anilox frequency at the final print. The finer anilox roll is required when using a flexographic printer in order to keep a cell aperture smaller than the minimum reproducible plate dot. The deeper the dot, the more stable the dot which lowers the tone value increase [4].

The anilox roller cell engraving specifications have great influence on how much ink is to be applied onto the substrate, which in turn affected the optical density and halftone reproduction of the final print. The rate of density increase for increasing anilox volume is higher at higher plate screen rulings than it is at lower plate screen rulings. An increased dot perimeter at the higher rulings per unit area on the plate explains this. The anilox cell capacity was the primary determinant of print quality, however other elements, such as the form of the cell, were also found to have an effect [5].

The properties of the paper surface will affect runnability, print registration, ink lay down, ink absorption, etc. in flexographic printing. An increase in the surface roughness of substrate may cause a sharp drop in print density and at the same time, the paper smoothness, which increases print density. The optical characteristics such as opacity and whiteness that directly affects print density. Furthermore, the anilox roller cell properties in flexography are important to guarantee precise print outcomes [6].

The roughness, porous surface and the inherent tone of the paper affect the print quality as well as the spread and absorption of ink. Spreading of ink on the print is directly correlated with the paper smoothness or roughness [7]. The lowest edge sharpness of the dot element is an expected print error in the case of uncoated paper [8].

The uncoated paper has open fibre textures that accelerate ink solvents seep through it and reduce print density. The coating surface that permits the fibre pores of paper to contract during printing, preventing ink from penetrating [9]. A thicker coating layer in halftone prints produces a surface with fewer surface peak features, reducing apparent dot gain by minimising surface light scattering [10].

Dot gain, dot area, print contrast and other quantitative analyses are likely to be used in the evaluation of print quality. The dot gain and dot area parameters are used to track the dot reproduction accuracy in the graphic reproduction. The print contrast value is a measure of how well shadow details are reproduced on the finished print [11]. When it comes to graphic reproduction, the AM dots perform better in middle tone areas to produce better results, while the FM dots perform better in highlight and shadow areas and also deliver better print results in those areas [12].

1.2. The Box Behnken Design

Box Behnken Design (BBD) was developed in 1960 by George E. P. Box and Donald Behnken. It is an experimental design and second order quadratic nonlinear model of the Response Surface Methodology. An experimental matrix required for the combination of the process parameter conditions is created by the Box-Behnken Design. The design aids in the development of the quadratic response surface model, which is employed in response value estimation and prediction, and also a common technique in the optimization of industrial processes and products [13].

The Box Behnken experimental designs for Response Surface Methods feature the following:

• Each factor is set at three equally spaced levels usually coded as −1, 0, +1.

• The treatment combinations are positioned at the centre and at the midpoints of the process space's edges.

• A quadratic model, or one with squared terms, products of two components, linear terms, and an intercept.

• The ratio of experimental points to coefficients should be judicious usually within the range of 1.5 to 2.6.

The estimation variance mostly depends primarily on the distance from the centre [14].

To conduct an experiment with BBD, just three levels and a minimum of three components are needed. These patterns can be rotated, or at least almost rotated. The main effect, interaction effect, and quadratic effect are all optimized with their support. The Box Behnken Design with three factors, for example, consists of three blocks, two of which are modified using the four potential combinations of high and low [15].

The number of Experimental Run, N with BBD can be calculated using the formula: $N = 2k(k-1) + C$ (where, k = number of factors, C = number of centre points in the design). The efficiency of the experimental design = (Number of coefficients in the estimated model) / (Number of experiments or run).The Box Behnken Design is a strong choice for response surface methodology since it allows for the following: (i) quadratic model parameter estimate; (ii) sequential design construction; (iii) model lack of fit detection; and (iv) block usage [16]. Figure 2 shows the basic structure of BBD.

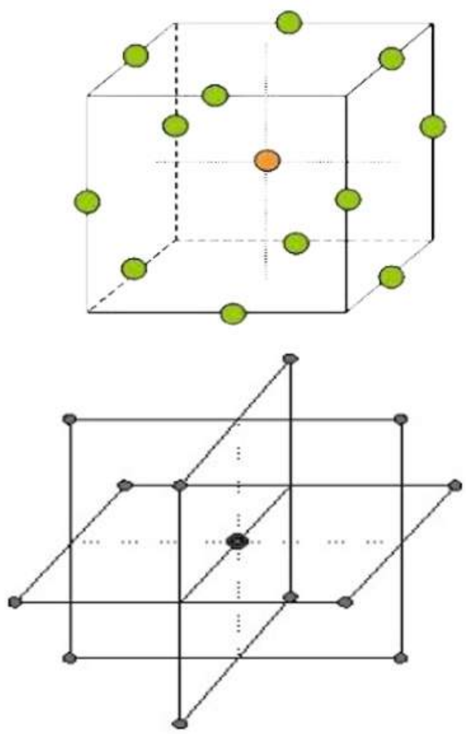

Figure 2 *Basic structure of BBD*

BBD experimental design is used by most industry sectors to optimize their goods or processes. Response Surface Methodology or Response Surface Modelling (RSM), is a commonly utilized technique for response optimization. The response surface methodology is a set of practical and efficient mathematical and statistical tools for creating, enhancing, and optimizing processes and/or products by improving the operational elements. Using this approach, the link between one or more response variables (dependent variables) and many explanatory variables (independent variables) is examined statistically to optimize the response or product [17].

An essential component of Response Surface Methodology (RSM) is design of experiments (DoE), which aims to identify the points at which response should be assessed. When employing the Response Surface Methodology, two stages are required: 1) creating an approximation function and 2) designing an experiment plan [18].

The BBD lacks any points at the vertices of the experimental region, it is acknowledged as a special three level design. Both the centre points and the midpoints of the edges should be used in a BBD. Because face points are frequently easier to execute than extreme (corner) points, a BBD uses them instead. The Box Behnken Design is often rotational or almost rotatable and can be used to a variety of variables, from three to twentyone [19].

In comparison to central composite designs with an equal number of elements, Box Behnken Designs frequently have fewer design points and can be executed at a lower cost. Nevertheless, they are not appropriate for sequential trials since they lack an embedded factorial design. The main benefit is that it addresses the question of where the borders of the experiment should be, specifically avoiding combinations of treatments that are too extreme [20]. The BBD is more efficient than CCD and FFD [21].

The design is not considering the vertices of the cube, so that it can avoid situations under which the experiments done at extreme conditions or the responses at these extreme conditions. This can eliminate unsatisfactory results. The BBD offers block orthogonality, which means the effects themselves are orthogonal to the block effects or it will not affect parameter estimates [22].

Analysis of variance (ANOVA) is a statistical tool which helps to identify the deviation of mean of experimental parameters. ANOVA helps to determine the actual state of the performance statistics of experimental parameters, errors, uncontrolled parameters etc. and also to crisscross the competence of the experimental model against the responses [23].

The BBD model is used to optimize the goods in terms of quality as well as production process. This model can avoid the situation when experimentation is performed under extreme condition as it is not considering the vertices of the cube. For the above reasons, BBD model was selected to optimize the print quality factors in flexographic printing process considering the input variables such as anilox roller screen rulings, paper roughness and dot percentages of images which are independent to each other.

This study is an experimental and statistical approach to determine the optimum process parameters for flexographic print quality that can be achieved with AM square shaped halftone dots on three grades of paper with different roughness under three anilox roller rulings.

2. METHODS

2.1. Experiment

The experiment was conducted by printing an ideal grey scale image with AM square dots onto three grades of paper substrates such as Coated, Uncoated and Calendared papers having different smooth textures or roughness. The roughnesses of the paper substrates were measured by Gurley 4340 Automatic Densometer & Smoothness Tester using contact method and given in Table 1. As the anilox roller acts as the core of flexographic printing process to deliver exact print quality, three different kinds of anilox roller screen rulings, such as 700 lpi (BCM 4.1), 1000 lpi (BCM 3.9) and 1300 lpi (BCM 3.8) (lines per inch) were employed at each print trials. The engraved cells have chosen for the work that features 60º hexagonal in geometry.

The printing work was executed in Flexographic printing machine, OMET LAB230 Iflex with Black colour UV ink. The plates used are photopolymer plate of 1.14 mm thickness with magnetic backing. The plate used is Dupont make and the hardness of the finished plate is 45 Shore A0. The printing speed (35 m/min), nip pressure (3 mm), room temperature (230C) and ink parameters are kept constant throughout the printing process. The ink used in the printing process is liquid ink. The values of the viscosity and surface tension of the ink used are 2.5 Poise and 36 x 10-3 N/m.

2.2. Measurements and data collection

Each element of the specified samples of printed sheets are subjected to visual inspection with a Digital Microscope (LEICA, S8APO) followed by the quantitative optical property measurement using Spectro-Densitometer (such as X-Rite Spectro Eye and TECHKON GmbH Spectro Dens). The quality analysis on the collected data followed by optimization of process parameters were done with the response surface methodology such as Box Behnken Design. In the computation process, 30%, 50% and 70% (that represents highlight, middle-tone and shadow areas respectively) tonal areas are targeted for the analysis of response such as Dot Gain and Print Contrast. The planning of experiment with Box Behnken Design has been performed with Minitab 17 Statistical Software.
The Table 1 shows different process parameters or factors, their values, corresponding levels and the response variable such as dot gain considering in this analysis process.

Table 1 *Process parameters or factors and their levels*

Factors	Unit	Symbol	Levels			Re-sponses
			1	2	3	
Anilox Roller Screen Rul-ings	Lines per inch (lpi)	A	700	1000	1300	Dot Gain & Print Con-trast
Paper Rough-ness	Millil-itre per minute (ml/min)	B	36	109	182	
Dot Per-centage	Per-centage (%)	C	30	50	70	

The influence of experimental variable parameters such as substrate, dot percentage and anilox roller screen rulings in flexographic printing corresponding to the possible dot gain and print contrast are investigated in the analysis part with ANOVA and Regression analysis process.

2.3. Box Behnken Design

The BBD design includes the following features:

3 factors with 3 levels.

1 base block and 3 centre points.

1 replicate with 15 base runs.

Total of 1 block and 15 experimental runs.
The Table 2 represents the design Table of BBD. The design represents the values 1 and -1 corresponding to high and low levels of factors. The 0 represents the centre point or the middle level value of factors. As per BBD, the total experimental run is 15.

Table 1 *Process parameters or factors and their levels*

Run	BLK	A	B	C
1.	1	-1	-1	0
2.	1	1	-1	0
3.	1	-1	1	0
4.	1	1	1	0
5.	1	-1	0	-1
6.	1	1	0	-1
7.	1	-1	0	1
8.	1	1	0	1
9.	1	0	-1	-1
10.	1	0	1	-1
11.	1	0	-1	1
12.	1	0	1	1
13.	1	0	0	0
14.	1	0	0	0
15.	1	0	0	0

3. RESULTS

As per the Box Behnken approach the conduct of experiments and the measurement of output responses at each experimental runs are prepared as shown in the Table 3. The Analysis of Variance (ANOVA) and Regression Analysis of the data are performed in detail. Table 3 represents the input data which were selected and measured with instruments for the purpose of BBD. Anilox roller screen rulings, paper roughness and dot percentage data were selected during the printing of the jobs. Dot gains were measured and calculated. Print contrast data were also measured from the printed copy using X-Rite Spectro Eye.

Table 3 *The dot gain and print contrast response at each experimental run*

Run Order	Factor 1: A Anilox Rulings (lpi)	Factor 2: B Paper Roughness (ml/min)	Factor 3: C Dot Percentage (%)	Dot Gain (%)	Print Contrast (%)
1.	700	36	50	15	76
2.	1300	36	50	10	71
3.	700	182	50	29	46
4.	1300	182	50	25	48
5.	700	109	30	13	81
6.	1300	109	30	13	78
7.	700	109	70	14	44
8.	1300	109	70	12	41
9.	1000	36	30	9	87
10.	1000	182	30	30	64
11.	1000	36	70	11	58
12.	1000	182	70	19	27
13.	1000	109	50	17	60
14.	1000	109	50	17	60
15.	1000	109	50	17	60

3.1. Graphical analysis

The graphical plots of the BBD results are given at Figures 3-15. The residual data of experiments, main effects and interaction effects of factors over responses, contour plots, 3D surface plots, 3D scatterplot of process parameters etc. are plotted in detail.

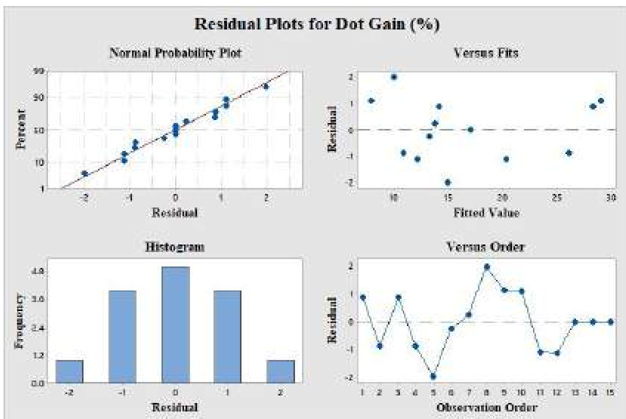

Figure 3 *Residual Plots for Dot Gain*

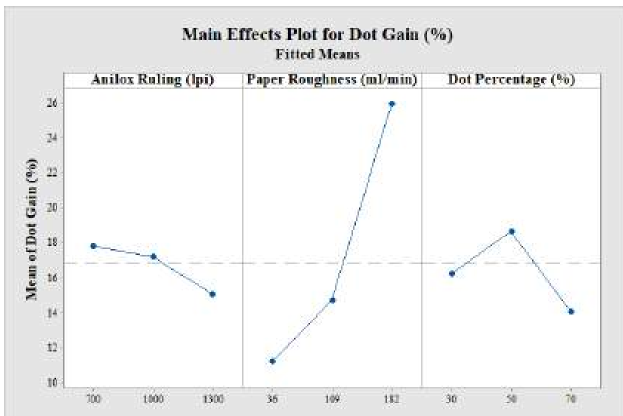

Figure 5 *Main effect plot for Dot Gain*

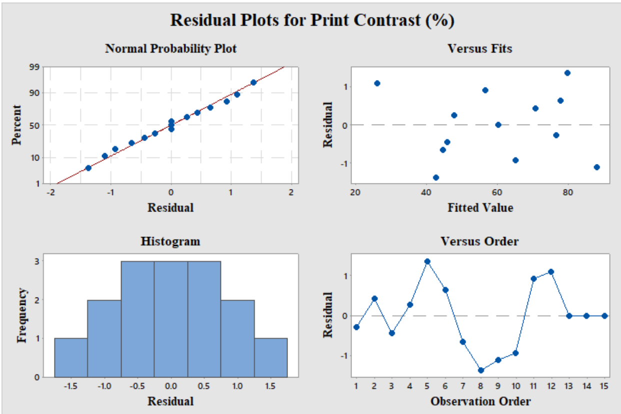

Figure 4 *Residual Plots for Print Contrast*

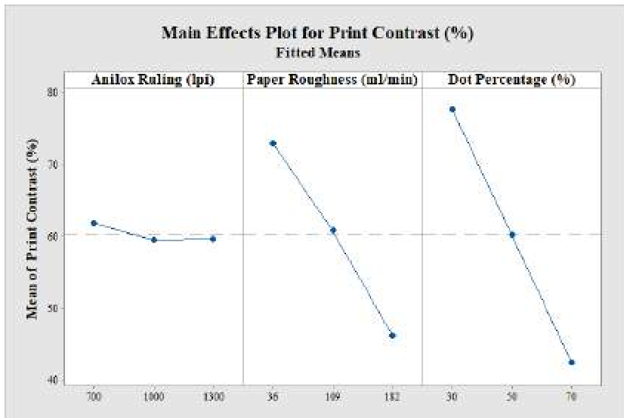

Figure 6 *Main effect plot for Print Contrast*

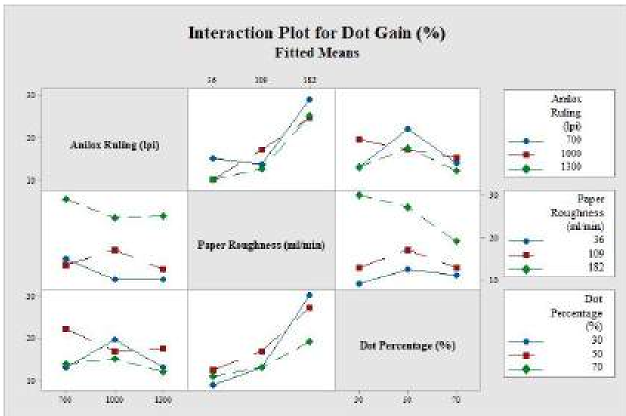

Figure 7 *Ineraction plot for Dot Gain*

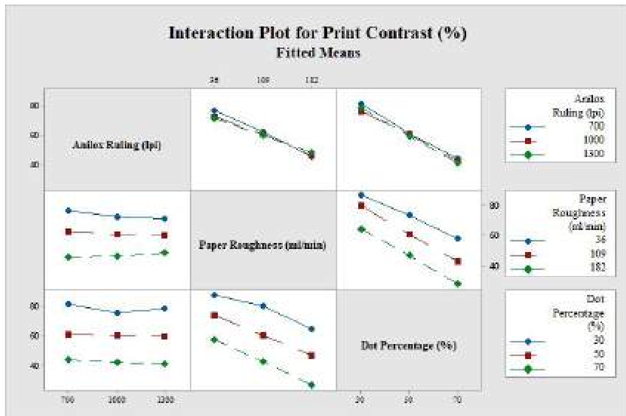

Figure 8 *Interaction plot for Print Contrast*

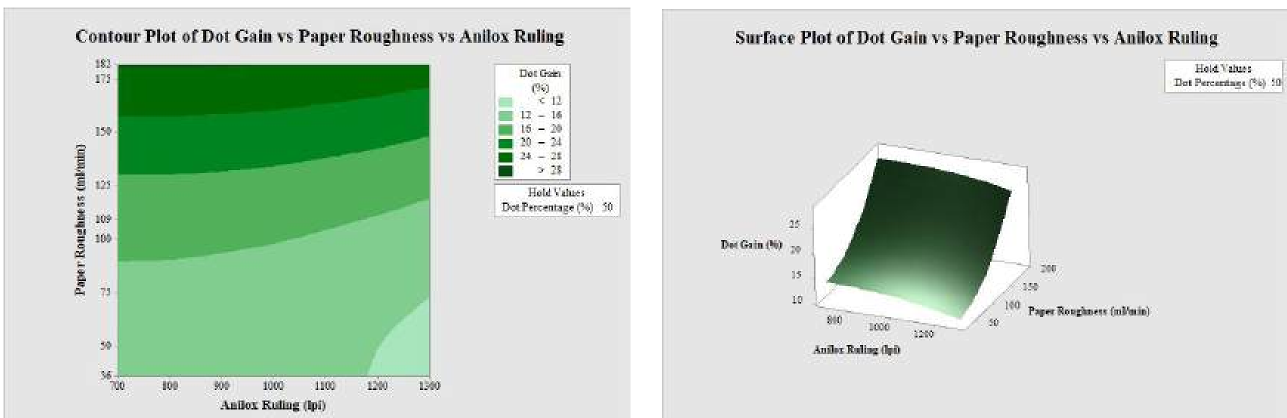

Figure 9 *Contour plot (left) and Surface plot (right) shows Dot gain against Paper Roughness and Anilox Roller Screen Rulings*

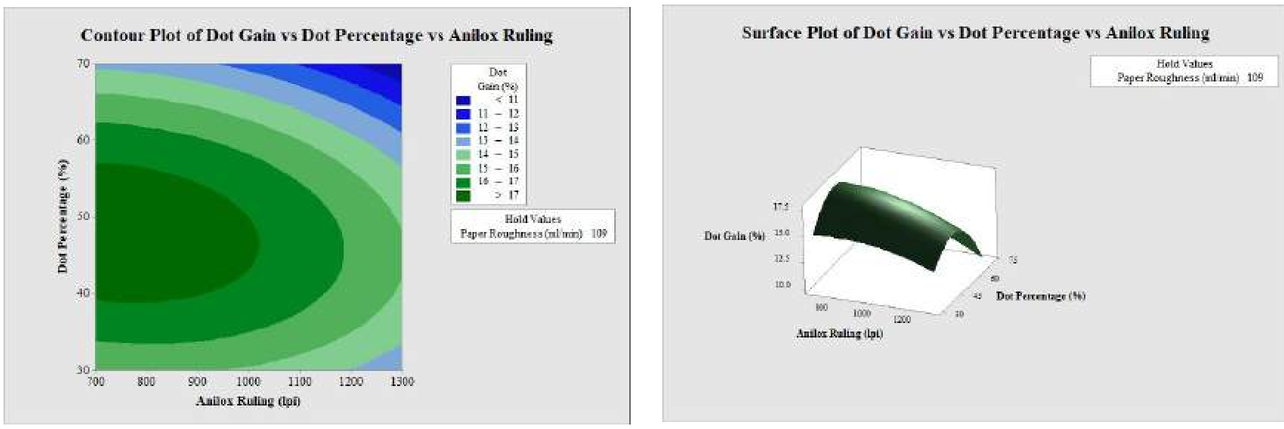

Figure 10 *Contour plot (left) and Surface plot (right) shows Dot gain against Dot Percentage and Anilox Roller Screen Rulings*

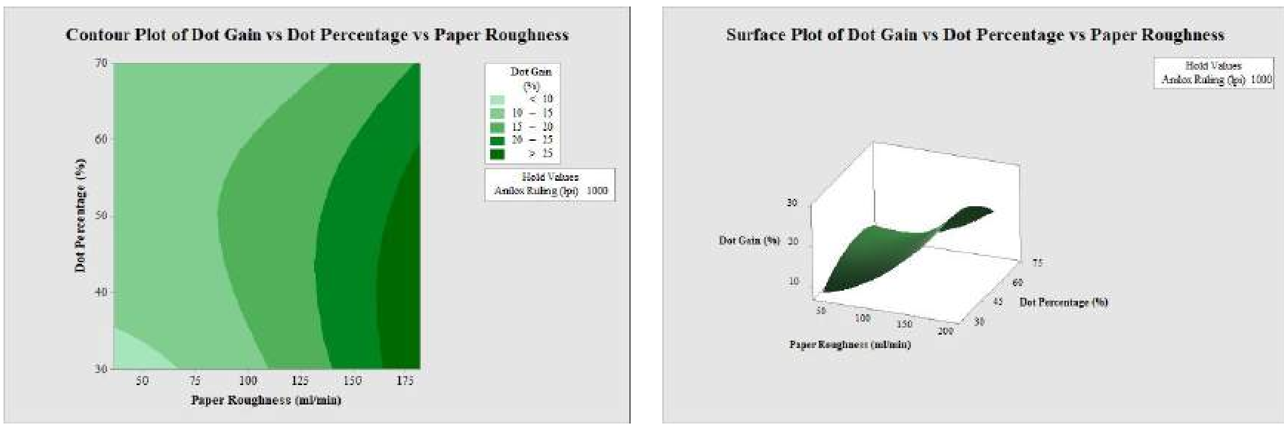

Figure 11 *Contour plot (left) and Surface plot (right) shows Dot gain against Dot Percentage and Paper Roughness*

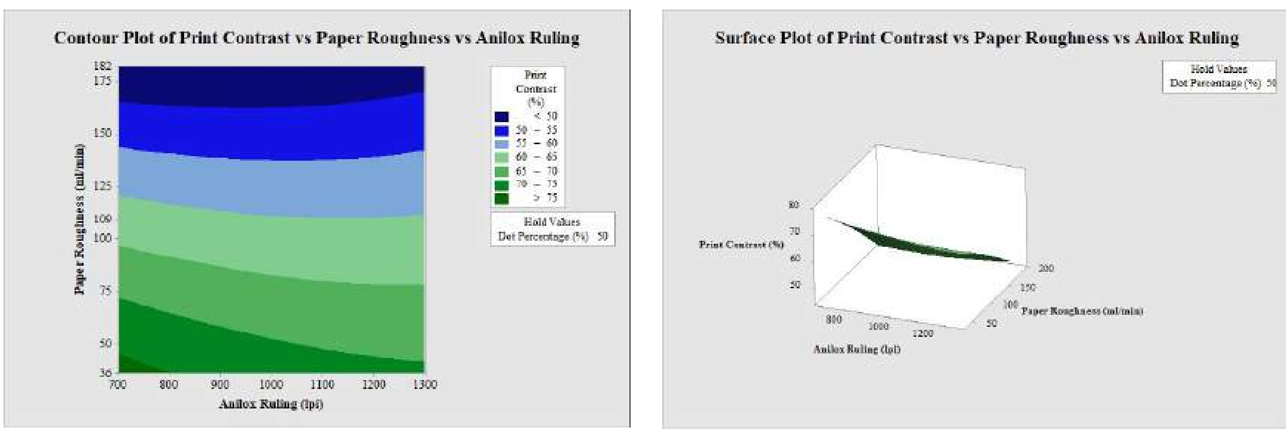

Figure 12 *Contour plot (left) and Surface plot (right) shows Print Contrast against Paper Roughness and Anilox Roller Screen Rulings*

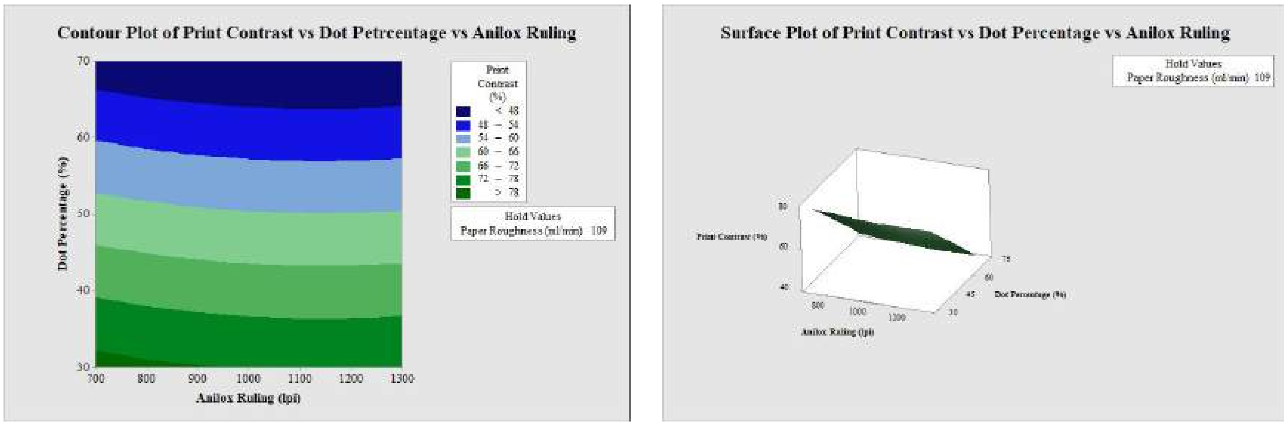

Figure 13 *Contour plot (left) and Surface plot (right) shows Print Contrast against Dot Percentage and Anilox Roller Screen Rulings*

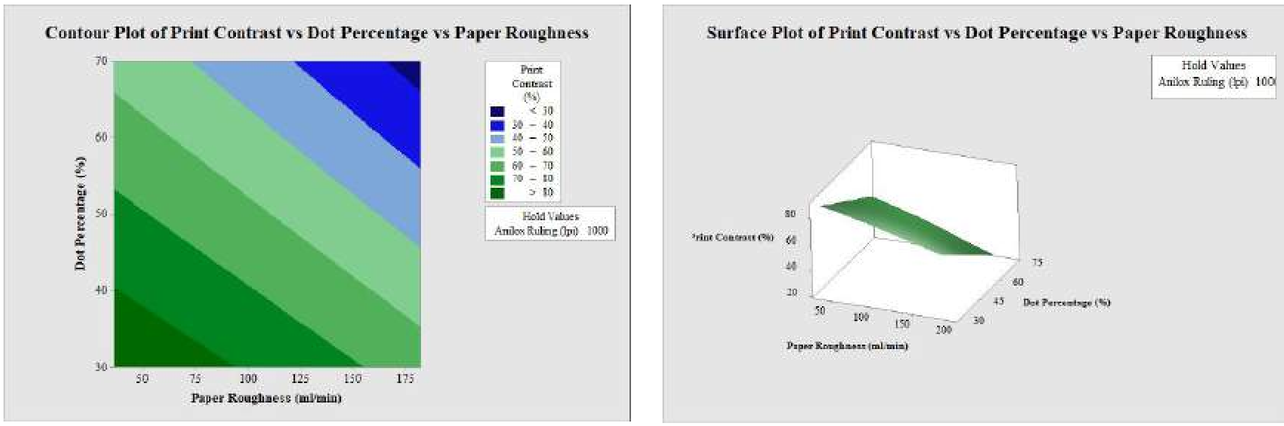

Figure 14 *Contour plot (left) and Surface plot (right) shows Print Contrast against Dot Percentage and Paper Roughness*

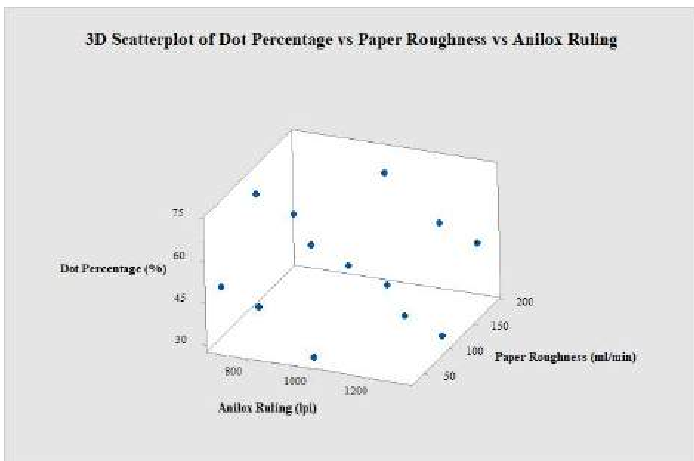

Figure 15 *3D scatterplot illustrates correlation between Dot percentage, Paper Roughness and Anilox Roller Screen Rulings*

3.2 Regression Analysis

The Tables 4-7 represent the ANOVA results of this experimental study that shows the Response surface regression of Dot Gain and Print Contrast against various process parameters such as anilox roller screen rulings, paper roughness and halftone dot percentages.

Table 4 *ANOVA result for Dot gain*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	9	595.619	66.180	20.60	0.002
Linear	3	456.492	152.164	47.35	0.000
A	1	15.120	15.120	4.71	0.082
B	1	431.427	431.427	134.26	0.000
C	1	9.945	9.945	3.09	0.139
Square	3	96.149	32.050	9.97	0.015
A*A	1	2.067	2.067	0.64	0.459
B*B	1	47.682	47.682	14.84	0.012
C*C	1	39.045	39.045	12.15	0.018
2-Way Interaction	3	42.979	14.326	4.46	0.071
A*B	1	0.251	0.251	0.08	0.791
A*C	1	1.000	1.000	0.31	0.601
B*C	1	41.728	41.728	12.99	0.015
Residual Error	5	16.066	3.213		
Lack-of-Fit	3	16.066	5.355		
Pure Error	2	0.000	0.000		
Total	14	611.686			

Model Summary:
S 1.79256
R-sq97.37%
R-sq(adj) 92.65%
R-sq(pred)57.97%

Table 5 *Coded coefficients for Dot Gain*

Term	Effect	Coef	SE Coef	T-Value	VIF
Constant		17.00	1.03	16.43	
A	-2.750	-1.375	0.634	-2.17	1.00
B	14.687	7.344	0.634	11.59	1.00
C	-2.230	-1.115	0.634	-1.76	1.00
A*A	-1.496	-0.748	0.933	-0.80	1.01
B*B	7.187	3.594	0.933	3.85	1.01
C*C	-6.504	-3.252	0.933	-3.49	1.01
A*B	0.501	0.250	0.896	0.28	1.00
A*C	-1.000	-0.500	0.896	-0.56	1.00
B*C	-6.460	-3.230	0.896	-3.60	1.00

Regression Equation for Dot Gain,

Dot Gain (%) = -22.2 + 0.0150 A + 0.0528 B+ 1.082 C- 0.000008 A*A+ 0.000674 B*B- 0.00813 C*C + 0.000011 A*B- 0.000083 A*C- 0.002212 B*C (1)

Table 6 *ANOVA result for Print Contrast*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	9	3964.94	440.55	236.82	0.000
Linear	3	3924.83	1308.28	703.28	0.000
A	1	8.81	8.81	4.74	0.081
B	1	1436.81	1436.81	772.38	0.000
C	1	2479.21	2479.21	1332.73	0.000
Square	3	10.22	3.41	1.83	0.259
A*A	1	4.50	4.50	2.42	0.181
B*B	1	4.85	4.85	2.60	0.167
C*C	1	0.10	0.10	0.05	0.826
2-Way Interaction	3	29.89	9.96	5.36	0.051
A*B	1	15.09	15.09	8.11	0.036
A*C	1	0.00	0.00	0.00	0.961
B*C	1	14.80	14.80	7.95	0.037
Residual Error	5	9.30	1.86		
Lack-of-Fit	3	9.30	3.10		
Pure Error	2	0.00	0.00		
Total	14	3974.24			

Model Summary:
S1.36391
R-sq99.77%
R-sq(adj) 99.34%
R-sq(pred)96.26%

Table 7 *Coded Coefficients for Print Contrast*

Term	Effect	Coef	SE Coef	T-Value	VIF
Constant		60.341	0.787	76.63	
A	-2.099	-1.050	0.482	-2.18	1.00
B	-26.803	-13.402	0.482	-27.79	1.00
C	-35.208	-17.604	0.482	-36.51	1.00
A*A	2.207	1.103	0.710	1.55	1.01
B*B	-2.291	-1.146	0.710	-1.61	1.01
C*C	-0.328	-0.164	0.710	-0.23	1.01
A*B	3.884	1.942	0.682	2.85	1.00
A*C	0.070	0.035	0.682	0.05	1.00
B*C	-3.847	-1.923	0.682	-2.82	1.00

Regression Equation for Print Contrast,
Print Contrast (%) = 139.3 - 0.0380 A- 0.1595 B - 0.701 C + 0.000012 A*A - 0.000215 B*B - 0.00041 C*C + 0.000089 A*B+ 0.000006 A*C- 0.001317 B*C (2)

Based on Box Behnken response surface model, the regression equation for the dot gain and print contrast are generated as equation (1) and (2) respectively and represented vides Figures 16 & 17 respectively.

3.3 Optimization for Responses

As per the Box Behnken Design of Response Surface Methodology, the optimum values found for the responses such as Dot Gain and Print Contrast are given at Table 8 and in Figures 16-17.

Table 8 *Summary of optimization result*

Response	Target	Optimal Solution of process parameters:	Optimal Fit of Response
	Optimal Fit of Response	Factor A: Anilox Roller Screen Rulings= 1300 lpi Factor B: Paper Roughness= 36 ml/min Factor C: Dot Percentage= 30%	6.01 % under 95% CI
Print Contrast (%)	40%	Factor A: Anilox Roller Screen Rulings=740.18 lpi Factor B: Paper Roughness=127.07 ml/min Factor C: Dot Percentage= 70 %	40 % under 95% CI
	60%	Factor A: Anilox Roller Screen Rulings=700 lpi Factor B: Paper Roughness=174.31 ml/min Factor C: Dot Percentage= 37.38 %	60 % under 95% CI

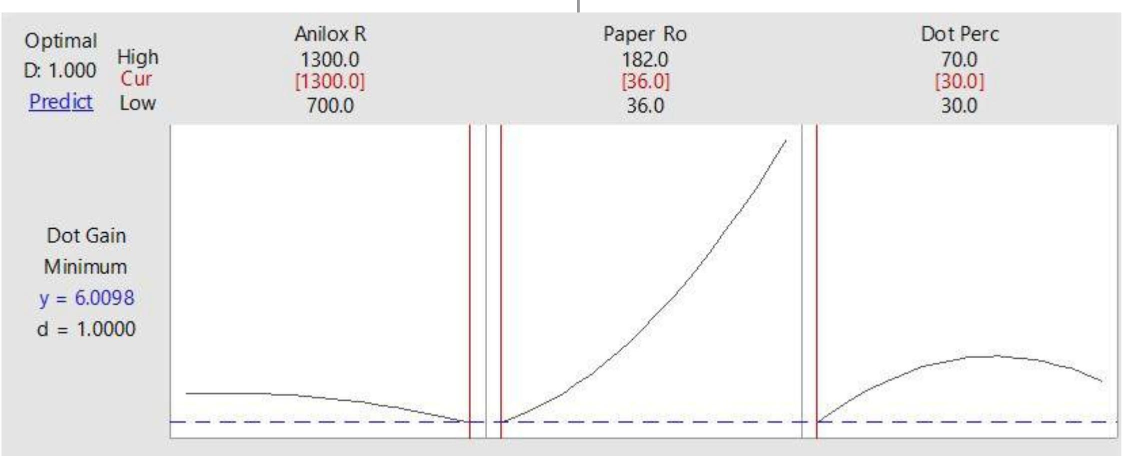

Figure 16 *Optimization result for Dot Gain*

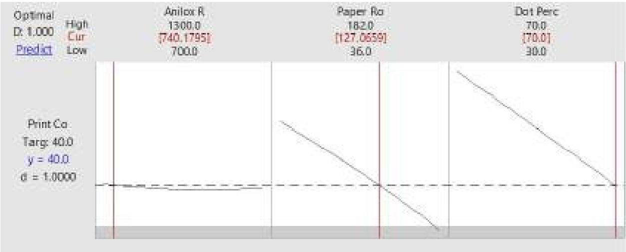

Figure 17 *Optimization result for 40% Print Contrast as target*

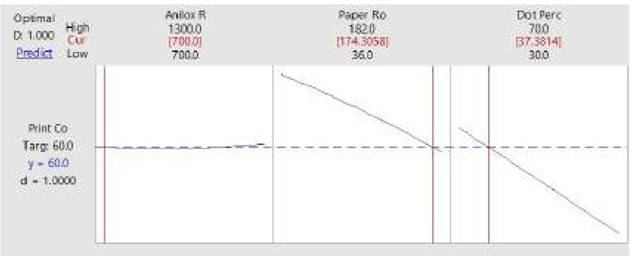

Figure 18 *Optimization result for 60% Print Contrast as target*

4. DISCUSSIONS

The Figures 3-4 shows the residual plots for dot gain and print contrast respectively. Each plot represents the appropriateness of linear model with the experimental data by evaluating the discrepancy between projected value by the regression model and actual observed value. In normal probability plot, the departure of data points from the straight line indicates the shift of response from normal distribution. In versus fits plot, the deviation of data points from the dash line represents the shift of observed value of response against the estimated regression line or the line of best fit. The data point on dash line indicates zero residuals. The non linearity, unequal errors, outliers can be visualized from the plotted data points.

The histogram shows the normal distribution of residuals. Versus order plot shows the correlation of errors in the sequence and it is related with the appropriateness of data collection in the experimental process. Data point on regression line means there is no serial correlation. Ideally the points should fall randomly on both sides of regression line rather than recognizable pattern.

The Figure 5 shows the relative strength of each factor against mean value of dot gain. The contribution of each factor to the dot gain is given separately. Steeper the line more will be the main effect. The paper roughness levels contribute dot gain comparatively than other factors.

In the Figure 6, the paper roughness and dot percentage shows more effects towards print contrast than anilox roller screen rulings.

The Figure 7 shows the interaction between factors that contribute to dot gain.

At all levels of anilox roller screen rulings, the paper with rough surface texture contributes higher dot gain especially at 50% tonal areas. The effect of paper roughness is more throughout the process. The coated paper at 30% tonal area contributes less dot gain but at uncoated grade paper it is high. At 50% tonal region the dot gain is high for all grades of paper but more for uncoated grade paper.

In the Figure 8, at all levels of anilox roller screen rulings, the print contrast is high for smoother grade paper.

The Figure 9 shows how the dot gain varies with change in anilox roller screen rulings and paper roughness while keeping the dot percentage as hold value. Based on the regression equation, the dot gain is minimum around 1300 lpi anilox roller screen rulings and paper roughness of 36 ml/min.

The dot gain is maximum at lower anilox roller screen rulings with paper roughness around 182 ml/min. This implies the fact that at lower anilox roller screen rulings the quantity of ink supply will be more than that with the anilox roller of higher screen rulings. At the same time, the surface irregularity of the substrate also influences dot gain at a considerable extent. Higher the paper roughness more will be the ink penetration into the paper than that of the desirable level.

This will increase the dot size at print than the required size. Also, the paper surface roughness promotes uneven ink distribution over the paper at printing.

The Figure 10 shows the attainment of dot gain based on the changing levels of anilox roller screen rulings with different dot percentages while holding out the paper roughness value. The contour plot and surface plot that visualizes the chance of higher dot gain at middle tone areas of square shaped halftone dots with lower anilox roller screen rulings.

The Figure 11 shows the variation of dot gain against various dot percentages and paper roughness with anilox roller screen rulings as hold value. The chance of dot gain is there at both highlight and middle tone areas when printing on paper having high roughness values. For smoother or coated paper, the dot gain is minimum around 30% tonal regions.

The Figures 12-14 show the attainment of print contrast against any of the two factors at a time while keeping the third factor levels as hold values.

The print contrast from 40-60% represents an ideal range of print contrast. This indicates the print reproduction with expanded tonal range and well reproduced image details at the shadow areas. From the graphical data it is found that the paper roughness shows a greater influence in controlling print contrast.

Higher the paper roughness greater will be the dot gain and thus the image details will be lost at shadow areas. This implies to a low print contrast. The high anilox roller screen rulings enhances precision in ink metering and thus promotes more controlled inking over shadow areas. Also, in order to analyse the print contrast, analysis of data points at shadow areas say 70-100% tonal region will be accountable.

The 3D scatterplot given in Figure 15 shows the visual information on the correlation between the process parameters such as Dot percentage, Paper Roughness and Anilox Roller Screen Rulings involved in the experiment.

This plot helps to visualize the direction, strength and linearity of relationship between variables.

The ANOVA result for the dot gain shown in Table 4 gives Sum of Square, R-sq as 97.37%. This implies that the regression model explains 97.37% of all variability in the dataset. It is the measure of the power of the model that suggests the fact that, the dot gain variable is capable of well explaining the variance in the dependent variable. The model does fit the data well and the model is more predictive. For factors B, B*B, C*C and B*C there is significant linear relationship with dot gain is found from the ANOVA Table.

Similarly, Table 6 shows the ANOVA result for the print contrast. The Sum of Square, R-sq is 99.77% that suggests the independent variable is capable of well explaining the variance in the dependent variable. The model does fit the data well and is more predictive. For the factors such as B, C, A*B and B*C there is significant linear relationship with print contrast.

The Tables 5-7 show the coded coefficients of regression equations for both dot gain and print contrast respectively.

The regression coefficient, Coef, expresses the strength and direction of the association between predictor and the response variable in the regression equation, which are actually the numbers that multiply the term values in model equation. The standard error of the coefficient, SE Coef, calculates the variation in coefficient estimations. The estimate is more accurate when smaller the standard error.

The Variance Inflation Factor (VIF) shown in The Tables 5-7 are always found below 1.5 that indicates the less occurrence of multi-collinearity in the regression models.

5. CONCLUSION

A mathematical model with three factors based on Box Behnken Design, was utilized to optimize the process parameters for flexographic printing's evaluation of print contrast and dot gain. The BBD model permits an easy way to generate a higher order response surface using fewer experimental runs. A total of fifteen experimental runs were carried out and both the dot gain and print contrast responses were recorded. The BBD is executed with Minitab 17 Statistical Software and the graphical analysis and regression analysis are done. The graphical analysis shows the influence of different factors over dot gain and print contrast. The result is analysed in detail with main effect plot, interaction plot, contour plots, surface plots etc. In the regression analysis part, main, squared, and interaction components are created. To identify which of the components are more important, a 95% confidence level was used.

The influence of paper roughness and anilox roller screen rulings influence the dot gain of flexographic print as shown in Figures 9-11.

The dot area percentage with square dots at middle tone areas are found more sensitive to dot gain. This effect will be more with the choice of low anilox roller screen rulings together with rough textured substrate in the printing process as controlled transfer of a liquid ink is essential to the flexographic printing process as shown in Figure 11.

The optimum level of process parameters in this experimental process are identified as anilox roller with higher screen rulings and substrate with smooth surface finish are better for halftone dot reproduction with flexography.

It has been found from Figures 12-14, print contrast is affected by the choice of anilox roller screen rulings, paper roughness and percentage dot area.

It has been found that print contrast varies from 40%-60% which indicates good tonal range and well reproduced image details at shadow areas. The roughness of the paper also influences the print contrast.

Higher the paper roughness, lower will be the print contrast. The square dot around 50% tonal regions promotes dot gain in an undesirable way, and so the dot shapes other than square dots will be a better choice around 50% tonal regions.

LITERATURE

[1] Kipphan, H. (2001) Handbook of print media: technologies and production methods. Springer, ISBN 3-540-67326-1. http://www.springer.de.

[2] Joshi, V.A. (2022) Optimization of flexo process parameters to reduce the overall manufacturing cost. An International Journal of Optimization and Control: Theories & Applications. Vol. 12, No. 1. https://doi.org/10.11121/ijocta.2022.1137.

[3] Kajondecha, P. & Hoshino, Y. (2008) Halftone dot size variation in offset, electrophotographic, and flexographic printing and its perception. Journal of Imaging Science and Technology. 52(6). https://doi.org/10.2352/(2008)52:6(060503).

[4] Dendge, R.R. (2023) Analysis of dot gain produced by interactions of flexographic plate and anilox roll screen frequencies. Acta Graphica. Vol. 31, No. 1. https://dx.doi.org/10.25027/agj2017.28.v31i1.229.

[5] Bould, C.D., Hamblyn, S.M., Gethin, T.D. & Claypole, C.T. (2010) Effect of impression pressure and anilox specification on solid and halftone density. Journal of Engineering Manufacture. 225(5). https://doi.org/10.1177/2041297510394072.

[6] Theohari, S., Fraggedakis, E., Tsimis, D., Tsigonias, M. & Mandis, D. (2014) Effect of paper properties on print quality by flexographic method. https://www.researchgate.net/publication/263847022.

[7] Tomasegovic, T., Pibernik, J., Poljacek, M.S. & Madzar, A. (2021) Optimization of flexographic print properties on ecologically favorable paper substrates. Journal of Graphic Engineering and Design. 12(1). http://doi.org/10.24867/JGED-2021-1-037.

[8] Valdec, D., Hajdek, K., Majnaric, I. & Cerepinko, D. (2021) Influence of printing substrate on quality of line and text reproduction in flexography. Journal of Applied Sciences. No.11 (2021). https://doi.org/10.3390/app11177827.

[9] Gencoglu, N.E. (2012) Influence of ink viscosity on dot gain and print density in flexography. Asian Journal of Chemistry. Vol. 24, No. 5. https://www.asianjournalofchemistry.co.in.

[10] Bhattacharya, A., Bandhyopadhyay, S. & Green, P. (2016) Characterizing coated paper surface for modelling apparent dot area of halftone prints. OPTICS EXPRESS 1708, Vol. 24, No. 2. https://doi.org/10.1364/OE.24.001708.

[11] Dharavath, N.H., Bensen, M.T. & Gaddam, B. (2005) Analysis of print attributes of Amplitude Modulated (AM) vs. Frequency Modu¬lated (FM) screening of multicolour offset printing. Journal of Industrial Technology, Vol. 21, No. 3. www.nait.org.

[12] Youssef, T.K. (2015) The impact of FM-AM hybrid screening and AM screening on flexographic printing quality. Journal of International Design. Vol. 5, Issue 4. https://doi.org/10.21608/idj.2015.93687.

[13] Iwundu, P.M. & Cosmos, J. (2022) The efficiency of seven-variable box-behnken experimental design with varying centre runs on full and reduced model types. Journal of Mathematics and Statistics. Vol. 18(2022): 196.207. https://doi.org/10.3844/jmssp.2022.196.207.

[14] Salagarkar, S., Salunkhe, S. & Doke, C. (2023) A review on Box-Behnken design for analytical method development. International Research Journal of Modernization in Engineering Technology and Science. Vol. 05, Issue 12. https://www.irjmets.com.

[15] Sz.Gulyas, N., Al-Tayawi, N.A., Horvath, Z., Laszlo, Z., Kertesz, S. & Hodur, C. (2023) Methods for experimental design, central composite design and the Box–Behnken design, to optimize operational parameters: A review. Journal of Acta Alimentaria. https://doi.org/10.1556/066.2023.00235.

[16] Ferreira, C.L.S., Bruns, E.R., Ferreira, S.H., Matos, D.G., David, M.J., Brandao, C.G., da Silva, P.G.E., Portugal, A.L., dos Reis, S.P., Souza, S.A. & dos Santos, L.N.W. (2007) Box-Behnken design: An alternative for the optimization of analytical methods. Journal of Analytica Chimica Acta. 597. https://doi.org/10.1016/j.aca.2007.07.011.

[17] Aziz, A.R.A. & Aziz, A.S. (2018) Application of Box Behnken Design to optimize the parameters for kenaf-epoxy as noise absorber. IOP Conference Series: Materials Science and Engineering. 454 (2018) 012001. https://doi.org/10.1088/1757-899X/454/1/012001.

[18] Rai, V.H., Modi, K.Y. & Pare, A. (2018) Process parameter optimization for tensile strength of 3D printed parts using response surface methodology. IOP Conf. Series: Materials Science and Engineering. 377 (2018) 012027. https://doi.org/10.1088/1757-899X/377/1/012027.

[19] Kechagias, D.J. & Nectarios, V. (2022) Parametric optimization of material extrusion 3D printing process: an assessment of Box Behnken vs. full factorial experimental approach. The International Journal of Advanced Manufacturing Technology, 121. https://doi.org/10.1007/s00170-022-09532-2.

[20] Manohar, M., Joseph, J., Selvaraj, T. & Sivakumar, D. (2013) Application of Box Behnken design to optimize the parameters for turning Inconel 718 using coated carbide tools. International Journal of Scientific & Engineering Research. Vol. 4, Issue 4. http://www.ijser.org.

[21] Ghasemi, M.S., Ghaderpoori, M., Moradi, M., Taghavi, M. & Karimyan, K. (2020) Application of Box–Behnken design for optimization of malachite green removal from aqueous solutions by modified barley straw. Journal of Global NEST. Vol. 22, No. 3. https://doi.org/10.30955/gnj.003089.

[22] Aliemeke, G.N.B. & Oladeinde, H.M. (2020) Box-behnken design optimization of sand casting process parameters. International Journal of Engineering Technologies-IJET, Vol.6, No.2. https://doi.org/10.19072/ijet.714473.

[23] Ishraq, F., Ahmed, R. & Joytun, N.J. (2021) Fabrication and process parameter optimization of a 3D printer using response surface methodology. International journal of research in industrial engineering. 10 (3). https://www.riejournal.com.