An Experimental Study of Key Factors Affecting Color Reproduction on Corrugated Board Using UV Wide-format Inkjet Printer

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Abstract

Packaging is one of the fastest growing segments in the print industry, specifically the digital packaging arena. The advances in inkjet heads, inks, media range and color management that evident in wide-format printing are helping to advance inkjet print in packaging. Color digital printing for corrugated is essentially all inkjet and has existed for at least 20 years. High quality packaging prototyping allows for greater client choice and more short-run finished corrugated products. To exam the color reproduction capability on corrugated board using UV wide-format inkjet printer, a Roland VersaUV LEJ-640 UV LED printer with Eco UV-curable inks was employed in this study. The quality of color reproduction depends on the ability of the corrugated board to reflect red, green, and blue light. The VersaUV LEJ-640 UV LED printer is capable of lying down a layer of white ink before color printing and running at different speed mode. The main purposes of this experimental study are to (1) identify the most important factors that influence color reproduction on the corrugated board using UV wide-format inkjet printing, and (2) establish optimum operating conditions so that the maximum yield of optical density and color gamut could be obtained. The experiment was conducted using a randomized 2^3 factorial design in which every factor was run at two specified levels (1 = high level, -1 = low level, fixed effects). The factorial levels were determined based upon the practical operating conditions of the UV wide-format printer. The three independent factors of this study are: 1) the corrugated board (X_1), 2) printing speed mode (X_2), and 3) white ink (X_3). The dependent variable (Y) is the color reproduction capability (optical density and gamut volume) of corrugated board. The treatment combination of (X_1, X_2, X_3) = (1, -1, 1) is suggested to achieve the maximum yield of optical density (yellow and cyan) and color gamut.

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1. Introduction

Corrugated board is a material made of flat sheets of paper with one or more layers of corrugated paper between them (Figure 1). On the outer side of the board, there is flat paper called liner. Inside, there are corrugated layers separated by a flat sheet. With different combinations of corrugated layers, different degrees of board toughness are achieved. Corrugated board is a very sturdy material. It does not break at folds and is, therefore, mostly used in making transport boxes[1].

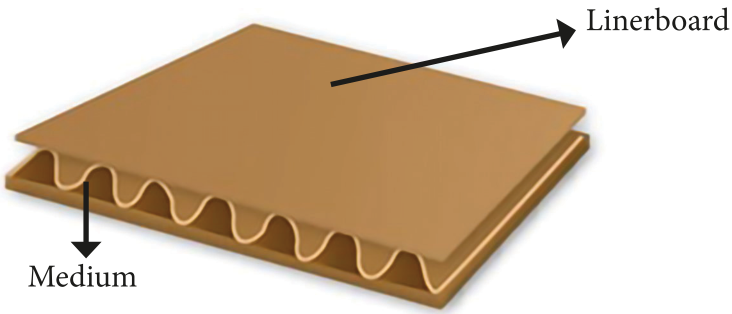

Figure 1. *Corrugated board*

1.1 Printing for Corrugated Packaging

Corrugated board presents difficult printing challenges. First, the fluted structure of corrugated can easily be damaged by excessive pressure during the conventional printing process where transferring ink requires intimate contact between the printing plate and the corrugated board. Secondly, changes in the way products are marketed have put pressure on corrugated box manufacturers to expand their print capabilities to enable the printing of more sophisticated images. For example, Point-of-purchase retailing has created a need for corrugated packaging to expand its role from a simple shipping container to a selling tool at the retail store[2].

Corrugated Board can be printed in inkjet printing. The advances in inkjet heads, inks, media range and color management are helping to advance inkjet print in packaging. Corrugated is seeing a lot of innovation in digital printing technology. Faster turnaround time, lower costs and fewer production steps are among the important benefits digital printing brings to the corrugated market. Digital packaging is also an ideal answer to market demands such as shorter runs, more customization, and regionalization[3, 4, 5].

1.2 Print Quality of Corrugated Board

With the graphic demands on corrugated board cases steadily rising, the corrugated board industry needs better knowledge of printing quality properties[6].

Striped surfaces are a distinctive feature of corrugated board. Some patterns make the board harder to print (i.e. washboarding and black streaks); some patterns give the printed surface a striped image (i.e. printed stripes). All the striped patterns occur on the liner surface and they coincide with the waves of the fluting. The stripes, which could be unprinted or printed, cause some quality problems for the corrugated board[6].

Washboarding is the most common type of unprinted stripes (Figure 2); it is the uneven, wavy pattern on the liner surface of a corrugated board[6, 7]. The wave tops correspond with the tips of the fluting. Washboarding occurs on the single-facer and the double-backer liners, which causes problems since it is normally the printing side. On white surfaces, the washboarding pattern causes a disturbing striped image. The wavy pattern is reflected and may dominate the image of a printed picture, making it disappear in the stripy environment[6].

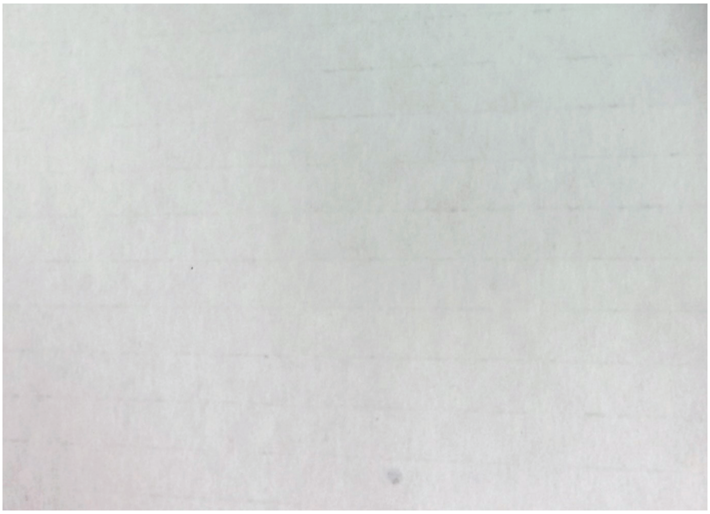

Figure 2. *Washboarding on unprinted board.*

1.3 The use of white ink

Today, the UV inkjet printer equipped with the special white ink allows users to achieve high density and concealment. High-density white allows for greater opacity on clear or dark substrates. Printing the area using white ink and the area using CMYK color inks simultaneously eliminates displacement during media feed, making stable, highly intricate printing possible. The white ink is suited to print on transparent media, and can be used it to create items for shop interiors and displays, PET bottles and other packagers, decals, and more[8].

2. Methodology

This study utilizes a randomized 2^3 factorial design in which every factor was run at two specified levels (fixed effects) determined based upon the practical operating conditions using a Roland VersaUV LEJ-640 UV LED printer. The three factors were corrugated board (X_1), speed (X_2), and white ink (X_3). This resulted in a total of eight different treatment combinations (Table 1). The run order for the eight treatment combinations was randomly determined by computer to reduce bias introduced by unplanned changes in the experiment. Five observations were systematically recorded for each of the right treatment combinations for a total sample size of 40.

	Speed: Standard		Speed: Artistic	
	Corrugated Board A	Corrugated Board B	Corrugated Board A	Corrugated Board B
White Ink: On				
White Ink: Off				

Factors	Factor Level	
	-1	1
Corrugated Board (X_1):	A	B
Speed (X_2):	Standard	Artistic
White Ink (X_3):	Off	On

Table 1. *2^3 Factorial design*

A digital four-color test chart was designed for this study. A CMYK test chart designed for X-Rite i1iO Spectrophotometer was created by the i1Profiler software. The test chart was printed with the UV LED printer. When the white ink setting is on, inks are overprinted in the sequence of white and then CMYK.

Optical densities were measured using an X-rite Exact Spectro-densitometer. Color measurements were made using an X-rite i1iO Spectrophotometer using illuminant D50 and a 2-degree observer for printed corrugated board. The measurement files were used to generate profiles using i1 Profiler 1.8.2. The color quality of corrugated board was evaluated in terms of optical density and color gamut. The color gamut was determined by using CHROMiX ColorThink Pro 3.0.4 software. The software packages employed to analyze the data was Minitab 18.0. The 2^3 factorial analyses were performed. Table 2 displayed the treatment combinations, their run orders, and mean values of optical densities and gamut volume.

No	Factor			Treatment Combination	Run order	Mean Density of Y	Mean Density of M	Mean Density of C	Mean Density of K	Mean Gamut Volume
	X_1	X_2	X_3							
1	-1	-1	-1	(1)	5	0.86	1.29	1.01	1.55	194,579
2	-1	-1	1	a	6	0.96	1.31	1.09	1.56	223,036
3	-1	1	-1	b	4	0.86	1.30	0.98	1.46	197,021
4	-1	1	1	ab	1	0.91	1.26	1.11	1.45	207,914
5	1	1	1	c	3	0.91	1.31	1.09	1.46	196,614
6	1	-1	1	ac	8	0.95	1.31	1.10	1.58	240,110
7	1	-1	-1	bc	2	0.86	1.30	1.01	1.54	208,867
8	1	1	-1	abc	7	0.85	1.29	0.98	1.45	191,567

Factor	Factor Level	
	-1	1
X_1: Corrugated Board X_2: Speed X_3: White Ink	A Standard Off	B Artistic On

Table 2. *The mean optical density and gamut volume for the eight runs*

3. Results and Discussion

3.1. The influence of white ink

Two commercially available white corrugated board A and B were used in the study. The L*a*b* value of based white corrugated board is 87.08, -0.02, 2.50. After lying down a layer of white ink as a base, the L*a*b* value of white corrugated board is 88.73, 0.23, 1.21. In other words, white ink shifts the based white corrugated board toward more neutral color. Figure 3 shows that the white corrugated board with white ink (wireframe) did expand the overall color gamut.

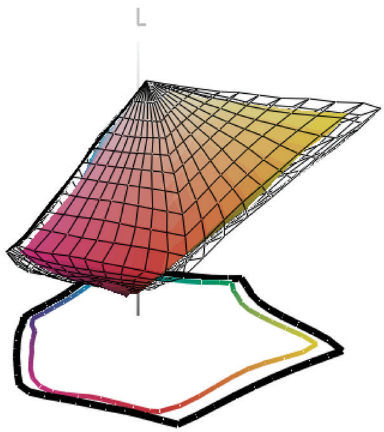

Figure 3. *Color gamut comparison of tested white corrugated board: without white ink (true color) vs. with white ink (wireframe).*

3.2. Descriptive Statistics

Figures 4-8 displays the boxplot of the optical density and color gamut. Based on the visual assessment, the tested white corrugated board does not have a very uniform coating. High variation on the color reproduction is to be expected.

For the optical density yellow, the treatment combination of (-1, -1, 1) yield the highest density of yellow (0.96), followed by the treatment combination of (1, -1, 1) (0.95). The greatest standard deviation value was found in the treatment combination of (-1, -1, 1). For the optical density magenta, treatment combinations (-1, -1, 1), (1, 1, 1), and (1, -1, 1) produce highest density of magenta (1.31). Overall, white corrugated board A has higher standard deviation values. For the optical density cyan, the treatment combination of (-1, 1, 1) yield the highest density of cyan (1.11), followed by the treatment combination of (1, -1, 1) (1.10). The greatest standard deviation value was found in the treatment combination of (-1, -1, 1). For the optical density black, the treatment combination of (1, -1, 1) yielded the highest density of black (1.58). The greatest standard deviation value was found in the treatment combination of (-1, 1, 1). For the color gamut, the treatment combination of (1, -1, 1) produced the highest gamut volume (240,119) with smallest standard deviation value.

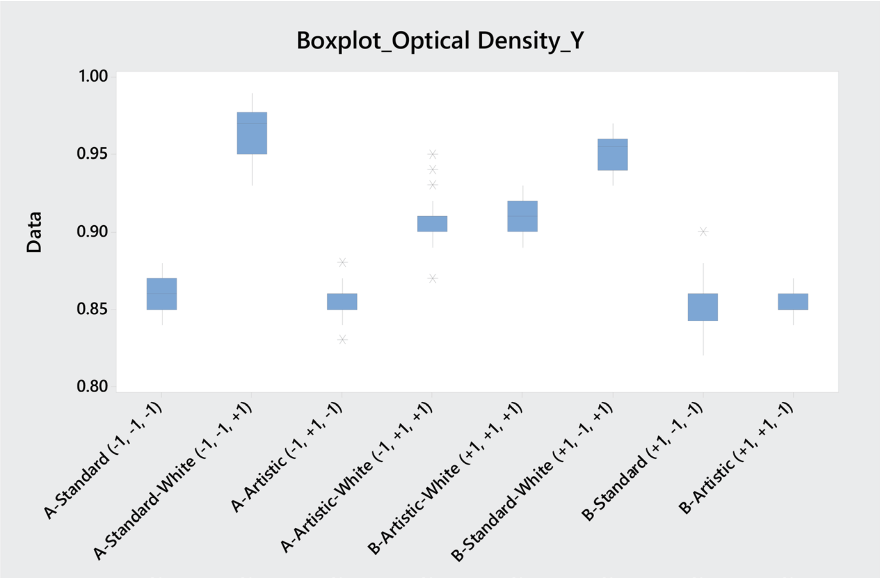

Figure 4. *Boxplot for the optical density of yellow.*

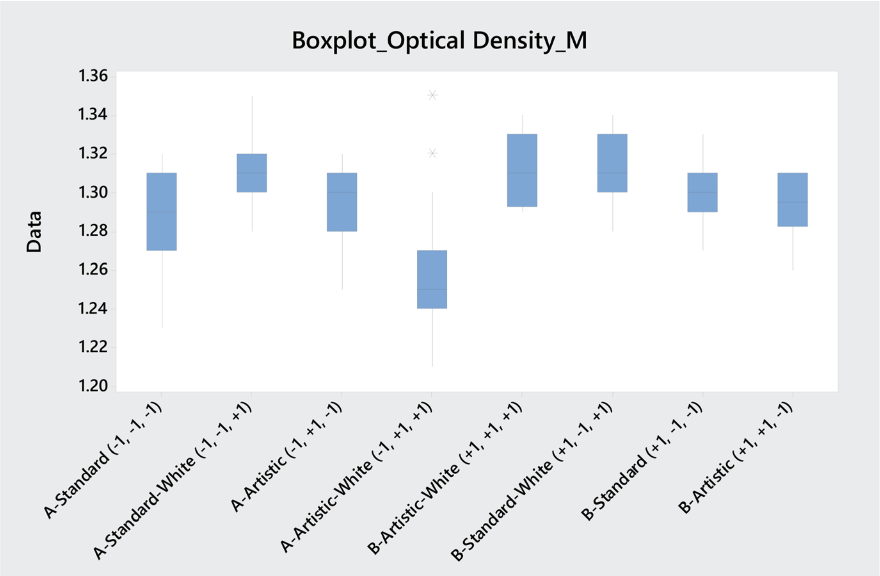

Figure 5. *Boxplot for the optical density of magenta.*

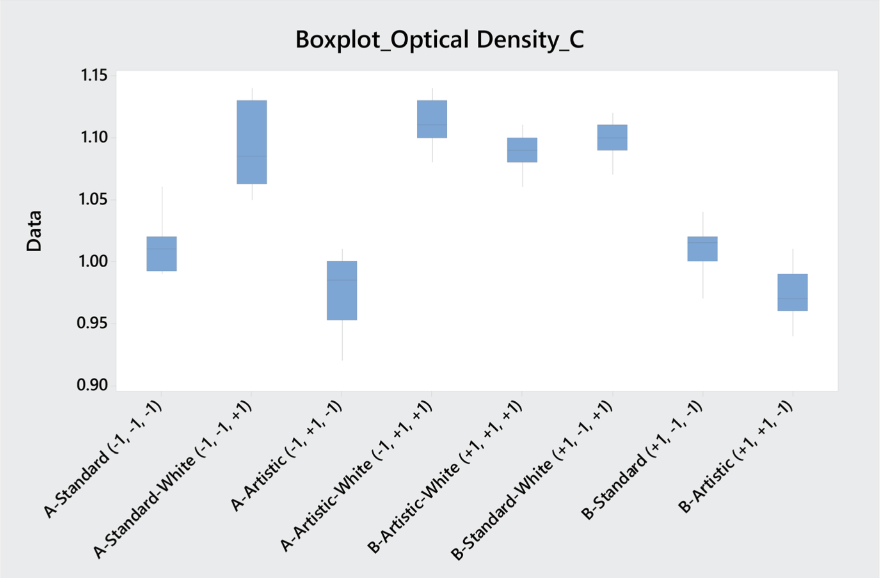

Figure 6. *Boxplot for the optical density of cyan.*

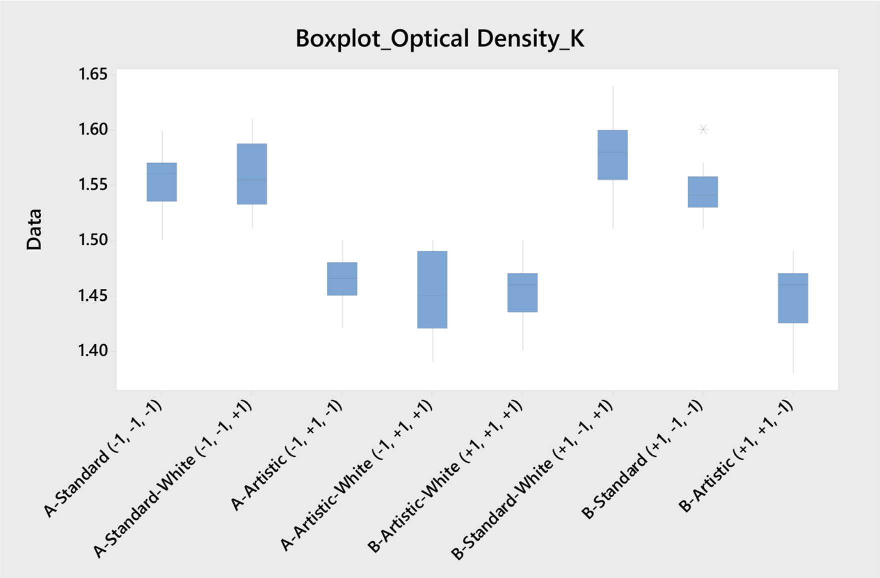

Figure 7. *Boxplot for the optical density of black.*

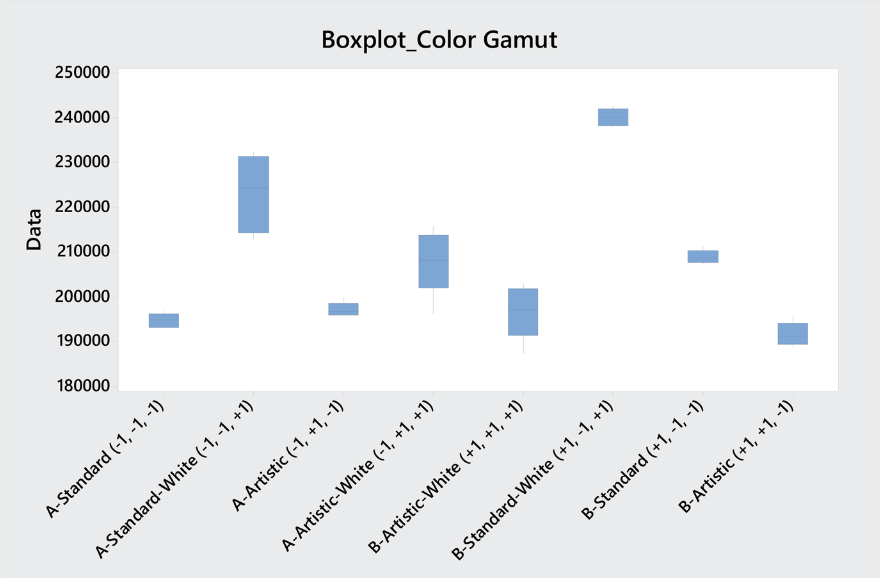

Figure 8. *Boxplot for the color gamut.*

3.3. The ANOVA and Regression analyses

This section discusses the results of the ANOVA and Regression analyses for the main effects of the independent variables and their interaction effects on the dependent variables. The significant level was set to be .05 for all the analyses, i.e., $\alpha = .05$. The full model derived from 23 the factorial design is:

$$\hat{Y} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_1 X_2 + \beta_5 X_1 X_3 + \beta_6 X_2 X_3 + \beta_7 X_1 X_2 X_3 + \varepsilon,$$

where X_1 = corrugated board; X_2 = speed; X_3 = white ink.

The findings and discussion for the optical density of yellow

Table 3 shows that the p-values of 0.000 for the speed (X_2), white ink (X_3) and the interaction between speed and white ink (X_2X_3) are less than 0.05. In other words, speed (X_2), white ink (X_3) and the interaction between speed and white ink (X_2X_3) have a significant effect on the optical density of yellow. Figure 9 show that the white ink (X_3) has the greatest effect on the optical density of yellow, followed by speed (X_2) and the interaction between speed and white ink (X_2X_3).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	0.072328	0.010333	160.32	0.000
Linear	3	0.066989	0.022330	346.47	0.000
Corrugated Board	1	0.000141	0.000141	2.18	0.149
Speed	1	0.006786	0.006786	105.29	0.000
White Ink	1	0.060063	0.060063	931.92	0.000
2-Way Interactions	3	0.005223	0.001741	27.01	0.000
Corrugated Board*Speed	1	0.000090	0.000090	1.40	0.246
Corrugated Board*White Ink	1	0.000003	0.000003	0.05	0.830
Speed*White Ink	1	0.005130	0.005130	79.60	0.000
3-Way Interactions	1	0.000116	0.000116	1.79	0.190
Corrugated Board*Speed*White Ink	1	0.000116	0.000116	1.79	0.190
Error	32	0.002062	0.000064		
Total	39	0.074390			

Table 3. *Analysis of variance for the optical density of yellow (full model)*

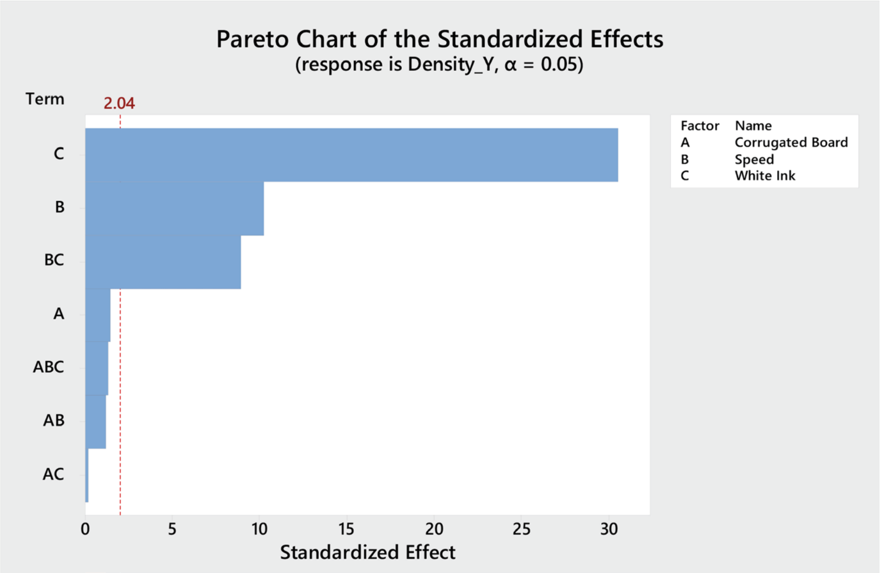

Figure 9. *Pareto chart for the optical density of yellow.*

Based on Figure 9 and Table 3, it was suggested that the terms of X_2, X_3, and X_2X_3 should be included in the reduced model. Therefore, a Fit Factorial procedure and a regression analysis that included only the terms of X_2, X_3, and X_2X_3 were performed and obtain the prediction information for the optical density of yellow. Table 4 displays the ANOVA information. It confirmed that that the p-values for the speed (X_2) and white ink (X_3) are less than 0.05. However, The p-value of 0.905 for the interaction between speed and white ink (X_2X_3) is greater than 0.05. Table 5 displayed the ANOVA information after the term of X_2X_3 has been removed from the reduced model. The estimated effects and coefficients are exhibited in Table 6. Table 6 confirmed that the speed (X_2) and white ink (X_3) have a significant effect on the optical density of yellow. The regression equation used to predict the optical density for yellow is

$$\textit{Optical density of yellow} = 0.89480 + 0.03875\, X_3 - 0.01302\, X_2 \qquad \textit{(Equation 1)}$$

The R^2 value (89.3%) in Table 6 implies that the reduced model explains approximately 89.31% of the total variability in the optical density for the yellow.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.066852	0.022284	106.41	0.000
White Ink	1	0.060062	0.060062	286.81	0.000
Speed	1	0.006786	0.006786	32.41	0.000
Speed*White Ink	1	0.000003	0.000003	0.01	0.905
Error	36	0.007539	0.000209		
Lack-of-Fit	4	0.005476	0.001369	21.24	0.000
Pure Error	32	0.002062	0.000064		
Total	39	0.074390			

Table 4. *Analysis of variance for the optical density of yellow (reduced model)*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	0.066849	0.033424	163.98	0.000
White Ink	1	0.060062	0.060062	294.66	0.000
Speed	1	0.006786	0.006786	33.29	0.000
Error	37	0.007542	0.000204		
Lack-of-Fit	1	0.005130	0.005130	76.58	0.000
Pure Error	36	0.002412	0.000067		
Total	39	0.074390			

Table 5. *Analysis of variance for the optical density of yellow (reduced model)*

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.89480	0.00226	396.38	0.000	
White Ink	0.03875	0.00226	17.17	0.000	1.00
Speed	-0.01302	0.00226	-5.77	0.000	1.00

Prediction Equation:

Optical density of yellow = $0.89480 + 0.03875\,X_3 - 0.01302\,X_2$

R-sq. = 89.86%, R-sq. (adj.) = 89.31%

Table 6. *Estimated effects and coefficients for the optical density of yellow (reduced model)*

The findings and discussion for the optical density of magenta

Table 7 shows that the p-values for the corrugated board (X_1), speed (X_2), the set of two-way interactions (X_1X_2, X_1X_3, and X_2X_3) and the set of three-way interaction ($X_1X_2X_3$) are less than 0.05. In other words, the corrugated board (X_1), speed (X_2), the interaction between corrugated board and speed (X_1X_2), the interaction between corrugated board and white ink (X_1X_3), the interaction between speed and white ink (X_2X_3), and the interaction among corrugated board, speed and white ink ($X_1X_2X_3$) have a significant effect on the optical density of magenta. Figure 10 also shows that the corrugated board (X_1) has the greatest effect on the optical density of magenta, followed by the interaction among corrugated board, speed and white ink ($X_1X_2X_3$) and the interaction between speed and white ink (X_2X_3).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	0.012185	0.001741	10.88	0.000
Linear	3	0.004553	0.001518	9.49	0.000
Corrugated Board	1	0.002814	0.002814	17.59	0.000
Speed	1	0.001556	0.001556	9.73	0.004
White Ink	1	0.000183	0.000183	1.14	0.293
2-Way Interactions	3	0.004868	0.001623	10.14	0.000
Corrugated Board*Speed	1	0.001076	0.001076	6.73	0.014
Corrugated Board*White Ink	1	0.001594	0.001594	9.96	0.003
Speed*White Ink	1	0.002198	0.002198	13.74	0.001
3-Way Interactions	1	0.002764	0.002764	17.28	0.000
Corrugated Board*Speed*White Ink	1	0.002764	0.002764	17.28	0.000
Error	32	0.005119	0.000160		
Total	39	0.017304			

Table 7. *Analysis of variance for the optical density of magenta (full model)*

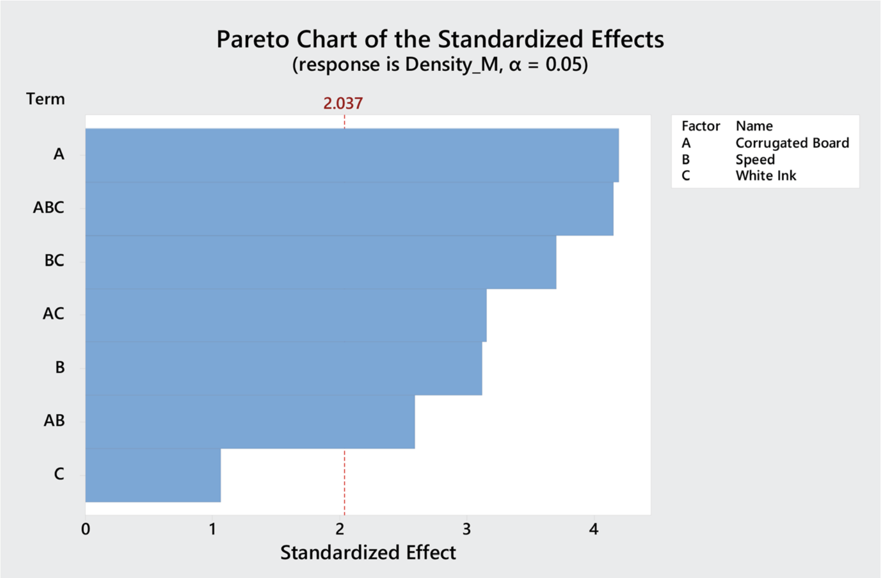

Figure 10. *Pareto chart for the optical density of magenta.*

Based on Figure 10 and Table 7, it was suggested that the terms of X_1, X_2, X_1X_2, X_1X_3, X_2X_3, and $X_1X_2X_3$ should be included in the reduced model. Therefore, a Fit Factorial procedure and a regression analysis that included only the terms of X1, X2, X_1X_2, X_1X_3, X_2X_3, and $X_1X_2X_3$ were performed and obtain the prediction information for the optical density of magenta. Table 8 displays the ANOVA information, and the estimated effects and coefficients are exhibited in Table 9. Again, Table 8 confirmed that X_1, X_2, and interactions of X_1X_2, X_1X_3, X_2X_3, and $X_1X_2X_3$ have a significant effect on the optical density of magenta. The regression equation used to predict the optical density for magenta is

$$\textit{Optical density of magenta} = 1.29571 + 0.00839 X_1 + 0.00831 X_1X_2X_3 + 0.00631 X_2X_3 - 0.00741 X_1X_3 - 0.00624 X_2 + 0.00519 X_1X_2$$

(Equation 2)

The R^2 value (63.79%) in Table 9 implies that the reduced model explains approximately 63.79% of the total variability in the optical density for the magenta.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	6	0.012002	0.002000	12.45	0.000
Corrugated Board	1	0.002814	0.002814	17.51	0.000
Corrugated Board*Speed*White Ink	1	0.002764	0.002764	17.20	0.000
Speed*White Ink	1	0.001594	0.001594	9.92	0.003
Corrugated Board*White Ink	1	0.002198	0.002198	13.68	0.001
Speed	1	0.001556	0.001556	9.69	0.004
Corrugated Board*Speed	1	0.001076	0.001076	6.70	0.014
Error	33	0.005302	0.000161		
Lack-of-Fit	1	0.000183	0.000183	1.14	0.293
Pure Error	32	0.005119	0.000160		
Total	39	0.017304			

Table 8. *Analysis of variance for the optical density of magenta (reduced model)*

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.29571	0.00200	646.50	0.000	
Corrugated Board	0.00839	0.00200	4.18	0.000	1.00
Corrugated Board*Speed*White Ink	0.00831	0.00200	4.15	0.000	1.00
Speed*White Ink	0.00631	0.00200	3.15	0.003	1.00
Corrugated Board*White Ink	-0.00741	0.00200	-3.70	0.001	1.00
Speed	-0.00624	0.00200	-3.11	0.004	1.00
Corrugated Board*Speed	0.00519	0.00200	2.59	0.014	1.00
Prediction Equation: Optical density of magenta = $1.29571 + 0.00839 X_1 + 0.00831 X_1X_2X_3 + 0.00631 X_2X_3 - 0.00741 X_1X_3 - 0.00624 X_2 + 0.00519 X_1X_2$					
R-sq. = 69.36%, R-sq. (adj.) = 63.79%					

Table 9. *Estimated effects and coefficients for the optical density of magenta (reduced model)*

The findings and discussion for the optical density of cyan

Table 10 shows that the p-values for the speed (X_2), white ink (X_3), the interaction between corrugated board and speed (X_1X_2), and the interaction between speed and white ink (X_2X_3) are less than 0.05. In other words, the speed (X_2), white ink (X_3), the interaction between corrugated board and speed (X_1X_2), and the interaction between speed and white ink (X_2X_3) have a significant effect on the optical density of cyan. Figure 11 shows that white ink (X_3) has the greatest effect on the optical density of cyan, followed by the interaction between speed and white ink (X_2X_3) and the speed (X_2).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	0.116372	0.016625	108.52	0.000
Linear	3	0.110923	0.036974	241.36	0.000
Corrugated Board	1	0.000214	0.000214	1.40	0.246
Speed	1	0.002081	0.002081	13.58	0.001
White Ink	1	0.108629	0.108629	709.09	0.000
2-Way Interactions	3	0.004844	0.001615	10.54	0.000
Corrugated Board*Speed	1	0.000727	0.000727	4.74	0.037
Corrugated Board*White Ink	1	0.000107	0.000107	0.70	0.409
Speed*White Ink	1	0.004010	0.004010	26.18	0.000
3-Way Interactions	1	0.000605	0.000605	3.95	0.056
Corrugated Board*Speed*White Ink	1	0.000605	0.000605	3.95	0.056
Error	32	0.004902	0.000153		
Total	39	0.121274			

Table 10. *Analysis of variance for the optical density of cyan (full model)*

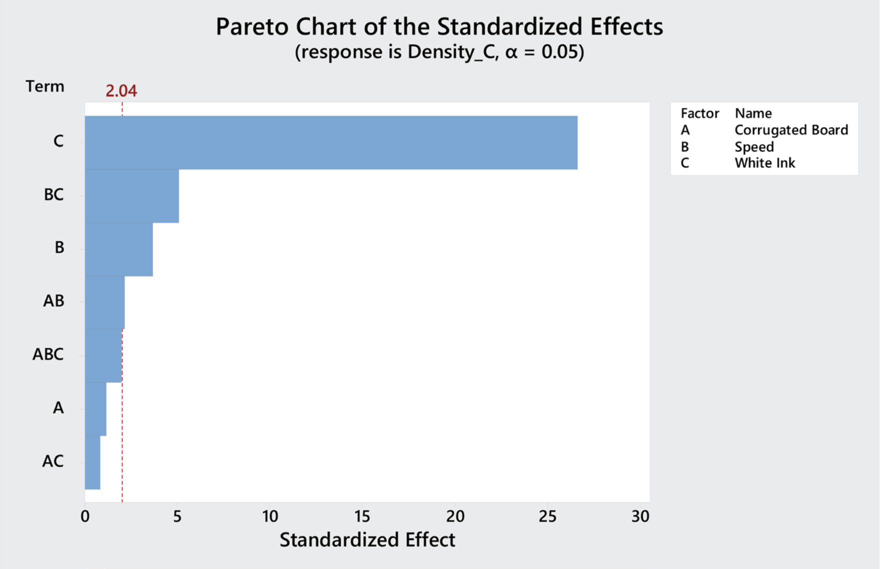

Figure 11. *Pareto chart for the optical density of cyan.*

Based on Table 10 and Figure 11, it was suggested that the terms of X_2, X_3, X_1X_2, and X_2X_3 should be included in the reduced model. Therefore, a Fit Factorial procedure and a regression analysis that included only the terms of X_2, X_3, X_1X_2, and X_2X_3 were performed and obtain the prediction information for the optical density of cyan. Table 11 displays the ANOVA information. It shows that the p-values for the interaction between corrugated board and speed (X_1X_2), and the interaction between speed and white ink (X_2X_3) are greater than 0.05. Table 12 displayed the ANOVA information after the terms of X_1X_2 and X_2X_3 have been removed from the reduced model. The estimated effects and coefficients are exhibited in Table 13. Again, Table 13 confirmed that speed (X_2) and white ink (X_3) have a significant effect on the optical density of cyan. The regression equation used to predict the optical density for cyan is

Optical density of cyan = 1.04559 + 0.05211 X_3 *- 0.00721* X_2

(Equation 3)

The R^2 value (90.82%) in Table 13 implies that the reduced model explains approximately 90.82% of the total variability in the optical density for the cyan.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	4	0.111543	0.027886	100.30	0.000
White Ink	1	0.108629	0.108629	390.73	0.000
Speed*White Ink	1	0.000107	0.000107	0.39	0.539
Speed	1	0.002081	0.002081	7.48	0.010
Corrugated Board*Speed	1	0.000727	0.000727	2.61	0.115
Error	35	0.009731	0.000278		
Lack-of-Fit	3	0.004828	0.001609	10.51	0.000
Pure Error	32	0.004902	0.000153		
Total	39	0.121274			

Table 11. *Analysis of variance for the optical density of cyan (reduced model)*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	2	0.110709	0.055355	193.87	0.000
White Ink	1	0.108629	0.108629	380.44	0.000
Speed	1	0.002081	0.002081	7.29	0.010
Error	37	0.010565	0.000286		
Lack-of-Fit	1	0.004010	0.004010	22.02	0.000
Pure Error	36	0.006555	0.000182		
Total	39	0.121274			

Table 12. *Analysis of variance for the optical density of cyan (reduced model)*

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.04559	0.00267	391.35	0.000	
White Ink	0.05211	0.00267	19.50	0.000	1.00
Speed	-0.00721	0.00267	-2.70	0.010	1.00
Prediction Equation:					
Optical density of cyan = 1.04559 + 0.05211 X_3 - 0.00721 X_2					
R-sq. = 91.29%, R-sq. (adj.) = 90.82%					

Table 13. *Estimated effects and coefficients for the optical density of cyan (reduced model)*

The findings and discussion for the optical density of black

Table 14 shows that the p-values for the speed (X_2), the interaction between corrugated board and white ink (X_1X_3), and the interaction between speed and white ink (X_2X_3) are less than 0.05. In other words, the speed (X_2), the interaction between corrugated board and white ink (X_1X_3), and the interaction between speed and white ink (X_2X_3) have a significant effect on the optical density of black. The Figure 12 shows that speed (X_2) has the greatest effect on the optical density of black.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	0.110976	0.015854	50.54	0.000
Linear	3	0.107315	0.035772	114.04	0.000
Corrugated Board	1	0.000003	0.000003	0.01	0.929
Speed	1	0.106502	0.106502	339.53	0.000
White Ink	1	0.000810	0.000810	2.58	0.118
2-Way Interactions	3	0.003604	0.001201	3.83	0.019
Corrugated Board*Speed	1	0.000109	0.000109	0.35	0.560
Corrugated Board*White Ink	1	0.002103	0.002103	6.70	0.014
Speed*White Ink	1	0.001392	0.001392	4.44	0.043
3-Way Interactions	1	0.000058	0.000058	0.18	0.671
Corrugated Board*Speed*White Ink	1	0.000058	0.000058	0.18	0.671
Error	32	0.010038	0.000314		
Total	39	0.121014			

Table 14. *Analysis of variance for the optical density of black (full model)*

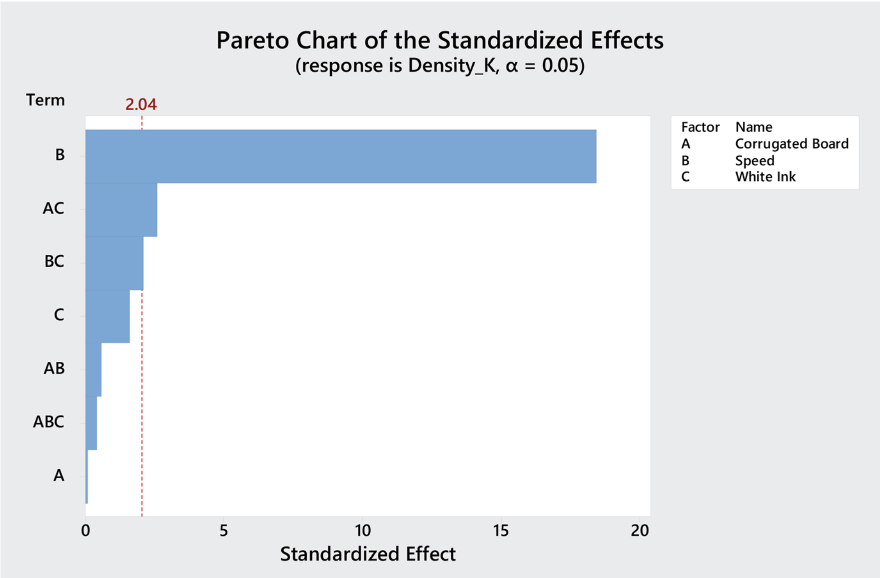

Figure 12. *Pareto chart for the optical density of black.*

Based on Figure 12 and Table 14, it was suggested that the terms of X_2, X_1X_3, and X_2X_3 should be included in the reduced model. Therefore, a Fit Factorial procedure and a regression analysis that included only the terms of X_2, X_1X_3, and X_2X_3 were performed and obtain the prediction information for the optical density of black. Table 15 displays the ANOVA information, and the estimated effects and coefficients are exhibited in Table 16. Again, Table 15 confirmed that the speed (X_2), the interaction between corrugated board and white ink (X_1X_3), and the interaction between speed and white ink (X_2X_3) have a significant effect on the optical density of black. The regression equation used to predict the optical density for black is

$$Optical\ density\ of\ black = 1.50655 - 0.05160 X_2 - 0.00590 X_1X_3 + 0.00725 X_2X_3$$

(Equation 4)

The R^2 value (90.14%) in Table 16 implies that the reduced model explains approximately 90.14% of the total variability in the optical density for the black.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.109997	0.036666	119.82	0.000
Speed	1	0.106502	0.106502	348.03	0.000
Corrugated Board*White Ink	1	0.001392	0.001392	4.55	0.040
Speed*White Ink	1	0.002103	0.002103	6.87	0.013
Error	36	0.011017	0.000306		
Lack-of-Fit	4	0.000979	0.000245	0.78	0.546
Pure Error	32	0.010038	0.000314		
Total	39	0.121014			

Table 15. *Analysis of variance for the optical density of black (reduced model)*

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.50655	0.00277	544.68	0.000	
Speed	-0.05160	0.00277	-18.66	0.000	1.00
Corrugated Board*White Ink	-0.00590	0.00277	-2.13	0.040	1.00
Speed*White Ink	0.00725	0.00277	2.62	0.013	1.00
Prediction Equation: Optical density of black = $1.50655 - 0.05160 X_2 - 0.00590 X_1X_3 + 0.00725 X_2X_3$					
R-sq. = 90.90%, R-sq. (adj.) = 90.14%					

Table 16. *Estimated effects and coefficients for the optical density of black (reduced model)*

The findings and discussion for the color gamut

Table 17 shows that the p-values for the main factors (X_1, X_2, and X_3), the interaction between corrugated board and speed (X_1X_2), and the interaction between speed and white ink (X_2X_3) are less than 0.05. In other words, the corrugated board (X_1), speed (X_2), white ink (X_3), the interaction between corrugated board and speed (X_1X_2), and the interaction between speed and white ink (X_2X_3) have a significant effect on the color gamut. The Figure 13 shows that the white ink (X_3) has the greatest effect on the color gamut, followed by the speed (X_2) and the interaction between corrugated board and speed (X_1X_2).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	9782700517	1397528645	60.65	0.000
Linear	3	7085445914	2361815305	102.51	0.000
Corrugated Board	1	133535431	133535431	5.80	0.022
Speed	1	3375065008	3375065008	146.48	0.000
White Ink	1	3576845475	3576845475	155.24	0.000
2-Way Interactions	3	2650596443	883532148	38.35	0.000
Corrugated Board*Speed	1	1447509766	1447509766	62.82	0.000
Corrugated Board*White Ink	1	5823979	5823979	0.25	0.619
Speed*White Ink	1	1197262698	1197262698	51.96	0.000
3-Way Interactions	1	46658160	46658160	2.03	0.164
Corrugated Board*Speed*White Ink	1	46658160	46658160	2.03	0.164
Error	32	737300136	23040629		
Total	39	10520000653			

Table 17. *Analysis of variance for the color gamut (full model)*

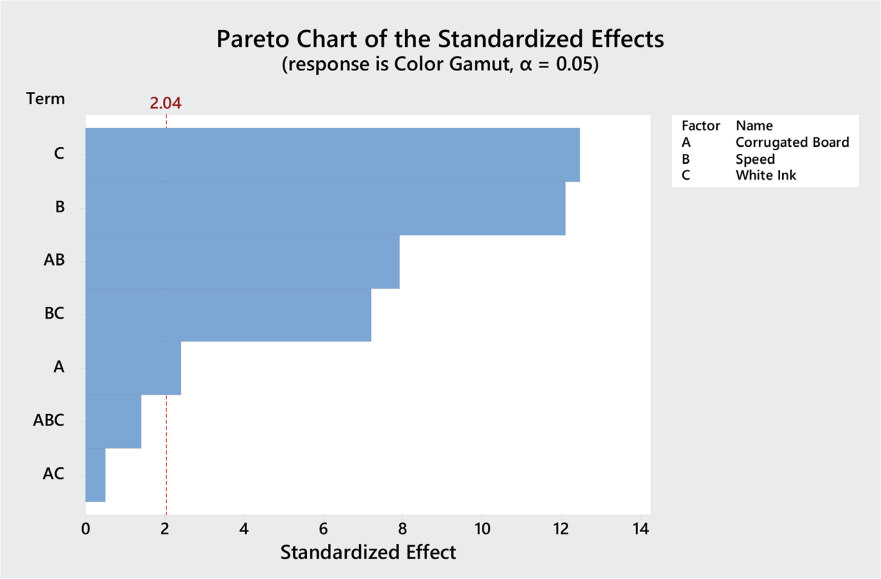

Figure 13. *Pareto chart for the color gamut.*

Based on Figure 13 and Table 17, it was suggested that the terms of X_1, X_2, X_3, X_1X_2 and X_2X_3 should be included in the reduced model. Therefore, a Fit Factorial procedure and a regression analysis that included only the terms of X_1, X_2, X_3, X_1X_2 and X_2X_3 were performed and obtain the prediction information for the color gamut. Table 18 displays that the p-values for the corrugated board (X_1) and interaction between speed and white ink (X_2X_3) are greater than 0.05. Table 19 displayed the ANOVA information after the terms of X_1 and X_2X_3 have been removed from the reduced model. The estimated effects and coefficients are exhibited in Table 20. Table 20 confirmed that the speed (X_2), white ink (X_3), and the interaction between corrugated board and speed (X_1X_2) have a significant effect on the color gamut. The regression equation used to predict the color gamut is

$$Color\ Gamut = 207465 + 9456\ X_3 - 6016\ X_1X_2 - 9186\ X_2$$

(Equation 5)

The R^2 value (78.16%) in Table 20 implies that the reduced model explains approximately 78.16% of the total variability in the color gamut.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	5	8538779659	1707755932	29.31	0.000
White Ink	1	3576845475	3576845475	61.38	0.000
Corrugated Board*Speed	1	1447509766	1447509766	24.84	0.000
Speed	1	3375065008	3375065008	57.92	0.000
Speed*White Ink	1	5823979	5823979	0.10	0.754
Corrugated Board	1	133535431	133535431	2.29	0.139
Error	34	1981220994	58271206		
Lack-of-Fit	2	1243920858	621960429	26.99	0.000
Pure Error	32	737300136	23040629		
Total	39	10520000653			

Table 18. *Analysis of variance for the color gamut (reduced model)*

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	8399420249	2799806750	47.53	0.000
White Ink	1	3576845475	3576845475	60.72	0.000
Corrugated Board*Speed	1	1447509766	1447509766	24.57	0.000
Speed	1	3375065008	3375065008	57.30	0.000
Error	36	2120580404	58905011		
Lack-of-Fit	4	1383280268	345820067	15.01	0.000
Pure Error	32	737300136	23040629		
Total	39	10520000653			

Table 19. *Analysis of variance for the color gamut (reduced model)*

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	207465	1214	170.96	0.000	
White Ink	9456	1214	7.79	0.000	1.00
Corrugated Board*Speed	-6016	1214	-4.96	0.000	1.00
Speed	-9186	1214	-7.57	0.000	1.00
Prediction Equation:					
Color Gamut = 207465 + 9456 X_3 - 6016 X_1X_2 - 9186 X_2					
R-sq. = 79.84%, R-sq. (adj.) = 78.16%					

Table 20. *Estimated effects and coefficients for the color gamut (reduced model)*

4. Conclusions

This study conducted a randomized 2^3 factorial design to identify key factors affecting color reproduction on the corrugated board using UV wide-format inkjet printer. Table 21 shows the ANOVA and Stepwise Regression summary for the main and interaction effects on the optical density and color gamut.

According to Table 21, the dominant effects on the optical density and color gamut of corrugated board were white ink (X_3) and speed (X_2), because its significance is ranked as either the top one, top two, or top three on the optical density or color gamut attributes, with exception of optical density magenta and black. Both treatment combinations (X_1, X_2, X_3) = (1, -1, 1) and (X_1, X_2, X_3) = (-1, -1, 1) are suggested to achieve the maximum yield of optical density yellow and cyan. In other words, the white corrugated board (X_1) has no significant effects on the optical density yellow and cyan. The treatment combinations (X_1, X_2, X_3) = (1, -1, 1) is also suggested to achieve the maximum yield of color gamut, that is, when using corrugated board B, printing speed was set at standard, and the white ink setting was on. However, applying a layer of white ink will spend three times as much time on printing a design. The treatment combination of (X_1, X_2, X_3) = (1, -1, -1) is suggested when the production efficiency is a major concern.

	Optical Density				**Color Gamut**
	Yellow	Magenta	Cyan	Black	
Sig. Level	$\alpha = 0.05$	$\alpha = 0.05$	$\alpha = 0.05$	$\alpha = 0.05$	$\alpha = 0.05$
Significant Effects	X_3 X_2	X_1 $X_1X_2X_3$ X_2X_3 X_1X_3 X_2 X_1X_2	X_3 X_2	X_2 X_1X_3 X_2X_3	X_3 X_1X_2 X_2
Prediction Equation ($\hat{Y}$)	0.89480 $+ 0.03875 X_3$ $- 0.01302 X_2$	1.29571 $+ 0.00839 X_1$ $+ 0.00831 X_1X_2X_3$ $+ 0.00631 X_2X_3$ $- 0.00741 X_1X_3$ $- 0.00624 X_2$ $+ 0.00519 X_1X_2$	1.04559 $+ 0.05211 X_3$ $- 0.00721 X_2$	1.50655 $- 0.05160 X_2$ $- 0.00590 X_1X_3$ $+ 0.00725 X_2X_3$	207465 $+ 9456 X_3$ $- 6016 X_1X_2$ $- 9186 X_2$
Best Treatment Combinations	X_1: B X_2: Standard X_3: On (1, -1, 1) or X_1: A X_2: Standard X_3: On (-1, -1, 1)	X_1: B X_2: Standard X_3: Off (1, -1, -1)	X_1: B X_2: Standard X_3: On (1, -1, 1) or X_1: A X_2: Standard X_3: On (-1, -1, 1)	X_1: B X_2: Standard X_3: Off (1, -1, -1)	X_1: B X_2: Standard X_3: On (1, -1, 1)
Estimated Max. Value	0.95	1.33	1.10	1.57	232,123
R^2	89.31%	63.79%	90.82%	90.14%	78.16%

Table 21. *Summary of ANOVA and regression analyses*

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