https://doi.org/10.2352/ISSN.2169-4451.2021.37.92

Color Reproduction Study on the Corrugated Packaging Using UV Wide-format Inkjet Printer

Yu Ju Wu
Appalachian State University, Boone, NC, USA

Abstract

Packaging is one of the fastest growing segments in the print industry, specifically the digital packaging arena. 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 the corrugated packaging using UV wide-format inkjet printer, a Roland VersaUV LEJ-640 UV LED printer with Eco UV-curable inks was employed in this study. Four print settings were tested on the selected B-flute corrugated boards. The main purposes of this experimental study are to (1) identify the most important factors that influence color reproduction on the corrugated packaging using UV wide-format inkjet printing, (2) exam the process capability of tested print settings, and (3) establish optimum print setting so that the maximum yield of optical density and print contrast could be obtained. It was found that the use of white ink is the most important factor and has a significant effect on the optical density. The print setting of standard mode with white ink is suggested to achieve the maximum yield of optical density and print contrast.

Introduction

Corrugated packaging 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[1, 2, 3]. Digital corrugated packaging delivers a unique service and can produce mock-ups, personalized boxes for marketing test[4].

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[5].

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[6].

Experimental

In order to study the color reproduction capability on the corrugated board using UV Wide-format Inkjet Printer, sets of test samples were prepared.

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. Four print settings were tested in this study.

Table 1: Tested print settings

Print Settings	Speed Mode	White Ink
Print Setting 1	Standard (720*1080 dpi)	Off
Print Setting 2	Standard (720*1080 dpi)	On
Print Setting 3	Artistic (1440*1440 dpi)	Off
Print Setting 4	Artistic (1440*1440 dpi)	On

A digital four-color test chart was designed for this study. The test chart was printed on the selected B-flute corrugated board with the UV printer. When the white ink setting is on, inks are overprinted in the sequence of white and then CMYK. Forty test charts were printed and collected for each of the tested print settings.

Optical densities and print contrast were measured using an X-rite Exact Spectro-densitometer (measuring condition: illuminant D50; 2-degree observer) for the printed corrugated boards. The color quality of B-flute corrugated board was evaluated in terms of optical density and print contrast. The software packages employed to analyze the data was Minitab 18.0. Descriptive Statistics, One-way (ANOVA), factorial analysis, and capability analysis were performed.

Descriptive Statistics

Figures 1-4 display the boxplots of the optical densities. Based on the visual assessment, the tested white B-flute corrugated board does not have a uniform coating. High variation on the color reproduction is expected. Tested corrugated boards printed with standard mode and white ink yield the highest optical density values. The greatest standard deviation value was found in the print setting of standard mode, with or without white ink. Overall, tested corrugated boards printed with white ink tends to yield higher density values.

Boxplots of print contrast were shown in Figures 5-8. Tested corrugated boards printed with artistic mode yield the highest print contrast for yellow and magenta, while print setting of standard mode and white yields the highest print contrast for cyan and black. Tested corrugated boards printed with standard mode and white ink tend to have greater standard deviation values, compared to other print settings.

One-way Analysis of Variance (ANOVA) statistical procedure was employed to determine whether the differences in optical density/print contrast of tested print settings were significant. The significant value of p is 0.000 < 0.05 (α) for all observed optical density and print contrast, in other words, at least one pair of the mean optical density or print contrast values is significantly different at 0.05 levels.

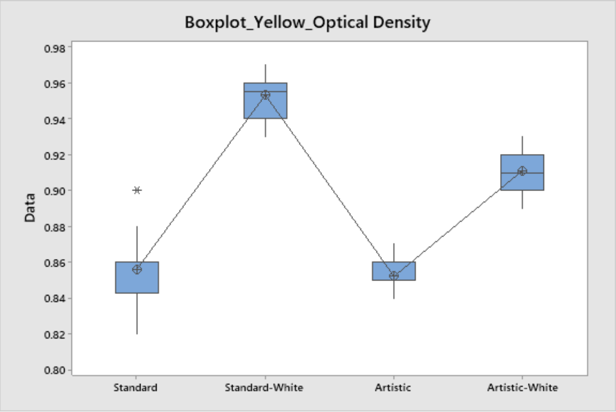

Figure 1: Boxplot for the optical density of yellow

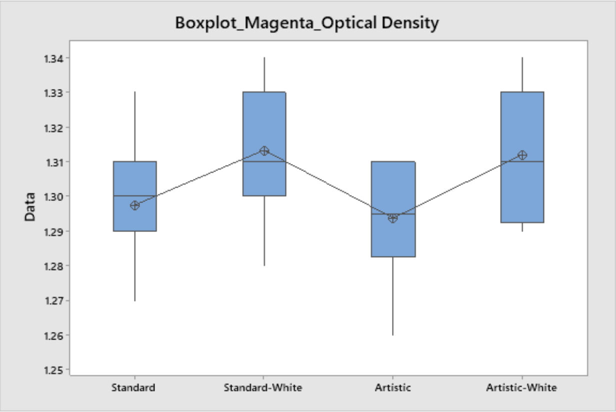

Figure 2: Boxplot for the optical density of magenta

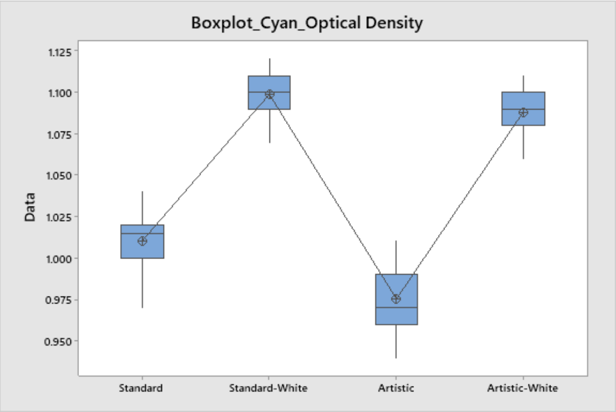

Figure 3: Boxplot for the optical density of cyan

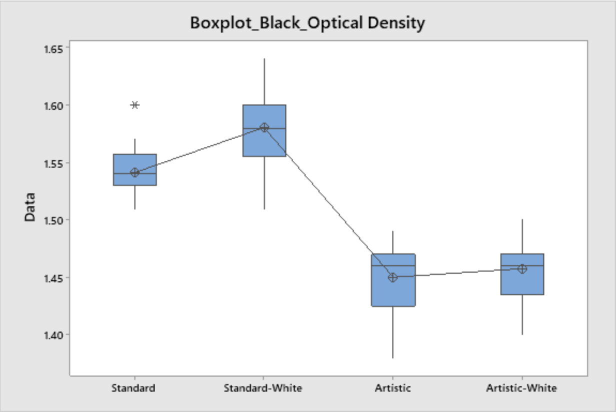

Figure 4: Boxplot for the optical density of black

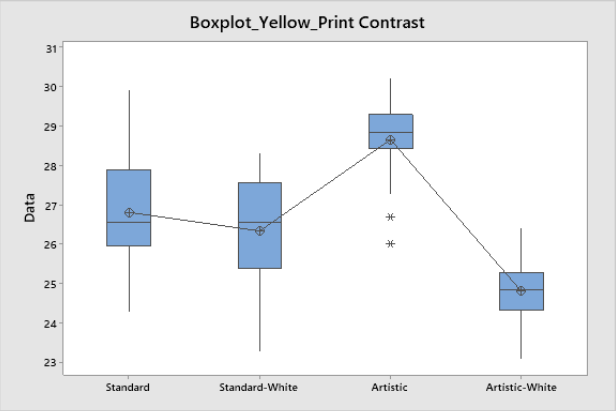

Figure 5: Boxplot for the print contrast of yellow

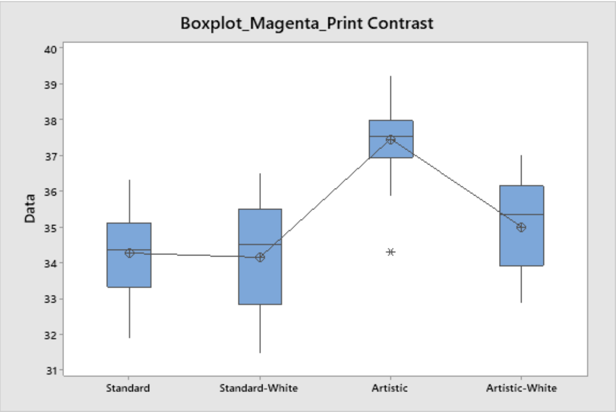

Figure 6: Boxplot for the print contrast of magenta

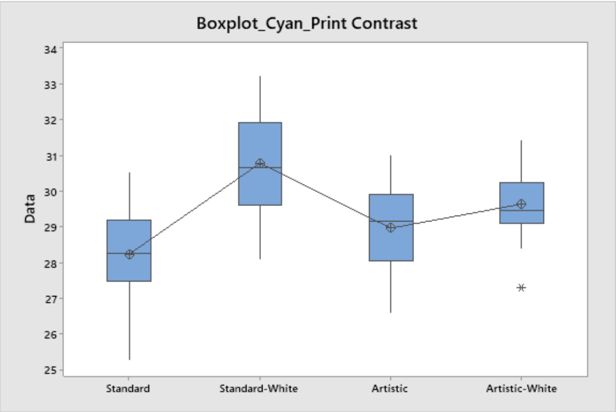

Figure 7: Boxplot for the print contrast of cyan

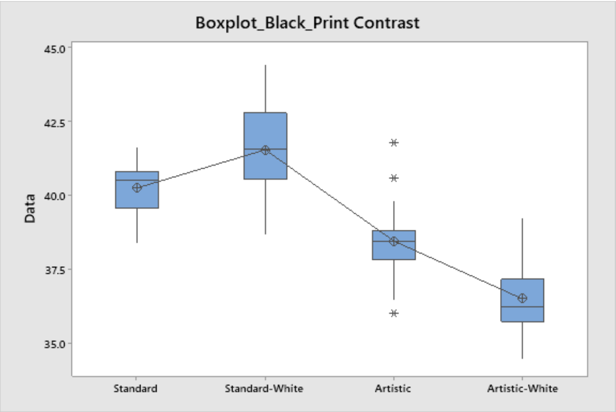

Figure 8: Boxplot for the print contrast of black

The influence of White Ink

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.

Factorial Analyses

This study utilized a randomized 2^2 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 two factors were printing speed mode (X_1), and white ink (X_2). This resulted in a total of four different treatment combinations (Table 2). Five observations were systematically recorded for each of the treatment combinations for a total sample size of 20. The dependent variable (Y) is print attributes (optical density and print contrast) of tested corrugated board.

Table 2: 2^2 Factorial Design

	Speed: Standard	Speed: Artistic
White Ink: Off		
White Ink: On		
Factors	Factor Level	
	-1	1
Speed (X_1):	Standard	Artistic
White Ink (X_2):	Off	On

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 2^2 the factorial design is:

$$\hat{Y} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_1 X_2 + \varepsilon,$$

where X_1 = printing speed; X_2 = white ink

The findings and discussion for the optical density of yellow

Table 3 shows that the p-values of 0.000 for the printing speed (X_1), white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) are less than 0.05. In other words, printing speed (X_1), white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) have a significant effect on the optical density of yellow. Figure 9 shows that the white ink (X_2) has the greatest effect on the optical density of yellow, followed by printing speed (X_1) and the interaction between speed and white ink (X_1X_2). The regression equation used to predict the optical density for yellow is:

$$\text{Optical Density of Yellow} = 0.89292 - 0.01152\, X_1 + 0.03902\, X_2 - 0.00962\, X_1X_2 \qquad (1)$$

The R^2 (adj.) value is 97.92%, which means the full model explains approximately 97.92% of the total variability in the optical density of yellow.

Table 3: Analysis of variance for the optical density of yellow

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.034968	0.011656	298.97	0.000
Linear	2	0.033116	0.016558	424.69	0.000
X_1	1	0.002657	0.002657	68.14	0.000
X_2	1	0.030459	0.030459	781.25	0.000
X_1X_2	1	0.001853	0.001853	47.52	0.000
Error	16	0.000624	0.000039		
Total	19	0.035592			

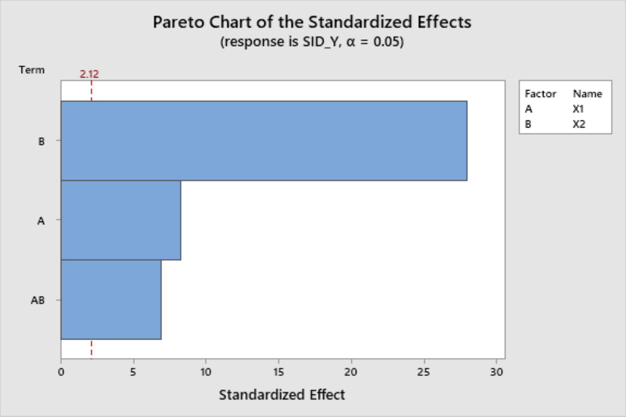

Figure 9: Pareto chart for the optical density of yellow

The findings and discussion for the optical density of magenta

Table 4 shows that the p-values of 0.000 for the printing white ink (X_2) is less than 0.05. In other words, white ink (X_2) has a significant effect on the optical density of magenta. Figure 10 shows that the white ink (X_2) has the greatest effect on the optical density of magenta. Based on Table 4 and Figure 10, it was suggested that printing speed (X_1) and the interaction between printing speed and white ink (X_1X_2) does not have a significant effect on the optical density of magenta. A Fit Factorial procedure and a regression analysis that included only the white ink (X_2) was performed and the regression equation used to predict the optical density for magenta is:

$$\text{Optical Density of Magenta} = 1.29565 + 0.01690\, X_2 \qquad (2)$$

The R^2 (adj.) value of the reduced model is 53.55%. In other words, the reduced model only explains approximately half of the total variability in the optical density of magenta.

Table 4: Analysis of variance for the optical density of magenta

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.001466	0.000489	7.21	0.003
Linear	2	0.001450	0.000725	10.70	0.001
X_1	1	0.000022	0.000022	0.33	0.576
X_2	1	0.001428	0.001428	21.08	0.000
X_1X_2	1	0.000016	0.000016	0.24	0.631
Error	16	0.001084	0.000068		
Total	19	0.002550			

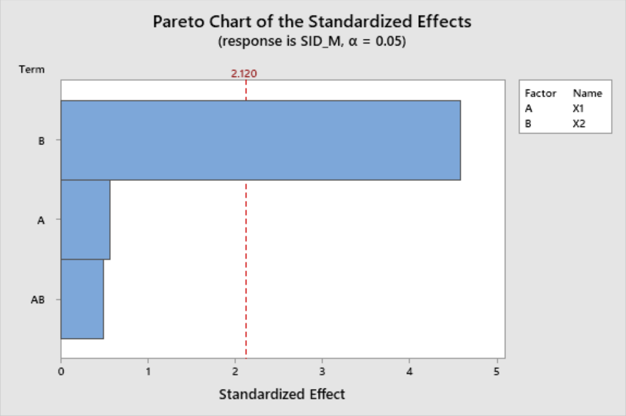

Figure 10: Pareto chart for the optical density of magenta

The findings and discussion for the optical density of cyan

Table 5 shows that the p-values of 0.000 for the printing speed (X_1), white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) are less than 0.05. In other words, printing speed (X_1), white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) have a significant effect on the optical density of cyan. Figure 11 shows that the white ink (X_2) has the greatest effect on the optical density of cyan, followed by printing speed (X_1) and the interaction between speed and white ink (X_1X_2). The regression equation used to predict the optical density for cyan is:

$$\text{Optical Density of Cyan} = 1.04327 - 0.01147\,X_1 + 0.05048\,X_2 + 0.00612\,X_1X_2 \quad (3)$$

The R^2 (adj.) value is 98.65%, which means the full model explains approximately 98.65% of the total variability in the optical density of cyan.

Table 5: Analysis of variance for the optical density of cyan

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.054338	0.018113	464.88	0.000
Linear	2	0.053588	0.026794	687.69	0.000
X_1	1	0.002634	0.002634	67.59	0.000
X_2	1	0.050955	0.050955	1307.78	0.000
X_1X_2	1	0.000750	0.000750	19.26	0.000
Error	16	0.000623	0.000039		
Total	19	0.054962			

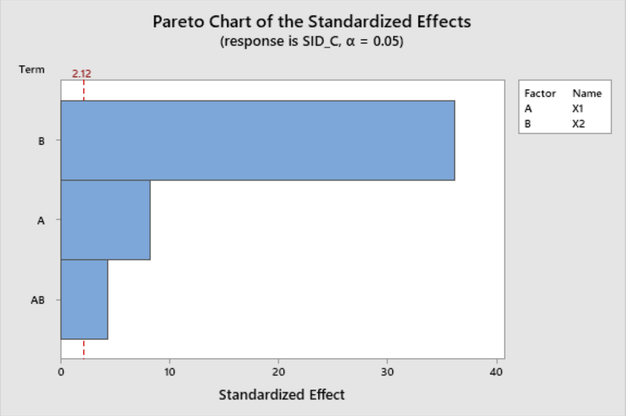

Figure 11: Pareto chart for the optical density of cyan

The findings and discussion for the optical density of black

Table 6 shows that the p-values for the printing speed (X_1) and white ink (X_2) are less than 0.05. In other words, printing speed (X_1) and white ink (X_2) have a significant effect on the optical density of black. Figure 12 shows that the printing speed (X_1) has the greatest effect on the optical density of black, followed by white ink (X_2). Based on Table 6 and Figure 12, it was suggested that the terms of X_1 and X_2 should be included in the reduced model. A Fit Factorial procedure and a regression analysis that included printing speed (X_1) and white ink (X_2) was performed and the regression equation used to predict the optical density for black is:

$$\text{Optical Density of Black} = 1.54830 - 0.10650\,X_1 + 0.02350\,X_2 \quad (4)$$

The R^2 (adj.) value of the reduced model is 91.18%. In other words, the reduced model explains approximately 91.18% of the total variability in the optical density of black.

Table 6: Analysis of variance for the optical density of black

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0.060481	0.020160	78.91	0.000
Linear	2	0.059472	0.029736	116.38	0.000
X_1	1	0.056711	0.056711	221.96	0.000
X_2	1	0.002761	0.002761	10.81	0.005
X_1X_2	1	0.001008	0.001008	3.95	0.064
Error	16	0.004088	0.000256		
Total	19	0.064569			

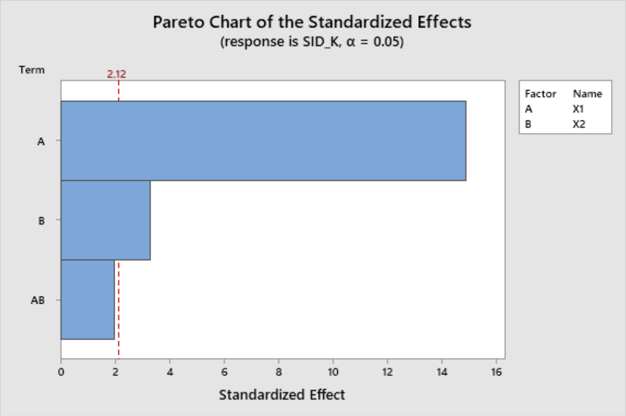

Figure 12: Pareto chart for the optical density of black

The findings and discussion for the print contrast of yellow

Table 7 shows that the p-values of 0.000 for the white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) are less than 0.05. In other words, white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) have a significant effect on the print contrast of yellow. Figure 13 shows that the white ink (X_2) has the greatest effect on the print contrast of yellow, followed by the interaction between printing speed and white ink (X_1X_2). Based on Table 7 and Figure 13, it was suggested that the terms of X_2 and X_1X_2 should be included in the reduced model. A Fit Factorial procedure and a regression analysis that included white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) was performed and the regression equation used to predict the print contrast of yellow is:

$$\text{Print Contrast of Yellow} = 28.582 - 2.190\,X_2 - 1.665\,X_1X_2 \quad (5)$$

The R^2 (adj.) value of the reduced model is 85.8%. In other words, the reduced model explains approximately 85.8% of the total variability in the print contrast of yellow.

Table 7: Analysis of variance for the print contrast of yellow

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	37.9653	12.6551	37.45	0.000
Linear	2	24.0959	12.0479	35.65	0.000
X_1	1	0.1044	0.1044	0.31	0.586
X_2	1	23.9915	23.9915	71.00	0.000
X_1X_2	1	13.8695	13.8695	41.04	0.000
Error	16	5.4065	0.3379		
Total	19	43.3718			

The findings and discussion for the print contrast of magenta

Table 8 shows that the p-values for the printing speed (X_1), white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) are less than 0.05. In other words, printing speed (X_1), white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) have a significant effect on the print contrast of magenta.

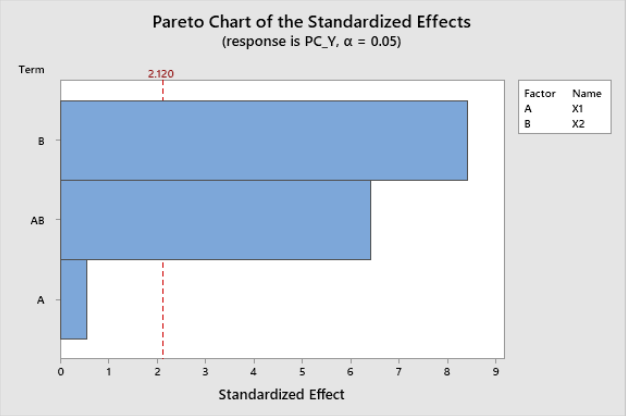

Figure 13: Pareto chart for the print contrast of yellow

Figure 14 shows that the printing speed (X_1) has the greatest effect on the print contrast of magenta, followed by white ink (X_2) and the interaction between speed and white ink (X_1X_2). The regression equation used to predict the print contrast of magenta is:

$$\text{Print Contrast of Magenta} = 35.223 + 1.032\ X_1 - 0.657\ X_2 - 0.568\ X_1X_2 \quad (6)$$

The R^2 (adj.) value is 82.66%, which means the full model explains approximately 82.66% of the total variability in the print contrast of magenta.

Table 8: Analysis of variance for the print contrast of magenta

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	36.354	12.1180	31.19	0.000
Linear	2	29.913	14.9564	38.50	0.000
X_1	1	21.280	21.2798	54.78	0.000
X_2	1	8.633	8.6330	22.22	0.000
X_1X_2	1	6.441	6.4411	16.58	0.001
Error	16	6.216	0.3885		
Total	19	42.570			

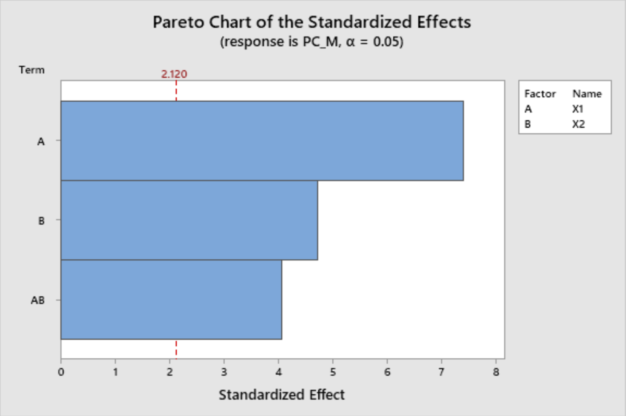

Figure 14: Pareto chart for the print contrast of magenta

The findings and discussion for the print contrast of cyan

Table 9 shows that the p-values for the white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) are less than 0.05. In other words, white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) have a significant effect on the print contrast of cyan. Figure 15 shows that the white ink (X_2) has the greatest effect on the print contrast of cyan, followed by the interaction between printing speed and white ink (X_1X_2). Based on Table 9 and Figure 15, it was suggested that the terms of X_2 and X_1X_2 should be included in the reduced model. A Fit Factorial procedure and a regression analysis that included white ink (X_2) and the interaction between printing speed and white ink (X_1X_2) was performed and the regression equation used to predict the print contrast of cyan is:

$$\text{Print Contrast of Cyan} = 29.092 + 1.571\ X_2 - 0.924\ X_1X_2 \quad (7)$$

The R^2 (adj.) value of the reduced model is 77.88%. In other words, the reduced model explains approximately 77.88% of the total variability in the print contrast of cyan.

Table 9: Analysis of variance for the print contrast of cyan

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	16.8829	5.6276	23.55	0.000
Linear	2	12.6140	6.3070	26.39	0.000
X_1	1	0.2738	0.2738	1.15	0.300
X_2	1	12.3402	12.3402	51.64	0.000
X_1X_2	1	4.2689	4.2689	17.86	0.001
Error	16	3.8237	0.2390		
Total	19	20.7065			

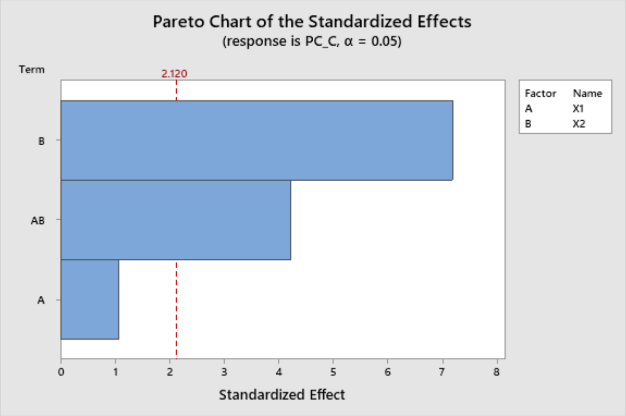

Figure 15: Pareto chart for the print contrast of cyan

The findings and discussion for the print contrast of black

Table 10 shows that the p-values of 0.000 for the printing speed (X_1) and the interaction between printing speed and white ink (X_1X_2) are less than 0.05. In other words, printing speed (X_1) and the interaction between printing speed and white ink (X_1X_2) have a significant effect on the print contrast of black. Figure 16 shows that the printing speed (X_1) has the greatest effect on the print contrast of black, followed by the interaction between printing speed and white ink (X_1X_2). Based on Table 10 and Figure 16, it was suggested that the terms of X_1 and X_1X_2 should be included in the reduced model. A Fit Factorial procedure and a regression analysis that included printing speed (X_1) and the interaction between printing speed and white ink (X_1X_2) was performed and the regression equation used to predict the print contrast of black is:

$$\text{Print Contrast of Black} = 41.670 - 3.431\ X_1 - 1.583\ X_1X_2 \quad (8)$$

The R^2 (adj.) value of the reduced model is 89.2%. In other words, the reduced model explains approximately 89.2% of the total variability in the print contrast of black.

Table 10: Analysis of variance for the print contrast of black

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	72.0833	24.0278	55.62	0.000
Linear	2	59.5618	29.7809	68.94	0.000
X_1	1	58.8417	58.8417	136.22	0.000
X_2	1	0.7201	0.7201	1.67	0.215
X_1X_2	1	12.5215	12.5215	28.99	0.000
Error	16	6.9116	0.4320		
Total	19	78.9949			

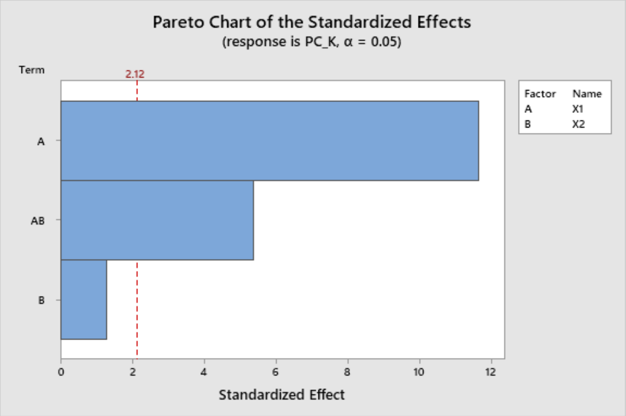

Figure 16: Pareto chart for the print contrast of black

Process Capability Analyses

The color reproduction consistency and capability of corrugated boards are discussed. Individual Control Chart (I Chart) and Capability Analyses were used to analyze the consistency. Process capability ratio (PCR or Cp index) is the simplest indicator of process capability, which is defined as the ratio of the specification range to the process range. This ratio expresses the proportion of the range of the normal curve that falls within the specification limits. The higher the Cp index, the more capable or more consistency the process is. In this study, the relative PCR were compared between different print settings due to the lack of historical parameters of lower specification limit (LSL) and upper specification limit (USL). After eliminating all out-of-control points, the final LSL and USL are obtained by subtracting from and adding to the average 3*Sigma for each print setting (the average Sigma was computed from the Sigmas of four print settings).

The capability analyses of color reproduction for the tested print settings are exhibited in Table 11. Overall, the print setting of artistic mode with white ink has higher relative PCR for optical density of cyan (Cp = 1.16), print contrast of yellow (Cp = 1.5), and print contrast of cyan (Cp = 1.27). That is, the artistic mode with white ink was the most capable print setting of producing consistent cyan optical density and print contrast for yellow and cyan in terms of relative PCR. The print settings of standard mode with or without white ink tend to have lower relative PCR. In other words, the standard mode with or without white ink were less capable print settings of producing consistent color reproduction across the print attributes, which were also reflected on their higher standard deviation values.

Table 11. Color reproduction capability analyses

Print Combination	Optical Density Yellow	 Magenta	 Cyan	 Black
Standard	0.70	1.21	0.81	0.92
Standard_White	0.89	0.85	1.07	1.02
Artistic	1.36	1.13	0.94	0.84
Artistic_White	0.99	0.90	**1.16**	0.78
Print Combination	**Print Contrast Yellow**	**Magenta**	**Cyan**	**Black**
Standard	0.83	0.89	0.97	1.39
Standard_White	0.87	0.68	0.91	0.80
Artistic	1.22	1.36	1.04	1.02
Artistic_White	**1.50**	0.82	**1.27**	1.04

Conclusions

With the graphic demands on corrugated board cases steadily rising, the corrugated board industry needs better knowledge of printing quality properties. Table 12 shows the ANOVA and Regression summary for the main and interaction effects on the optical density and print contrast. According to Table 12, the dominant effect on the optical density of tested corrugated board was white ink (X_2) as its significance is ranked as the top one on the optical density, with exception of optical density black. For the print contrast, white ink (X_2) was the dominant effect on the print contrast of yellow and cyan, while printing speed (X_1) was the dominant effect on the print contrast of magenta and black. The print setting of standard mode with white ink is suggested to achieve the maximum yield of optical density and print contrast. However, this print setting will expect higher variation on the color reproduction during the press run. The print setting of artistic mode with white ink, on the other hand, was the most capable print setting of producing consistent color reproduction results.

Table 12: Summary of ANOVA and regression analyses

	Optical Density Yellow	 Magenta	 Cyan	 Black
Sig. Level	α = 0.05	α = 0.05	α = 0.05	α = 0.05
Significant Effects	X_2 X_1 X_1X_2	X_2	X_2 X_1 X_1X_2	X_1 X_2
Best Print Setting	X_1: Standard X_2: White Ink On	X_1: Standard X_2: White Ink On Or X_1: Artistic X_2: White Ink On	X_1: Standard X_2: White Ink On	X_1: Standard X_2: White Ink On
R^2 (adj.)	97.92%	53.55%	98.65%	91.18%
	Print Contrast Yellow	**Magenta**	**Cyan**	**Black**
Sig. Level	α = 0.05	α = 0.05	α = 0.05	α = 0.05
Significant Effects	X_2 X_1X_2	X_1 X_2 X_1X_2	X_2 X_1X_2	X_1 X_1X_2
Best Print Setting	X_1: Artistic X_2: White Ink Off	X_1: Standard X_2: White Ink Off	X_1: Standard X_2: White Ink On	X_1: Standard X_2: White Ink On
R^2 (adj.)	85.80%	82.66%	77.88%	89.20%

References

[1] Elizabeth Quirk, “Package Creation – Digital Innovations for Finishing”, Digital Output, vol. XXIV, No. 4, pg. 27-31. (2018).

[2] Bob Leahey, “Digital Print for Packaging: Much Accomplished More, More to Come”, The Journal of the Specialty Graphic Imaging Association, Vol. 21, No. 6, pg. 5-10. (2017).

[3] David Savastano, “Corrugated Inkjet Market is Thriving”, Ink World Magazine, https://www.inkworldmagazine.com/contents/view_online-exclusives/2018-12-06/corrugated-inkjet-market-is-thriving (2018).

[4] Frank Jacobs, Digital Printing Applications for Packaging and Labels, “IS&Ts International Conference on Digital Production Printing and Industrial Applications”, pg. 168-169. (2003).

[5] Corrugated Curricula, ICPF International Corrugated Packaging Foundation. (2006).

[6] LEJ-640 User’s Manual, UV LED Printer VersaUV. (2011).

Author Biography

Yu-Ju Wu is an Associate Professor in the Department of Art at Appalachian State University. She received her PhD degree in Paper Engineering, Chemical Engineering and Imaging from Western Michigan University. Her research interests are digital printing and color management, printability analysis, process control, sustainability, and packaging design.