The Relationship between the Chroma Values of Neutral Gray and Important Print Attributes

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Abstract: Gray balance is the first important step undertaken by color separators, in determining the color content and contrast that the final printed piece will have. It is a significant factor in determining what the overall color gamut will be. Gray Balance is the measurement of an ink set's ability to produce neutral gray with cyan, magenta, and yellow when printed at standard densities. Proper gray balance ensures that a tone of appropriate Cyan (C), Magenta (M) and Yellow (Y) tint values is visually perceived as neutral gray.

This study was an experimental research in nature and funded by the National Science Council (NSC) of Taiwan (NSC 93-2212-E-144-001). The purposes of this research were (1) to identify the optimum CMY combinations that produce the most neutral gray, and (2) to explore the relationship between the chroma values of neutral gray and important print attributes such as solid ink density, tone value increase, ink trapping, and print contrast.

More than 35 high quality commercial sheetfed lithographic printers were invited to participate in the study. A GATF Gray Balance Chart was used as a process standardization target for determining the three-color dot requirements for CMY to reproduce a neutral scale at four different tone values (7%, 30%, 60%, 80% tints). A spectrophotometer was used for measuring the Gray Balance Chart to investigate the colorimetric values (L*a*b* color) of the squares selected as most neutral. In addition, the spectrophotometer was used to read commonly-measured print attributes for the purpose of exploring the relationship between the minimum chroma values and values of the print attributes. The results of the study can be used as the reference for offset printers to set the gray balance for their in-house color reproduction and make prediction on their print attributes.

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1. Introduction

Gray balance is the ability to reproduce rich neutral black and varying amounts of neutral grays using the correct amounts of Cyan (C), Magenta (M), and Yellow (Y). Process inks that quickly achieve gray balance require less time to match the prepress proof, thereby shortening makereadies. A process that reaches gray balance readily will also yield a more accurate color reproduction. Gray balance is also the first important step undertaken by the color separator, in determining the color content and contrast that the final printed substrate will have.

1.1 Motivation and Need of the Study

Because of the limitations of the pigments in the process inks, when equal amounts of cyan, magenta, and yellow are printed on white paper, they do not reflect equal amounts of red, green and blue to produce gray. Each of the process inks absorbs or reflects an unequal amount of its share of the red, green, and blue of the spectrum. As such, if equal amounts of cyan, magenta, and yellow are printed, they would make a brownish color rather than a neutral gray ("Understanding the Importance of Gray Balance," n.d., p. 2). A lack of proper gray balance will cause the color print as a whole to have a color cast. That is why printers say that the color balance depends upon gray balance settings.

Gray balance is also a significant factor in determining what the overall color gamut will be. Proper gray balance ensures that a tone of appropriate cyan, magenta and yellow tint values is visually perceived as neutral gray. Theoretically, equal amount of CMY should produce neutral gray; unfortunately, pigments of printing inks that comprise the process colors are not as pure as the theory suggests. They possess some hue error. Therefore, in order to achieve the most neutral grays, optimum combinations of CMY must be empirically determined.

Since gray balance plays a vital role in controlling overall quality of color reproduction, there is a great need to measure for gray balance because each individual's perception of color is different. Unfortunately, there are no industry-wide specifications of gray balance for the sheetfed lithography industry in Taiwan. Therefore the author strongly feels that Taiwan's printing industry now needs to develop a set of gray balance specification so that the printers understand how to print their target densities to achieve neutral gray. Moreover, once the target density for neutral gray is identified, the relationship between neutral gray and important print attributes such as density, tone value, ink trapping, and print contrast are very useful information for printers to maintain their quality of color reproduction.

1.2 Purposes of the Study

Gray balance is the ability to reproduce rich neutral black and varying amounts of neutral grays using the correct amounts of yellow, magenta, and cyan. If gray balance can be maintained throughout the job, the rest of the printed color gamut should follow. Several factors affecting gray balance include the color of the light source, ink color density, ink color purity, TVI (dot gain), paper color and surface, and the viewer's color perception. (GRACoL, 2002, p. 60). In this paper only the ink color density is concerned. Based on the motivation and need of the study, this study was designed to (1) investigate the optimum CMY combinations to achieve the most neutral gray for highlights and shadows for the sheetfed offset lithographic industry in Taiwan., and (2) explore the relationship between the chroma values of neutral gray and important print attributes such as solid ink density, tone value increase, ink trapping, and print contrast.

1.3 Limitations of the Study

The following limitations must be considered when interpreting the results of this study:

- The participants were not randomly selected; instead they volunteered to partake in the study.
- No two printing systems were the same; a wide variety of presses were employed for this research. The make, age, and physical condition of the presses differed. Their effects on the results were not discussed.
- Due to budget constraint, the paper used in the study was limited to coated paper.
- Pressroom temperature and relative humidity were not controlled; hence, they were not considered constant variables. Their effects for this research were not studied.
- The printing plates, blankets, fountain solution, and other press materials were not controlled. Their effects on the results of this study were not explored.
- The in-house density aim-points differ; they were measured and controlled by the participants with their own densitometers.
- The platemaking process and actual pressruns of the participants for this study were not observed due to budget and travel constraints.

2. Literature Review

Gray Balance is the measurement of an ink set's ability to produce neutral gray with cyan, magenta, and yellow when printed at standard densities. Process inks that quickly achieve gray balance require less time to match the prepress proof, thereby shortening make readies. An ink that reaches gray balance readily will also yield a more accurate reproduction ("Printability Characteristics," 1998).

Usually, neutral gray is produced by unequal dot sizes of CMY inks with the cyan dot always larger than the yellow and magenta. In other words, the size of yellow and magenta dots must be reduced in relation to cyan. The amount of the reduction is based on the contamination of the colors, so the combined dots absorb equal amounts of red, green and blue light (SWOP, 2001, p. 34). Process ink density and other important print attributes such as dot area (tone value), ink trapping, and print contrast must be controlled in the production rum in order to maintain gray balance. That is why the study is aimed to investigate the relationship between neutral gray and those important print attributes.

All three process color inks fail to follow their theoretical curves. Magenta is by far the least efficient of the three inks. To compensate for these deficiencies black is added in the midtones through the shadows to improve the balance of color. The amount of compensation is dependent the plates, blankets, inks, paper, and press settings among the many variables that need to be characterized for each press. The more sophisticated color management software programs used today incorporate the process of running a gray balance test. The importance and need for gray balance has not changed, it has been integrated into the automated process that is helping to balance the color better on the printed sheet relevant to all of the printing variables and not just the ink deficiencies (GRACoL, 2002, p. 61).

To accomplish gray balance and reproduction of a neutral gray using CMY inks, SNAP recommends using a tone scale calling for larger dot size for cyan and smaller dot sizes for magenta and yellow since this relationship of dot sizes among the three colors yields a neutral gray to the human eye. Tone value increase values must be monitored, adjusted, and controlled throughout the scanning, proofing, film creation, and printing process in order to maintain the relative halftone dot values required for gray balance to be achieved (SNAP, 2000, pp. 14-15).

Calibrating gray balance involves performing a simple test to identify the dot percentages (aim points) of each color that will produce neutral gray with a particular ink set on a given substrate. Once gray balance aim points are identified, the color separator can set up the camera, high-end scanner, or desktop color separation program to make properly color-balanced scans the first time (Adams II & Terbrack, 1992, p. 23).

2.1 The Factors Influencing Gray Balance

Gray balance is the ability to reproduce rich neutral black and varying amounts of neutral grays using the correct amounts of yellow, magenta, and cyan. If gray balance can be maintained throughout the job, the rest of the printed color gamut should follow. The factors that affect gray balance are the color of the light source, ink color density, ink color purity, TVI (dot gain), paper color and surface, and the viewer's color perception (GRACoL, 2002, p. 60).

Gray balance is a function of ink hue, ink film thickness and the percentage of dot area being printed. It is also affected by print color sequence, ink trapping, press characteristics and tone value increase ("Color Separations," 2000, p.20; Williams, 2002). Tone value increase (dot gain), which has a strong influence on gray balance, does not always have a regular symmetrical relationship with the tone scale. It can be selected. Sometimes the shadow tone exhibit disproportional

According to literatures ("Understanding the Importance of Gray Balance," n.d., pp. 6-7; Adams II & Terbrack, 1992, p. 23), many materials and press variables that influence gray balance include:

Tone value increase

- The balance of dot sizes between the various colors
- Choice of scanner gradation
- Dot shape
- Screen ruling
- Incorrect containing of film and/or plates
- Plate and blanket choice

The trapping efficiencies with regard to over printing of the inks

- Ink formulations
- Press blanket packing
- Choice of stock
- Choice of printing plates

The density of the 100% solid prints

- Ink formulations
- Target solid density values

The hue error and grayness of the process colors

- Ink formulations
- Coloration of the printing stock
- In line ink contamination at press

The materials and press variables

- Hues of process color inks
- Quality and color of paper surface
- Ink film thickness printed on paper
- Ink trapping
- Printing sequence
- Press printing characteristics

2.2 The Methods to Determine Optimum Gray Balance Combinations

Recognizing the complexity of attaining gray balance, GATF offered a test image in 1969 for determining gray balance requirements for a particular combination of ink, paper, and press. The chart consists of patches of varying yellow and magenta tint percentages at different tone values. Each tone level consists of matrix of tint patches, with varying magenta values in rows and yellow values in columns. The cyan dot size is constant for all squares in a given matrix (Adams II & Terbrack, 1992, p. 25).

After the chart is printed on a press operating within normal production control limits, the most neutral patch in each matrix of squares is located. For visual evaluation, a photographic or printed halftone gray scale can be used as a reference for comparison under standard viewing conditions. Punching holes in the gray scale makes it easier to compare with the patches. If a gray scale or standard viewing conditions are not available, the target can be evaluated with a color reflection densitometer to find the patch in each matrix with equal red, green, and blue filter densities. For more accurate instrument readings, a colorimeter may be used to identify the patch that measures the closest to the paper in CIELAB color space, that is, with a* (red-green) and b* (blue-yellow) values closest to those of the paper, to which the eye adapts as neutral white (Adams II & Terbrack, 1992, p. 25).

Usually such aim points specify equal magenta and yellow printers, with cyan dot area slightly higher. The cyan generally runs about 2-4% higher in the highlights, 10-15% higher in the midtones, and 3-10% higher in the shadows. It is important to note that gray balance is influenced by many printing variables. Ideally, a gray balance test should be run for frequently used ink/paper/press combinations (Adams II & Terbrack, 1992, pp. 26-27).

3. Research Design and Procedure

This study was an experimental research in nature and it was designed to empirically determine optimum combinations of CMY to achieve the most neutral gray. Since equal halftone dot percentages of process-color inks do not produce a neutral gray, but rather a brown color, printing a gray balance test target with process inks is recommended to identify halftone dot percentages of CMY that will produce a neutral gray. This section describes the test form, the sampling procedure, measuring process, and the method of determining the best CMY combinations to achieve neutral gray.

3.1 The Test Form

A digital four-color test form was designed for this study (See Appendix 1). The test form is 25x35-in. press form which includes test targets and photographic images. The photographs on the test form are GATF test images, which emphasize different color reproduction challenges. The other process characterization targets of the test form include:

- Gray balance chart, which is the main test target for determining the best CMY combinations to achieve neutral gray in this study
- CMYKRGB and 4K tint patches of 5%, 10%, 15%, 20%, 25%, 30%, 35% ,40%, 45%, 50%, 55%, 60% ,65%, 70%, 75%, 80%, 85%, 90%, 100%
- PTRI color control bar
- GATF six-color two tiered control bars: one is a repeating series of solid CMYK ink patches; the other contains tints, overprints, and star targets.
- Ink coverage target
- IT8.7/3
- CMYKRGB and 3K solid patches
- Tone scales of CMYKOG
- Color correction target
- CMYK tint patches of highlights (1%~10%) and shadows (90%~100%)
- Micro line target

3.2 Sampling Procedure

The target population of this study was high quality commercial sheetfed lithographic printers in Taiwan. The criteria for selecting the participants as high quality are that the printers who are active member companies of PIT (Printing Industry of Taiwan) or PTRI (Printing Technology Research Institute) and the printers have established themselves as commercially successful printers. Most of the printers have their own in-house platemaking facilities. For those who did not have, they were asked to prepare the plates, either conventional PS or CTP plates, on their own. More than 35 high quality commercial sheetfed lithographic printers were recommended by the PIT or PTRI. They were called and invited to participate in this study. A total of 10 companies, representing 6 from the north, 3 from central, and 1 from the south of Taiwan, submitted a total of 12 sets of printed samples for this study. Table 1 summarizes the information about the participants.

Table 1. The information about the participates and their sample sizes

	North	Central	South	Total
No. of Participants	6 companies	3 companies	1 company	10 companies
No. of Sets Submitted	8sets	3 sets	1 sets	12 sets
No. of Sheets Sampled	280 (8×35)	105 (3×35)	35 (1×35)	420 sheets

3.3 Procedure of Measuring and Determining the Best CMY Gray Combinations

A digital GATF Gray Balance Chart (see Figure 1) was composed into the big test form in Appendix I and used as a process standardization target for determining the three-color dot requirements for cyan, magenta, and yellow dots to reproduce a neutral gray at four different tints (7%, 30%, 60%, 80% tone value). The big test form shown in Appendix was available to the participants in either CD-ROM containing TIFF or EPS files, or conventional film to print 100 gloss-coated sheets according to their own in-house density aim points. To meet this requirement, the participants were asked to run their presses based on their in-house standard operating procedures and conditions.

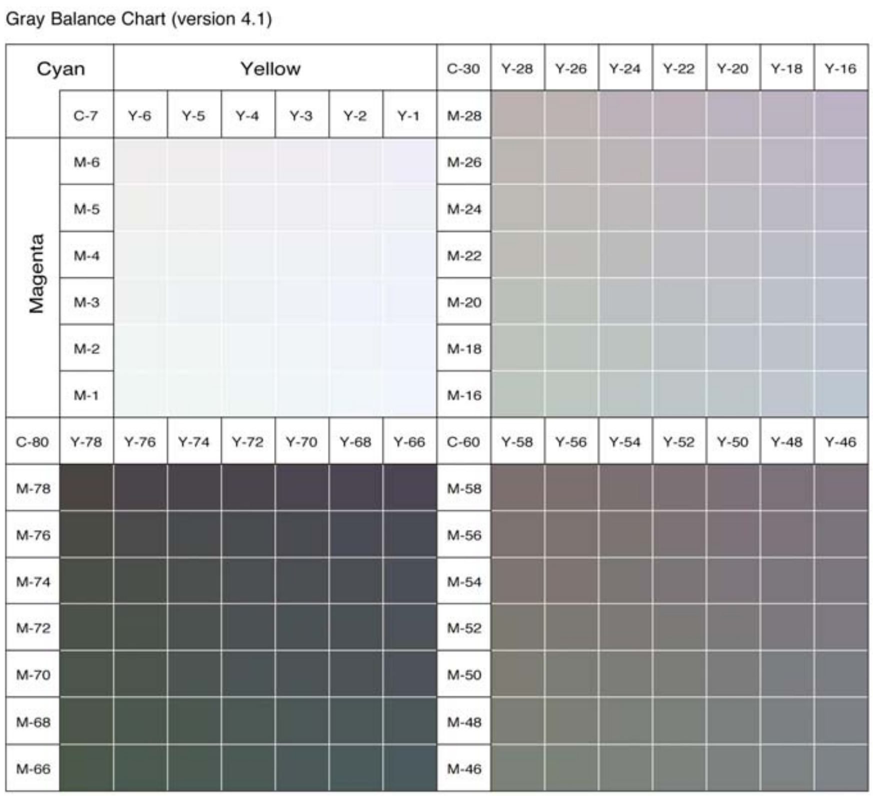


Figure 1. GATF Gray Balance Chart

After receiving the big test form, participants were asked to output the test form at 175 lpi screen ruling. Proofs of the test form were not supplied. After target densities were achieved across the press, 100 samples were labeled and sent to the authors. All participants used four- or six-color presses to print the test form for the research. The weight of the paper was limited to 150-175 lb coated stocks.

After the chart is printed on a press operating within normal production control limits, the most neutral gray patch in each matrix of squares can be located visually or instrumentally. For visual evaluation, a photographic or printed halftone gray scale can be used as a reference for comparison under standard viewing conditions. Punching holes in the gray scale makes it easier to compare with the patches. If a gray scale or standard viewing conditions are not available, the target can be evaluated with a color reflection densitometer to find the patch in each matrix with equal red, green, and blue filter densities (Adams II & Terbrack, 1992, p. 25). However this study employed a more accurate method suggested by Hutton & Stanton (2000)□a spectrodensitometer was used for reading the Gray Balance Chart to obtain the colorimetric values (L*a*b* color) of the squares selected as most neutral gray, or to measure various squares to find the most neutral squares (where the a* and b* values are closest to zero, or minimum chroma values). Status "T" density readings were made from these samples with Murray-Davies equation (n=1) on the 7% and 80% tint patches (the study did not investigate the midtones areas). It is important to note that each specific patch on the sampled sheets was measured only one time due to time constraints.

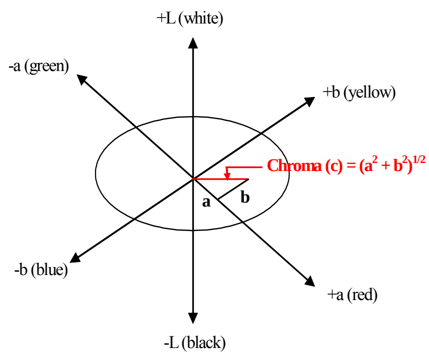
The Gray Balance Chart is a process standardization target used to determine the three-color dot requirements for the cyan, magenta, and yellow films to reproduce a neutral scale at 7%, 30%, 60%, and 80% tone values. As shown in Figure 1, the chart consists of four matrices of squares with various combinations of cyan, magenta, and yellow coverage. Each tone level consists of matrix of tint patches, with varying magenta values in rows and yellow values in columns. The cyan dot size is constant for all squares in a given matrix and it is identified by the number in the upper left corner of each matrix of squares. The film dot values that printed the square are identified by the numbers that head the rows and columns containing the selected square (Hutton & Stanton, 2000). The calculation and determination method for selecting the most neutral gray CMY combination (where the a* and b* values are closest to zero) is listed below:

1. For each of the 7% and 80% tint patches, a spectrodensitometer was applied to read each of the square patches to obtain the a* and b* values for the square.
2. The Chroma (c) value of each square was then computed using Pythagoras' Theorem ($a^2 + b^2 = c^2$) (see Figure 2).
3. In each matrix, the square that has the chroma value closest to zero (minimum chroma value) would be selected as the most neutral gray CMY combination. As the example shown in Figure 2, the square with minimum chroma value is C7/M5/Y6 and its chroma value is 0.38. Therefore

C7/M5/Y6 is identified as the most neutral gray combination for the 7% matrix.

4. Each of printed samples was measured and the readings were analyzed using the above 3 steps to obtain the most neutral squares. For example, since there were 420 gloss-coated paper sampled (see Table 1), the study would have 420 possible combinations to be identified as the most neutral squares. Finally, all possible combinations were then entered onto SPSS statistical software for frequency analyses.
5. The combination identified most frequently as the most neutral square was selected as the best CMY combination to reproduce neutral gray.

After the best CMY combinations for neutral gray and their chroma values were specified, a spectrophotometer was then used to read commonly-measured print attributes including solid ink density, tone value increase, ink trapping, and print contrast for the purpose of exploring the relationship between the chroma values of the best neutral gray and the print attribute values obtained from the print.



Cyan		Yellow					
	C-7	Y-6	Y-5	Y-4	Y-3	Y-2	Y-1
Magenta	M-6	0.99	1.15	1.50	1.32	2.24	2.87
	M-5	0.38	0.79	0.95	1.55	1.91	2.21
	M-4	1.47	0.59	1.04	1.42	1.45	1.80
	M-3	1.85	1.81	1.43	1.92	1.78	2.05
	M-2	2.02	1.77	1.68	1.83	1.78	1.77
	M-1	2.32	2.36	2.05	1.74	1.72	2.37

Figure 2. The calculation and determination method for selecting the CMY combination to achieve most neutral gray

4. Results and Findings

The printing systems used to run this study by the participants include Heidelberg (41.7%), Mitsubishi (16.7%), Komori (25%), Akiyama (8.3%), and Man Roland (8.3%). All of submitted stocks were printed with K-C-M-Y color sequence. Japanese inks such as DIC, Tiger, Butterfly, Toyo, 4CS, Hyeco, etc were mostly employed to run this study by the participants. The paper used for this study is 150-175 lb gloss-coated paper. None of samples were printed with stochastic screens or hybrid screens.

Since gray balance is significantly influenced by the density of the print, the solid ink density (SID) values must be reported in order to interpret the CMY gray combinations correctly. The solid ink density attribute measured from the submitted stocks was displayed in Table 2. The averages or "means" are given as a value ± another value. The number after the "±" is the "margin of error" of the mean calculation. For this study the margin of error is a statistical precision evaluation of derived from computing the 95% confidence interval of the mean. The average in-house SID of gloss-coated paper were 1.21 for yellow (Y), 1.27 for magenta (M), 1.62 for cyan (C), and 1.73 for black (K). It is interesting that the SID results are different from several US specifications such as GRACoL, WOP, and SNAP, especially in yellow and cyan inks.

Table 2. Solid ink density values of the gloss-coated paper

	Y	M	C	K
Solid Ink Density	1.21 ± 0.01	1.27 ± 0.02	1.62 ± 0.02	1.73 ± 0.03

4.1 The Most Neutral Gray Combinations at 7% Tints

Table 3 displays the results of the frequency analyses for the 7% matrices on the coated stocks. As shown in Table 3, for 420 gloss-coated paper, the frequencies of combinations identified as the most neutral squares (chroma values closest to zero) indicate that the best CMY combination to achieve neutral gray is C7/M5/Y6. It has a maximum frequency of 116 (27.6%) and a mean chroma value of .56.

Table 3. The frequencies analysis of CMY gray combinations at 7% tints

Combination	frequency	percent	cumulative %	Combination	frequency	percent	cumulative %
C7/M1/Y1	0	0	0	C7/M4/Y1	0	0	44.0
C7/M1/Y2	0	0	0	C7/M4/Y2	3	.7	44.8
C7/M1/Y3	4	1.0	1.0	C7/M4/Y3	5	1.2	46.0
C7/M1/Y4	0	0	1.0	C7/M4/Y4	0	0	46.0
C7/M1/Y5	0	0	1.0	C7/M4/Y5	24	5.7	51.7
C7/M1/Y6	0	0	1.0	C7/M4/Y6	46	11.0	62.6
C7/M2/Y1	1	.2	1.2	C7/M5/Y1	2	.5	63.1
C7/M2/Y2	1	.2	1.4	C7/M5/Y2	0	0	63.1
C7/M2/Y3	0	0	1.4	C7/M5/Y3	0	0	63.1
C7/M2/Y4	9	2.1	3.6	C7/M5/Y4	0	0	63.1
C7/M2/Y5	26	6.2	9.8	C7/M5/Y5	3	.7	63.8
C7/M2/Y6	20	4.8	14.5	C7/M5/Y6	***116***	***27.6***	***91.4***
C7/M3/Y1	2	.5	15.0	C7/M6/Y1	1	.2	91.7
C7/M3/Y2	3	.7	15.7	C7/M6/Y2	3	.7	92.4
C7/M3/Y3	31	7.4	23.1	C7/M6/Y3	1	.2	92.6
C7/M3/Y4	1	.2	23.3	C7/M6/Y4	0	0	92.6
C7/M3/Y5	55	13.1	36.4	C7/M6/Y5	0	0	92.6
C7/M3/Y6	32	7.6	44.0	C7/M6/Y6	31	7.4	100.0

In addition, the study computed the averages of the minimum chroma values for the gloss-coated paper; the result shows that the average of the minimum chroma values is .47. In other words, most of the selected patches were less than 1.0 chroma unit from the origin.

4.2 The Most Neutral Gray Combinations at 80% Tints

Table 4 displays the results of the frequency analyses for the 80% matrix on the coated stocks. As shown in Table 4, the best CMY combination to achieve neutral gray is C80/M74/Y66, with a maximum frequency of 69 (16.4%) and a mean chroma value of 2.28. The average of the minimum chroma values is also computed and it is 2.93. In other words, the averages of minimum chroma values for all squares identified as best neutral gray of 80% tints are greater than 2.0 chroma unit from the origin. These averages are significantly greater than those of the 7% tint.

Table 4. The frequencies analysis of CMY gray combinations at 80% tints

Combination	frequency	percent	cumulative%	Combination	frequency	percent	cumulative%
C80/M66/Y66	6	1.4	1.4	C80/M72/Y74	4	1.0	30.0
C80/M66/Y68	1	.2	1.7	C80/M72/Y76	8	1.9	31.9
C80/M66/Y70	0	0	1.7	C80/M72/Y78	19	4.5	36.4
C80/M66/Y72	8	1.9	3.6	C80/M74/Y66	***69***	***16.4***	***52.9***
C80/M66/Y74	9	2.1	5.7	C80/M74/Y68	4	1.0	53.8
C80/M66/Y76	35	8.3	14.0	C80/M74/Y70	3	.7	54.5
C80/M66/Y78	20	4.8	18.8	C80/M74/Y72	3	.7	55.2
C80/M68/Y66	19	4.5	23.3	C80/M74/Y74	16	3.8	59.0
C80/M68/Y68	0	0	23.3	C80/M74/Y76	3	.7	59.8
C80/M68/Y70	0	0	23.3	C80/M74/Y78	21	5.0	64.8
C80/M68/Y72	0	0	23.3	C80/M76/Y66	0	0	64.8
C80/M68/Y74	0	0	23.3	C80/M76/Y68	0	0	64.8
C80/M68/Y76	0	0	23.3	C80/M76/Y70	2	.5	65.2
C80/M68/Y78	0	0	23.3	C80/M76/Y72	2	.5	65.7
C80/M70/Y66	4	1.0	24.3	C80/M76/Y74	7	1.7	67.4
C80/M70/Y68	8	1.9	26.2	C80/M76/Y76	0	0	67.4
C80/M70/Y70	0	0	26.2	C80/M76/Y78	47	11.2	78.6
C80/M70/Y72	1	.2	26.4	C80/M78/Y66	14	3.3	81.9
C80/M70/Y74	1	.2	26.7	C80/M78/Y68	22	5.2	87.1
C80/M70/Y76	3	.7	27.4	C80/M78/Y70	8	1.9	89.0
C80/M70/Y78	1	.2	27.6	C80/M78/Y72	1	.2	89.3
C80/M72/Y66	0	0	27.6	C80/M78/Y74	0	0	89.3
C80/M72/Y68	0	0	27.6	C80/M78/Y76	18	4.3	93.6
C80/M72/Y70	2	.5	28.1	C80/M78/Y78	27	6.4	100.0
C80/M72/Y72	4	1.0	29.0				

4.3 The Relationship between Chroma Values of the Most Neutral Gray and Important Print Attributes

In lithography, gray balance is influenced by many materials and press variables such as hues of process color inks, quality and color of paper surface, ink film thickness printed on paper, ink trapping, printing sequence, press printing characteristics, tone value increase and so on (Adams II & Terbrack, 1992). In order to make properly color-balanced the first time and use as the reference for offset printers to set the gray balance for their in-house color reproduction and make prediction on their print attributes, this study tried to explore the relationship between the chroma values of the most neutral gray and important print attributes such as solid ink density, tone value increase, ink trapping, and print contrast.

Table 5 displays the measured print attributes values of the gloss-coated paper for the best CMY combination (C7M5Y6) to achieve neutral gray at 7% tints. The average tone value increase (TVI) values showed that black color had the greatest TVI, followed by cyan, yellow, and magenta. For solid ink density (SID), the average SID of C7M5Y6 combination were 1.21 for yellow (Y), 1.22 for magenta (M), 1.68 for cyan (C), and 1.81 for black (K). In addition, the greatest print contrast was found in black color (48.93%), followed by cyan color (44.68%), magenta (39.02%) and yellow (36.23%). As for ink trapping, the green trap (cyan-yellow overprint) had the largest trap value, followed by blue (cyan-magenta overprint) and red trap (magenta-yellow overprint).

Table 5. Print attributes measured for the best neutral gray combination of 7% tints (C7M5Y6)

	Y	M	C	K
7% TVI	2.70 ± 0.34	2.47 ± 0.16	2.75 ± 0.20	3.72 ± 0.19
solid ink density	1.21 ± 0.01	1.22 ± 0.02	1.68 ± 0.03	1.81 ± 0.04
print contrast	36.23 ± 1.10	39.02 ± 0.40	44.68 ± 1.37	48.93 ± 0.67
ink trapping	Red-MY	Green-CY	Blue-CM	
	66.73 ± 0.85	82.19 ± 1.03	80.22 ± 0.91	

Table 6 displays the measured print attributes values of the gloss-coated paper for the best CMY combination (C80M74Y66) to achieve neutral gray at 80% tints. The average TVI showed that yellow color had the greatest dot area, followed by black, cyan, and magenta. For solid ink density, the average SID of C80M74Y66 combination were 1.26 for yellow (Y), 1.42 for magenta (M), 1.82 for cyan (C), and 1.93 for black (K). For print contrast, the greatest print contrast was found in black color (54.15%), followed by cyan color (53.26%), magenta (42.83%) and yellow (36.01%). As for ink trapping, the green trap (cyan-yellow overprint) and blue (cyan-magenta overprint) had larger trapping values, compared with the red trap (magenta-yellow overprint).

Table 6. Print attributes measured for the best neutral gray combination of 80% tints (C80M74Y66)

	Y	M		C		K
80% TVI	13.20 ± 0.44	9.06 ± 0.50		9.48 ± 0.33		10.90 ± 0.58
solid ink density	1.26 ± 0.02	1.42 ± 0.01		1.82 ± 0.01		1.93 ± 0.05
print contrast	36.01 ± 0.82	42.83 ± 0.66		53.26 ± 0.58		54.15 ± 0.87
ink trapping	Red-MY		Green-CY		Blue-CM	
	67.51 ± 0.28		81.20 ± 0.70		81.03 ± 1.23	

In this section, linear regression statistical procedure was employed to explore the relationship between the chroma values of the most neutral gray and important print attributes. Linear regression can estimate the coefficients of the linear equation, involving one or more independent variables that best predict the value of the dependent variable. The dependant variable in this study is the chroma value of the most neutral gray (7% and 80% tints) and the independent variables are print attributes. Since GATF gray balance chart is composed of certain amount of cyan, magenta, and yellow for printing processes, the full regression model should include print attributes of cyan, magenta, and yellow inks in the same model (see Full Model I and II). The significant level (α) was set at .05 for all statistical tests. Stepwise method, the most commonly used method for model building, was employed to select independent variables. The variable selection criterion uses probability of F method. The variables with a probability of F lower than .05 (Entry = .05) were entered into the model and the variables with a probability of F greater than .10 (Removal = .05) were removed from the model. The two full models for hypothesis testing are listed below:

Chroma @ 7% tint = $\alpha + \beta_1$ (C_PA) $+\beta_2$ (M_ PA) $+\beta_3$ (Y_ PA) + E ***Model 1***

Chroma @ 80% tint = $\alpha + \beta_1$ (C_PA) $+\beta_2$ (M_ PA) $+\beta_3$ (Y_ PA) + E ***Model 2***

Where,

α is the intercept and β is the coefficient of the regression
C_PA is the print attributes of cyan
M_PA is the print attributes of magenta
Y_PA is the print attributes of yellow
E is the error term of the regression

Note: Print attributes in the study include 7% tone value increase (7%TVI), 80% tone value increase (80%TVI), Solid Ink Density (SID), Print Contrast (PC), and Ink Trapping (Trap).

1. The relationship between chroma values of the most neutral gray at 7% tints and important print attributes

ANOVA Analysis. The ANOVA analysis results about the relationship between the chroma values of the most neutral gray at 7% tints and important print attributes are exhibited in Table 7. In Table 7, for each print attribute (PA), the significant factors (C_PA, M_PA, and/or Y_PA) affecting chroma values are identified (shown in the "predictor" column) respectively and their R-square change values are also specified. As shown in Table 7, for tone value increase (TVI), Y_7%TVI is identified as significant factor affecting the chroma value of the neutral gray at 7% tints. In terms of solid ink density (SID), Y_SID and C_SID are identified as significant factors. For print contrast factor (PC), C_PC, Y_PC, and M_PC are all significant. For ink trapping (TRAP) factor, only $B_{(C+M)}$_TRAP is identified as the significant one.

Table 7. ANOVA analyses on the relationship between chroma values and print attributes measured for the most neutral gray at 7% tints

The chroma value of the most neutral gray at 7% tint vs. 7% Tone Value Increase								
Model	Sum of Squares	df	Mean Square	F	Sig.	Predictors	R^2	ΔR^2
1 Regression Residual Total	4.505 4.555 9.060	1 114 115	4.505 .040	112.753	.000	Constant, Y_7%TVI	 .497	 .497
The chroma value of the most neutral gray at 7% tint vs. Solid Ink Density								
Model	Sum of Squares	df	Mean Square	F	Sig.	Predictors	R^2	ΔR^2
1 Regression Residual Total	4.196 4.864 9.060	1 114 115	4.196 .043	98.345	.000	Constant, Y_SID	 .463	 .463
2 Regression Residual Total	5.990 3.070 9.060	2 113 115	2.995 .027	110.249	.000	Constant, Y_SID C_SID	 .463 .661	 .463 .198
The chroma value of the most neutral gray at 7% tint vs. Print Contrast								
Model	Sum of Squares	df	Mean Square	F	Sig.	Predictors	R^2	ΔR^2
1 Regression Residual Total	5.182 3.878 9.060	1 114 115	5.182 .034	152.336	.000	Constant, C_PC	 .572	 .572
2 Regression Residual Total	5.715 3.345 9.060	2 113 115	2.857 .030	96.522	.000	Constant, C_PC Y_PC	 .572 .631	 .572 .059
3 Regression Residual Total	5.844 3.216 9.060	3 112 115	1.948 .029	67.842	.000	Constant, C_PC Y_PC M_PC	 .572 .631 .645	 .572 .059 .014
The chroma value of the most neutral gray at 7% tint vs. Ink Trapping								
Model	Sum of Squares	df	Mean Square	F	Sig.	Predictors	R^2	ΔR^2
1 Regression Residual Total	5.331 3.729 9.060	1 114 115	5.331 .033	162.994	.000	Constant, B_TRAP	 .588	 .588

Regression Model. The significant factors identified in Table 7 are then selected into regression analysis procedure to build the optimum prediction models for chroma values of the most neutral gray. The final prediction model summary (model 3, 4, 5, 6) for 7% tint chroma values (labeled as Ŷ_7% Tint_Chroma) are displayed in Table 8. It is important to note that the R-square value of each model is also calculated to report how much the total variability in 7% Tint_Chroma can be explained by the model. The R-square value (ranged from 0 to 1) is also an indictor of how well a regression model (or the significant independent variables in the model collectively) predicts the dependent variable (i.e., 7% Tint_Chroma in this case). The higher the R-square value, the stronger strength of estimation (prediction ability) of the model is. The R-square values of the model 3-6 are ranged from .50 to .66. In other words, the estimation strength the four models are moderate.

Table 8. Prediction models for the relationship between chroma values and print attributes measured for the most neutral gray at 7% tints

Independent variable	Sig. Factor	ΔR^2	R^2	Prediction Model
7% TVI	Y_7 TVI	.50	.50	Ŷ_7% Tint_Chroma = - 0.485 + 0.108 (Y_7%TVI) ***model 3***
Solid Ink Density	Y_SID	.463	.66	Ŷ_7% Tint_Chroma = 1.66 - 1.83 (Y_SID) + 0.673 (C_SID) ***model 4***
	C_SID	.198		
Print Contrast	C_PC	.572	.65	Ŷ_7% Tint_Chroma = 1.38 - 0.0278 (C_PC) - 0.0143 (Y_PC) + 0.0241 (M_PC) ***model 5***
	Y_PC	.059		
	M_PC	.014		
Ink Trapping	$B_{(c+m)}$_Trap	.588	.59	Ŷ_7% Tint_Chroma = 4.03 - 0.0433 (B_Trap) ***model 6***

Note: significant level (α) = .05

Residual Diagnostics. In any regression analysis, it is important to examine the residuals and check for violations of basic assumptions that could invalidate the results. Therefore, four residuals plots (see Figure 3-6) based on the regression model 3-6 are constructed respectively by Minitab 13 to diagnose the residuals. The points on the normal probability plot of the residuals in Figure 3-6 lie reasonably close to a straight line, and therefore, the assumption of normality is satisfied. The histogram of residuals reveals that the residuals appear to be approximately normally distributed and symmetrically about zero. This suggests that there are no problems with normality and equality of variance.

The plots of "Residuals versus Fitted Value" in Figure 3-6 are the plots of residuals versus the predicted chroma values (Fits) obtained from model 3-6, respectively. The plots appear to be reasonable because there is no particular pattern and most of the residuals fall between $\pm 3\sqrt{MSE}$. Although these plots do not reveal any severe problems, special attention should be given to the differences in residual spread. Note that there might be a minor problem with the assumption of constant variance because there is a mild tendency for the variability of the residuals to increase as the predicted chroma value increases. The problem, however, is not severe enough to have a dramatic impact on the analysis and conclusions. Since a simple model with a reasonable strength of estimation is preferred by printing personnel, therefore, transforming the values of the dependent variable (chroma values) was not considered.

The last plots of the residuals (Residuals versus Observation Order) show that the residuals appear to fluctuate randomly about zero with no particular trend as the observation number changes (Note: the observation number is identical to the run order). This suggests that the observations on the dependent variable (chroma value) are statistically independent.

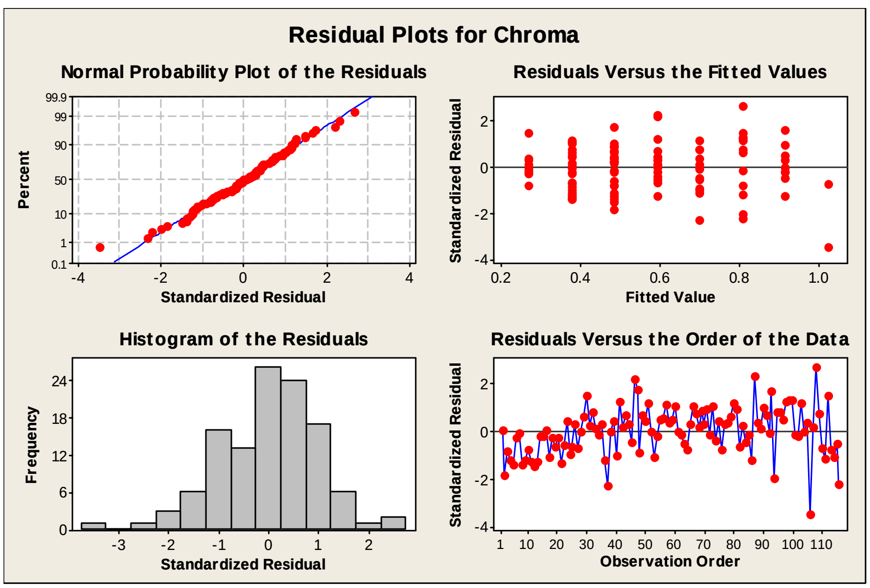


Figure 3. Residual diagnostics for the model of chroma values v.s. tone value increase of the most neutral gray at 7% tints

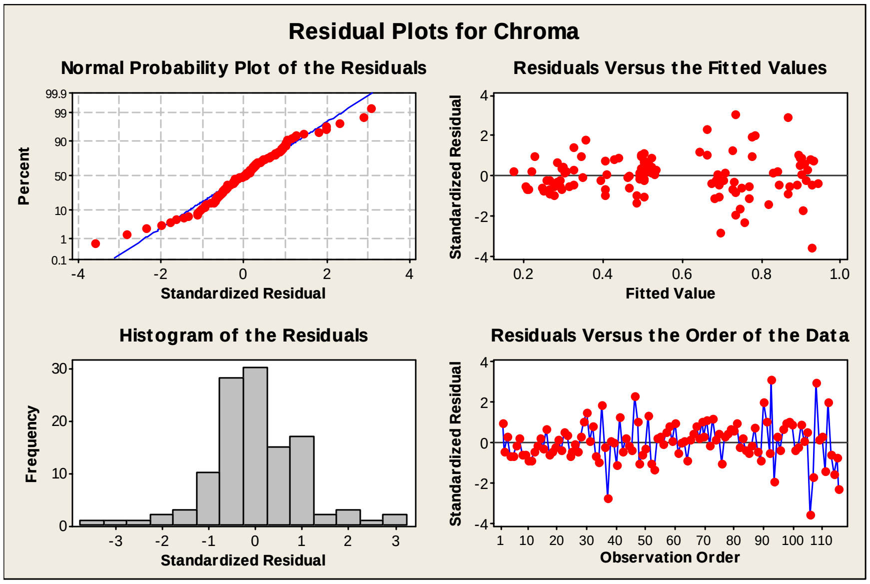


Figure 4. Residual diagnostics for the model of chroma values v.s. solid ink density of the most neutral gray at 7% tints

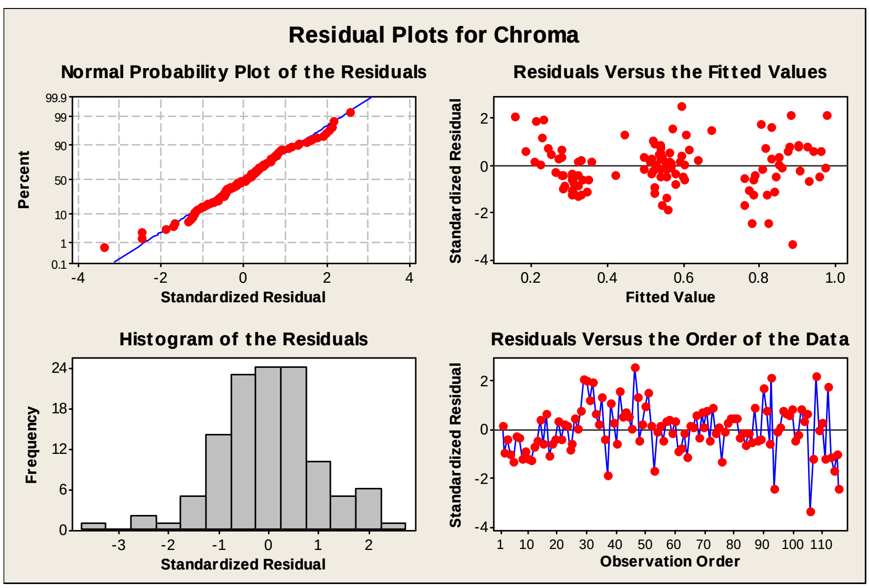


Figure 5. Residual diagnostics for the model of chroma values v.s. print contrast of the most neutral gray at 7% tints

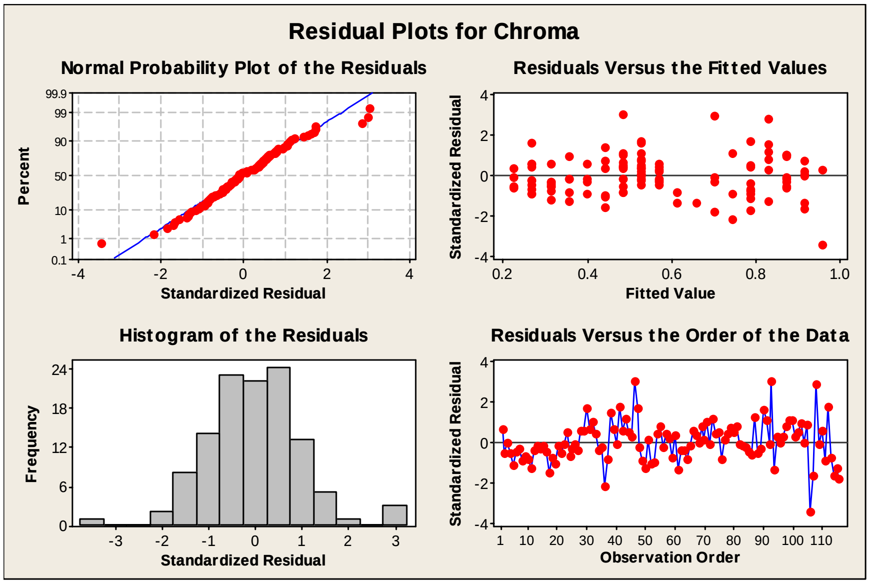


Figure 6. Residual diagnostics for the model of chroma values v.s. ink trapping of the most neutral gray at 7% tints

2. The Relationship between chroma values of the most neutral gray at 80% tint and important print attributes

ANOVA Analysis. The ANOVA analysis results about the relationship between the chroma values of the most neutral gray at 80% tints and important print attributes are exhibited in Table 9. In Table 9, for each print attribute (PA), the significant factors (C_PA, M_PA, and/or Y_PA) affecting chroma values are identified respectively and their R-square change values are also specified. As shown in Table 9 for TVI, M_80%TVI and Y_80%TVI are identified as significant factor affecting the chroma value of the neutral gray at 80% tints. In terms of SID, M_SID and C_SID are identified as significant factors. For PC factor, Y_PC and M_PC are identified as significant factors. For TRAP factor, only $B_{(C+M)}$_TRAP is identified as significant one.

In Table 9, it is interesting to note that the significant factors (M_80%TVI, M_SID, M_PC, $B_{(C+M)}$_TRAP) affecting chroma values at 80% tints are all involved with magenta ink. Moreover, the R-square values of M_80%TVI, M_SID, M_PC, and $B_{(C+M)}$_TRAP are all greater than .80; this implies that the strength of the linear estimation of the four variables to the chroma values of the best neutral gray in shadows are considerably high.

Table 9. ANOVA analyses on the relationship between chroma values and print attributes measured from the most neutral gray at 80% tints

Model	Sum of Squares	df	Mean Square	F	Sig.	Predictors	R^2	ΔR^2
The chroma value of the most neutral gray at 80% tint vs. 80% Tone Value Increase								
1 Regression	81.499	1	81.499	423.331	.000	Constant,		
Residual	12.899	67	.193			M_80%TVI	.863	.863
Total	94.398	68						
2 Regression	82.346	2	41.173	225.462	.000	Constant,		
Residual	12.053	66	.183			M_80%TVI	.863	.863
Total	94.398	68				Y_80%TVI	.872	.009
The chroma value of the most neutral gray at 80% tint vs. Solid Ink Density								
1 Regression	81.578	1	81.578	426.355	.000	Constant,		
Residual	12.820	67	.191			M_SID	.864	.864
Total	94.398	68						
2 Regression	85.014	2	42.507	298.967	.000	Constant,		
Residual	9.384	66	.142			M_SID	.864	.864
Total	94.398	68				C_SID	.901	.036
The chroma value of the most neutral gray at 80% tint vs. Print Contrast								
1 Regression	76.357	1	76.357	283.571	.000	Constant,		
Residual	18.041	67	.269			Y_PC	.809	.809
Total	94.398	68						
2 Regression	78.236	2	39.118	159.741	.000	Constant,		
Residual	16.162	66	.245			Y_PC	.809	.809
Total	94.398	68				M_PC	.829	.020
The chroma value of the most neutral gray at 80% tint vs. Ink Trapping								
Model	Sum of Squares	df	Mean Square	F	Sig.	Predictors	R^2	ΔR^2
1 Regression	81.803	1	81.803	435.171	.000	Constant,		
Residual	12.595	67	.188			B_TRAP	.867	.867
Total	94.398	68						

Regression Model. The significant factors identified in Table 9 are then selected into regression analysis procedure to build the optimum prediction models for chroma values of the most neutral gray. The final prediction model summary (model 7, 8, 9, 10) for 80% tint chroma values (labeled as $\hat{Y}$_80% Tint_Chroma) are displayed in Table 10. The R-square values of the model 7-10 are ranged from .83 to .90. In other words, the estimation strength the four models are considerably high.

Table 10. Prediction models for the relationship between chroma values and print attributes measured from the most neutral gray at 80% tints

Independent variable	Sig. Factor	ΔR^2	R^2	Prediction Model
80% TVI	M_80%TVI	.863	.87	$\hat{Y}$_80% Tint_Chroma = - 47.4 + 0.380 (M_80%TVI) + 0.174 (Y_80%TVI) ***model 7***
	Y_80%TVI	.009		
Solid Ink Density	M_SID	.864	.90	$\hat{Y}$_80% Tint_Chroma = - 6.98 + 18.5 (M_SID) - 7.49 (C_SID) ***model 8***
	C_SID	.036		
Print Contrast	Y_PC	.809	.83	$\hat{Y}$_80% Tint_Chroma = 17.0 - 0.161 (Y_PC) - 0.196 (M_PC) ***model 9***
	M_PC	.020		
Ink Trapping	$B_{(c+m)}$_Trap	.867	.87	$\hat{Y}$_80% Tint_Chroma = - 14.6 + 0.214 (B_Trap) ***model 10***

Note: significant level (α) = .05

Residual Diagnostics. Four residuals plots (see Figure 7-10) based on the regression model 7-10 are constructed respectively to diagnose the residuals. The points on the normal probability plot of the residuals in Figure 7-10 lie reasonably close to a straight line, and therefore, the assumption of normality is satisfied. The histogram of residuals reveals that the residuals appear to be approximately normally distributed and symmetrically about zero. This suggests that there are no problems with normality and equality of variance.

The plots of "Residuals versus Fitted Value" in Figure 7-10 are the plots of residuals versus the predicted chroma values (Fits) obtained from model 7-10, respectively. The plots appear to be reasonable because there is no particular pattern and most of the residuals fall between $\pm 3\sqrt{MSE}$.

The last plots of the residuals (Residuals versus Observation Order) show that the residuals appear to fluctuate randomly about zero with no particular trend as the observation number changes. This suggests that the observations on chroma values are statistically independent.

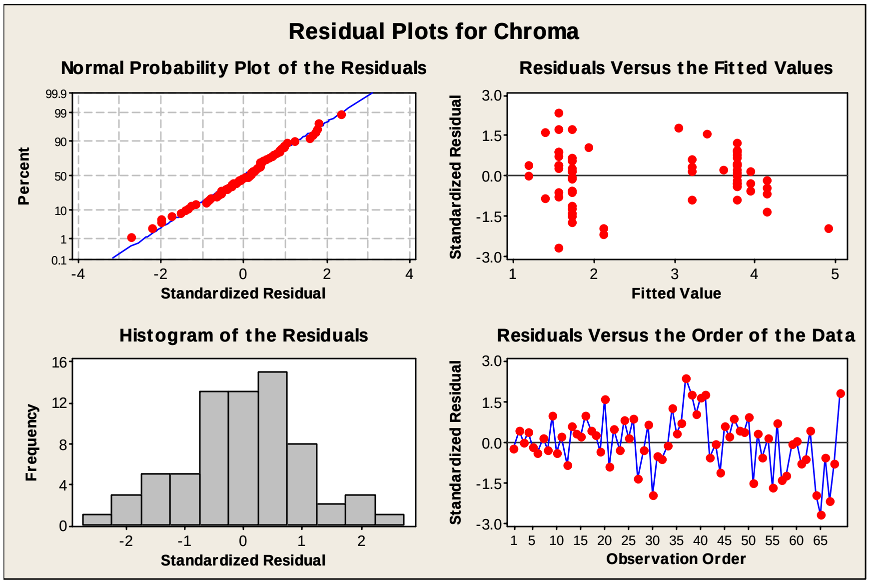


Figure 7. Residual diagnostics for the model of chroma values v.s. tone value increase of the most neutral gray at 80% tints

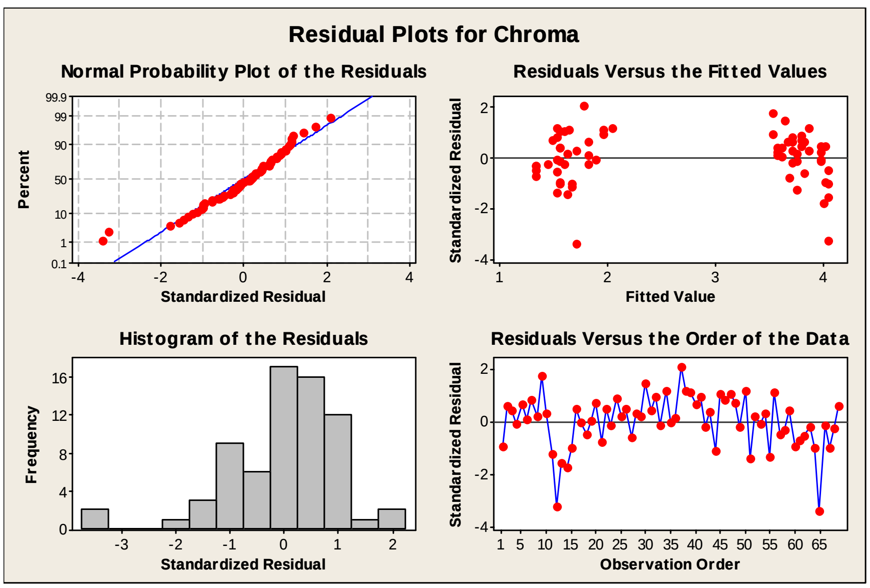


Figure 8. Residual diagnostics for the model of chroma values v.s. solid ink density of the most neutral gray at 80% tints

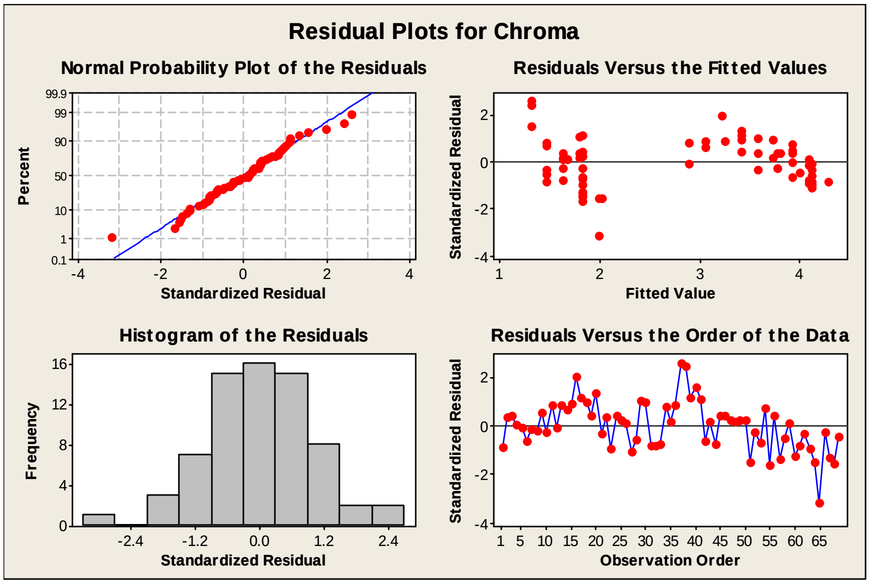


Figure 9. Residual diagnostics for the model of chroma values v.s. print contrast of the most neutral gray at 80% tints

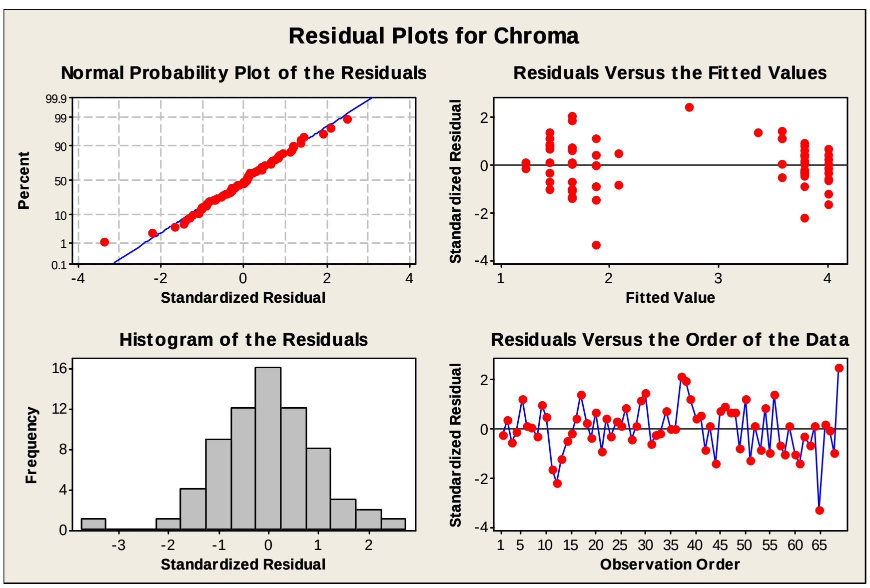


Figure 10. Residual diagnostics for the model of chroma values v.s. ink trapping of the most neutral gray at 80% tints

5. Conclusions

Gray balance is probably the most important factor influencing the general appearance of color reproduction. A gray balance target should be printed and analyzed to determine the proper dot percentages of cyan, magenta, and yellow that are necessary to produce a neutral gray in the different areas of the tone scale (Koehler, 1999, p. 22). In this study, a digital four-color form of GATF Gray Balance Chart (see Figure 1) was used as the test target. In addition, it is well known that equal halftone dot percentages of process-color inks do not produce a neutral gray, but rather a brown color. Therefore, printing the GATF test form with process inks was performed to identify halftone dot percentages of YMC producing a neutral gray. The major conclusions of the study include:

1. The optimum CMY combination to achieve the most neutral gray for the highlights (7% tints) is C7/M5/Y6 for gloss-coated paper, and the mean chroma value of the most neutral gray combination is .56.
2. The optimum CMY combination to achieve the most neutral gray for the shadows (80% tints) is C80/M74/Y66 for gloss-coated paper, and the mean chroma value of the most neutral gray combination is 2.28.
3. The mean chroma values and their variations of the most neutral gray combinations of the 80% tints are greater than those of 7% tints. In other words, the 80% tints are more difficult than 7% tints to be printed as neutral gray consistently. In contrast, the 7% tints are much easier to be printed as neutral gray than the 80% tints since their mean chroma values and variations of the most neutral gray combinations are far less than those of the 80% tints.
4. Several literatures indicate that gray balance is usually influenced by many factors such as ink hue, substrate quality and color, ink film thickness, ink trapping, print color sequence, print contrast, and tone value increase (dot gain). However, very few empirical researches have been done to investigate the relationship between gray balance and important print attributes. Therefore, this study tried to investigate the relationship between chroma values of gray balance and the print attributes. The research results indicate that the total variability in the chroma values of neutral gray explained by 7% tone value increase, solid ink density, print contrast, and ink trapping are approximately 60%, respectively. In other words, the estimation strengths of the models (shown in Table 8) are only moderately strong. This implies that there might be some other factors affecting gray balance not included in this study. Therefore the study recommends further studies be conducted to investigate other possible significant factors affecting gray balance.
5. As to the 80% tints, the total variability in the chroma values of neutral gray explained by 80% tone value increase, solid ink density, print contrast, and ink trapping are all greater than 7% tints. That means that the

estimation strengths of the four linear models (shown in Table 10) are considerably high and their residual diagnostics results show that there are no violations of basic assumptions that could invalidate the prediction. Therefore, printers can use those important attributes to predict their in-house chroma values of the neutral gray.

6. Recommendations

1. Further researches are recommended to study the best CMY combinations to achieve neutral gray for midtones and other tint patches, according to various combinations of experimental conditions such as press type, ink type, paper type and so on.
2. Due to the budget and time constraints, this research only investigates the relationship between neutral gray and tone value increase, solid ink density, print contrast, and ink trapping at the 7% and 80% tone areas on the coated paper. Further researches are recommended to study the relationship at other tone areas (such as midtone area) and on various substrates (such as uncoated paper).
3. The best CMY combinations for neutral gray were determined based on the frequency analyses (see Table 3 and 4), the chroma values of the best combinations were then computed using Pythagoras' Theorem. Further researches are recommended to establish optimum ranges for CMY numbers, rather than just a particular combination of CMY value.
4. The linear regression models (shown in Table 10) to estimate the relationship between chroma values of the neutral gray and important print attributes for shadows (80% tints) are very effective. In Table 8, the four linear models to estimate the relationship between chroma values of the neutral gray and important print attributes for highlights (7% tints) are only moderate effective. There might be a non-linear relationship (such as Logarithmic, Inverse, Quadratic, Cubic) between chroma values of the neutral gray and important print attributes in highlights. The study recommends that further researches be necessary to investigate those possible non-linear relations or linear ones after mathematical transformation.

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Appendix I. Test Form of the Study