A Study of High-Chroma Inks for Expanding CMYK Color Gamut

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A Study of High-Chroma Inks for Expanding CMYK Color Gamut

by Sanyukta Sanjay Hiremath

A Thesis submitted in the partial fulfillment of the requirements
for the degree of Master of Science in Print Media
in the School of Media Sciences
in the College of Imaging Arts and Sciences
of the Rochester Institute of Technology

May 2018

Primary Advisor: Dr. Elena Fedorovskaya
Secondary Advisor: Professor Robert Chung
Abstract

The number of possible reproducible colors in a printing method is called the color gamut. The need to satisfy the growing quality demands and produce color match has given rise to the use of expanded color gamuts. There are many ways to achieve an expanded color gamut, including printing with Cyan, Magenta, Yellow, Black (CMYK) plus additional inks, printing with higher ink film thickness (IFT), and printing with high-chroma inks. The purpose of this research is to study the relationship between color gamut volume, metric chroma (C*), IFT, and solid ink density (SID) for regular and high-chroma inks in offset printing process. This is done by performing ink drawdowns to understand the behavior of high-chroma and regular inks in order to determine IFT and corresponding ink saturation densities using the Tollenaar and Ernst equation.

Subsequently, the research compares color gamut volume between regular and high-chroma inks using Presstek 52DI offset printing process. The measurement is carried out with i1 Pro 2 spectrophotometer and X-Rite i1 Isis2.
Acknowledgements

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# Table of Contents

Abstract ........................................................................................................................................... i

Acknowledgements ......................................................................................................................... ii

List of Tables .................................................................................................................................. vi

List of Figures ................................................................................................................................... vii

Introduction and Statement of the Problem ..................................................................................... 1
  Problem Statement ........................................................................................................................... 3
  Reason for Interest ....................................................................................................................... 4

Theoretical Basis .............................................................................................................................. 5
  The Role of Pigment in Ink Composition ...................................................................................... 5
  Ink Film Thickness, Density, and the Tollenaar and Ernst equation ...................................... 6
  Process Ink Gamut and CRPCs ..................................................................................................... 7
  Press Calibration using G7 Methodology ..................................................................................... 9
  Summary of Theoretical Background ......................................................................................... 11

Literature Review ............................................................................................................................ 12
  Color, Colorfulness, and Chroma ............................................................................................... 12
  Ways to Achieve Expanded Color Gamut Printing Condition .................................................. 13
  Change of Substrate .................................................................................................................... 14
  Number of Primaries .................................................................................................................... 16
  Amount of IFT ............................................................................................................................. 18
  Increase Pigment Concentration ............................................................................................... 22
Type of screening .................................................................................................................. 23
Summary of Literature Review ............................................................................................ 24
Research Objectives ............................................................................................................. 26
Methodology .......................................................................................................................... 27
Key Variables ......................................................................................................................... 32
Results .................................................................................................................................. 33
Condition 1: Printing with the Toyo OSF inks (reference color gamut) .................. 44
Run 1 with Toyo OSF inks using linear plates ................................................................. 44
Run 2 with Toyo OSF inks using curved plates ............................................................... 46
Comparison of Toyo OSF and CRPC6 color gamut after Run 2. Figure 20 illustrates the comparison of the gamut between the G7 calibration process with the OSF inks and the CRPC6 gamut ........................................................................................................ 47
Run 1: Toyo Kaleido inks using Toyo OSF curved plates .............................................. 48
Run 2 with Toyo Kaleido inks using curved plates ......................................................... 51
Comparison of Toyo Kaleido Run 1 and Run 2 for CMYKR   ........................................ 52
Comparison of Toyo OSF and Toyo Kaleido color gamuts ............................................ 53
Summary and Conclusions ................................................................................................. 57
Further Research ................................................................................................................ 58
References ............................................................................................................................. 60
Appendix I .............................................................................................................................. 66
Steps for Drawdowns ........................................................................................................... 66
Steps for Determining Kaleido SIDs .................................................................................. 67
Appendix II ............................................................................................................................ 68
Test Form Used for Press Run for Toyo OSF and Toyo Kaleido Inks .......................... 68
List of Tables

Table 1. Gamut volume of CRPCs ................................................................. 9
Table 2. Sustrate Values of CRPCs ............................................................... 15
Table 3. Andersson's SID levels .................................................................. 19
Table 4. Effect of increase in SID on color gamut ......................................... 19
Table 5. SIDs of CRPC6 and XCMYK ............................................................ 20
Table 6. Gamut volume in L*a*b* cubic volume ........................................... 21
Table 7. Saturation densities of CMYK of OSF and Kaleido inks .................. 40
Table 8. Statistical test results - saturation densities ....................................... 41
Table 9. CRPC6, Toyo OSF, and Toyo Kaleido SIDs ...................................... 43
Table 10. Repeatability between Run 1 and Run 2 of Kaleido inks .................. 53
Table 11. Gamut volume difference between OSF and Kaleido ..................... 53
Table 12. Statistical test results - chroma ..................................................... 56
List of Figures

Figure 1. Density (d) vs. IFT (w) on the paper. ................................................................. 7

Figure 2. The 7 ISO 15339 RPC gamuts. ........................................................................ 15

Figure 3. Comparison among color gamuts of CRPC6, CRPC7, and XCMYK2017IT8.
   Generated by using ColorThink™ Pro 3.0................................................................. 21

Figure 4. Comparisons among color gamuts of gravure press........................................... 22

Figure 5. Thesis research steps. ......................................................................................... 28

Figure 6. Toyo Kaleido SID determination (Cyan). ............................................................ 30

Figure 7. Cyan ink drawdowns and Spectral Reflectance Curve ....................................... 33

Figure 8. Print density vs. IFT for cyan ink sets................................................................. 34

Figure 9. Magenta ink drawdowns and Spectral Reflectance Curve ................................. 35

Figure 10. Print density vs. IFT for magenta ink sets.......................................................... 36

Figure 11. Yellow ink drawdowns and Spectral Reflectance Curve ................................. 37

Figure 12. Print density vs. IFT for yellow ink sets............................................................. 37

Figure 13. Black ink drawdown and Spectral Reflectance Curves ...................................... 38

Figure 14. Print density vs. IFT for black ink sets............................................................... 39

Figure 15. Toyo Kaleido SIDs determination for Magenta, Yellow, and Black inks............. 42

Figure 16. CRPC6 Solids and overprints color conformance evaluation for Run 1 with
   Toyo OSF inks ................................................................................................................ 44

Figure 17. Tonality and gray balance conformance evaluation for Run 1 with Toyo OSF
   inks ................................................................................................................................ 45
Figure 18. Four 1-D adjustment curves generated in Curve3™ for Run 1 with Toyo OSF inks.......................... 46

Figure 19. Tonality curves for CMY obtained in Run 2 printing with the Toyo OSF inks demonstrating conformance with the G7 specification. ........................................ 47

Figure 20. Gamut borders of CRPC6 and Toyo OSF. ................................................................. 48

Figure 21. Toyo Kaleido inks Solids and overprints demonstrating bends in red and green overprints in Run 1 with Toyo Kaleido inks......................................................... 49

Figure 22. Tonality curves for CMY obtained in Run 1 printing with the Toyo Kaleido inks demonstrating an out of conformance with the G7 specification...................... 50

Figure 23. Four 1-D adjustment curves generated in Curve3™ for Run 2 with Toyo Kaleido inks. ......................................................... 51

Figure 24. A screenshot from the Curve4™ software demonstrating the out-of-conformance behavior for printing with Toyo Kaleido inks. .......................... 52

Figure 25. Gamut comparison between press runs with OSF and Kaleido ink sets. ....... 54

Figure 26. Toyo Kaleido inks demonstrating bends and limiting gamut expansion in red and green overprints......................................................... 55
Chapter 1

Introduction and Statement of the Problem

The problem of communicating and matching color has gripped the printing industry since its inception. In the current printing industry, there is a drive to maximize color gamut for achieving more colorful reproduction. However, there are limitations to achieving pleasing and colorful pictorial reproduction, as well as brand color match. There have been several approaches over the past 30 years to address these limitations and to expand a printed color gamut. These approaches include:

- Printing with higher ink film thickness (IDEAlliance, 2016)
- Using spot colors (Sheth, 2008)
- Printing with more-than-Cyan, Magenta, Yellow and Black (CMYK) inks, e.g., Hexachrome (CMYK + Orange, Green), and 7-color (CMYK + Orange, Green, Violet) (Pantone HEXACHROME)
- Printing with more saturated inks or high-chroma inks (Chung & Hsu, 2006)

Essentially, printing is putting an ink layer on paper. The thickness of this layer, also known as ink film thickness (IFT), is difficult to measure. In printing process control, IFT can be controlled by measuring solid ink density (SID). SID and IFT are directly proportional (using the Tollenaar and Ernst equation) up to a certain density level. However, the relationships between IFT and SID, and between IFT and chroma, are not well understood.
A spot color ink is a specially formulated ink used to achieve a very specific color when printed (Sheth, 2008). Spot colors are generally used as brand or logo colors for their exclusivity of color appearance (Prakhya, 2008), e.g., Coca-Cola Red. Spot color ink is usually chosen with the intent of printing it using one printing unit, one printing plate, and one spot colorant (ISO/CD 19302, 2016). There is a limitation in reproducing spot color accurately by process color printing using only four inks.

Printing with more-than-CMYK inks requires additional printing stations. Using CMYK, in combination with Orange, Green, and Violet (OGV), makes it possible to achieve more colors without using spot colors (Sharma, 2017). However, the set-up of additional printing units lead to extra costs, which must be justified.

Chung and Hsu (2006) achieved extension in the red and green region of the color gamut by increasing ink concentration in the gravure process. However, little research has been conducted using high-chroma inks to expand the process ink gamut for offset printing.

In order to standardize color reproduction and gamut controls for different substrates and applications, the International Organization for Standardization (ISO) provides guidelines for different printing specifications (ISO/CD 15339-1). These specifications are called *Characterized Reference Printing Conditions* (CRPCs), and they differ in gamut volume. According to ISO 15339-2 (2015), a limited set of CRPCs that differ in gamut volume, CRPC1 ~ CRPC7, are typically used for the following printing applications:

- CRPC1 - Newsprint
• CRPC2 - Improved newsprint
• CRPC3 - Utility printing
• CRPC4 - General printing
• CRPC5 - Publication printing
• CRPC6 - Commercial printing
• CRPC7 - Inkjet printing

CRPC7 has the largest gamut volume, which is a specification for inkjet printing technology. CRPC6 is offset-based, but it has a smaller gamut volume. The present research explored the potential to increase the color gamut volume for offset lithography printing using high-chroma inks.

**Problem Statement**

Printing with high-chroma inks has a potential to provide an expanded color gamut for offset printing. After an extensive review of the literature, the question, “Is there a significance difference in color gamut when printing with high-chroma inks, compared to printing with standard inks, in offset lithography printing?” remains unanswered. In order to control the printing process, the relationship between IFT and SID, and the relationship between IFT and chroma, must be understood with respect to high-chroma inks. The purpose of this research was to study the relationship between color gamut volume, metric chroma, IFT, and SID for regular and high-chroma inks in the offset printing process.
**Reason for Interest**

The researcher has worked in the field of color management during her undergraduate course of studies and has continued the same work at the School of Media Sciences (SMS) at Rochester Institute of Technology (RIT). The researcher’s previous project involved exploring the possibility of predicting press calibration in terms of color reproduction results on an offset press by using a Virtual Press Run (Chung et al., 2016). This made her interested in looking into more cost-effective ways to achieve required color reproduction using actual presswork. One of the ways to achieve this goal is to achieve an expanded color gamut with only four inks.
Chapter 2
Theoretical Basis

This chapter provides the theoretical basis required to develop a sound methodology to study high-chroma inks for expanding a CMYK color gamut. The following terminologies, equations, and testing procedures are explained:

- The role of pigment in ink composition
- Ink film thickness (IFT), density, and the Tollenaar and Ernst equation
- Process ink gamut
- Characterized Reference Printing Conditions (CRPCs)
- Press calibration using G7 methodology

The Role of Pigment in Ink Composition

The main components of printing inks are:

- Colorants (i.e., pigments, dyes)
- Vehicles (i.e., binders)
- Additives
- Carrier substances (i.e., solvents) (Kiphan, 2001)

Colorants are divided into these two types:

1. Pigments are organically or inorganically colored, and are insoluble in the ink vehicle. They are solid particles that must be held in suspension in a base liquid.
2. Dyes are organic compounds that are dissolved in a base.
Pigment-based inks are advantageous in terms of their light-fastness and their ability to make stable ink impressions. Printing inks normally contain pigments (with the exception of inks used in inkjet technology), with varying pigment content of 5% to approximately 30%. The content depends on the color tone (Kipphan, 2001).

ISO 2834 specifies the procedures for testing printing inks in laboratory conditions. ISO 2846-1 defines the color and transparency of lithographic printing inks. For each of the inks that were evaluated, a number of test prints needed to be made, each produced at a different IFT, according to the conditions specified in ISO 2834-1. Zhang (2012) studied the relationship between SIDs and IFT. Instead of using the traditional ISO 2834 method of ink sample preparation, he used a graduated gauge, having varying IFTs, and a proof press to prepare ink samples. This research used a graduated gauge and a proof press to prepare ink samples.

**Ink Film Thickness, Density, and the Tollenaar and Ernst equation**

The relationship between IFT and density was modeled on the work of Tollenaar and Ernst (1961).

The Tollenaar and Ernst Equation is formulated as:

\[ d = SD \left[1 - \exp\left(-mw\right)\right] \]

- where SD is the density of an infinitely thick ink film (Saturation Density),
- m is the rate at which the Saturation Density is approached,
- w is the ink layer thickness, and
- d is the density of the print.

As shown in Figure 1, print density (d) depends on IFT (w), the Saturation Density (SD) and the rate at which the SD is approached (m).

SID and IFT are linear until SID approaches its plateau, a state of little or no change. The beginning of the plateau is termed, saturation density. In other words, SIDs cannot be increased indefinitely. When contemplating expansion of color gamut by increasing IFT, an important step is to determine the SD of the inks used.

**Process Ink Gamut and CRPCs**

Ink gamut can be defined as the range of colors that can be interpreted by a color model or generated by a specific device (X-Rite, n.d.). It can also be defined as the range of colors produced by a coloration system which is used to describe an entire range of perceived colors that may be obtained under stated conditions (Berns, Billmeyer &
Saltzman, 2000). Process color gamut refers to a range of colors that a printing device can render using process inks. The full tones (0-100% dots) of process inks (cyan, magenta, and yellow) and their two-color overprints (red, green, and blue) mark the six end points of a device gamut (Chung & Hsu, 2006). The lightness in the CIELAB color scale is symbolized with L*, redness and greenness are expressed as +a* and –a*, respectively, and yellowness and blueness are defined as +b* and –b*, respectively.

The relationship between CMYK values and the color (CIELAB) produced on the printed sheet by those values in a specific printing process is described by CRPCs (ISO/PAS 15339:1, 2015). CRPCs are used to generate ICC profiles with the help of ICC-based profiling software. ICC profiles are specified by the International Color Consortium, and they provide information needed to understand the capabilities of the device (Zhao, 2001). Furthermore, ICC profiles are used to calculate color gamut volume of a CMYK device using profile inspection software, e.g., ColorThink™ Pro (R. Chung, personal communication, February, 2017).

The output color gamuts contain a reference tabulation of the CMYK values corresponding to the CIELAB values for colors that can be reproduced. Such a reference printing condition is known as a dataset. This within-gamut dataset is defined for a printing system under ideal circumstances and is used for data exchange and reference. Each reference printing condition corresponds to a different gamut volume, and they are defined in seven CRPCs (Characterized Reference Printing Conditions 1-7). These CRPCs comprise datasets that effectively address a range of print and paper conditions adopted in modern commercial printing that uses ISO 2846 inks (McDowell, 2012).
Table 1 displays the gamut volume of each CRPC. Using CRPC6 as a reference, the inkjet-based CRPC7 is 35% larger by gamut volume.

### Table 1.

**Gamut volume of CRPCs.**

<table>
<thead>
<tr>
<th></th>
<th>CRPC1</th>
<th>CRPC2</th>
<th>CRPC3</th>
<th>CRPC4</th>
<th>CRPC5</th>
<th>CRPC6</th>
<th>CRPC7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Cubic (Lab)</td>
<td>84,280</td>
<td>151,311</td>
<td>165,764</td>
<td>253,711</td>
<td>331,416</td>
<td>389,023</td>
<td>525,551</td>
</tr>
<tr>
<td>Ratio</td>
<td>0.22</td>
<td>0.39</td>
<td>0.43</td>
<td>0.65</td>
<td>0.85</td>
<td>1.00</td>
<td>1.35</td>
</tr>
</tbody>
</table>

### Press Calibration using G7 Methodology

Press calibration is the process of adjusting a press’s current printing condition to match a set of printing aims (densitometric or colorimetric) (R. Chung, personal communication, February, 2017). Printing aims are derived from a corresponding reference printing condition. These reference printing conditions can be one of the seven CRPCs. Traditional printing aims are based on a specified paper color.

However, CGATS (Committee for Graphic Arts Technology Standards) TR015 defines a paper-independent approach in terms of colorimetric aims. According to the CGATS TR015 specifications,

- the CMY values are specified that result in the “neutral” or gray scale tonal reproduction,
• the CIE L* values of the 3-color (CMY) neutral scale relative to input cyan tonal values (TV) as a function of substrate L* and L* of 3-color solid are specified,

• the CIE L* values of the K (black) scale vs input K TV as a function of substrate and solid L* are specified, and

• finally, the substrate corrected aim CIE a* and b* values of the grey scale are specified (McDowell, 2013).

The G7 press calibration method is the commercial implementation of the process described in TR015. In G7, two printing press runs are involved. Run 1 is carried out by adjusting the solid IFT to produce the specified coloration, according to substrate-corrected colorimetric aims. Run 2 involves generation of G7 adjustment functions, or curves, for output CMYK values using a software tool, e.g., Curve3™ software. These values are then entered in the Raster Image Processor (RIP) during platemaking, and Run 2 is made with new plates containing G7 curves. Assuming that the printing process is repeatable, the G7 press calibration procedure results in the G7 calibrated press conditions.

According to ISO 15339, all seven CRPCs adhere to a common neutral appearance (gray). For this reason, this research followed the G7 press calibration procedure to achieve a larger-than-CRPC6 color gamut using an offset press and high-chroma inks.
Summary of Theoretical Background

This section provided the theoretical background of ink composition, IFT, density, the Tollenaar and Ernst Equation, process ink gamut, CPRCs, and G7 press calibration. Key points are summarized below:

- Pigment provides the ink with color. An increase in pigment results in a more colorfulness and an increased chroma in printed color.
- Saturation Density is the limiting factor of IFT for reaching higher density values.
- Process ink gamut refers to the range of colors reproduced by a CMYK device. CRPC is a look-up table relating the input tonal values and their corresponding color values, e.g., CMYK to CIELAB.
- G7 is a press calibration method that provides common neutral appearance across different printing devices.

This study used a graduated gauge and a proof press to prepare ink samples. This study used Tollenaar’s model to explore the influence of pigment on SID and its resulting color gamut under G7 calibrated press conditions.
Chapter 3

Literature Review

The literature review chapter begins with an overview of why colorfulness in an image is desirable and how chroma plays an important role in determining the color gamut. The next section discusses the origin of expanded color gamut in the early 1990s, followed by the review of the various studies on expanding a process ink gamut. The chapter concludes with the discussion on how to achieve an increased color gamut (considering the factors discussed in previous studies) and how the factors lead to the formulation of the present research.

Color, Colorfulness, and Chroma

Color is one of the basic qualities to measure and determine print quality (Sheth, 2013). The colorfulness of packaging, newspapers, magazines, or any other printed material can be a significant factor in the eyes of purchasers when deciding whether or not to buy a product. Hunt (1977) proposed the term, colorfulness, to represent the characteristic of a visual sensation according to which an area appears to exhibit more or less chromatic color for a given chromaticity. Achieving a high colorfulness to an image is always desirable, as higher chroma produces more vivid and saturated colors. Chroma (C*) plays an important role in color gamut, as shown by Sheth (2013). He calculated the chroma effect on a color gamut for different ink overprints of different ink sequences. In color reproduction, color characteristics (including chroma) are limited by the device gamut, which depends on the number and properties of primaries, i.e., color pigments or
inks used in printing. This is where printing to an expanded color gamut condition is required.

During the early 1990s, Davis and Carli (as cited in Andersson, 1997) introduced the term, *HiFi color printing*. By definition, HiFi color is printing with a color gamut larger than normal process color printing. This implies changes or addition to a standard four-color process ink-set in order to achieve greater visual impact and better color reproduction (Hutcheson, 1999). Some of the benefits of using HiFi printing are:

- Consumer packages printed with HiFi sell more because they catch a consumer’s eye more effectively.
- An ad or a magazine cover printed with HiFi is more likely to capture a reader’s attention.
- The expanded gamut of HiFi helps fine art printers to achieve color match to the originals with bright and saturated colors (Hutcheson, 1999).

However, Hutcheson (1999) states that it is more difficult and expensive to produce more than four-color printing due to the need for extra plates and printing units, and added equipment and material costs. This accounted for the scarcity of HiFi printers and the HiFi printing market during that period.

**Ways to Achieve Expanded Color Gamut Printing Condition**

This section discusses these methods to expand a process ink gamut:

- Change of substrate
- Number of primaries
- Amount of IFT
• Increase pigment concentration

• Type of screening

Change of Substrate

Each reference printing condition is based on different applications using these substrates:

• CRPC1 - ColdsetNews

• CRPC2 - HeatsetNews

• CRPC3 – PremUncoated

• CRPC4 – Super Cal

• CRPC5 - PubCoated

• CRPC6 - PremCoated

• CRPC7 - Extra Large (McDowell, 2012)

Table 2 shows the lightness (L*) values of different substrates based on each CRPC. There are also studies that discuss how the substrate whiteness affects the color gamut. The profiles have been copyrighted by X-Rite Inc., and the target data are available to download online at www.color.org.
Table 2.
Substrate values of CRPCs.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Paper</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRPC1</td>
<td>ColdsetNews</td>
<td>85</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>CRPC2</td>
<td>HeatsetNews</td>
<td>87</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>CRPC3</td>
<td>PremUncoated</td>
<td>95</td>
<td>1</td>
<td>-4</td>
</tr>
<tr>
<td>CRPC4</td>
<td>SuperCal</td>
<td>89</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>CRPC5</td>
<td>PubCoated</td>
<td>92</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CRPC6</td>
<td>PremCoated</td>
<td>95</td>
<td>1</td>
<td>-4</td>
</tr>
<tr>
<td>CRPC7</td>
<td>Extra Large</td>
<td>98</td>
<td>1</td>
<td>-4</td>
</tr>
</tbody>
</table>


Figure 2 shows the gamut of each of these seven CRPCs conditions determined by paper, ink, and process capability (McDowell, 2012)
As seen in Table 2 and Figure 2, it can be said that the brighter the substrate is, the larger the color gamut will be. Paper manufacturers can also make substrates brighter by adding artificial whiteners, also known as optical brightening agents (OBAs). The addition of an OBA in a substrate is desired by print buyers, but it complicates printing conformity (Changlong, 2014). For example, it has been investigated that cyan and magenta display more blueness on an OBA paper than they display on a paper without an OBA (Chung & Tian, 2011). Alternatively, the size of the color gamut is also limited by the saturation of the ink colorants. Furthermore, paper white can be considered as a fifth color since it affects the saturation and hue of the colorants. After studying the interaction between substrates, ink, and color gamut, the researcher determined that the current research would be printed on Endurance Gloss, a PremCoated stock, and with CMYK high-chroma inks. The Endurance Gloss stock used in the research has colorimetric values: 96.1/1.9/-6.4 (measured with X-Rite i1Pro spectrophotometer). As seen in Table 2, CRPC6 specifies PremCoated stock with values: 95/1/-4. The Endurance Gloss stock is well within the permissible tolerance of ISO/PAS 15339-1.

Number of Primaries

This section discusses the number of colors that can be used to expand color gamut.

4-Color. This process adds a second plate of cyan, magenta, yellow and black to regular CMYK plates, e.g., DuPont’s HyperColor.

6-Color. Hexachrome, CMYK plus Orange and Green, is capable of covering about 90% of the Pantone color palette.
Costa (2004) compared PANTONE Hexachrome and 4-color printing processes. He concluded that Hexachrome has more colorfulness in pictorial color reproduction than 4-color printing has.

Politis et al. (2015) reviewed the developments and trends in expanded gamut printing and assessed its feasibility for commercial printing. When reviewing the PANTONE Hexachrome, they observed that, due to the use of additional colors, color gamut substantially increased and photographic images were reproduced with higher accuracy and more vibrancy (U.S. Patent Application No. US 14/413,979).

7-Color. Equinox is Esko’s solution for the implementation of expanded gamut printing. The press is standardized on CMYK+ 2 or 3 extra inks (e.g., orange/green/blue). The benefits of expanded gamut printing are:

- Reduced press downtime
- Reduced wash-ups on the press
- Higher productivity in the press room
- Reduced ink stock

Sharma (2017) discusses the benefits of expanded color gamut printing using 7 colors. According to Sharma, using CMYK in combination with Orange, Green, and Violet (OGV) makes it possible to achieve more colors without using spot colors, therefore providing options for cost effectiveness using process color printing and ganging printing jobs.
Andersson (1997) studied factors that influence color gamut and studied three of those factors in detail. According to Andersson, methods to obtain a larger color gamut without using more than four process inks are:

- Increased SID
- Process inks with more ideal reflection and absorption of the light
- Use of fluorescence in the printing inks
- Choice of screening method
- Increased transparency of the ink
- Better wet trapping
- Higher paper quality
- Higher pigment concentration in the ink

Andersson investigated how the ink set, SID, and screening method influenced the color gamut individually and in combination. He used two ink sets in the experiment, both having four CMYK inks. The standard ink set was the normal sheet-fed ink, and the alternative ink set had magenta and yellow inks with fluorescence. Andersson then determined three levels of SIDs from low to high, using an IGT tester for all the inks. He compared the color gamut volume at all SID levels with both amplitude-modulated (AM) and frequency-modulated (FM) screening. His experiment showed that an increase in SIDs increases colorfulness of all colors, but also decreases the lightness.

Andersson used the method of increasing SIDs (by increasing IFT) as one of the ways to achieve an expanded color gamut condition. Table 3 shows the densities used in
his study. Table 4 shows the summary of effect of increase in SID on color gamut. He concluded that there is significance difference in color gamut volume when the SID is increased. He also concluded that FM screening is an effective solution to increase the color gamut.

Table 3.

*Andersson’s SID levels.*

<table>
<thead>
<tr>
<th></th>
<th>Black</th>
<th>Cyan</th>
<th>Magenta</th>
<th>Yellow</th>
</tr>
</thead>
<tbody>
<tr>
<td>SID Level 1</td>
<td>1.75</td>
<td>1.85</td>
<td>1.40</td>
<td>1.00</td>
</tr>
<tr>
<td>SID Level 2</td>
<td>1.85</td>
<td>1.85</td>
<td>1.60</td>
<td>1.15</td>
</tr>
<tr>
<td>SID Level 3</td>
<td>1.85</td>
<td>1.20</td>
<td>1.80</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Table 4.

*Effect of increase in SID on color gamut.*

<table>
<thead>
<tr>
<th>SID Level 1</th>
<th>AM screening</th>
<th>FM screening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Gamut increase</td>
<td>Mean Gamut increase</td>
</tr>
<tr>
<td>Gamut Volume</td>
<td>512866 Reference</td>
<td>547219 7%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SID Level 2</th>
<th>AM screening</th>
<th>FM screening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Gamut increase</td>
<td>Mean Gamut increase</td>
</tr>
<tr>
<td>Gamut Volume</td>
<td>578596 13%</td>
<td>653381 27%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SID Level 3</th>
<th>AM screening</th>
<th>FM screening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Gamut increase</td>
<td>Mean Gamut increase</td>
</tr>
<tr>
<td>Gamut Volume</td>
<td>592482 16%</td>
<td>679765 33%</td>
</tr>
</tbody>
</table>

19
An important point to note in Andersson’s study is that it did not have an industry standards (such as ISO 15339) to compare the expanded gamut results with. The current research overcame this by comparing the expanded color gamut volume with CRPC6 and CRPC7. Furthermore, the ongoing research used the Tollenaar and Ernst equation to understand the effect of increasing IFT on SIDs.

A study, XCMYK Expanded -Gamut CMYK Beta Program, conducted by IDEAlliance (2016), aimed at increasing C, M, Y, K solid ink densities above traditional levels without unwanted side effects for the offset printing. One of the goals of the program was to identify practical solid CIELAB target values so that a new dataset could be developed, based on the outcome of the project. In this study, standard CMYK inks were used with higher IFT and FM screening. However, this research did not provide any explanation on how to achieve the XCMYK SID aims. The SID aims of CRPC6 and XCMYK are shown in Table 5. IDEAlliance released the new dataset for the project, XCMYK2017IT8 (IDEAlliance, 2016). The projected XCMYK gamut is 46% larger than CRPC6 gamut, as shown in Table 6, using ColorThink™ Pro 3.0 software.

Table 5.

<table>
<thead>
<tr>
<th>SID</th>
<th>CRPC6</th>
<th>XCMYK</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.4</td>
<td>1.85</td>
</tr>
<tr>
<td>M</td>
<td>1.4</td>
<td>1.85</td>
</tr>
<tr>
<td>Y</td>
<td>1.0</td>
<td>1.20</td>
</tr>
<tr>
<td>K</td>
<td>1.7</td>
<td>2.0</td>
</tr>
</tbody>
</table>

SIDs of CRPC6 and XCMYK.
Table 6.

Gamut volume in $L^*a^*b^*$ cubic volume.

<table>
<thead>
<tr>
<th>Color Gamut</th>
<th>Gamut Volume</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRPC6</td>
<td>389,309</td>
<td>1.0</td>
</tr>
<tr>
<td>XCMYK2017</td>
<td>569,984</td>
<td>1.46</td>
</tr>
<tr>
<td>CRPC7</td>
<td>525,551</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Figure 3 illustrates the color gamut volume in $a^*$ vs $b^*$ plots of CRPC6, CRPC7 and XCMYK2017IT8. The figure was generated using ColorThink™ Pro 3.0 using ICC profiles of CRPC6, CRPC7 and XCMYK2017. These profiles are available to download from https://www.idealliance.org/gracol/.

Figure 3. Comparison among color gamuts of CRPC6, CRPC7, and XCMYK2017IT8. Generated by using ColorThink™ Pro 3.0
Increase Pigment Concentration

A possibility to expand gravure printing color gamut by adjusting pigment concentrations was investigated by Chung and Hsu (2006). They measured the metric Chroma (C*) of CMY solids to identify the optimized gamut corners. Figure 4 shows a comparison of the color gamut of the gravure press under its initial inking (shown by the dotted line) and increased concentration (shown by the solid line) condition. The major change between the two gamut conditions is the expanded chroma of the yellow ink. Red and green regions of the gamut are also expanded. The effects of expanded color gamut using the method of Chung and Hsu were observed in pictorial color image reproductions, where red and green hues appeared more colorful.

Toyo Ink America corporation has developed high-chroma inks, Toyo Kaleido inks, that are specially formulated for the waterless offset printing and that have higher pigment concentration (Toyo, 2008). The inks are formulated to expand the CMYK gamut and to provide similar results to 6- or 7-color printing using a 4-color process. These inks aim to offer richer, deeper colors than conventional 4-color process inks offer. However, there is no published case study to support that claim.

Type of screening

There are two halftone screening methods used in the graphic arts (Kipphan, 2001). AM screening is defined as periodic screening that simulates continuous tones by using individual dots that are spaced the same distance apart, but have different diameters and shape (periodic screening). FM screening is a method of screening whereby the individual dots have the same diameter, but are placed at different distances apart (non-periodic screening).

Three studies are reviewed in this research to compare color gamuts achieved by two different screening methods.

Paul and Rosenberg (1999) studied the improvement in color gamut when using FM screening. They determined that, “compared to the conventionally screened prints, areas of equal tone value showed a higher chroma and/or lightness when FM-screened, especially in the midtone region” (p. 595). They performed color measurements on FM prints and AM prints. They found that in prints with FM screening, the midtone range of ink density values exhibited higher lightness at the same chroma levels. They attributed the reason for this to be a uniform distribution of ink on paper.
Janjomsuke (2004) compared color gamut between AM and FM screening. He analyzed press sheets from the first and the second Heidelberg Sunday 2000 test runs for the publication of Test Targets 4.0. It was found that the FM screening produced a larger color gamut than conventional AM screening produced when using the same inks, substrates, and a press.

Sigg (2017) demonstrated that FM screening results in more saturated pastel colors when compared to AM screening. Sigg attributes this to the use of thinner ink film by FM dots, compared to the use of thicker ink film by AM dots. In order to produce a given tone value, the FM dots, being lighter, need to cover more paper than AM dots do. Therefore, a continuous tone ink transfer will cover more paper with FM screening. This results in more saturated colors and an increase in color gamut.

Summary of Literature Review

A number of studies were reviewed as a part of literature review for the current research. It began with discussion on the importance of chroma and how it affects the color gamut. The section then explored various studies carried out to achieve an expanded color gamut condition. The key points of this literature section are related to:

- **Substrate**: The substrate color affects color gamut. The present research used Endurance Gloss stock that conforms to CRPC6 tolerances.

- **IFT**: Expanding color gamut by printing with four inks can be done by printing at higher solid ink densities (SIDs) and printing with high-chroma inks. This research achieved an expanded color gamut using high-chroma inks.
Type of screening: Studies have shown that better color gamut expansion is obtained with FM screening, compared to AM screening. Therefore, this research used FM screening in the experiments.
Chapter 4
Research Objectives

This research investigated how an expanded color gamut can be achieved by printing with high-chroma ink for offset printing. To this end, this research looked at the parameters of IFT that were found to influence color gamut in the offset printing process. The aim was to study the change in color gamut volume, while changing the parameters of ink. The comparison was carried out quantitatively through examining printed samples.

The two research questions addressed in this Thesis are:

1. Is the saturation density (SD) of high-chroma inks significantly larger than that of standard inks?
2. Is the color gamut of the high-chroma ink set significantly larger than that of the standard ink set?
Chapter 5
Methodology

This research compares the Saturation Density and gamut volume achieved by offset printing with standard and high-chroma inks. To understand the relationship between ink film thickness (IFT), solid ink density (SID), and metric chroma (C*) of CMYK solids, an experiment is carried out on the Little Joe proofer (H model) with a graduated grind gage (0-10-micron range), a steel scraper, and Tango C1S paper.

To attain a larger-than-CRPC6 gamut, Presstek’s 52DI waterless offset printing press is used to obtain test prints. The experiment is conducted with two printing conditions where the first printing condition uses Toyo OSF (standard) inks, and the second printing condition uses Toyo Kaleido (high-chroma) inks using the Endurance Gloss paper. The difference in gamut volume with both ink sets is calculated using ColorThink™ Pro 3.0 software.

Thesis Research Steps

Figure 5 is a workflow diagram showing all the steps in the research. A detailed explanation of the research steps follows the diagram.
Step 1. Conduct ink drawdowns with Little Joe proofer for Toyo Standard and Kaleido ink using Tango C1S paper

Step 2. Analyze the drawdowns

Step 3. Investigate the relationship between SID (SID) and IFT (IFT) using Tollenaar & Ernst equation to answer the first research question

Step 4. Determine SID for printing with Toyo Kaleido ink-set

Step 5. Calibrate press according to G7 specification using 52DI offset press with Toyo Standard inks and Toyo Kaleido inks using Endurance Gloss paper

Step 6. Create printer profiles for both ink sets and conduct colorimetric analysis

Step 7. Calculate color gamut volumes for Toyo OSF and Toyo Kaleido inks to answer the second research question

Figure 5. Thesis research steps.
Step 1

The drawdowns experiment was conducted in the Printing Applications Laboratory (PAL) at RIT. A Little Joe Proofer was used. The methodology to produce samples was derived from Zhang’s 2012 study; the description and steps for the proofer are discussed in detail in Appendix 1.

Step 2

To investigate the relationship between IFT, SID, and C* of CMYK solids, colorimetric analyses of the drawdowns were carried out. Spectral Reflectance Curves (SRC) for CMYK inks were plotted. SRCs determined the color of a surface (e.g., paper) by demonstrating reflectance of light from a substrate throughout the visible spectrum (380 to 740 nm) (PrintWiki, n.d). This analysis includes plots of C* (Chroma) vs. IFT and C* vs. SID, for cyan, magenta and yellow inks of both ink sets. For black, L* vs. IFT and L* vs. SID plots were used instead.

Step 3

The plots in Step 2 were used to determine SID vs. IFT for CMYK inks of the Toyo OSF and Toyo Kaleido ink sets. These plots determined SD of both ink sets and helped to Research Question 1 of the current study. The research used statistical modeling software, JMP 13 Pro. Non-linear modeling was used to determine the Saturation Density for all eight inks based on the Tollenaar and Ernst equation.

Step 4

There are no available SID values for using Toyo Kaleido inks on an offset press. To provide further help in determining SID, an IFT vs. SID graph was used. For the OSF
press run, the starting solid ink densities were the same as CRPC6. For the Kaleido press run, a ray-tracing technique was used to determine the starting Kaleido SID having the same IFT as the OSF inks. Figure 6 illustrates the Cyan SID determination. Refer to Appendix II for the ray-tracing technique steps.

Figure 6. Toyo Kaleido SID determination (Cyan).

**Step 5**

The G7 calibration was performed for each of the ink sets, namely Toyo OSF and Toyo Kaleido, on Endurance Gloss substrate using FM screening with Momentum RIP on Presstek’s 52DI waterless offset press.

The G7 methodology followed these steps:

1. The test forms for Toyo OSF and Toyo Kaleido were the same. Page 1 of the test form included IT8.7/4 target, P2P51 calibration target, and 10-patch target. G7 calibration involved two press runs for each of the ink set.

2. Run 1 involved printing of Page 1 without any color management adjustments to understand the press’s original condition when printing to specified SIDs.
3. P2P51 calibration target on Page 1 was measured with i1 Pro2 spectrophotometer in terms of colorimetric values (CIELAB).

4. The above colorimetric data were then used to derive adjustment curves to attain G7 conformance. These curves were calculated by Curve3™ software.

5. Run 2 used these adjustment curves (put in through RIP) to print Page 1 again.

6. The colorimetric values of adjusted P2P51 target were then measured. These measurement data points constituted an input to the Curve3™ software to verify whether a neutral gray appearance of CMY solids was achieved and whether the press was passing G7 conformance requirements.

Step 6

The press run on 52DI waterless offset involved printing a test form using Endurance Gloss paper with an IT8.7/4 Printer Profiling Target that was used for colorimetric analysis and for constructing printer ICC profile via i1 Profiler software. X-rite’s i1 Pro 2 and i1 ISis 2 (M1 measurement conditions) were used. Based on these measurements, color gamut and density values were calculated. Colorimetric analyses were performed in Microsoft Excel, i1 Profiler and CHROMiX ColorThink™ 3.0 Pro software.

Step 7

The printer profiles for both ink sets created in Step 6 were used in ColorThink™ Pro 3.0. This software displays color gamut volume and also various plots in order to answer the Research Question 2, i.e., if there is a significant gamut volume difference between the Toyo OSF and the Toyo Kaleido inks. The difference between gamut
volume of these two ink sets were calculated to answer Research Question 2 of the current research.

**Key Variables**

The two printing conditions utilizing different inks that were used to evaluate color gamut and density are:

- Printing with Toyo OSF inks (standard)
- Printing with Toyo Kaleido inks (high-chroma)

Therefore, the independent variable is the ink pigment condition with two levels.

The dependent variables in this experiment are: Saturation Density and Color Gamut Volume.
Chapter 6

Results

To answer the research questions (whether the Saturation Density of high-chroma [Toyo Kaleido] inks is significantly larger than that of standard inks [Toyo OSF], and the color gamut of the high-chroma ink sets is significantly larger than the color gamut of the standard ink sets) the analysis of each ink-set, standard and high-chroma, was performed.

The detailed analysis of each of the inks is described below.

As seen in Figure 7, left, Kaleido cyan ink appears more saturated and intense than the OSF cyan ink. When the reflectance spectra of these inks are plotted, one can see that Kaleido cyan ink shows relatively more absorption in the long wavelength (red) region, compared to the OSF cyan.
Figure 8. Print density vs. IFT for cyan ink sets.

Figure 8 shows the relationship between IFT and Print density of both cyan inks. The points on the graph represent the measurements obtained through the drawdowns. The regression lines are generated using JMP software. For a given IFT, the Kaleido SID for cyan is higher than the OSF SID cyan. Using Tollenaar and Ernst equation and non-linear modeling in JMP, the calculated SD of OSF cyan ink equals 1.68, and that of Kaleido cyan ink is 2.35.
Figure 9. Magenta ink drawdowns (left) and spectral reflectance curve (right).

As seen in Figure 9, Toyo OSF and Toyo Kaleido magenta inks display different light reflectance characteristics. There is an increased reflectance in short (blue) wavelengths region and decreased reflectance in medium-long wavelengths region of the spectrum. As a result, Kaleido magenta inks appear more saturated and less red, compared to the OSF magenta inks. These characteristics are considered desirable because they improve color reproduction in blue region of the color gamut.
Figure 10. Print density vs. IFT for magenta ink sets.

Figure 10 shows the relationship between IFT and print density of both magenta inks. The points on the graph represent the measurements obtained through the drawdowns. The regression lines are generated using JMP software. For a given IFT, the Kaleido SID for magenta is higher than the OSF SID. Using the Tollenaar and Ernst equation and non-linear modeling in JMP, the calculated SD of OSF magenta ink equals 1.66 and that of Kaleido magenta ink is 1.77.
Figure 11. Yellow ink drawdowns (left) and spectral reflectance curve (right).

As seen in Figure 11, the appearance of the yellow inks is similar. This similarity of appearance is based on the similar spectral reflectance characteristics. The maximum reflectance is in the medium and long wavelength, and the minimum reflectance is in the short wavelength of the spectrum.

Figure 12. Print density vs. IFT for yellow ink sets.
Figure 12 shows the relationship between IFT and print density for both the OSF and Kaleido yellow inks. The points on the graph represent the measurements obtained through the drawdowns. The regression lines are generated using JMP software. Unlike in the case of cyan and magenta inks, the Kaleido SIDs are lower than those of OSF inks in the region below 5microns. As IFT exceeds 5 microns, the Kaleido SID for yellow is higher than the OSF SID is. Using the Tollenaar and Ernst equation and non-linear modeling in JMP, the calculated SD of OSF yellow ink equals 1.16 and that of Kaleido yellow ink is 1.59.

![OSF vs Kaleido](image)

*Figure 13. Black ink drawdown (left) and spectral reflectance curves (right).*

The drawdowns shown in Figure 13 appear visually similar. Both ink sets show similar spectral reflectance characteristics, and the reflectance is nearly constant across the entire spectrum.
**Figure 14.** Print density vs. IFT for black ink sets.

Figure 14 shows the relationship between IFT and print density. The points on the graph represent the measurements obtained through the drawdowns. The regression lines are generated using JMP software. Unlike for cyan, magenta and yellow inks, the Kaleido SIDs for black are lower than corresponding OSF SIDs. Using the Tollenaar and Ernst equation and non-linear modeling in JMP, the calculated SD of OSF black ink equals 2.12 and that of Kaleido black ink is 1.84. The SDs of CMYK of OSF and Kaleido inks are listed in Table 7.
Table 7.

*Saturation densities of CMYK of OSF and Kaleido inks.*

<table>
<thead>
<tr>
<th></th>
<th>SD OSF</th>
<th>SD Kaleido</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.68</td>
<td>2.35</td>
</tr>
<tr>
<td>M</td>
<td>1.66</td>
<td>1.77</td>
</tr>
<tr>
<td>Y</td>
<td>1.16</td>
<td>1.59</td>
</tr>
<tr>
<td>K</td>
<td>2.12</td>
<td>1.84</td>
</tr>
</tbody>
</table>

To answer Research Question 1, regarding the significant difference between saturation densities for both ink sets, a t-test was used to compare the resulting SD values. The null hypothesis ($H_0$) assumes there is no significant difference in the saturation densities of standard and high-chroma inks. The alternative hypothesis ($H_1$) claims that there is significant difference. To accept or reject the null hypothesis, the p-value from the t-test was used. The p-value represents the probability of the variables being drawn from the same distribution. If the p-value is below 0.05, the null hypothesis ($H_0$) is rejected.

To calculate the t-statistics, the following formula was used:

$$t = \frac{b_{02} - b_{01}}{\sqrt{(std\ error_1)^2 + (std\ error_2)^2}}$$

where $b_{01}$ is the value of Saturation Density for Toyo OSF; $b_{02}$ is the value of Saturation Density for Toyo Kaleido, established using non-linear modeling; and $std\ error_1$ and $std\ error_2$ are standard error values for each ink-set obtained from the non-linear modeling.
The raw data from ink drawdowns and non-linear modeling in JMP software was used for each ink to determine SD values for CMYK inks for both Toyo OSF and Toyo Kaleido. Next, one tail t-test was performed at the 0.05 level of significance. As shown in Table 8, as the p-value was less than 0.05, the null hypothesis was rejected. This indicates that there is a significant difference between the SDs of Toyo OSF and Toyo Kaleido inks.

Table 8.

*Statistical test results – saturation densities*

<table>
<thead>
<tr>
<th>Primary</th>
<th>SD OSF</th>
<th>Std Error_OSF</th>
<th>SD Kaleido</th>
<th>Std Error_Kaleido</th>
<th>t value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.68</td>
<td>0.02</td>
<td>2.35</td>
<td>0.03</td>
<td>16.59</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>M</td>
<td>1.66</td>
<td>0.04</td>
<td>1.77</td>
<td>0.03</td>
<td>2.09</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Y</td>
<td>1.16</td>
<td>0.01</td>
<td>1.59</td>
<td>0.06</td>
<td>6.70</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>K</td>
<td>2.12</td>
<td>0.04</td>
<td>1.84</td>
<td>0.04</td>
<td>-5.07</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
Figure 15 shows the results of determination of Kaleido SIDs for magenta, yellow, and black inks.

Figure 15. Toyo Kaleido SIDs determination for Magenta, Yellow, and Black inks. Inks are designated with their corresponding colors.

The results of Step 4 of the methodology are discussed in Table 9 below. The solid ink densities for Toyo Kaleido inks, having the same IFT as the OSF inks, were determined to be as shown. Regarding the anomaly of the black ink finding, according to
the ink expert, the black inks for high-chroma and standard inks should be very similar and they should exhibit nearly identical behavior. Therefore, the observed difference was attributed to batch-to-batch variation. Based on the data obtained in the present research, the Kaleido black ink should be printed as high as possible in the press run.

Table 9.

*CRPC6, Toyo OSF, and Toyo Kaleido SIDs.*

<table>
<thead>
<tr>
<th></th>
<th>CRPC6 SID</th>
<th>Toyo OSF SID</th>
<th>Toyo Kaleido SID</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.40</td>
<td>1.40</td>
<td>1.82</td>
</tr>
<tr>
<td>M</td>
<td>1.40</td>
<td>1.40</td>
<td>1.62</td>
</tr>
<tr>
<td>Y</td>
<td>1.00</td>
<td>1.00</td>
<td>1.06</td>
</tr>
<tr>
<td>K</td>
<td>1.70</td>
<td>1.70</td>
<td>1.52</td>
</tr>
</tbody>
</table>

To answer Research Question 2, regarding the significant difference in color gamut volumes, the calibration of the waterless offset press using two printing inks was performed, and the resulting color gamuts were compared. The press was calibrated to G7 specifications with two printing conditions to satisfy solids, gray balance, tone reproduction, and dataset conformance requirements:

- Condition 1: Printing with the Toyo OSF inks (reference color gamut);
- Condition 2: Printing with the Toyo Kaleido inks (expanded color gamut).

The G7 calibration process and the obtained results are described below in detail.
Condition 1: Printing with the Toyo OSF inks (reference color gamut)

Refer to Appendix II for the test form used for Run 1 and Run 2 for Toyo OSF inks.

Run 1 with Toyo OSF inks using linear plates

Testing conformance to CRPC6 solids and overprint colors. Figure 16 represents the screenshot from Curve3™ software showing the gamut corners for solid cyan, magenta, and yellow, and overprint red, green, and blue colors (CMYRGB). As seen, those colors are located within the yellow circles that correspond to the CRPC6 tolerances. Therefore, the solid colors conform to the substrate-corrected CRPC6 solid aims.

![Figure 16. CRPC6 Solids and overprints color conformance evaluation for Run 1 with Toyo OSF inks.](image)

Testing conformance to CRPC6 tonality and gray balance. As seen from screenshot from Curve3™ in Figure 17, the tonality curves for CMY are out of
conformance for Run 1. The acceptable G7 tolerance values are listed as average wΔL* = 1.5 and maximum wΔL* = 3.0. However, for the tested condition the corresponding values (highlighted in red) exceed the tolerance levels. At the same time, the CMY a*, CMY b* and CMY ∆Ch are close to 0 (highlighted in green), i.e., they are close to neutral position, which means that the gray balance is in conformance.

![Image](image_url)

*Figure 17.* Tonality and gray balance conformance evaluation for Run 1 with Toyo OSF inks. Out of conformance values are highlighted in red, in-conformance values are highlighted in green.

*Adjusting tone reproduction and gray balance.* To adjust the tone reproduction, four 1-D adjustment curves are generated using Curve 3 (Figure 18).
Figure 18. Four 1-D adjustment curves generated in Curve3™ for Run 1 with Toyo OSF inks.

Run 2 with Toyo OSF inks using curved plates

Verifying tonality and gray balance for G7 conformance. Figure 19 shows that Run 2 conforms to G7 Gray. This indicates that the Presstek 52DI press reproduces neutral grays using CMY inks with no visible color bias. All the values are highlighted in green.
Figure 19. Tonality curves for CMY obtained in Run 2 printing with the Toyo OSF inks demonstrating conformance with the G7 specification.

Comparison of Toyo OSF and CRPC6 color gamut after Run 2. Figure 20 illustrates the comparison of the gamut between the G7 calibration process with the OSF inks and the CRPC6 gamut.
Figure 20. Gamut borders of CRPC6 and Toyo OSF.

**Condition 2: Printing with the Toyo Kaleido inks (expanded color gamut)**

Refer Appendix II for the test form used for Run 1 and Run 2 for Toyo Kaleido inks.

*Run 1: Toyo Kaleido inks using Toyo OSF curved plates*

There is no standard for larger-than-CRPC6 gamut condition for offset printing. Therefore, there are no SID for Toyo Kaleido inks. The goal for Run 1 for Toyo Kaleido inks is to evaluate the solids and overprint behavior. In addition, Run 1 is printed using the OSF curved plates to find out if it meets tonality and gray balance requirements in accordance with the G7 methodology.
Evaluation of the Kaleido color gamut. For the Toyo Kaleido inks, SID aims are specified based on the ink drawdowns and are presented in Table 9. Figure 21 shows the gamut corners for Kaleido solid cyan, magenta, and yellow, and overprint red, green, and blue colors (CMYRGB).

Figure 21. Toyo Kaleido inks Solids and overprints demonstrating bends in red and green overprints in Run 1 with Toyo Kaleido inks.

Unlike for the Toyo OSF inks, Toyo Kaleido inks display two distinct “bends” in the green and red overprint ramps. This is attributed to the fact that ink additive from Toray was used to fix background tinting (in cyan and yellow) caused by the viscosity of the high-chroma Kaleido inks. The presence of the blue pigment in the magenta ink (Rubine) has resulted in the deviation of magenta ramp towards the blue region. The positions of cyan, yellow and blue colors on the graph extend beyond the CRPC6
standard tolerance values toward more saturated colors. This observation is in accordance with the expected results.

*Evaluation of tonality and gray balance.* Figure 22 shows that the tonality curves for CMY are out of conformance, slightly exceeding the G7 aims. Out-of-conformance values are highlighted in red and in-conformance values are shown in green.

![Figure 22. Tonality curves for CMY obtained in Run 1 printing with the Toyo Kaleido inks demonstrating an out of conformance with the G7 specification.](image)

*Adjusting tone reproduction and gray balance.* To adjust the tone reproduction, four 1-D adjustment curves are generated using Curve3™ (shown in Figure 23).
Figure 23. Four 1-D adjustment curves generated in Curve3™ for Run 2 with Toyo Kaleido inks.

Run 2 with Toyo Kaleido inks using curved plates.

Verifying tonality and gray balance for G7 conformance. Figure 24 shows that Run 2 does not conform to G7 Gray balance. Almost all the values listed in the Figure 25 are highlighted in red. Four 1-d adjustment curves applied in Run 2 did not fix the bends. This was determined by evaluating the gray balance portion of the Figure 23. The spikes can be seen at around 85% tonal values, which result in the bends seen in Figure 24.
Figure 24. A screenshot from the Curve4™ software demonstrating the out-of-conformance behavior for printing with Toyo Kaleido inks.

Comparison of Toyo Kaleido Run 1 and Run 2 for CMYKRGB

Table 10 shows the L*a*b* values for solid CMYK inks and RGB overprints, and ΔE00 differences between Run 1 and Run 2. As seen in Table 10, while CYMK have reasonable repeatability, large differences are observed for the two-color overprints, especially green and red. This can be explained by the bends observed in red and green overprints due to the additives described earlier, which cannot be properly controlled.
Table 10.

*Repeatability between Run 1 and Run 2 of Kaleido inks.*

<table>
<thead>
<tr>
<th>Solids</th>
<th>Kaleido_Run1</th>
<th>Kaleido_Run2</th>
<th>∆E 00</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>46.9</td>
<td>47.5</td>
<td>5.8</td>
</tr>
<tr>
<td>M</td>
<td>46.6</td>
<td>46.9</td>
<td>1.7</td>
</tr>
<tr>
<td>B</td>
<td>18.4</td>
<td>18.8</td>
<td>2.1</td>
</tr>
<tr>
<td>C</td>
<td>47.9</td>
<td>51.1</td>
<td>3.4</td>
</tr>
<tr>
<td>G</td>
<td>41.2</td>
<td>42.9</td>
<td>6.3</td>
</tr>
<tr>
<td>Y</td>
<td>88.7</td>
<td>88.0</td>
<td>1.4</td>
</tr>
<tr>
<td>R</td>
<td>46.9</td>
<td>47.5</td>
<td>5.8</td>
</tr>
<tr>
<td>K</td>
<td>10.9</td>
<td>7.4</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Comparison of Toyo OSF and Toyo Kaleido color gamuts

To answer the Research Question 2, regarding the significant difference between the gamut volume of two ink sets, the gamuts of Toyo OSF and Toyo Kaleido are calculated and compared. Table 11 provides data for OSF and Kaleido conditions in terms of L*a*b* coordinates for CMYKRGB, gamut volumes, and gamut volume differences between these conditions. As seen in the table, the color gamut of Run 2 using Kaleido inks is 20% larger than when OSF inks were used.

Table 11.

*Gamut volume difference between OSF and Kaleido.*

<table>
<thead>
<tr>
<th>CRPC</th>
<th>Paper</th>
<th>C100</th>
<th>M100</th>
<th>Y100</th>
<th>K100</th>
<th>R100</th>
<th>G100</th>
<th>B100</th>
<th>Gamut Volume</th>
<th>Gamut Volume Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSF</td>
<td>96</td>
<td>1</td>
<td>-5</td>
<td>54</td>
<td>34</td>
<td>54</td>
<td>48</td>
<td>75</td>
<td>-3</td>
<td>-7</td>
</tr>
<tr>
<td>Kaleido</td>
<td>96</td>
<td>1</td>
<td>-4</td>
<td>51</td>
<td>-35</td>
<td>53</td>
<td>47</td>
<td>79</td>
<td>-15</td>
<td>-10</td>
</tr>
<tr>
<td>∆E 00</td>
<td>1.4</td>
<td>2.8</td>
<td>4.8</td>
<td>3.4</td>
<td>3.2</td>
<td>2.2</td>
<td>6.0</td>
<td>7.5</td>
<td>20%</td>
<td></td>
</tr>
</tbody>
</table>

53
Figure 25. Gamut comparison between press runs with OSF and Kaleido ink sets.

Figure 25 illustrates the comparison of the gamut achieved by Toyo OSF and Toyo Kaleido inks for the Presstek 52DI. There is a substantial increase of the gamut in the blue region for Kaleido inks. Additionally, there is an increase in gamut in the yellow region. In other regions, the gamut volume for Kaleido is limited due to the bends in reds and greens, and it does not result in an increase, compared to the Toyo OSF printing condition.
Figure 26. Toyo Kaleido inks demonstrating bends and limiting gamut expansion in red and green overprints.

The bends (circled in red in Figure 26) illustrate a reversal of chroma in red and green regions of the gamut after the yellow ink peaked at the 85% dot area. This means that the yellow ink can no longer transfer more yellow ink to colors where cyan and magenta are also present. This results in the bends, which are seen in the a*b* plot in Figure 26. These bends are assumed to be caused by the additives in yellow ink that were added to avoid background tinting issues during production runs. While the ink additives resolve the tinting problem, they change a rheological property of the yellow ink, its trapping property. Although high-chroma inks expanded the color gamut in cyan,
magenta, and yellow hue directions, their usage did not yield the anticipated results in the red and green hue directions, therefore, limiting the color gamut expansion.

It is not possible to determine whether the gamut volume differences presented in Table 11 between the OSF inks and the Kaleido inks are significant based on one data (volume) point. Therefore, metric chroma of CMYRGB outer gamut colors of the two inks were used in the hypothesis testing. There is a total of 72 outer gamut colors that are seen on the color gamut plots in Figure 25.

To evaluate the statistical significance between the ink conditions matched pairs, a t-test was used. The result of this one-tailed t-test is presented in Table 12. The p-value, <0.0001, indicates that there is a significant chroma difference between Toyo OSF and Kaleido CMYRGB ramp colors. This proves that there is significant expansion of gamut for the Kaleido high-chroma inks, compared to the standard OSF inks.

Table 12.

Statistical test results - Chroma

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LAB_C Kaleido</td>
<td>45.91</td>
</tr>
<tr>
<td>LAB_C OSF</td>
<td>42.639</td>
</tr>
<tr>
<td>Mean Difference</td>
<td>3.27</td>
</tr>
<tr>
<td>Standard Error</td>
<td>0.755</td>
</tr>
<tr>
<td>N</td>
<td>72</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.98</td>
</tr>
<tr>
<td>p-value</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
Chapter

Summary and Conclusions

In order to satisfy the growing quality demands to produce more saturated colors, and expand color gamut, printing with higher IFT and printing with high-chroma inks have been recently proposed.

The purpose of this research is to understand the relationship between color gamut, metric chroma, IFT, and SID for regular and high-chroma inks in offset printing process in order to expand the color gamut.

This research aimed at answering two research questions:

1. Whether there is significant difference in the saturation density between standard inks and high-chroma inks used in waterless offset
2. Whether there is significant difference in gamut volume between standard inks and high-chroma inks

The results of the experimental study showed that the standard inks (Toyo OSF inks) used in waterless offset printing have significantly lower saturation density, compared to the high-chroma inks (Toyo Kaleido). The significant difference between saturation densities of high-chroma inks and standard inks indicates that using high-chroma inks will result in higher solid ink densities, thus providing the possibility of expanding color gamut, compared to standard inks. Moreover, these higher SIDs of high-chroma can be achieved at the same IFT as the standard inks. This means that more saturated color can be achieved using the same amount of ink.
This research also demonstrated that SD is a limiting factor in achieving color gamut expansion through increasing solid ink densities. Valuable time and resources can be saved when SID aims are within the saturation density.

In answering the second research question, the study also showed that there is a 20% increase in gamut volume when high-chroma ink and standard ink conditions are compared. These differences are statistically significant based on the analysis of metric chroma values for outer gamut colors (CMYRGB).

This result provides an experimental evidence that printing with high-chroma inks indeed leads to expanded color gamut reproductions. While the gamut difference was found to be statistically significant, the expanded color gamut was not optimized.

**Further Research**

The determination of the Saturation Density depends on the ink and paper interactions and a repeatable ink transfer condition. The research used the Tango C1S substrate in the ink drawdown test and the Endurance Gloss substrate in the press run. This may have caused a discrepancy.

IDEAlliance has recommended the XCMYK densities. These densities exceed saturation density values obtained using the Endurance Gloss paper in the present study. It will help to determine if Toyo OSF inks can be run to higher densities than their saturation densities using a specified substrate.

The calibration of Kaleido inks for G7 was not successful due to repeatability problems and poor ink trapping. Future experiments can be focused on achieving printing stability.
A practical and important future study will need to address the cost evaluation and comparison of printing conditions for standard inks and high-chroma with various levels of solid ink densities and IFT.

In addition, ink manufacturers (Toyo) need to address the problem of ink trapping of overprints in order to optimize the color gamut.
References


60


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Appendix I

Steps for Drawdowns

Appendix I discusses the ink drawdowns of Toyo OSF and Toyo Kaleido ink-sets on the Little Joe proofer derived from Zhang’s 2012 study. The proofer has a graduated gage (0-10-micron range). The substrate used is Tango C1S. The steps are discussed in detail below:

1. Clean the gage, blanket cylinder, and scraper with a solvent-wetted rag and then with a dry rag.
2. Take a three-minute break to let the system dry completely.
3. During the break, clip a 3x12 inch Tango C1S (coated on one side) paper with the spring clamp on the plate.
4. Apply the ink along the left end of the gage.
5. Use a scraper to squeeze off the ink along the surface of the printing plate with uniform pressure. The ink might not be uniformly distributed along the gage. Therefore, to fully cover the indented area, use the scraper to draw down four more times until the ink film is uniformly distributed with no scratches.
6. Wipe off the redundant ink at the ends of the printing plate.
7. Press both green buttons on the operation station simultaneously to drive the blanket cylinder to start printing.
8. Remove the sample and press both green buttons again to drive the blanket cylinder back to the home position.
9. Clean the gage, blanket cylinder, and scraper by repeating steps (1) and (2).
10. Repeat steps (4) through (8) for more IFT samples.

Repeat steps (1) to (10) for all the experimental Toyo OSF and Toyo Kaleido inks.

Steps for Determining Kaleido SIDs

The following procedure is used to determine the starting Kaleido SIDs.

1. Start from the regression lines for OSF and Kaleido inks.
2. Use the CRPC6 Cyan SID (1.40) to locate the intersection with the OSF regression line.
3. Bounce to the Kaleido regression line to locate the corresponding Kaleido SID.
4. Repeat steps (2) and (3) to determine other SIDs.
5. Using the ray-tracing techniques, the Kaleido SIDs, having the same IFT as the OSF inks, are determined.
Appendix II

Test Form Used for Press Run for Toyo OSF and Toyo Kaliedo Inks