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Statistical evaluation of a Color Managed Digital Printing Workflow (CMDPW) consistency [4th C of CMW]

ABSTRACT

The purpose of this applied research was to determine the Color Managed Digital Printing Workflow (CMDPW) consistency (4th C of the color management) over a period of time [100 days, (N = 100)]. The quality of digital color printing is determined by these influential factors: screening method applied, type of printing process, calibration method, device profile, ink (dry-toner or liquid-toner), printer resolution and the substrate (paper). For this research, only the color printing attributes such as the overall average color deviation [ACD, $\Delta E_{(2000)}$] and the solid ink density (SID) were analyzed to examine the CMDPW process consistency in a day-to-day digital printing operation. These are the color attributes which are monitored and managed for quality accuracy during the printing. Printed colors of the random sample size (n = 80) were measured against the GRACoL2013 standards to derive the colorimetric/densitometric values. Reference colorimetric values used in the analysis were the threshold deviations (acceptable color deviations) as outlined in the ISO12647-7 standards (GRACoL2013). A control charts analysis was applied for further determining the process (CMDPW) SID and ACD variation. The data collected were run through multiple software applications (MS-Excel/SPSS/Minitab) to apply various statistical methods. Analyzed data from the experiment revealed that the printed colorimetric values were in match (aligned) with the GRACoL 2013 (reference/target). Since the SID values of CMYK colors were in control throughout the process, this enabled the CMDPW to produce consistent acceptable color deviation (Average Printed $\Delta E_{(2000)}$ = 2.978; SD = 0.437; Acceptable Threshold color deviation is $\Delta E_{(2000)} \leq 3.00$).

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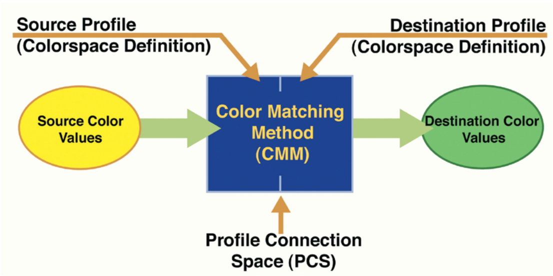
calibration, color deviation, solid ink density, control chart, output profile, colorimetry, gamut, screening

Introduction

Over the past three decades, the printing (graphic arts or graphic communications) industry has been revolutionized. Technology, workflow, management strategy, markets, and customer expectations have changed. Today, print is just one of many media channels which consumers can access. Advancements in science and engineering fields are enabling the printing and graphic professionals to apply scientific research methods across prepress, print production (press area), and quality control areas for quality color reproduction. Applying these methods heightens the importance of proper print production workflow. The value and role of printing is changing, and the use of print is being merged across multiple communications channels: web, mobile, devices and social media. Recent developments in the computing, networking and digital printing technologies enable the digital print media to become a powerful multi-channel marketing and communications tool. Due to these changes, there is an increased demand for an educated, skilled and technically competent workforce. These changes have resulted in both opportunities and challenges and have created a need for this workforce who understand the entire graphics and print media process and possess the skills necessary to manage print and non-print operations. In a quest to empower students to better understand the quality improvement techniques, this applied research examined the industry standard printing process and quality management practices similar to those a student would encounter upon entering into the industry. Hence, for a student to consistently deliver a quality print, managing and controlling color from the input device to a multicolor output device is a major concern for the graphics and imaging educator.

Modern printing has evolved from a craft-oriented field toward a color management science. This is demanding a greater color control among the display, input/color capturing, and output devices (printing and non-printing) and the substrates used in the printing and imaging industry. The quality of color image reproduction of any type of printing (digital or traditional) is largely influenced by the properties of substrate/paper (Wales, 2008). A modern and up-to-date commercial printing workflow requires a Color Management System (CMS) to produce a quality color printing. A CMS enables the color producer (printer operator or the designer) to deliver accurate output colors regardless of device color capacities with the use of proper color management techniques (see Figure 1). Analyzing the color image by examining its quantitative attributes eliminates the subjective judgment of color quality evaluation of printed colors or colors in nature.



» **Figure 1:** *Schematic of PCS of CMS (Courtesy of Adobe Systems, Inc.)*

Rationale for literature review

A continuous-tone color image is composed of a full spectrum of shades and color, from near white to dense black. In a traditional printing (offset, digital offset, gravure or flexography) workflow, the method by which continuous-tone photographic images are transformed to a printable image is called halftoning. In this method, varying percentages of the printed sheet are covered with halftone dots to represent the varying tones in the image. The ink (paste or liquid ink or dry toner) printed by each dot, of course, has the same density. At normal viewing distance, the dots of a printed image create an optical illusion of a continuous tone image. In contrast, a simple digital image could be a binary picture, [h (x, y)], with each point being either completely black or completely white (Pnueli & Bruckstein, 1996). A digital halftone is a pixel map, with bit depth, that gives the impression of an image containing a range of gray shades or continuous tones. An 8-bit grayscale image contains 256 different levels of gray from white to black.

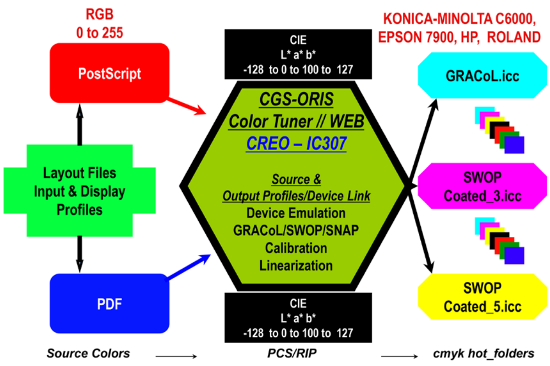
Digital printing methods differ in that they usually do not have a direct physical impact on the substrate. Inkjet printing utilizes different methods of transferring liquid ink droplets to a substrate to create an image. Another digital printing technology known as color-electrophotography, or laser printing, is commonly used and employs charged toner particles that transfer electrostatically to the substrate and create an image that is fused to the surface. Laser and ink-jet printing generate the majority of digitally printed materials in the industry. Digital printing technologies today have reached a level of quality that is comparable to traditional printing methods. In studies of print quality using process color ink systems, there are a number of variables, such as dot gain, that may cause tonal variations, and can have negative influences on the accuracy of color reproduction. Measuring and recording certain color print attributes may enable the technologist to make controlled adjustments and then check these variables to see if positive changes can be affected and maintained.

Overview of Color Management Digital Printing Workflow (CMDPW)

Color Managed Digital Printing Workflow (CMDPW) is represented through schematic illustrations of activities that reflect the systematic organization of analog and digital devices used during the print and image production process (see Figure 2). A print ready e-file (.PDF or .JPEG or .PSD or PostScript, etc.) is likely to be manipulated and later printed by an array of output digital devices [computer-to-plate (CTP), digital printers and printing presses].

Given each family of devices tends to create and produce color differently, the challenge is to manage color consistency across the entire workflow. Digital color print reproduction involves physical/mechanical interaction among the imaging cylinder, dry/liquid toner, and the substrate (Novaković & Avramović, 2012). The outcome of this interaction is the color print. Review of numerous reports revealed that the study of color is a science and the optical aspects of color only are quantitatively analyzable and measurable. The human eye, however, perceives color more subjectively, which poses a challenge at times for the printing and image reproduction industry.

Input (scanners or digital cameras) and output (monitors or printers) devices produce colors differently because they depend on their own color capabilities. The color management system simplifies and improves the reproduction of color images accurately from device to device.



» **Figure 2:** *Schematic of CMW at Laboratory for this Research*

The International Color Consortium (ICC) was formed in 1993 and it defines the standards for color device characterization (Adams & Weisberg, 2000). Today, ICC represents more than seventy industry and honorary members (International Color Consortium, 2009). This device characterization is presented in terms of specially formatted files, which have come to be called profiles. Unfortunately, the use of color management systems has not yet solved all the problems of color reproduction (Fleming & Sharma, 2002). However, it has made possible the quantification of problems. As always, in quality control, with quantification comes the ability to control and, with control, quality management becomes possible (Fleming & Sharma, 2002).

Color Management Workflow (CMW) or Color Management System (CMS) uses a set of hardware tools and software applications working together to create accurate color among various input (image capturing), display, and output devices (printing). A CMS consists of device profiles (characterization of devices), which control and document the working performance of the scanner, monitor, and the printer. A device color transformation engine (Color Management (matching) Module (method) or CMM) is one that interprets the color data among the scanner, display, and the printer. The gamut compensation mechanism of the CMS addresses differences among the color capabilities of input, display and output device. A device independent color space (Profile Connection Space or PCS) is a space through which all color transformation occurs from one device-dependent color space to another (see Figure 1). The PCS is based on the spaces (color models) derived from CIE color space (color model). This device color characterization file (profile) passes in and out of PCS to complete the color transformation (Fleming & Sharma, 2002). The PCS of the CMS is the central hub of the CMS in which a particular color value is considered absolute and not subject to interpretation (Fleming & Sharma, 2002).

The 4 C's (Calibration, Characterization, Conversion, and Control) of CMS or CMW

To implement the CMS successfully, all the devices (monitor, scanner or digital camera, and printer or printing press) which are used for printing and imaging purposes must be calibrated, characterized (profiled) and their color capabilities (RGB and CMYK) converted into an independent color space (CIE L* a* b* space). A calibration process means standardizing the performance of the devices according to the device manufacturer specifications so that the results of the devices are repeatable. A profiling process (or characterization) refers to colorimetric assessment of the device color performance and creation of an ICC (International Color Consortium) profile specific to that device. The characterization process requires CMS hardware tools and software. Characterization of the devices is converted into an ICC profile file format. It communicates measured color output of devices in response to known output. Conversion refers to translating color image data from one device color space to another device space. It is also known as color transformation. Control or Consistency (the fourth C) means the user of a CMW must monitor and analyze the use of the CMW process through the use of statistical process control (SPC) tools in order to avail the benefits of the CMW.

Statistical Process Control (SPC) tools

Statistical process control, the creation of internal standards, and equipment performance tracking are becoming increasingly important in the color managed digital printing workflow (Kipman, 2001). In a given Color Managed Digital Printing Workflow (CMDPW) scenario where visual methods are currently being used to evaluate image quality in production printing, measurement methods can either replace or augment results adding objective judgement, traceability and validity. Therefore, this increased efficiency becomes an added benefit to the CMDPW. Quality improvement (QI) practices represent a leading approach to the essential, and often challenging, task of managing organizational change (Burnes, 2000). Statistical process control (SPC) is, in turn, a key approach to QI (Wheeler & Chambers, 1992). SPC was developed in the 1920s by the physicist Walter Shewhart to improve industrial manufacturing (Thor et al., 2007).

In a CMDPW, use of SPC is a scientific technique to control, manage, analyze and improve the performance of a process by eliminating special causes of variation in the digital printing process (Thor et al., 2007). It is a powerful collection of problem-solving tools useful in achieving process stability and improving capability through education on variability (Abtew et al., 2018). There are seven original SPC tools: Flow-Charts, Check-Sheets, Histograms, Pareto Diagrams, Cause-and-Effect Diagrams, Scatter Diagrams and Control Charts (Mears, 1995). SPC enables us to control quality characteristics of the methods, machines, workforce, and products. There are two kinds of variations that can occur in all manufacturing processes, including the digital printing, which causes subsequent variations in the final product (Abtew et al., 2018). The first is known as the common cause of variation and consists of the variation inherent in the process as it is designed (Abtew et al., 2018). It may include variations in temperature, properties of raw materials, ink/toner, etc. The second kind of variation is known as a special cause of variation and happens less frequently than the first (Abtew et al., 2018). For an example, failed calibration and characterization methods could be carried into the production processes.

A control chart is the best tool for determining whether a process (CMDPW) is in-control or not in-control. An in-control process is one that lacks “assignable causes” or “special causes” of variation. This means that the processes output will be consistent over time. This is not to say that the process will be capable of meeting your needs or your customer’s expectations, just that the results will be relatively consistent (Blevins, 2001). Good color reproduction requires consistency in the CMW. Accurate color reproduction is dependent upon several factors. One of the factors is the cyan, magenta, yellow, and black (CMYK) ink densities and quality of device profiles. To achieve acceptable printing results, it is important to establish aim points (target values or control limits of the process) and monitor the aim points consistency during the production process. With the use of specific process control techniques (SPC tool), one can determine if the consistency is in-control or not in-control. If the average density or color deviation values (Delta E) and range of the process fall between the established aim points the process is said to be within the specific process control. Contrarywise, if the color deviation and density values are not within the aim points, they would be not in-control (out of control).

Purpose of the research

The experiment was conducted in a color managed digital printing workflow (CMDPW). The purpose of this applied study is to determine the consistency (4th C of CMW) of colorimetric variation among the printed colors overall average color (CMYK-RGB) deviation (ΔE) and CMYK solid ink density (SID) variation in the electro-photographic color printing process over a period of time (100 days). To determine the statistically significant process variation among these color deviations over a period of time (OAPOT), a control chart analysis technique was employed. Reference colorimetric values are the threshold deviations (acceptable color deviations) as outlined in the ISO12647-7 standards. To accomplish this, the following guiding objectives have been established:

1. Determine the deviation in color printing average/overall (CMYK+RGB) ΔE over a period of time (100 days) by comparing the printed colorimetry against the reference colorimetry.
2. Determine the deviation in the Solid Ink Density (SID) of CMYK colors over a period of time (100 days) by comparing the printed colorimetry against the reference colorimetry.

Limitations of the research

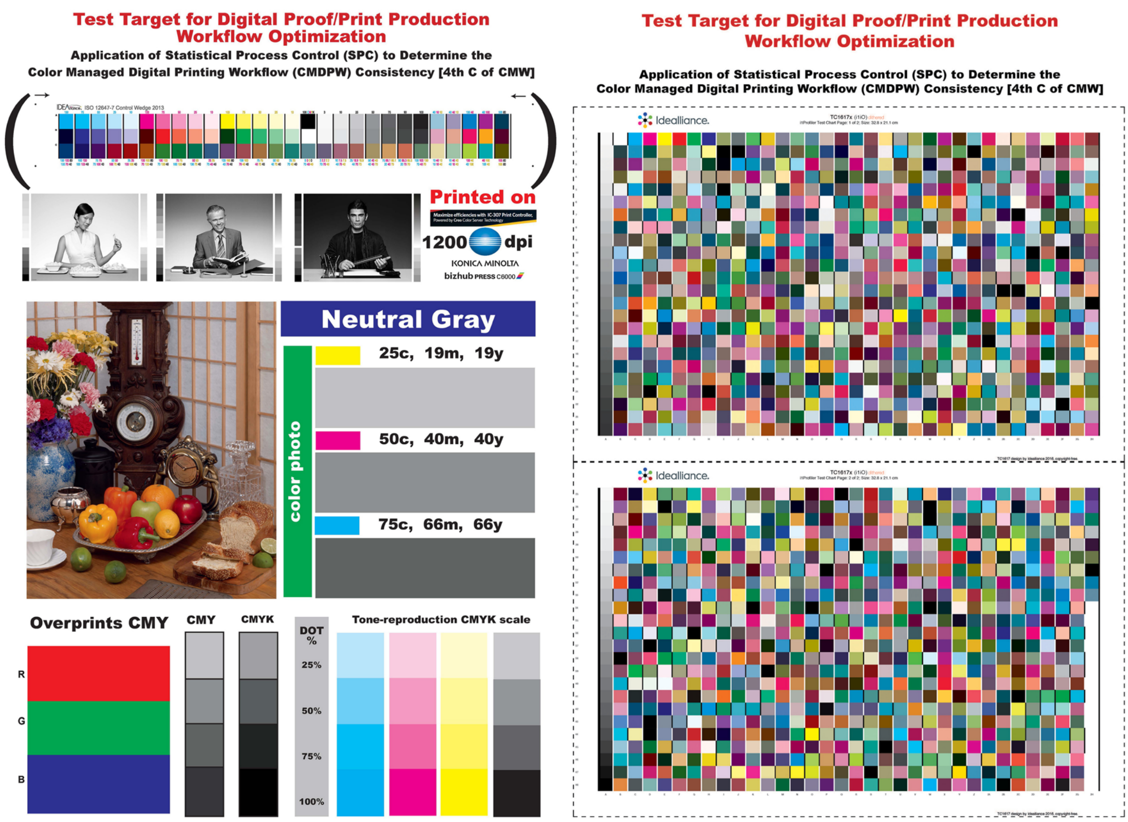
No engineering or mathematics or physics or statistical equations or computational methods were manually developed/utilized/applied during the experiment or data analysis stage. Industry standard software applications were used. For this research, limitations in the technology of the graphics laboratory were acknowledged. Prior to printing and measuring the samples, the digital color output printing device and color measuring instruments (spectrophotometer and densitometer) were calibrated against the recommended reference. The print condition associated with this experiment was characterized by, but not restricted to, the inherent limitations: colored images (TC1617x, ISO300, and ISO12647-7) chosen for printing. Additionally, the desired rendering intent applied, type of digital printer, type of paper, type of toner, resolution, screening technique, color output profiles, and calibration data applied are acknowledged. Several variables affected the facsimile reproduction of color images in the CMDPW, and most were mutually dependent. The scope of the research was limited to the color laser (electrophotographic) digital printing system (printing proof/printing), substrates, types of color measuring devices, color management and control applications (data collection, data analysis, profile creation, and profile inspection) used within the university graphics laboratory. Findings were not expected to be generalizable to other CMDPW environments. It is quite likely, however, that others will find the method used and data collected both useful and meaningful. The research methodology, experimental design, and statistical analysis were selected to align with the purpose of the research, taking into account the aforementioned limitations.

Research methodology

The digital color printing device used in this experiment is a Konica-Minolta bizHub C6000 Digital Color Press. It uses a Creo IC-307 raster image process (RIP) application (front-end system). A two-page custom test image (12”x18” size) was created for proofing and printing use for the experiment (See Figure 3). Table 1 presents the variables, materials, conditions, and equipment associated with this experiment.

Table 1
Experimental and Controlled Variables

Variable	Material/Condition/Equipment
Test image	Custom Test Target (See Figure 3)
Control strips/targets	ISO 12647-7 (2013), TC1617x
Other Images	B/W and Color for Subjective Evaluation
Profiling Software	X-Rite i1PROFILER 1.8
Profile Inspection Software	Chromix ColorThink-Pro 3.0
Image Editing Software	Adobe PhotoShop-CC
Page Layout Software	Adobe InDesign-CC
Source Profile (CMYK)	GRACoL2013.icc
Destination Profile (CMYK)	Custom, Konica-Minolta.icc
Reference/Source Profile (CMYK)	GRACoL2013.icc
Color Management Module (CMM)	Adobe (ACE) CMM
Rendering Intents	Absolute
Computer & Monitor	Dell OPTIPLEX/LCD
Raster Image Processor (RIP)	Creo IC-307 Print Controller with Profiling Tools
Digital Press/Printer	Konica-Minolta bizHub C6000 Color Laser
Calibrated CMYK Solid Ink Density	C = 1.75; M = 1.60; Y = 1.00; and K = 2.04
Type of Screen and Screen Ruling	Amplitude Modulated (AM), 190 LPI
Print Resolution	1200 x 1200 DPI
Toner	Konica-Minolta Color Laser
Type of Paper Weight/thickness	Mohawk 100LB Gloss Coated, Sheetfed
Type of Illumination/Viewing Condition	D50
Color Measurement Device(s)	X-Rite Eye-One PRO Spectrophotometer with Status T, 2^0 angle, and i1iO Scanning Spectrophotometer
Data Collection/Analysis Software	Minitab, MS-Excel, SPSS, and CGS-ORIS Certified Web



» **Figure 3:** *Test Target Image*

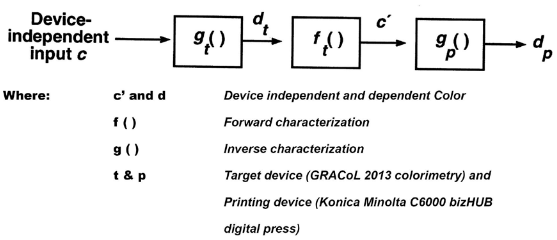
The test target contained the following elements: generic images for subjective evaluation of color, an ISO 12647-7 Control Strips (2013, three-tier), and a TC1617x target for gamut/profile creation. Colorimetric, Densitometric, and Spectrophotometric data were extracted by using an X-Rite Eye-One Spectrophotometer and an X-Rite i1iO Scanning Spectrophotometer from the color printed samples for the analysis. The process (CMDPW) was monitored for a total of 100 days. A total of 100 samples of target color images were printed/collected for daily measurement/analysis purpose. 100 prints were noted by letter "N" (N = 100). Of 100 samples, 80 samples (n = 80) were randomly selected and measured, noted by the letter "n" (n = 80). This sample size was selected in order of the specific confidence interval (α = 0.05). Glass & Hopkins (1996) provides an objective method to determine the sample size when the size of the total population is known. This sample size is needed to make sure the reliability of data is accurate. It is well documented that a large sample size is more representative of the sampling (subjects) population (Glass & Hopkins, 1996). The following formula was used to determine the required sample size, which was 80 (n) printed sheets for this study (Glass & Hopkins, 1996):

$$n = [\chi^2 NP (1-P)] / [d^2 (N-1) + \chi^2 P (1-P)] \quad (1)$$

n = the required sample size
χ^2 = the table value of chi-square for 1 degree of freedom at the desired confidence level (3.84)
N = the total population size
P = the population proportion that it is desired to estimate (.50)
d = the degree of accuracy expresses as a proportion (.05)

CMW setup for the digital press

The digital output device used in this experiment is a Konica-Minolta (KM) C6000bizHub color printer (or digital press). KM C6000 uses a Creo IC-307 raster image process (RIP) server (front-end system) based workflow application. This workflow application (the RIP) enables the printer (or designer or operator) to emulate/simulate (See Figure 4) the color device to print as per the ISO 12647 series digital color printing production standards.



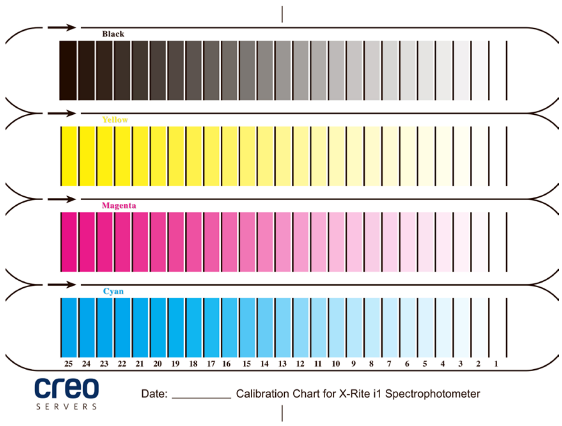
» **Figure 4:** *Color Transformation of Device Emulation/ Simulation (Proof/Printing)*

The RIP provides software tools for calibrating the printer and creating an ICC device profile. This simulation process requires the characterization data (an ICC profile) from the printing device (destination printer) as well as the data from the target device (an ISO 12647-7 reference colorimetry or other target device profile). Figure 4 illustrates how a device emulation is accomplished from characterizations of the proofing and target (printing) devices (Raja, 2002). Emulation/ simulation is not possible without two profiles.

In this scenario, target colors are the source colors outlined in the General Requirement for the Applications in the Commercial Offset Lithography (GRACoL2013) standards and the printed colors are the destination colors of a device (Konica Minolta bizHUB C6000 digital press). Many up-to-date CMYK workflows emulate the printed colors to GRACoL standards by default, because the GRACoL reference colorimetry provides an optimal color balance based on the traditional CMYK (offset printing) workflows (Xerox, 2009).

Digital press calibration

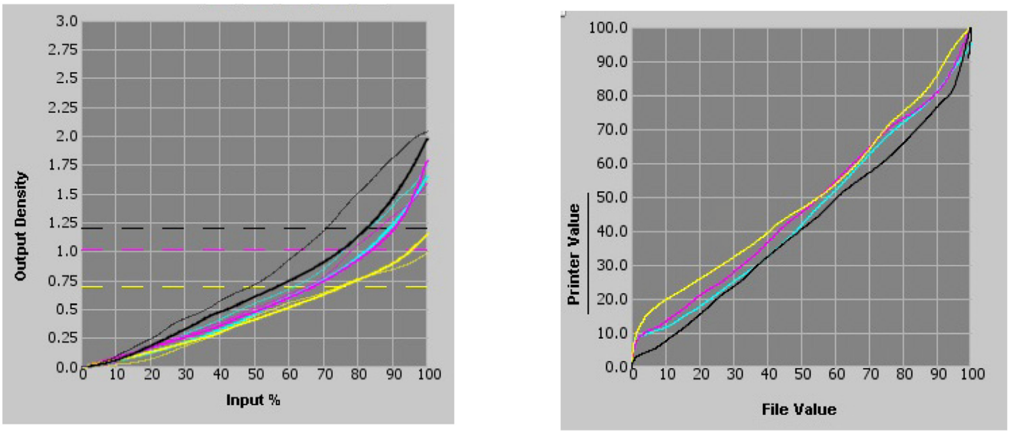
A calibration process means standardizing the performance of the devices according to the device manufacturer specifications so that the results of the devices are repeatable. Prior to printing the patches/ target image, the printer was calibrated for amplitude modulated (AM) screening technique with 1200 x 1200 dots per inch (DPI) resolution as per the manufacturer's specifications for a 100 lb gloss coated paper. The calibration chart (See Figure 5) was printed and measured by using an X-Rite Eye-One Spectrophotometer.



» **Figure 5:** *Calibration CMYK Chart*

A calibration step in a CMDPW is designed to assure repeatable results by standardizing the performance of the devices according to the device manufacturer specifications. The calibration curve consists of the maximum and minimum printable (or acceptable) solid ink densities (SID) of each color (CMYK) used for the printing (See Figure 5A). The calibration data (range of

PRINTER CALIBRATION FOR 100 LB GLOSS COATED PAPER



Measured Solid Ink Density (SID) of:

C	M	Y	K	
				Printer Resolution 1200 DPI
1.75	1.60	1.00	2.05	**AM Screening with 190 LPI**

Reference Solid Ink Density (SID) of:

C	M	Y	K
1.65	1.79	1.14	1.98

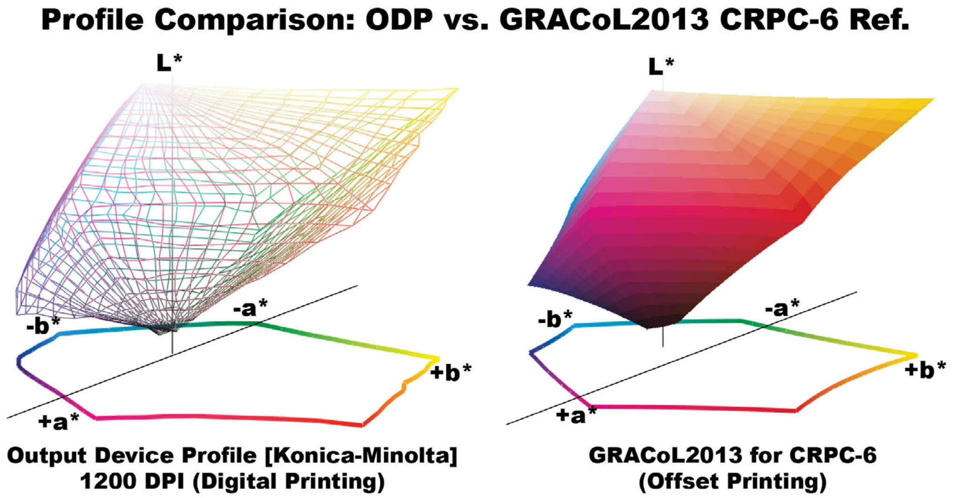
» **Figure 5A:** *Calibration of a Digital Printing Press*

CMYK densities) were saved in the calibration lookup tables (LUT) of the RIP and a calibration curve was created. Printed Test target TC1617x (Page 02 of the target image) was used for the output device profile creation process. Measured and Reference (or target) SID values are extracted from the digital press LUT of the RIP.

Digital printing press/Printer profile

The test target image (TC1617x) was placed into an Adobe InDesign-CC layout of 12" W x 18" H size and a PDF file was created devoid of any image/color compression (see Figure 3). Mohawk 100 LB gloss coated digital color printing paper 12" x 18" was used for printing the target image. A total of 100 sheets/copies of TC1617x were printed with the calibration curve attached. Also, an amplitude modulated (AM) halftone screening technique with 190 lines per inch (LPI) and 1200 DPI as the printer resolution was applied during the printing. No color management or color correction techniques were applied during the printing. Printed patches of TC1617x were measured in CIE L* a* b* space using the i1PROFILER application with an X-Rite i1iO spectrophotometer. The printer profile was then created and stored. The profile format version is 4.00 and it is considered as the Output Device (printing device) Profile (ODP). This profile was used as a destination profile (DP) in the workflow. The source profile (SP) used in the experiment is a GRACoL2013 for characterized reference printing conditions-6 (CRPC-6). See Figure 6 for an output device profile comparison of GRACoL 2013 profile vs. ODP, gamut volume of the profiles, and L* a* b* values of each profile used.

Visual examinations of both the profiles indicate that the ODP (printer profile/digital press) color gamut volume (CGV) is higher than the target device profile/GRACOl2013 (see Figure 6). The CGV, a volume in CIE L* a* b* space can be interpreted as the number of colors which are discernable within a tolerance of ΔE =√3 (Chovancova-Lowell & Fleming, 2009). Each profile is an indication that it has different color capabilities because it represents different imaging devices. Color gamut mapping can be completed by one of the four ICC recognized colorimetric rendering intents: perceptual, absolute, relative, and saturation. The rendering intent determines how the colors are processed that are present in the source gamut but out of gamut in the destination (output). For this experiment, absolute colorimetric intent was chosen. It intends to produce in-gamut color exactly and clips out-of-gamut colors to the nearest reproducible hue by scarifying saturation (chroma or vividness) and lightness (Fraser, 2001). The experiment had successfully calibrated the press and created the ODP for use in the remainder of the experiment.



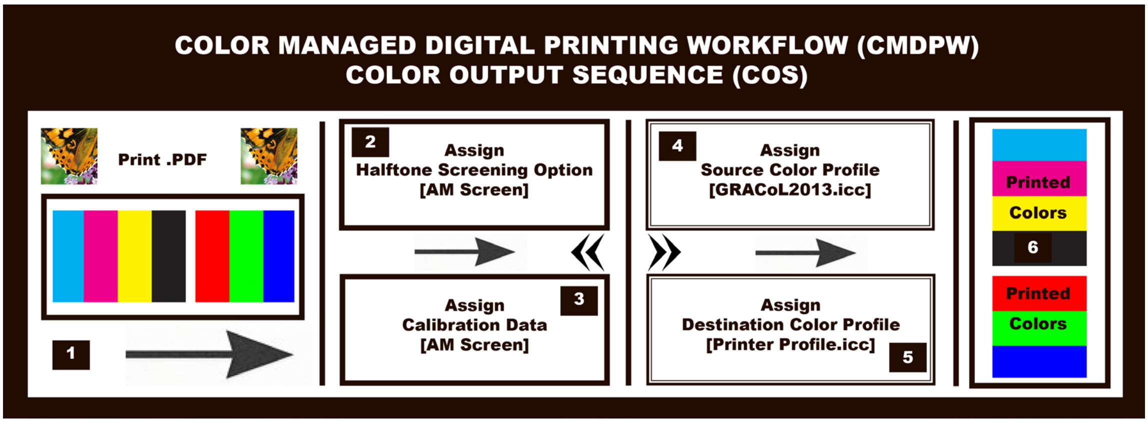
Gamut Volume 492, 149					Gamut Volume 389, 023				
Colors					Colors				
L*	53	50	91	11	L*	56	48	89	16
a*	-34	78	-11	1	a*	-32	75	-4	0
b*	-54	-4	96	-1	b*	-50	-4	93	0

» **Figure 6:** *Comparison of ODP vs. GRACoL2013 CRPD-6 Ref.*

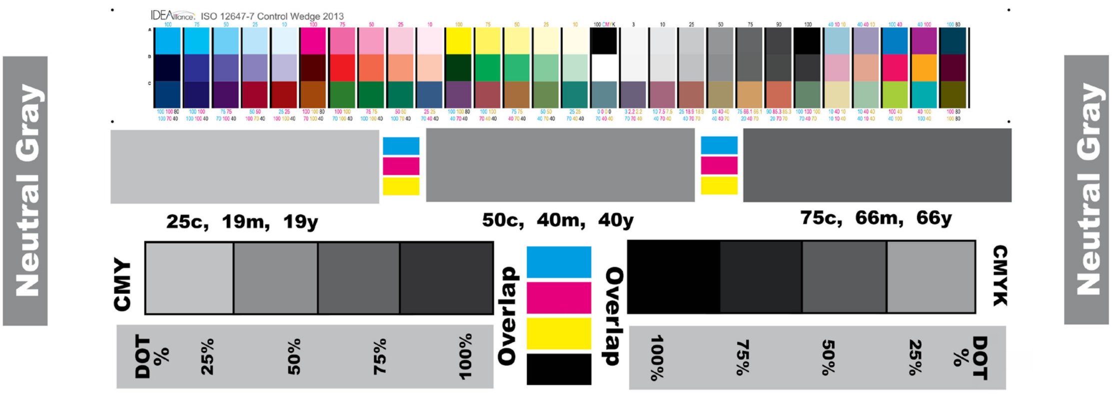
Printing with target (source) and destination profiles

As stated earlier, AM screening technique was applied during the calibration and profile creation process in the experiment. The CMDPW was considered a group (process) within the experiment. A group involves a set of print parameters, such as a digital halftone screening technique [amplitude modulate (AM)], a calibration curve (of AM screened), a color source profile [General Requirements for Applications in Commercial offset Lithography for characterized reference printing conditions-6 (GRACoL2013 for CRPC-6)], and a color destination profile of a digital press (AM screened). As parameters illustrate in Figure 7 (Schematic Illustration of Sequence of Print Parameters for CMDPW), the test target of 12” x 18” (two pages) was printed for use in the experiment. The test target contained the following elements: TC1617x target, ISO 12647-7 (2013) control strip, an ISO 300 and custom images of color and b/w for subjective evaluation of color. A total of 100 sheets/samples were printed for the screening technique used by enabling the color management technique at the RIP. The digital press calibration curve, destination profile, and the source profiles all were applied during the printing (see Figure 7).

The group printing performances were monitored for a period of 100 days to determine the fluctuations in the color consistency (4th C of CMW) by printing multiple printing jobs on the same type of paper with the same print sequences. Prior to start of the printing for the day, the test target (Figure 3) was printed, measured for the colorimetric and densitometric data and the sample was kept aside for a later stage analysis. A total of 100 target images were printed/collected for the analysis. Of the 100 printed samples (from 100 days, N = 100), data were generated from the randomly pulled 80 printed samples (80 days samples, n = 80). The test image consists of a printed ISO 12647-7 (2013) control strip (see Figure 8). By using Eye-One-Pro spectrophotometer with interface application, such as the CGS-ORIS Certified WEB, the printed image was measured against the GRACoL2013_ CRPC6 reference data. Measured colorimetric data (CIE L* a* b*) from ISO 12647-7 (2013) control strip were used to determine the color deviations. Data derived from ISO 12647-7 (2013) control strip (sample) is the difference between the characterization data set (full



» **Figure 7:** *Schematic Illustration of Sequence of Print Parameters for CMDPW*



» **Figure 8:** *ISO 12647-7 (2013) control strip with additional Color Patches*

IT8.7/4 target) and the sample. The control strip (wedge) image is intended primarily as a control device for pre-press proofs but may also be used to control production printers or presses. The wedge has 3 rows and 84 patches, and it contains only a small sub-sample of the total printable color gamut. The wedge contains too few patches to prove an accurate match to a specification like GRACoL or SWOP (Specifications for Web Offset Publications). It does contain enough patches to monitor the stability of a system that has previously been tested with a target such as the IT8.7/4 (CMYK target image). The reference file content for this image (IT8.7/4) are the CMYK dot percentage values and the nominal CIE L* a* b* characterization data values for the GRACoL2013-CRPC6 reference. Colorimetric, densitometric, and spectrophotometric computations were used to determine the color deviations and CMYK solid ink densities. Colorimetric and densitometric formulae and formats were presented in the following section (DATA ANALYSIS) for each of the color deviations/attributes investigated.

Data analysis & research findings

Colorimetric computations and statistical process control methods were used for the color deviations and process variations. Analyzed collected data were presented in the following pages/tables. Subjective judgment on color difference or any deviations was not used in this particular study because the subjective judgment of color difference could differ from person to person. For example, people see colors in an image not by isolating one or two colors at a time (Goodhard & Wilhelm, 2003), but by mentally processing contextual relationships between colors where the changes in lightness (value), hue, and chroma (saturation) contribute independently to the visual detection of spatial patterns in the image (Goodhard & Wilhelm, 2003). Instruments, such as colorimeters and spectrophotometers¬, eliminate subjective errors of color evaluation perceived by human beings.

Solid Ink Densities (SID) of CMYK average variation

Solid Ink Density (SID) is defined as the ability of a material (ink/substrate/surface area) to absorb light, and it is a function of the percentage of light reflected from that material (Committee for Graphic Arts Technologies Standards, 1993). The reproduction of printed images during the press run (digital or analog processes) is susceptible to tonal and color variations mainly because of the dot size and SID. Reports reveal that it is important for the CMYK ink densities to be kept in balance during the printing. If ink densities are not in balance, color (hue) will shift. Therefore, monitoring solid ink density during a press run is essential when comparing any printed material in terms of quality. Digital printing device RIP keeps (holds/stores) acceptable SID values in the calibration/linearization look-up-tables (LUT's) and enables an operator to apply the curve during the printing.

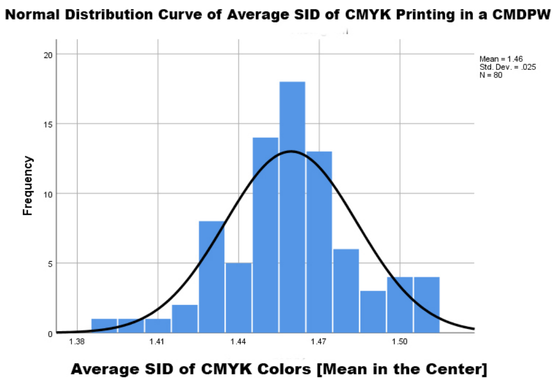
In the CMDPW (process or the group) of this experiment, the printed SID values of CMYK toners/inks were monitored for over a period of 100 (population size, N = 100) days by printing and measuring the SID values from the randomly selected samples [sample size, N = 100, n = 80, n_i = 4 (CMYK)]. Data (SID) collected were compiled in MS-Excel/SPSS/Minitab and analyzed to derive the $\overline{X}$ (average), SD (standard deviation) and $\overline{R}$ (range average) and used for further analysis. Also, a normality test was performed by using the compiled SID data (see Table 2, Figure 9). A normality test is used to determine whether sample data (SID values) has been drawn from a normally distributed population (within some tolerance). Any research involving use of statistical tests requires data from a normally distributed sample. The normal distribution (ND) is the most important probability distribution in statistics because it fits many natural phenomena. It is practically feasible to measure the distances under the normal curve in terms of z-scores (fractions or multiples of-/+ of 3 standard deviations from the mean).

Table 2

Descriptives of Normality Test for Average SID of CMYK in a CMDPW

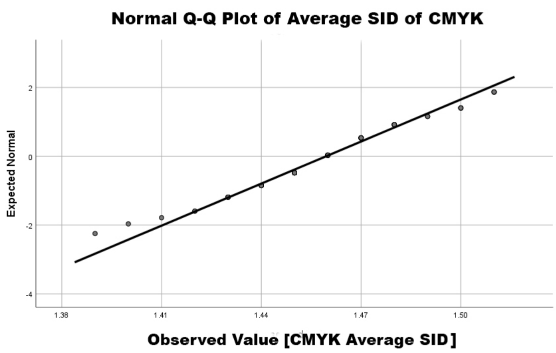
Attributes/Variables	Statistics	Standard Error
Average (Mean) SID of CMYK [C = 1.420; M = 1.710; Y = 1.030; K = 1.670]	1.459	0.003
Median (Med)	1.460	
Standard Deviation (SD)	0.0245	
Skewness	-0.099	0.269
Kurtosis	0.430	0.532

The ND curve is symmetrical around the mean, showing that data of SID values near the average ($\overline{X}$ = 1.46, SD = 0.025) are more frequent in occurrence than the SID values far from the $\overline{X}$. The Standard Error (Std Err or SE) is 0.003 of SID. It is an indication of the reliability/accuracy of the average SID of the CMYK in the process. A small SE is an indication that the produced average is a more accurate reflection of the actual population mean. A larger sample size will normally result in a smaller SE (while SD is not directly affected by sample size). Further normality validation was performed by visually evaluating the SID of CMYK values by plotting in the Quantile-Quantile (Q-Q) chart (see Figure 10). It plots the quantiles of SID values (values that split a dataset into equal portions) of the dataset instead of every individual data point of the collected data. Also, Q-Q plot is easier to interpret when there is a large sample size (in this case, N = 100, n = 80).



» **Figure 9:** *Normal Distribution Curve of Average SID of CMYK in a CMDPW*

The Skewness of the ND is -0.099 (with SE 0.269) and it is interpreted as the data is symmetrical (-0.5 and 0.5). The Kurtosis of the ND of the SID of CMYK colors of the process is 0.430 (with SE 0.532). If the Kurtosis is +1.00 of the ND of the SID of CMYK, then the distribution would be too peaked; if there is an indication of-1.00 of the ND of the SID of CMYK, the distribution is too flat. Distributions exhibiting skewness and/or kurtosis that exceed these guidelines are considered non-normal (Hair, Hult, Ringle, and Sarstedt, 2017). In graphs (see Figures 9 & 10), normal distribution appears as a bell shape curve and Q-Q plot represents a straight line. Therefore, the data collected (SID values of CMYK) were valid and will be used for further statistical analysis to determine the SID consistency of the CMDPW process.



» **Figure 10:** *Q-Q Plot of Average SID of CMYK Colors in a CMDPW*

The average and range control charts analysis was applied for further determining the process (CMDPW) SID consistency. The SPSS application was used to calculate/construct the graphs of the control limits of average (X-Bar) and range variation. The control limit (CL x-double bar), upper control limit (UCL x-bar) and lower control limit (LCL x-bar) values associated with the SID (CMYK) average variations of the CMDPW are compiled in Table 3. Differences were found in the SID values of printed colors when comparing with the GRACoL standards. However, overall the process was consistent from day to day over a period of 100 days (see Figure 11) and concluded to be in-control.

Table 3

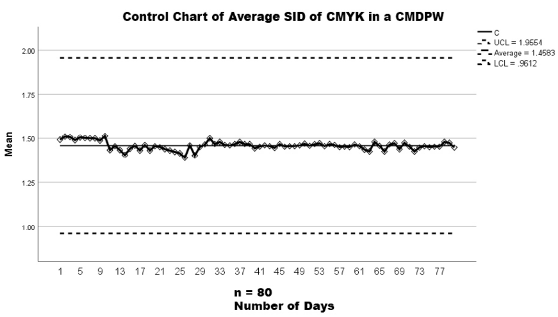
Solid Ink Density Average Variation of Printed Samples in a CMDPW

Color	GRACoL SID Standards	Printed Sample n = 80 Mean (average) n_i = 4	Printed Samples n = 80 Std. Deviation n_i = 4
Black	1.75	1.67	0.03
Cyan	1.40	1.42	0.07
Magenta	1.50	1.70	0.05
Yellow	1.00	1.03	0.02

Printed Samples Average Control Limits		
UCL $\overline{X}$	1.95	
CL (X-Double Bar)	1.46	
LCL $\overline{X}$	0.96	

Source for GRACoL SID Standards: Guidelines & Specifications (International Digital Enterprise Alliance, 2007)

The Solid Ink Density (SID) X-Bar (average) and R (range) variation were monitored by comparing them to calculated tolerances (control limits of the process). If the variations are within the tolerances, then the SID of CMYK colors are accepted. If the variations are not within the established tolerances, then they are not accepted. The X-Bar chart illustrates how the SID average varied over a period of time (100 days), while the R-Chart illustrated the dispersion (variation) within the samples studied (monitored). These charts have three lines parallel to the x axis, while the average values are parallel to the y axis. The average and range of SID values (see Figures 11 and 12) fall closely along the control limit line (within the control limits), indicating the SID of the process was very consistent.



» **Figure 11:** *Control Chart of Average SID of CMYK*

SID Range Variation

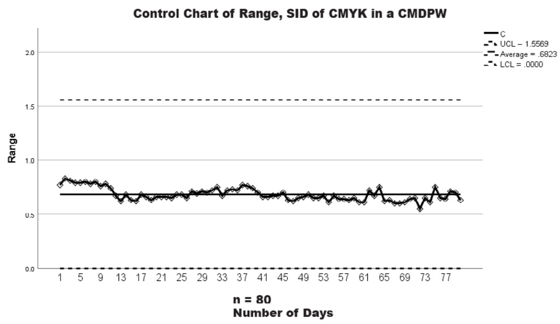
The control limit (CL r-bar), upper control limit (UCL r) and lower control limit (LCL r) values associated with the SID (CMYK) range variation of the CMDPW are compiled in Table 4. The SID range variations of CMYK printed colors over a period of time are in control. (see Figure 12).

Table 4

Solid Ink Density Range Variation of Printed Samples in a CMDPW

Color	Average Maximum SID	Average Minimum SID	Printed Sample n = 80 Range Mean (average)
CMYK	1.71	1.03	0.68

Printed Samples Range Control Limits		
UCL (Range)	1.55	
CL (R Bar)	0.68	
LCL (Range)	0.00	

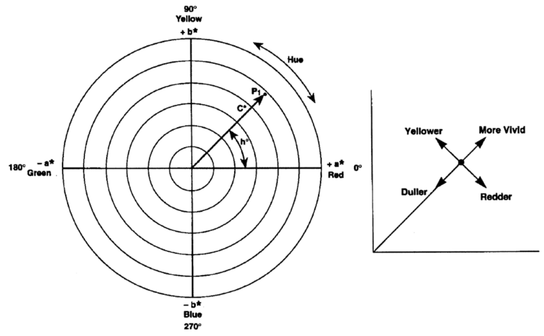


» **Figure 12:** *SID Range Variation of CMDPW*

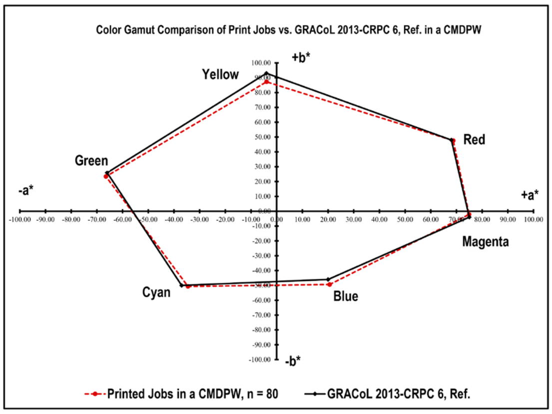
Colorimetric variation [CIE L* a* b* and Delta E (ΔE_{2000})] in a CMDPW

Colorimetric values of printed colors against original colors and the deviations (Delta E) can be used to determine the visual variation in overall colors, hue, chroma, and lightness. The a*, b* coordinates correspond approximately to the dimensions of redness – greenness and yellowness – blueness respectively in the CIE L* a* b* color space and are orthogonal to the L* dimension. Hence, a color value whose coordinates a* = b* = 0 is considered achromatic regardless of its L* value. Assessment of color is more than a numeric expression. It is an assessment of the difference in the color sensation (delta) from a known standard. In the CIELAB color model, two colors can be compared and differentiated.

The expression for these color differences is expressed as ΔE [Delta E or Difference in Color Sensation). In comparing the color differences between two colors, a higher deviation (ΔE) is an indication that there is more color difference and a lesser deviation (ΔE) is an indication of less color difference. In this scenario of the color measuring/evaluation stage, a consistent and standardized light source (D50 or D65) and angle of viewing (2° or 10°) are important (Committee for Graphic Arts Technologies Standards, 2003).



» **Figure 13:** *Schematic of L* a* b* & c*, h * Coordinates*



» **Figure 14:** *Printed Images vs. GRACoL 2013-CRPC-6 Ref.*

Overall color variation (ΔE) of printed jobs vs. GRACoL 2013 Ref. in a CMDPW

The CIE L* a* b* values associated with the CMYK+RGB colors of printed jobs vs. G7 GRACoL 2013 [CGATS21-2-CRPC6 (reference)] are compiled in Table 5 (International Digital Enterprise Alliance, 2014). Numerical color differences (ΔE) were found when comparing the average printed colors vs. GRACoL within all seven colors (CMYK+RGB). Also, noticeable visual color differences were found in the solid color area. Overall, both groups of images are similar in colors (See Figures 14), with the exception of the printed image consisting of lower L* a* b* values. This results in producing the slightly higher ΔE for these colors.

This higher color deviation (yellow, black, red, and green) might be the result of the substrate (paper) or toners used (age, condition, quality, etc.) or measurement error. These are the darker colors which produced lower L* value and in turn affected the slightly higher color deviation. The 2D color gamut comparison (see Figure 14) reveals that the colors of the printed image closely match the reference colors.

The goal was to determine the consistency /deviations among various attributes of colors over a period of 100 days in a CMDPW. The comparison is an indication that, in a color managed workflow (CMW), color matching of a target image can be achieved from device to device regardless of device color characterization and original colors. Subjective judgment was not used for the color comparison.

Table 6

Descriptives of Normality Test for Average Color Deviation [$\Delta E_{(2000)}$] in a CMDPW

Attributes/Variables	Statistics	Standard Error
Average Color Deviation [ACD (CMYK RGB)]	2.978	0.048
Acceptable ACD Threshold $\Delta E_{(2000)}$	≤ 3.00	
Median (Med) of ACD	3.015	
Standard Deviation (SD)	0.437	
Skewness	-1.509	0.269
Kurtosis	3.931	0.532

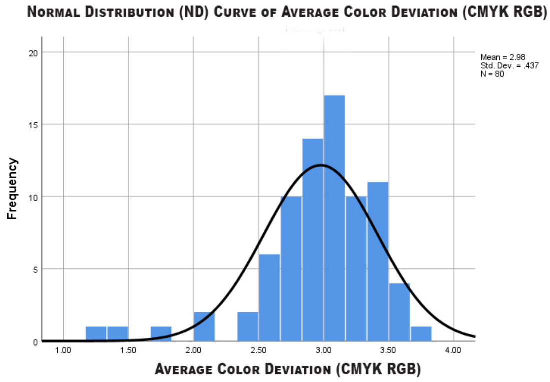
Table 5

Overall Color Variation of CMYK+RGB: Printed Jobs vs. GRACoL 2013, CRPC-6 Ref.

CIE Color(s)	Printed Jobs Average			GRACoL 2013			Color Difference $\Delta E_{(2000)}$
	L*	a*	b*	L*	a*	b*	
	Color 1 N = 80*			Color 2 N = N/A			
White (W)	95.99	1.22	-6.22	95.02	0.98	-4.02	1.890
Cyan	56.21	-34.54	-50.65	56	-37	-50	1.691
Magenta	47.15	74.92	-2.15	48	75	-4	2.307
Yellow	88.06	-3.94	87.23	89	-4	93	2.749
Black (K)	9.87	-0.18	0.08	16	0	0	3.272
Red	48.75	68.74	47.61	47	68	48	4.657
Green	52.43	-66.48	23.39	50	-66	26	4.038
Blue	24.55	20.66	-49.38	25	20	-46	2.125

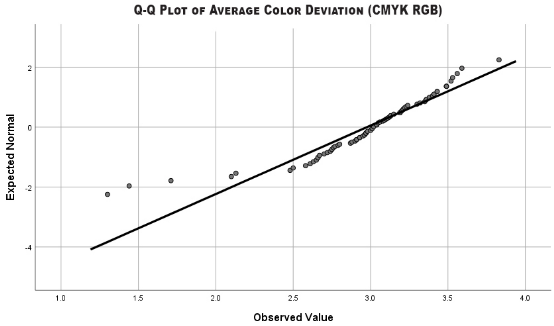
Average Printed $\Delta E_{(2000)}$ = 2.978; SD = 0.437; Acceptable Threshold $\Delta E_{(2000)}$ ≤ 3.00

The ND curve is not symmetrical around the mean (average) but it is skewed to the left (see Figure 15) showing that the average of color deviation (ACD) is lower than the median of ACD ($\bar{X}$ = 2.978, Med = 3.015, SD = 0.437). GRACoL 2013 guidelines indicate the acceptable ACD is 3.00 ($\Delta E_{(2000)} \leq 3.00$). Most of the printed jobs produced $\Delta E_{(2000)} \leq 3.00$. The ACD values are more frequent in occurrence to the left (see Figure 15) than the right of $\bar{X}$. The Standard Error (Std Err or SE) is 0.048 of ACD. It determines the reliability/accuracy of the average ACD of the CMYK RGB colors in the process. A small SE is an indication that the produced average is a more accurate reflection of the actual population mean. A larger sample size will normally result in a smaller SE while the SD is not directly affected by sample size. Further normality validation was performed by visually evaluating the ACD of CMYK RGB values by plotting in the Quantile-Quantile (Q-Q) chart (see Figure 16). It plots the quantiles of ACD values (values that split a dataset into equal portions) of the dataset instead of every individual data point of the collected data. Also, Q-Q plot is easier to interpret when there is a large sample size (in this case, N = 100, n = 80).



» **Figure 15:** *Normal Distribution Curve of ACD of CMYK RGB Colors*

The skewness of the ND is-1.509 (with SE 0.048) and it is interpreted as the data is not symmetrical. It is negatively skewed (-1 and-0.5). The kurtosis of the ND of the ACD of CMYK RGB colors of the process is 3.931(with SE 0.532). The distribution of ACD of CMYK RGB colors is leptokurtic (Kurtosis of > 3) because this type of distribution is longer and tails are fatter. The peak of the curve is higher and sharper, which means that data are heavy tailed or there is a profusion of outliers. If the kurtosis is +1.00 of the ND of the ACD of CMYK RGB colors, then the distribution would be too peaked; if there is an indication of-1.00 of the ND of the ACD of CMYK, the distribution would be too flat. Distributions exhibiting skewness and/or kurtosis that exceed these guidelines are considered non-normal (Hair et al., 2017), which the CMDPW was expected to produce. In the graphs (see Figures 15 & 16), normal distribution does not appear as a bell shape curve and Q-Q plot represents almost a straight line (see Figure 16).



» **Figure 16:** *Q-Q Plot of ACD of CMYK RGB Colors in a CMDPW*

The average and range control charts analysis was applied for further determining the process (CMDPW) ACD consistency ($\Delta E_{(2000)}$). The SPSS application was used to calculate/construct the graphs of the control limits of average (X-Bar) and range variation. The control limit (CL x-double bar), upper control limit (UCL x-bar) and lower control limit (LCL x-bar) values associated with the ACD (CMYK RGB) variations of the CMDPW are compiled in Table 7.

Differences were found in the ACD of CMYK RGB values of printed colors when comparing with the GRACoL standards. However, overall the process was consistent from day to day over a period of 100 days (see Figure 17) and concluded to be in-control.

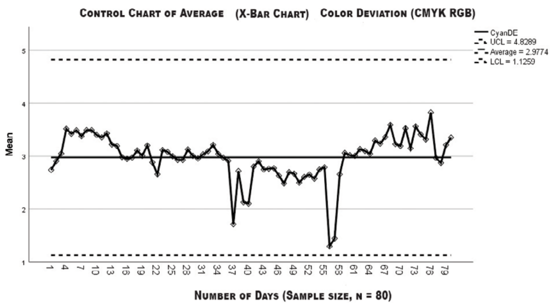
Table 7

Average Color Deviation(ACD) or Color Variation [$\Delta E_{(2000)}$] of Printed Samples in a CMDPW

Color Attributes/Variable	Printed Sample n = 80 Mean (average) n_i = 7	Printed Samples n = 80 Std. Deviation n_i = 7
Mean Color Deviation [$\Delta E_{(2000)}$] of CMYK RGB	2.978	0.437
Printed Samples Average Color Deviation Control Limits		
UCL $\bar{X}$	4.828	
CL (X-Double Bar)	2.978	
LCL $\bar{X}$	1.125	

The average color deviation [$\Delta E_{(2000)}$] X-Bar (average) and R (range) variation were monitored by comparing them to calculated tolerances (control limits of the process). If the variations are within the tolerances, then the ACD of CMYK RGB colors are accepted. If the variations are not within the established tolerances, then they are not accepted. The X-Bar chart illustrates how the average color deviation of CMYK RGB varied over a period of time (100 days), while the R-Chart illustrated the dispersion (variation) within the samples studied (monitored).

These charts have three lines parallel to the x axis, while the average values are parallel to the y axis. The average and range color deviation [$\Delta E_{(2000)}$] values (see Figures 17 and 18) fall closely along the control limit (CL) line (within the control limits) or below the CL indicating the ACD of the process was very consistent. ACD less than CL (Average Printed $\Delta E_{(2000)}$ = 2.978) is an indication of lower color deviation between the printed and reference.



» **Figure 17:** *Control Chart of Average Color Deviation of CMYK RGB in a CMDPW*

ACD range variation

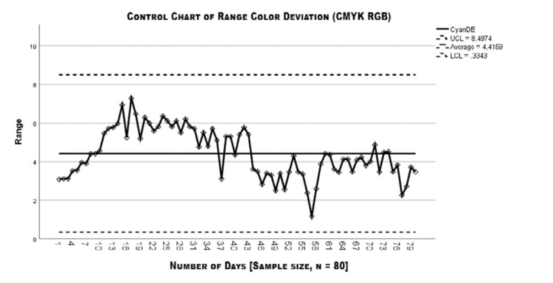
The control limit (CL r-bar), upper control limit (UCL r) and lower control limit (LCL r) values associated with the color deviation (CMYK RGB) range variation of the CMDPW are compiled in Table 8. The ACD range variations of CMYK printed colors over a period of time are in control (see Figure 18).

Table 8

Average Color Deviation Range Variation [$\Delta E_{(2000)}$] of Printed Samples in a CMDPW

Color Attributes/Variables	Average Maximum $\Delta E_{(2000)}$	Average Minimum $\Delta E_{(2000)}$	Printed Sample n = 80 Range Mean (average)
CMYK RGB	5.49	1.42	4.415

Printed Samples Range Color Deviation Control Limits	
UCL (Range)	8.497
CL (R Bar)	4.415
LCL (Range)	0.334



» **Figure 18:** *Control Chart of Color Deviation Range Variation of CMYK RGB in a CMDPW*

Summary/Conclusions

This applied research experiment was conducted in a Color Managed Digital Printing Workflow (CMDPW). The workflow was observed and monitored for 100 days in Fall 2020. It was aimed at determining the average color deviation consistency over a period of 100 days. The conclusions of this study are based upon an analysis of colorimetric and densitometric data, visual assessment, and associated findings. The guiding objectives of this study allowed testing of an accepted color management practice to gain a better understanding of the presumptions associated with the application of statistical process control (SPC) in a digital printing environment. The experiment examined the importance of calibration, characterization and the color evaluation processes of the digital press which was capable of printing colors to match or be in proximity of GRACoL 2013 standards. Printed samples from the experiment were measured against the GRACoL 2013 (CGATS21-2-CRPC6) standards in CIE L* a* b* space using CGS-ORIS CertifiedWEB application interface with an X-Rite eye one spectrophotometer. The data collected were run through multiple software applications (MS-Excel/SPSS/Minitab) to apply various statistical methods. Analyzed data from the experiment revealed that the printed colorimetric values were in match (aligned) with the GRACoL 2013 (reference/target). Since the SID values of CMYK colors were in control throughout the process, this enabled the CMDPW to produce consistent acceptable color deviation ($\Delta E_{(2000)}$).

It is evident that integration of device profiles is important in a CMW and it also enables/allows the workflow process to meet specific industry standards of ICC based CMW. This study represented specific printing or testing conditions. The images, printer, instrument, software, and paper that were utilized are important factors to consider when evaluating the results. The findings of the study cannot be generalized to other digital printing workflows. However, the result of this research may be of interest to others when exploring similar methodologies to other printing workflows. The findings determined that only the optical aspects of color are quantitatively analyzable and measurable because humans perceive color subjectively. It will be hard to document and measure the color values we see or detect. Additionally, the implementation of a CMDPW is costly, time consuming and a tedious process. It does, however, benefit those who implement this workflow to get consistent color from device to device. Applied statistical methods and the outcome of the analyzed data enabled the determination of the process consistency (4th C of CMW). It is important to reiterate the fact that having a CMW will not replace the SPC. Employing quality improvement techniques or strategies must be part of any manufacturing process or digital printing. The colorimetric data of this experiment also led to the conclusion that the application of a correct print parameters set-up is an important step in a CMDPW in order to output accurate colors of choice for a desired use/purpose. Mismatch of print parameters could result in a color management discrepancy or inconsistency.

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