Journal of Imaging Science and Technology® 54(6): 060504–060504-13, 2010.

Evaluation of Ink Optimization Technology in Offset Color Printing

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Abstract. *This research relates to ink optimization technology as used in prepress workflows. A primary objective of ink optimization processing is that cyan, magenta, and yellow (CMY) inks can be replaced by a given amount of black (K) ink, appropriately chosen to create the same visual color as the original but with less total ink coverage. Ink optimization technology incorporates aspects of under color removal (UCR) and gray color replacement (GCR) technologies in black channel generation, but extends these concepts to include ink savings, press stability, and workflow integration. Ink optimization systems are used to process images to create color separations of RGB to CMYK or color re-separations, from CMYK to CMYK. This technology is currently used in all areas of color printing, but in particular in relation to web and sheet-fed offset lithographic printing, where high-quality images and long press runs offer the opportunity for maximum ink savings. This research establishes evaluation criterion and benchmarking statistics for ink optimization technologies. The tests show that ink optimization works—the systems are able to process files in real time, new optimized files have lower CMY values, reduce ink consumption on press, are more stable on press, yet files still retain colorimetric accuracy to the original and do not introduce imaging artifacts.*
[DOI: 10.2352/J.ImagingSci.Technol.2010.54.6.060504]

INTRODUCTION

Ink optimization is a new term now used in all areas of color printing, in particular in relation to web and sheet-fed offset lithographic presses, although their use in digital (xerographic) presses is possible. Offset and other print processes use three chromatic colorants which are commonly chosen to be the subtractive primaries cyan, magenta, and yellow (abbreviated to C, M, and Y). In addition we often use an achromatic, or black colorant (abbreviated as K). Images may be acquired from input technologies such as a scanner and digital camera or computer generated imagery, these images are usually encoded in the additive primaries of red, green, and blue (abbreviated to R, G, and B). Ink optimization refers to software technology that is used to process images to create color separations of RGB to CMYK or color reseparations, from CMYK to CMYK.

A primary objective of ink optimization processing is that CMY inks can be replaced by a given amount of black ink, appropriately chosen to create the same visual color as the original but with less total ink coverage. Ink optimization not only provides net volume ink savings, but also reduces the amount of expensive CMY inks with increase of often cheaper, K ink. The reduction of CMY inks has a number of advantages such as lower ink/printing costs, better color stability on press, and shorter drying times, etc. Ink optimization image processing can also potentially cause imaging artifacts and issues with smooth tonal gradients and moiré, and even color change when printed. This article describes research in which the results of different ink optimization procedures were evaluated in a qualitative and quantitative manner.

Overview of Experiment

In this research, 11 proprietary ink optimization solutions were evaluated:

Agfa: Apogee InkSave,
Alwan CMYK Optimizer ECO,
Beijing Founder EcoInk,
CGS ORIS INK SAVER,
FineEye ICEserver Litho,
GMG InkOptimizer,
KODAK COLORFLOW software with Ink Optimization option,
MPX360 Colorserver,
OneVision PlugINKSAVEin,
ppi Media InkReduction,
TGLC PerfX Pro/PerfX DeviceLink Pro.

In addition, manual CMYK separations were created in Adobe Photoshop CS4. A series of test forms were designed with elements containing standard components such as test target patches, images with memory colors, flesh tones, overprint elements, black on white text and the reverse, and test items that included moiré. Standard control bars such as the IDEAlliance 12647–7 Digital Control Strip do not contain many CMY overprint patch values, and these color patches would be largely ignored by the optimization solutions, so a special test target was designed. The test images were provided remotely to each supplier, the processing was monitored via remote desktop sharing as the files were processed

Received Jun. 11, 2010; accepted for publication Aug. 4, 2010; published online Nov. 5, 2010.
1062-3701/2010/54(6)/060504/13/$20.00.

by each operator. On completion of processing, test forms were retrieved using a drop box or web site.

Matlab was used to compute the CMYK ink coverage in the image test file, before and after processing by each supplier, to predict the ink savings created by each re-separation solution. The images were proofed on an Epson 9900 ink jet printer and printed on a 40″ Roland 700 offset sheetfed press. The printing/proofing condition met GRACoL #1 reference printing conditions. Colorimetric measurements were based on three different scenarios—from the digital file, the ink jet proof, and the press sheet. Visual analysis of the printed output was assessed by color professionals. Increase or decrease in metamerism due to changes of the CMYK composition of the images was evaluated using spectral data calculations and illuminants D50 and F2. During the press run, variations of ±0.2 magenta density were induced to simulate press drift, this press result was used to evaluate the ability of ink optimized images to withstand small color deviations on press.

Ink Saving

Ink optimization solutions reduce the amount of ink required to print color images and often incorporate aspects of earlier UCR and GCR technologies (Under Color Removal and Gray Component Replacement). Ink optimization software works by reducing the amount of CMY inks required to produce a color, replacing them with black ink. In subtractive color synthesis, using CMYK printing inks, we theoretically need only cyan, magenta, and yellow to create any desired spectral color. In *theory*, images can be printed using the CMY color space, where a mixture of the three colors is used to produce black. In *practice*, printing with only the three subtractive ink colors does not produce a convincing black, the black color from the addition of CMY is often a muddy brown. The physics of the situation predicts a black color, but in practice due to nonideal response curves and secondary absorptions in the spectral behavior of the inks, it is necessary to use in addition to the basic three process color inks, an additional black (K) ink.

The introduction and use of black ink immediately introduces redundancy—we have many different CMYK combinations that can all create the same visual color response. Stated formally we may say that “the number of device channels is greater than the number of colorimetric dimensions. Hence different combinations of device signals can result in the same colorimetric output.[1]” In this situation it is possible, therefore, to choose different combinations of CMYK that while creating the same color on output, do this by using less amount of CMY ink, and more K ink.

A fundamental test parameter to evaluate is by how much does each supplier reduce the CMY ink amount, how much does the K inking level increase, and what is the resultant reduction in ink volume when the reseparation is compared to the original separation. Results to show the decrease in ink volume for each system are presented in graphical format.

Ink Amount on Press

The CMYK process can theoretically allow for 400% ink coverage—100% for each of the four channels. While this level of inking is theoretically possible, in practice in many different printing processes, applying this much ink would lead to ink pooling, long drying times, setoff, back trapping, etc. The amount of ink that a print process can comfortably accept differs with each print process. For this reason, industry segments and printer groups have set limits on the acceptable total ink coverage (TIC)/total area coverage (TAC) for different print processes. The magazine industry, for example, through SWOP, has recommended a total dot area coverage limit of 280–310 %, while for commercial offset printing through GRACoL there are limits of 300–320 % TAC. For newsprint with lighter paper types, based on SNAP, we can only hold a sum total TAC of 240%. A function of ink optimization software is to reduce the amount of inking levels in the incoming file in order that the processed file meets any of the above specifications. Ink optimization software may optionally be able to analyze images from different sources within a single document and harmonize the TAC among disparate image types.

Colorimetric Matching

In all instances, the aim of an ink optimization process is to retain an identical or near-identical rendition of the image when the new separation is printed, proofed or viewed, as compared to the original separation. There are numerous methods for computation of the new black channel information. Methods for creating a new CMYK separation include those described as UCR and GCR, and commonly involve examining each individual pixel of an image using the lowest or “lightest” of the three cyan-magenta-yellow colors to determine the amount of black to be added. We can determine black replacement for two cases—one with equal levels of CMY and the other with unequal levels of CMY. When there is an unequal distribution in the CMY channels, we seek to determine the level of black replacement for a given pixel, and then to adjust the other colors accordingly to take account of the black addition.

It is important to realize that the replacement of CMY by K is not merely a mathematical operation; thus it is usually not adequate to simply replace C=50%, M=50%, Y=50%, with K=50%. It is necessary to consider the behavior of each colorant and the color reproduction behavior of the relevant print process. We see therefore that commercial solutions are often based on the colorimetric intent of the output as specified by a reference printing condition or ICC output profile.

Up until recently, single channel, i.e., one-dimensional tone reproduction curves were used. A traditional approach is to transform the source CMYK to the destination CMYK by (1D) tone curves and color lookup tables. This method applies a blanket transformation and is generally unable to accurately transform colors with adequate colorimetric accuracy.

In order to create a reseparation it is possible to consider a CMYK to CMYK transform, using as the basis, an existing ICC profile or profiles. In an ICC color managed workflow, the color management module (CMM) uses the A2B, device to PCS (Profile Connection Space) table from a source ICC profile to convert a color from the source color space to CIELAB and then takes a B2A table (PCS to device) from a destination profile to convert the color from PCS to the destination color space.[2] This process ensures equivalency of the original separation to the reseparation in terms of colorimetric accuracy. We may describe this method as a four-dimensional CMYK to CMYK lookup table that exists as a well defined construct called an ICC device link profile.[3] It should be noted that this approach utilizes source and destination profiles to generate the device link profile, and thus locks or "hard-wires" the source and destination color spaces, thus also locking the source and destination devices.

It is a general requirement in printing that we should maintain K-only components such as black text, and should not separate text or other elements into "4-color black" for reasons of possible misregistration and poor color reproduction. Creating a device link ICC profile by simple concatenation of separate source and destination ICC profiles does not inherently preserve the K channel information. The A2B and B2A look-up tables in an ICC profile provide a valid conversion of colors from device space to PCS, and from PCS to device color space, but have no constraints in terms of K. In this instance a K-only pixel value is easily converted from a K inking value to CIELAB, and then possibly to a 4-channel CMYK inking value, so called "4-color black." A solution to this problem therefore, is to use a specialized or "smart" CMM that can preserve K for a limited number of colors by mapping those CMYK colors to some carefully chosen PCS colors.

In summary we may say that different implementations have been developed to control K in CMYK to CMYK printing including—generation of an ICC device link profile, generation of a proprietary device link profile, using a smart CMM, artificial intelligence, and others.[4,5] There are many ways to compute the new CMY:K ratio and once calculated there are more ways to store that information and implement the solution in run-time applications. In this research we did not implicitly examine the process used to create the conversion, rather we evaluated the efficiency of each technology by analysis of the processed imagery.

A common practical reseparation implementation is to specify a base or starting ICC profile that determines the colorimetric intent of the output, but does not have the desired ratio of CMY to K in all pixels. The user is usually required to adjust the relationship between CMY and K to a new desired level using a GUI-based slider or other mechanism and the software produces a new processing configuration implemented via a hot folder, which processes image files and ensures that the files produce the same color on press as the original but which have new CMY to K pixel value ratios.

In this research an appropriate ICC profile and reference printing condition were identified. Printing and colorimetry were done in accordance with the GRACoL 2006 ICC profile that represents the ISO 12647–2:2004 reference printing condition for Grade #1 paper. This ICC output profile is provided by IDEAlliance and is freely available from the ICC profile registry.[6]

CMYK pixel values can be converted to CIELAB using the reference ICC profile. This operation can be done for both the original image and the reseparated image. The Delta E color difference between these two data sets can be calculated as was done here. The Delta values are very low when we directly analyze a digital file, but progressively higher as we evaluate accuracy in ink jet proofing and even higher when considering the offset press run. When we analyze only the nonprinted digital file, we see that the Delta E difference is very low, Delta $E < 1.0$. For the digital analysis we expect the color error to be low because the system being tested will have used this same profile in order to determine the new CMYK pixel values. The errors increase for images that are printed and measured. The figures presented here are in accordance with the magnitude of errors normally expected due to ICC profile accuracy, interpolation, and measurement variations.[7]

Ink Optimization and Press Drift

In the early days of RGB to CMYK separation using scanner-based systems, there was less awareness of the impact and relevance of the separation in the press room. While the principles of black generation have been discussed and documented a long time ago,[8] these early publications were unable to consider the modern press room. The separation process was implemented at the scanning stage and operators would often choose a look-up table based, scanning style file that directly produced CMYK pixel values. The process was far removed from the press room. Today we are much more cognizant of the relationship between the prepress file and the implications on press. Ink optimization reduces the proportion of C, M, and Y in the midtones and quarter-tones, and as C, M, Y inks may naturally vary in a press run, the reduced amount of these inks reduces the impact of any variations in the press operations. In order to investigate and quantify this claim an offset press run was conducted and the press was intentionally forced to drift.

Visual Assessment

In this research reseparated, ink optimized images were proofed on an ink jet proofer and also printed on an offset sheet-fed press. These prints were observed and rated by 11 expert judges. There is a balance to be struck between ink savings and color reproduction, including colorimetric accuracy. It is possible for a system to sacrifice absolute lowest Delta E in order to achieve some other image-wise effects. In this research, data were obtained from each supplier system based on the GRACoL color space and typical "normal" ink saving. Each system tested used a realistic ink reduction setting that is typical to an end-user implementation and while not necessarily providing the maximum ink savings could be used for most types of images without introducing artifacts or colorimetric inaccuracy. In a practical situation it is not ideal for an operator to change the ink optimization setting for each image type, there should be a well-balanced configuration that provides reasonable savings and economies for the majority of images without introducing any visual artifacts. There are different ways to approach the "ideal" setting, it is possible to make a profile with either ink minimization mode that limits as to how much a reproduced color can deviate from a requested color or a high accuracy mode that ensures the color error will be minimized between the requested and reproduced color, regardless of the amount of ink consumed.[9]

One of the parameters in most systems is the point at which black generation starts. A K start of 10%, means for example, that black will appear when CMY values are 10% or more. The algorithms must consider this transition point, and must have an elegant implementation as the human eye will discern as a discontinuity any changes to a smooth tonal gradient in the image. An interesting feature of one of the systems evaluated in this research includes an area or "spatial" control,[10] whereby the system can be programmed to ignore a single high pixel value but optimize that same pixel value when the spatial area of this pixel value crosses a threshold. Another way to use this particular interface is to tolerate a rectangle of print size $1\times 9\ \mathrm{cm}^2$ but detect and process a $3\times 3\ \mathrm{cm}^2$ square even though the total areas of these two objects is the same. Thus a single or small number of pixels that technically trigger the need for TAC reduction and reseparation may be ignored and thus avoid the risk of creating a sudden discontinuity in an image that originally appeared blemish free.

Benchmarking Supplier Systems

One of the motivations for this research was to establish technical evaluation criterion and benchmarking statistics for ink optimization technologies. Recent articles in the trade press, conference presentations, and discussion forums provide an indication of the high level of interest in ink optimization solutions.[11,12] There are financial reasons that drive interest in this technology, printers are struggling in a tough market place accentuated by the growing challenges from social media and internet based alternatives to conventional print marketing and advertising. So we see that there is considerable interest and urgency surrounding adoption of this technology in the print media industry today.

There is little information in the peer-review literature on ink optimization and with the absence of technical literature on the subject most suppliers have developed material that describes the benefits of ink optimization, see for example a downloadable pdf report.[13] The consumer is faced with an array of solutions and marketing material that they must view with a discerning eye. End users currently must rely on marketing literature and decide how much to believe from marketing claims and counterclaims. It is helpful for the consumer to have an independent, third-party, "consumer report."

Every industry has a number of standards and specifications that provide a common benchmark; these can help both the consumer and the supplier. The motor car industry has crash ratings, highway, and city mpg, etc. In any testing process it is important to measure parameters that are relevant to users and consumers of the technology. It is appropriate, therefore, to begin to develop a series of test protocols and quality metrics for benchmarking of ink optimization as applied to offset and other forms of color printing. This research identifies a number of test parameters and then defines relevant test procedures, and finally applies those protocols to commercially available ink optimization supplier systems.

There are a number of available solutions for ink optimization from different manufacturers, research presented here helps users determine if ink optimization software is right for them and which of the many offerings best fits their needs. If a solution for example, provides maximum ink savings, and cost is the only factor, then that may be the best solution for a particular user, on the other hand if fine-tuning of the feature set, or colorimetric accuracy—the client's file must not change color—are more important, then the user may chose a different solution. This research identifies the relevant questions to ask and provides an indication of the magnitude of answers to expect. Benchmarking is also useful for the supplier. The supplier gains competitive knowledge and establishes target values to aim for and can use these to continually improve the accuracy of their product and extend the functionality of their solutions.

A good ink optimization system should be easy to integrate into a prepress workflow and should be able to process either native files or more commonly today, PDF files. A solution should maintain K-only components such as black text, and should not separate this into 4-color black. The reseparation should not introduce anomalies in trapping, registration, overprints or gradients.

In 2008, an ink optimization study was undertaken by Eric Neumann at Printing Industries of America and presented at the TAGA Annual Technical Conference the following year.[14] That study analyzed RGB$\rightarrow$CMYK separations and CMYK$\rightarrow$CMYK reseparations but considered analysis of digital files only and not a press run. The researchers but did not identify individual results, and in anonymous ranking found ink savings of 17–27 %, for a CMYK-CMYK reseparation, which is in general agreement with that particular test in this research.

It should be noted that ink optimization and prepress workflow software is continuously changing and improving and the commercial data presented here is merely presented to show some indicative numbers and a benchmark or snapshot of the industry at the present time. (Testing was conducted at Ryerson University, Toronto, from January–May, 2010.) It is inevitable in a survey of this type that some vendors appear to fare better than others, however this should not be taken as an endorsement of any particular product or manufacturer; these numbers are only provided to demonstrate a process and procedure for evaluation of ink optimization technology. It is not possible to include every system on the market, in this situation, the inclusion of a named supplier system does not in any way provide an endorsement, similarly if a supplier system is not included—that does not have a negative connotation.

In considering the following experimental results it is useful to consider all the tests in a holistic manner. A solution could have good colorimetric accuracy, yet introduce imaging artifacts, or, greatly reduce inking amounts, for example, but have poor colorimetry. Thus it is not adequate to merely reduce the amount of CMY ink—when output on proofer or press the image must still create the visual color of the original. It is thus important to consider all tests together as they contribute to a full "report card," akin to a student in a class that has english, math, science, art—and must show competency in all areas in order to become a successful candidate.

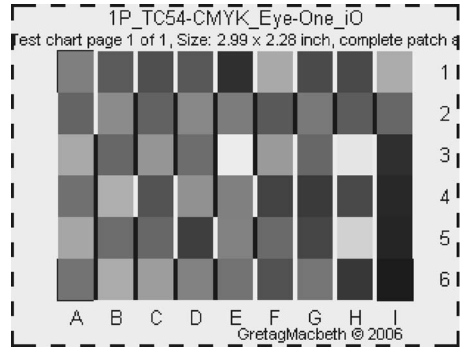

Figure 1. For this research a 54 patch target called the Optimization Control Strip was constructed.

EXPERIMENTAL DETAILS

When interpreting and evaluating the provided data, the reader should note that these numbers are based on a test form with specific content, and "actual results may vary." In general the amount of ink savings will depend on the content of the form and the settings chosen to create the separation. It is important to note that the *absolute* values of the data shown in this research will depend on the images being processed, the accuracy that is achievable on a real offset press and the instruments used in measurement and analysis. The same conditions, however, were used for all supplier systems so it is a level playing field when comparing the systems *relative* to each other.

The reader is also urged to consider not merely the height of the columns in each graph, but to also consider the scale on the y axis. Often there may be a difference of <1.0 Delta E, and it is well known that such small differences are not visually significant and are often dwarfed by variations in ink jet and offset printing.

Optimization Control Strip

In the research we seek to determine a methodology to determine the colorimetric accuracy of an ink optimization system. For calibration and colorimetric testing in color printing and proofing, it is customary to use the ANSI IT8.7/4 1617 patch target.[15] The colorimetric values for this target are defined in different reference printing conditions. Due to size limitations on the press sheet, it was not feasible to print offset, an IT8.7/4 target for each system tested.

Instead of using a full IT8.7/4 target, another established test target is the ISO IDEAlliance 12647–7 Digital Control Strip. This target is smaller in size, approximately $10\times 1''$, and while this smaller control strip may be used to calculate colorimetric accuracy of optimized and nonoptimized images, the patch values are not ideal. The IDEAlliance Digital Control Strip contains 54 patches (which are largely contained within the IT8.7/4 target). The patch values of the Digital Control Strip are intended for press and proofer calibration and verification, and contain patches of single or 2-color overprints, e.g., 100,0,0,0 or 100,0,0,60—not many of the patches in the Digital Control Strip are expected to be affected by ink optimization.

Patches with values of CMYK (100, 0, 0, 0) or (100, 0, 0, 60) for example, are not expected to be altered by ink optimization solutions that are either not able to find a replacement CMYK value and/or have an algorithm that directs the software to ignore certain pixel values where it is not useful to apply ink optimization. Most solutions, for example should ignore processing of black text and not convert black only text to 4-color black as this could introduce registration problems and/or other printing artifacts, as described earlier. Of the 54 patches in the Digital Control Strip, 46 patches do not contain CMY triplets and therefore are not expected to be affected by any ink optimization solution. Worse, the Delta E of these patches on an ink jet or offset press will primarily represent the Delta E of the press and proofer fluctuations and instrument and measurement errors—and not the error introduced by the ink optimization software. Only eight patches contain CMY triplets that would be subject to ink optimization. If only 8 patches are affected by the process, it is not useful to attribute the Delta E to the optimization process, as most of the error is attributable to printing and measuring errors.

In order to address this issue, a new 54 patch target called the Optimization Control Strip was constructed, Figure 1. In the Optimization Control Strip, all 54 patches were specially chosen so that each patch contains CMY triplets that will be potentially affected by ink optimization software. The new patches were chosen from within the GRACoL data set and a full list of the CMYK values and corresponding CIELAB values for this specially designed control strip are available on request.

Ink jet and Press Test Forms

The study was based on processing Form A, Form B and Form C, Figure 2. Form A was processed by each supplier and then proofed on an Epson ink jet printer. Form A was also used for digital analysis of ink coverage. Form B and Form C were processed by each supplier before being composited onto a press sheet and printed offset. All files were CMYK PDF/X-1a and all color was intended for GRACoL #1.

The physical size of Form A was $22\times 34''$ and the file size was 283 MB. The file size is noted for a particular reason. In the original research plan, there existed the intention

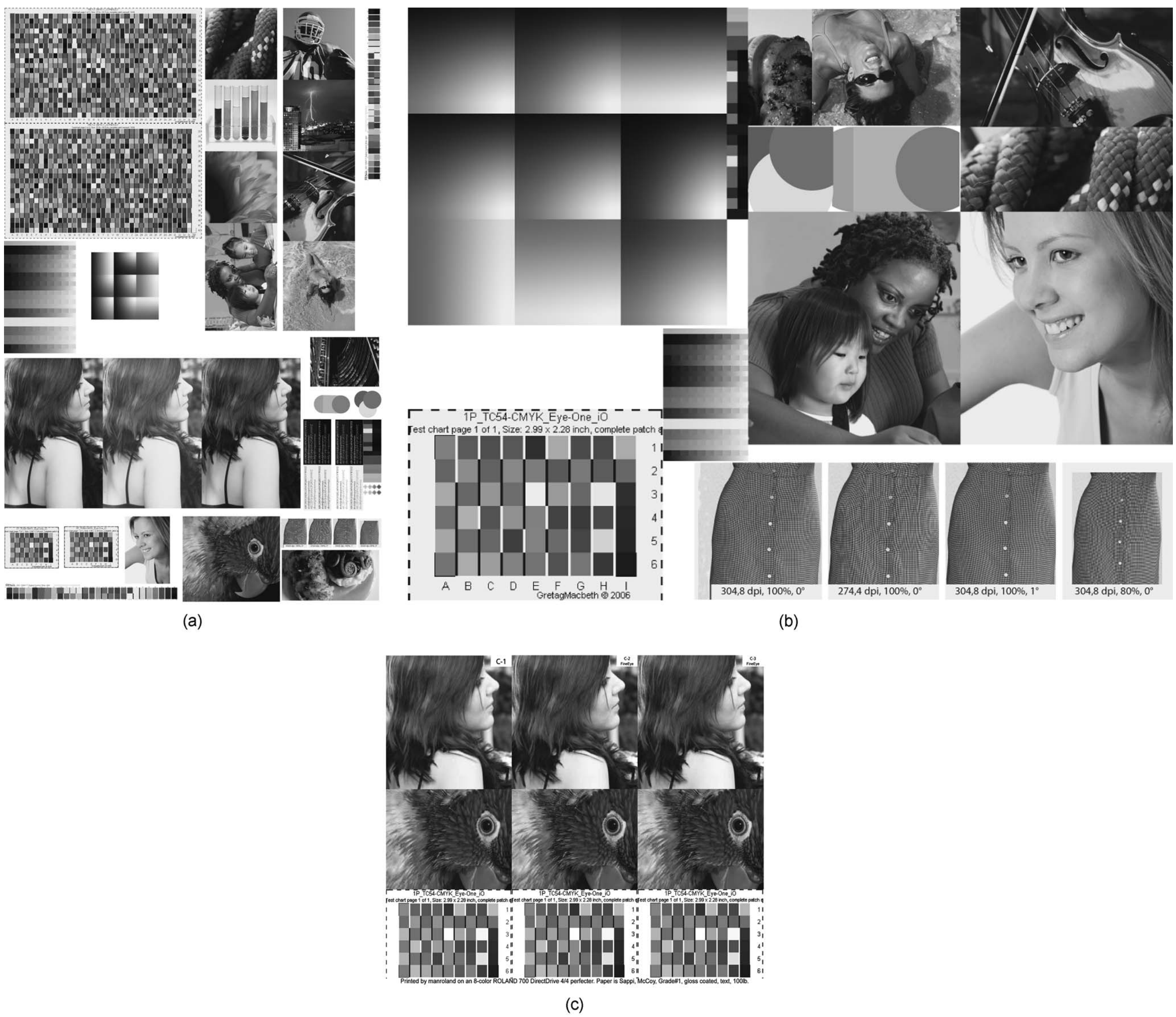

Figure 2. This research used three specially constructed CMYK forms containing standard test elements. Form A was proofed on an Epson 9900 ink jet proofer, while Forms B and C were printed on an offset sheet-fed press.

to note the time it took to process the supplied files in the different systems. In a prepress workflow the ink optimization stage should not introduce a lengthy delay in the production process. During initial testing it became apparent that the time to process images was extremely small and effectively "real-time" processing was observed. In this context we chose not to further investigate this parameter only to mention here that in conducting this experiment, real-time processing was observed.

Form B was printed offset and has a physical size of $10 \times 8''$ and a file size of 95 MB. This form contains the Optimization Control Strip, an image from the Altona Suite for moiré, overprint gradients, pure vignettes, four-color imagery, and flesh tones.

Each vertical "slice" of Form C had a physical size of $3 \times 7.5''$. The file size of each slide was 19 MB. C1 (left slice) was a nonoptimized CMYK image—the "original." C2 (middle) was an image optimized by the supplier with a "typical" setting. C3 was a slice also optimized by the supplier, but with a different level of ink saving usually with more aggressive ink savings.

Amount of Ink Saving

As each supplier creates a new separation of the supplied file, there is the opportunity to reduce the amount of expensive CMY inks and create a new CMYK combination that creates the same visual color on press but with a lower amount of expensive CMY ink. A fundamental test parameter to evaluate is—by how much does each supplier reduce the CMY ink amount?

To test the reduction in CMY inks, the CMYK file Form A, was provided to each supplier. The "before" and "after" version of Form A from each supplier was evaluated by importing the image into MATLAB (version R2009b). The inking level in each pixel for C-M-Y-K is summed and the total is divided by the number of pixels in the image,

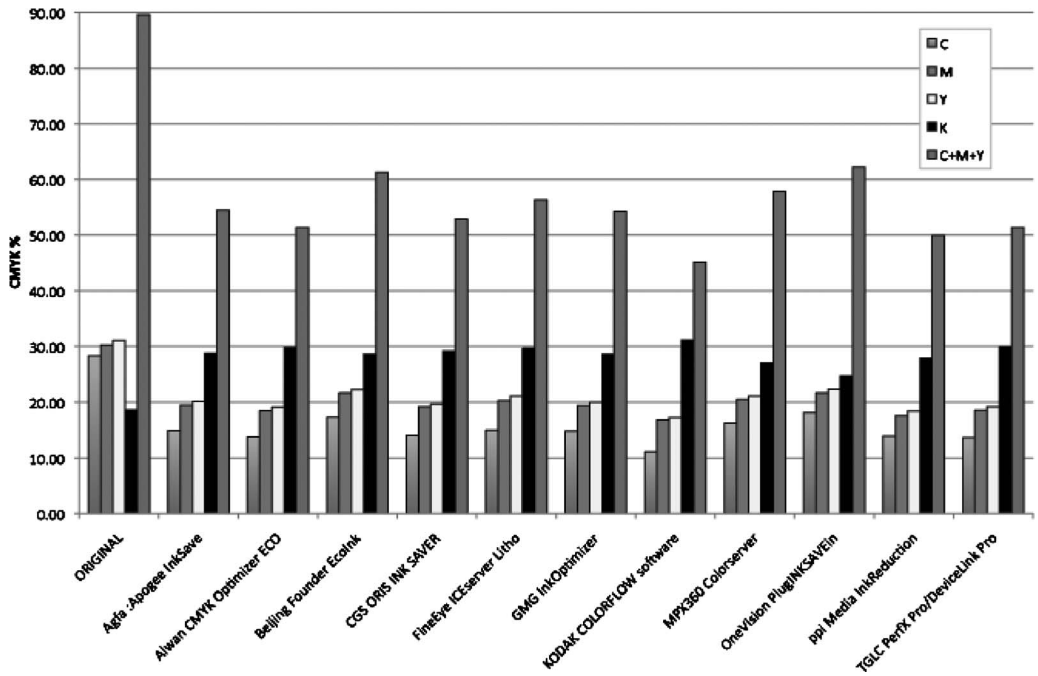

Figure 3. Form A had a *C+M+Y* coverage of nearly 90%; after processing most systems reduce the amount of *C+M+Y* inks to 45−60 % ink coverage.

$$\text{Cyan area coverage, } C = \frac{\sum_{i=1}^{n} C\%}{n}, \tag{1}$$

$$\text{Magenta area coverage, } M = \frac{\sum_{i=1}^{n} M\%}{n}, \tag{2}$$

$$\text{Yellow area coverage, } Y = \frac{\sum_{i=1}^{n} Y\%}{n}, \tag{3}$$

$$\text{Black area coverage, } K = \frac{\sum_{i=1}^{n} K\%}{n}, \tag{4}$$

where n is the total number of pixels in an image and C%, M%, Y%, K% are the pixel values in each of the four channels.

The CMYK ink volume is thus given by

$$\text{CMYK ink volume} = C + M + Y + K. \tag{5}$$

In this test no printing or proofing was done; this test was based only on digital analysis of the processed file. This test was conducted by measuring the CMYK values of the "original" Form A and comparing those values to the form after it has been processed by each ink optimization solution. The coverage for each channel and total percentages for all channels was computed and graphed.

Each supplier's data are then plotted as shown in Figure 3. In this graph a lower number for the C+M+Y column is better as it represents less use of expensive CMY inks which have been replaced by black ink. In Fig. 3 we see that the starting version of Form A had an average C+M+Y coverage of nearly 90%, and that after CMYK→CMYK processing most suppliers reduce this amount to 45−60 % ink coverage. It is relevant to note that this is not the amount of ink savings rather this is only the change in C+M+Y ink coverage of the form before and after the ink optimization process.

An important factor that is evident in Fig. 3 is the relative amount of CMY inks compared to K ink. For a true return on investment (ROI) and "bottom line" calculation it is necessary to consider the differential in price between CMY and K inks and the run length of the job. The typical retail cost of an economy ink set for sheet fed is around \$15–18/pound for each of the process inks and web fed inks are around \$7–8/pound.[16] An ROI calculation may be an easier way to communicate the impact of ink savings to a print shop owner.

The data shown in Fig. 3 can be expressed in a different way. If we take into account the fact that a system reduces CMY inks but to do so increases the black ink then it is possible to create a graph of "change in total volume," Figure 4. Fig. 4 shows how much change has occurred when we compare the C+M+Y+K of the original separation with the reseparated file. We see that the overall total volume change in ink consumption is reduced by 17−30 %. Real-world ink savings have been measured to give another 5%

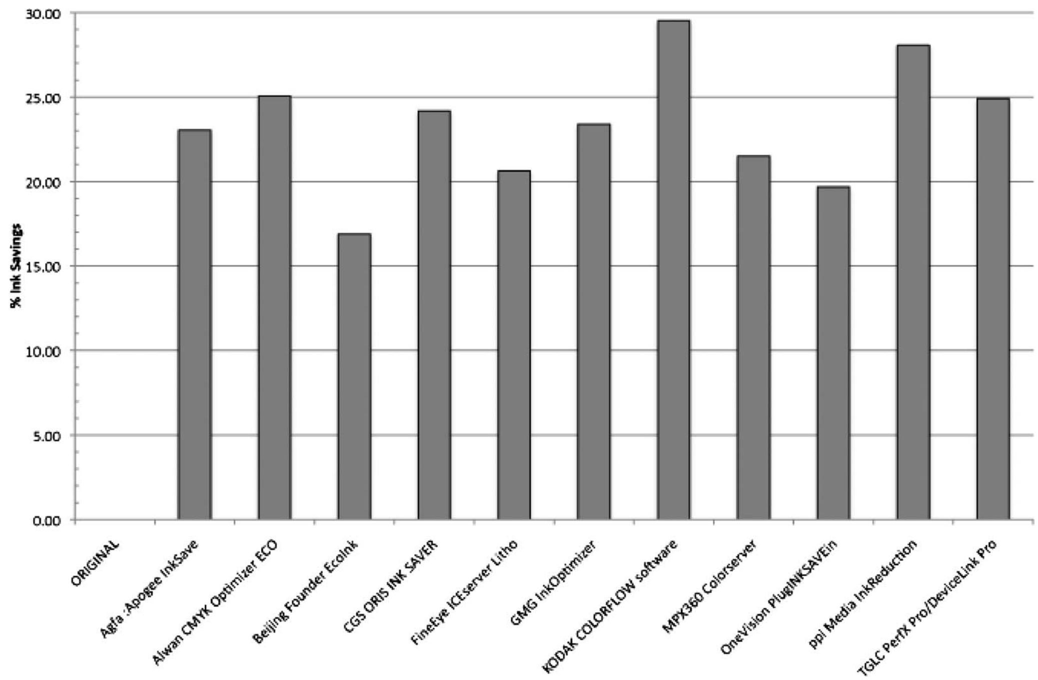

Figure 4. This graph shows that the new separation created by each system used between 17–30 % less CMY ink volume compared to the original file. The analysis is based on Form A.

savings in ink weight as measured on a controlled web press when tests were performed at RIT for a print job containing typical content.[17]

There are other cost advantages that can be considered. The use of less volume of ink has practical advantages. It is possible to use a lighter weight paper for the job; the drying time of the press sheet is reduced so the job can be turned around quicker, this reduces storage costs; the job can be invoiced quicker; we may consume less energy when using an inline dryer, etc. So the ROI calculation can include many factors that are not immediately obvious and when we begin to consider all the cost savings of ink optimization we begin to draw a very compelling argument for this technology.

Delta E Colorimetric Change

A basic assumption in ink optimization is that the colors in the image are unchanged from the original file. In other words, during reseparation we have found a new CMYK combination this has used less ink but ideally does not result in any change to the color when this file is printed. In this test, we estimate the colorimetric change that occurs from the application of ink optimization using (i) the IT8.7/4 target contained in Form A via analysis of the digital file (ii) proofing and measuring of the IT8.7/4 target on an Epson 9900 ink jet proofer and (iii) via printing and measuring the Optimization Control Strip on a ROLAND 700 offset press.

In order to analyze the Delta E in the digital file, the CMYK pixel values in the original target were converted from CMYK to CIELAB using the GRACoL ICC profile and the absolute colorimetric rendering intent. Next we repeated the process with a target that had been optimized by each supplier's system. We computed Delta E(2000) between the CIELAB values predicted by the original target and compared those to the values extracted from the supplier optimized version of the IT8.7/4, Figure 5 (left). Note that we did not use the characterization reference file, but instead a more realistic result that incorporates interpolation errors.

Fig. 5 (left) shows the average Delta E(2000) based on 1617 patches. As no printing and measuring was involved, we see Delta E values that can be very low and in the order of <0.5. It is also of interest to provide an indication of the maximum errors that may occur in the IT8.7/4 sample set, so in order to present an indication of the outliers that have a high Delta E we plot Delta E at the 90th percentile.

The Delta E in the IT8.7/4 target is expected to be low because the primary method to determine a new CMYK value is to use an ICC output profile to determine the new value, so this test is just a repeat of that process, and serves as a "sanity" check before images are proofed or run on press. Another reason for the low Delta E in Fig. 5 (left) is that there are no errors due to printing or interinstrument agreement.

Figure 5 (right) shows the Delta E for the IT8.7/4 target on Form A when printed and measured on an Epson 9900 ink jet proofer, using a certified proofing RIP and processes that fall within certification tolerances. Delta E was computed between the target on each optimized proof and the GRACoL reference data set. In this test we determine the colorimetric change that occurs from the application of ink optimization—during proofing. In general, we expect the results from the middle graph in Fig. 5 to be similar in nature to the top graph. The reason to show the target on an ink jet proofer is that we seek to better demonstrate to the end-user that the effect of ink optimization is to reduce the amount of CMY inks without changing the printed

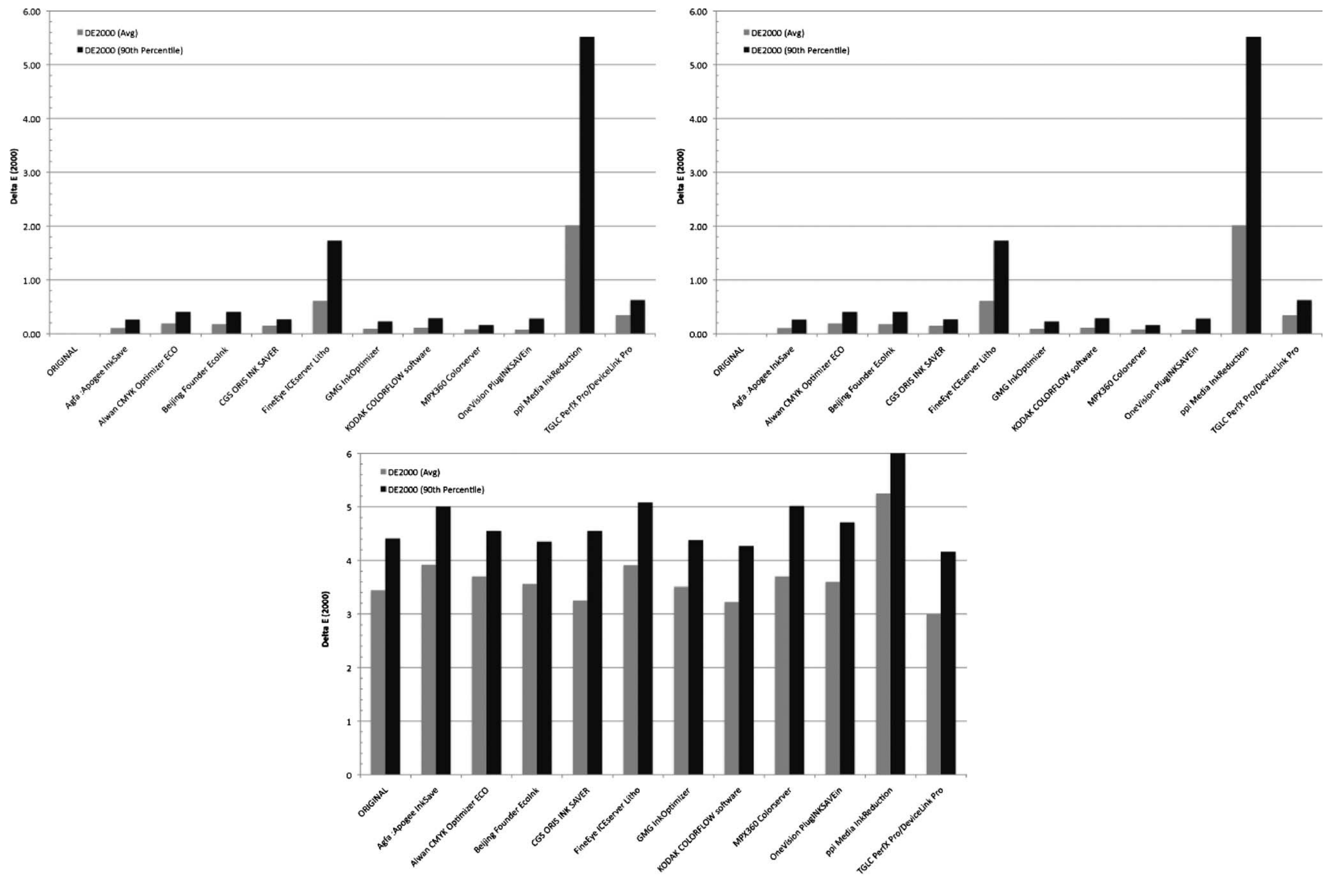

Figure 5. Test targets were optimized by each system. Colorimetric error between the GRACoL numbers and the values created by each system was computed. Mean and 90th percentile Delta E (2000) analysis is shown for three situations—analysis of digital file (left), ink jet proofing (right) and from the offset press sheet (bottom). It is clear to see that printing and measuring introduces significant errors.

color—so it is necessary to print the images. Fig. 5 (right) is in terms of average and 90th percentile, Delta E (2000) based on 1617 patches. In this figure it is important to note that the nonoptimized ORIGINAL form also has some Delta E error. The ORIGINAL IT8.7/4 is merely the standard target with CMYK values as specified by the CGATS standard.[14] The error in the ORIGINAL represents systematic errors due to the inevitable variations introduced by the ink jet proofing and measuring process and thus provides a baseline for the other results in this graph.

Just as we assume that ink optimization should introduce no color change in the digital file or on the ink jet proof, similarly we expect the color should be unchanged on press. The ultimate destination of most images in printing is an offset press therefore it was important to verify the results when printed on an offset press. To obtain colorimetric data from the offset press, Form B was used. Colorimetry was determined from the Optimization Control Strip patches (the IT8.7/4 could not be included on the press form due to size limitations). The optimized versions of Form B were assembled onto an offset press form and run on press. One of the images in Form B was an nonoptimized, original image, measurement of this image provides the first column in Fig. 5 (bottom). In each case, the press sheet was measured and Delta E between these values and the GRACoL data set was computed. Note that on press, each set of images is aligned below different ink keys and that each image (including the nonoptimized image) was compared to GRACoL.

The nonoptimized part of the form provides an indication of the Delta E deviation from the GRACoL data set which will give us information on how close the printing is to GRACoL, while the Optimization Control Strips provide an indication of the performance of each solution. If ink optimization creates more accurate printing on press, it is conceivable that the ink optimized images could show lower Delta E than the original.

It is important to note that even the nonoptimized original image, has some Delta E error, the error in the ORIGINAL column represents systematic errors due to the inevitable variations introduced by the offset printing process. The values in the Optimization Control Strip were directly extracted from the GRACoL reference data file, so if the printing was exactly to GRACoL, the ORIGINAL column would show Delta $E=0$. The fact that the Delta $E \neq 0$ is expected and acceptable as no press can print exactly to any specified print condition such as GRACoL, in our case. The data in the ORIGINAL column is very useful as it represents the tolerance or "error bar" that should be used to interpret the other data in this graph. Using this argument we can say

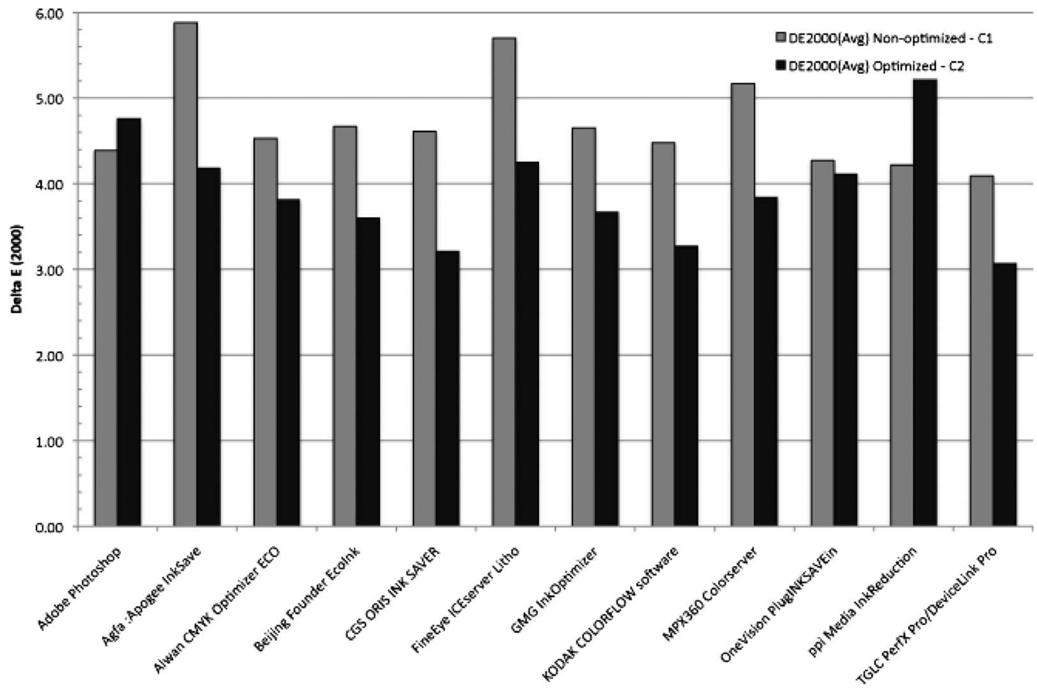

Figure 6. A press was run was conducted with intentionally 0.2 higher density in the magenta channel. Measurement of the Optimization Control Strip was compared to the GRACoL reference values. The benefit of optimization, second column in each case, is shown by a lower Delta E when compared to measurement of the non-optimized target (first column in each case).

that the columns for each supplier system are not expected to be <3.0 Delta E due to the practical impossibility of creating exact GRACoL printing on an offset press. In the wider sense, this result also provide information to answer the question—how close (colorimetrically) can a press run be to a given data set?

As we are trying to measure the effect of ink optimization, Fig. 5, left, right, and bottom, are based on the similar underlying data, and only differ in the manner we have proofed or printed the images. We conclude, therefore, that the increased errors—as we go from digital image analysis only, to ink jet proofing to offset printing—are due to the variations in the printing and measurement process. As mentioned above, the data are variable in terms of *absolute* measurements, but *relative* to each other the data provides an accurate depiction. Whichever measurement is chosen, the data shows that for the systems evaluated, *ink optimization can create ink savings without changing the printed color*.

Evaluation of Press Stability

There is anecdotal evidence that ink optimization reduces the proportion of C, M, Y in the midtones and quartertones, and as C, M, Y inks may naturally vary in a press run, the reduced amount of these inks reduces the impact of any variations of the press.

To verify this statement we used Form C, and changed the target density on the press sheet from the optimum setting. The press was initially run at the normal GRACoL target density and CIELAB values. After the press had stabilized the print density was changed via the press console's ink keys to simulate variations or drift in ink density. While a number of press variations were conducted, in this section we describe the analysis of one of those variations in which the press was changed by +0.2 magenta density units. A novel procedure was developed to measure the colorimetric stability afforded by ink optimization during press drift.

To contend with the considerable fluctuations present in the offset printing process, a novel procedure was developed using Form C, Fig. 2. The left-most strip on Form C was a default separation or starting image, the middle strip was separated with typical ink optimization setting, and the right-hand strip was a supplier separation with different (usually more aggressive) ink optimization setting. The right hand slice can be ignored for the present discussion. The strips were combined and assembled onto a press form and put on press. The press was changed to simulate a drift of +0.2 magenta density. The press sheets visually showed a reddish color cast in the left most image, but in most results a neutral reproduction in the middle image of Form C.

We seek to measure and document the relative stability of the middle image due to ink optimization. In order to demonstrate the change due to ink optimization we measured the left image (nonoptimized or "original") target in terms of CIELAB—for *each* system tested. We computed a Delta E between these values and the GRACoL reference data set. This is the first column in each case of Figure 6, and represents the inherent accuracy in that part of the press sheet. Next we measured the CIELAB values of the 54 patches contained in the middle (optimized) part of the form. We computed Delta E between the middle patch val-

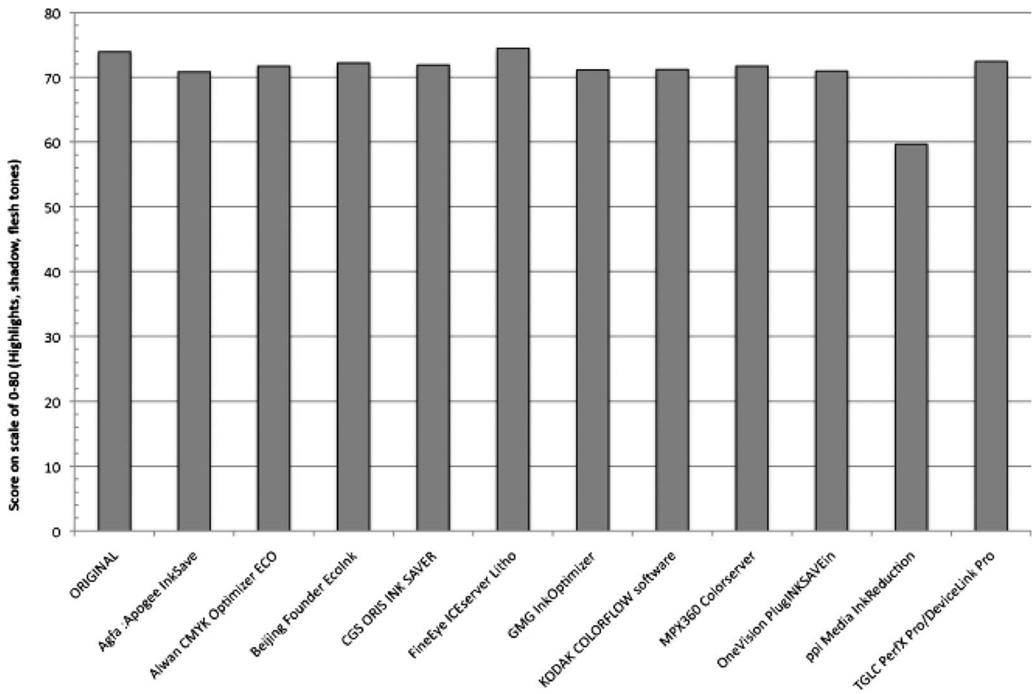

Figure 7. Eleven experienced professionals judged offset printed Form B. Judges provided anonymous numerical ranking of Form B as compared the nonoptimized original. The maximum score possible is 80.

ues and the GRACoL reference data set. This is shown as the second column in each case of Fig. 6.

In order to interpret the data in Fig. 6, we can say that accuracy of the printing in that local area of the press sheet is depicted by the first Delta E column in each case, and this error is due solely to the print process. This is different for each system as it is based on their position on the press sheet. What is important in Fig. 6 is whether the supplier optimized image (the second column) shows an improvement in Delta E, i.e., a lower Delta E, which suggests that the optimization process created images with a combination of CMYK that showed less color variation when the press was made to "drift." If the Delta E is lower in the second column we can infer that the optimized image showed less warm, reddish color cast compared to the original, and that in a real press situation the optimized image would be more stable and less susceptible to press density variations.

A result introduced on this press sheet is a separation using Adobe Photoshop CS4 (first pair of columns in Fig. 6). As each test image already included the nonoptimized target, we could use a spare slot on the press sheet to make a separation in Adobe Photoshop using the Convert to Profile > Custom CMYK. A custom separation was made using as the solid ink values the CMYK GRACoL end points. This separation shows an increase in Delta E which shows that Photoshop was not a very efficient ink optimized solution.

Visual Analysis of Press Sheets

In order to be successful, ink optimized images need to preserve the look of an unoptimized image. If the quality of the optimized images is reduced, the results will be unacceptable to many print buyers. A number of the above sections have evaluated the colorimetric accuracy of ink optimization, but often the real test is—do the images look good? Measurement values are useful, Delta E is indicative of expected errors, but at the end of the day, the real litmus test is for printers and users to see real images on real press sheets.

A group of experts were invited to visually evaluate offset press sheets containing printed Form B. Form B was cut to approximately letter/A4 size. The supplier information was removed from the sheets to make them anonymous. We conducted anonymous reviews with prepress professionals in Chicago, New York and Michigan.

To review the images, each judge was provided with instructions and a grading grid. An interesting variation in this test was the blind inclusion of a duplicate original, to see how the judges unwittingly compared an original to an original! Each judge scored each form on a 1–10 scale and the results for all of the experts were complied and averaged, Figure 7. The graph is based on 11 observations. The judges opinion in general was very consistent, the tabulated data showed very little variation.

The optimized images were compared to unoptimized images in terms of highlight detail, shadow detail, flesh tones, color cast, gray balance, gradients, overprints, moiré, artifacts and overall similarity to the original image. While all judges were instructed to use standard D50 lighting booths the judging was not conducted as a controlled experiment. During an initial analysis the good visual quality of all systems on the press sheet was noted. It was also noted that the systems were very similar to each other. In this situation the time and cost expense of undertaking a formal ranking and judging experiment was considered unnecessary.

It is a verification of the process that the ORIGINAL when compared anonymously to another copy of the original was ranked highly. It is even more interesting to note that one solution was judged to be marginally better than the original—FineEye ICEserver.

Metamerism Testing

Metamerism is caused by interaction between the pigments of printing inks and the viewing light source.[18] If we change the amount of colored (CMY) inks in the make up of a color this could affect the metameric properties of the print. We seek to determine if the image will change color under different illuminants. Is the optimized image more or less metameric compared to the unoptimized print? In creating ink optimization algorithms, we seek to determine if a system considers the spectral properties of the inks or simply colorimetric accuracy.

In this test we used spectral measurements from the Optimization Control Strip printed on the offset press sheet. The Optimization Control Strip was measured using an X-Rite i1i0 in spectral mode, and the spectral data were converted to $L^*a^*b^*$ (D50) and $L^*a^*b^*$ (F2). Finally Delta E average between these two data sets was calculated. The Delta E between $L^*a^*b^*$(D50) and $L^*a^*b^*$(F2) for the unoptimized image was also computed.

The average Delta E (2000) between the two data sets was in the order of 2.5. We noted that most suppliers have very similar results however the solution from ppi media had a slightly lower Delta E than other systems and this could indicate some algorithmic consideration for metamerism of printed samples.

DISCUSSION

The tests show that ink optimization works—the systems are able to process files in real time, the new optimized files have lower CMY values, reduce ink consumption on press, are more stable on press, yet files still retain colorimetric accuracy to the original.

In particular the research considered digital analysis of the separation of a CMYK file, before and after ink optimization processing. The overall reduction in ink volume and graphs were presented to show that ink optimization procedures can provide between 17–30 % savings in ink volume, for the test form used in this research.

There are other cost advantages that can be considered. The use of a lower volume of ink has practical advantages. The ROI calculation can include many factors that are not immediately obvious and when we begin to consider all the cost savings of ink optimization, we begin to draw a very compelling argument for this technology.

One of the methodologies developed in this research was the Optimization Control Strip. While a number of established test targets already exist (IT8.7/4, IDEAlliance Digital Control Strip), many of the patches in these targets are not expected to be affected by ink optimization. A new target called the Optimization Control Strip was constructed, in which all 54 patches were specially chosen so that each patch contains CMY triplets that will be potentially affected by ink optimization software. The new patch values were chosen from within the GRACoL data set.

The Delta E accuracy with which a system can reduce the inking level yet still provide color accuracy on output was measured. For a digital file the Delta E(2000) can be quite low, <0.5. Due to variations in printing and measuring, when the same data is computed from an ink jet proof or offset press sheet, the error is higher.

There is anecdotal evidence that ink optimization reduces the proportion of C, M, Y in the press image and as C, M, Y inks may naturally vary in a press run, the reduced amount of these inks reduces the impact of any variations of the press. In this research it was reassuring to clearly demonstrate this principle and show that in most systems a larger color cast was evident in the unoptimized press image while optimization reduced the color cast by 1–1.5 Delta E when compared against the GRACoL reference values.

Other useful tests developed in this research included a system to evaluate the metameric influence of ink optimization. An "informal" visual analysis of the results was conducted using 11 prepress professionals from within the USA.

While ink optimization includes many of the aspects (and benefits) of UCR and GCR there are new parameters that are incorporated into this technology concept. Some important new aspects of ink optimization include equalizing TAC when dealing with imagery from disparate sources, identification and computation of cost savings, relationship to ink savings on press, aspects of ROI—both in ink savings and also in "collateral" aspects such as drying time and drying energy, quicker turn around time, etc. methods for black preservation and image processing techniques that consider spatial area sensibilities.

One of the motivations for this research project was to establish some criteria and benchmarking statistics. There is little information in the peer-review literature and end users must rely on marketing literature. These data and the associated consumer/user level report—IPA Ink Optimization RoundUP—provide reputable, independent data. Studies of this nature improve prepress technologies and allow the technology to grow and be applied beyond only offset lithographic printing, to fit, for example, the vastly variable printing requirements of the newspaper industry.

This research identified a number of test parameters and then defined relevant test procedures and finally applied those protocols to commercially available ink optimization systems. The intention was not to rank or identify "best" systems but to explore the state-of-the-art as it relates to ink savings and press performance. The commercial data presented here are merely presented to show some indicative numbers and a benchmark or snapshot of the industry at the present time.

ACKNOWLEDGMENTS

We would like to acknowledge Steve Bonoff and Joe Fazzi of IPA/IDEAlliance for their comments and for supporting this project and allowing publication of the results. We are extremely grateful to Hal Stratton at manroland for providing press time and materials. We would like to specially mention the generous donation of paper from David Niles of Sappi Fine Paper North America. We are grateful to Scott Tait and Eden Kim at Fujifilm, Toronto, for providing resources for ink jet proofing. We are extremely grateful to the suppliers that participated and allocated resources and personnel to participate in the testing and often lengthy conference calls and communications relating to procedures and practicalities. We have enjoyed a constructive dialog with individuals at the following companies—Agfa, Alwan, Beijing Founder, CGS, FineEye, GMG, KODAK, MPX360, OneVision, ppi Media and TGLC. Abhay Sharma is partially supported in this work by a Canadian NSERC Discovery Grant (Grant No. 341606-2008).

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