# Image Quality and Cost Assessment of Print-On-Demand Books from Web-Based Vendors Offering One-Off Printing

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## Abstract

*Due to the emergence of e-commerce and developments in print engines designed for economical output of very short runs, there are increased business opportunities and consumer options for print-on-demand books. The current state of this printing mode allows for direct uploading of book files via the web, printing on non-offset printers, and distributing by standard parcel or mail delivery services. The goal of this research is to assess the image quality and relative cost of a soft cover book printed by various web-based vendors offering one-off printing. Six vendors were identified. Sixteen observers rank ordered overall quality of a subset of individual pages from each book. Observers also applied overall quality ratings to the perfect bound books. Objective metrics of color gamut, color accuracy, overall contrast, ICC profiling accuracy, sharpness, noise, and actual cost were obtained. None of the objective metrics was an indication alone of overall quality. For example, printers with smaller color gamut, lower color accuracy or lower contrast were still able to achieve high overall image quality. Photographic quality was highly correlated with overall quality assessments, more so than text quality. Overall image quality had positive correlation to actual cost. One publisher had a cost model that was significantly lower than the other one-off vendors.*

## Introduction

Digital color imaging is seeing the fastest growth rate in the non-offset digital printing category [1]. The print engines have begun to enable inexpensive output of very short run documents right down to one-off books that can sell for as little as $10 a unit. The Internet has spawned new business models such as print-on-demand art books or books where individuals can self-publish for small or no fee by uploading their content online [2,3,4]. Web-based publishers have begun to capitalize on this new approach, creating menus and information guides for individuals wishing to print and publish books [5,6,7,8,9,10]. Some websites even offer assistance in obtaining ISBN numbers [e.g., 5,11]. In addition, websites are creating new international social networking environments for book publishers [5].

The goal of the study described here was to baseline the current state of one-off standard books in terms of delivered image quality and price expectations. An approximately 90-page book with most pages one-sided was designed for the purposes of the study and through web interfaces was uploaded to each of six on-line vendors for soft-cover publication. The one-off printed and bound books were delivered through typical services such as UPS, Federal Express and US Mail. Psychophysical experiments were run to gain understanding of how perceived image quality responses corresponded to physical measurements and cost. Observers evaluated individual pages that had been removed from the books and also evaluated books in their intended format as perfect bound books.

## Stimuli

### *Content*

Book content was collected for this experiment with the goal of having appropriate material for the assessment of pictorial and text image quality as well as to determine the influence each plays in determining overall image quality within this application. In addition, the pages were designed to allow analysis of ICC profile accuracy, color gamut volume, line quality, overall contrast and print uniformity. Pages included the IT8.7/3 Extended Ink Value Data Set [12], a simulated Macbeth ColorChecker created from BabelColor sRGB code values [13], and ISO/CD 12640-3 CIELAB SCID images [14]. Photos included various skintones and other key memory colors such as sky, foliage, and fruit. Color encodings in the book included RGB, CMYK, K only, and 16-bit CIELab. The final book content was ninety-one pages. Most pages had only one side of printed content.

### *Profiles*

In order to assess the ICC profile interpretation accuracy, a target comprised of 4 sub-images was utilized [15]. Each quadrant contains a unique embedded profile and associated code values such that the target looks like a single image when printed correctly. When profile misinterpretation or disregard takes place, the quadrants should appear distinct.

In addition to images with profiles, the book also contained objects without embedded profiles. This allowed us to see how untagged CMYK, K and RGB elements were handled.

### *Preparation*

The book files were constructed using Adobe InDesign CS2/CS3, then exported as pdf files. Confirmation of correct profiling was performed with a trial version of an Adobe Acrobat plugin (Quite Revealing 1.8a (EN), Quite Software). The pages were created at either 300 or 600 dpi, depending of the spatial needs of the page content.

### *Printing*

Table I contains the names and printer information for the six vendors selected for this experiment. At the time of selection during the summer of 2007, these six vendors were identified as online options in the United States that offered one-off printing for less than $150 per book. One exception was UBuildABook that had a minimum of "two-off" printing, but was added to the pool in order to have more vendors to evaluate.

**Table I. Information about the six Internet vendors that provided one-off print-on-demand books. Printer information was obtained from each vendor.**

| Designation | Vendor | Printer |
|---|---|---|
| A | UBuildABook | Xerox DocuColor DC250 |
| B | Lulu | Xerox iGen |
| C | Flexpress | Xerox iGen |
| D | NetPublications, Inc. | IBM InfoColor 70 |
| E | StarNet Digital Publishing | HP Indigo 1000 |
| F | R and R Images | HP Indigo 5000/5500 |

## Psychophysical Testing

### *Individual Pages and Perfect Bound Books*

The psychophysical testing was divided into two parts: evaluation of individual pages and evaluation of perfect bound books. A rank order method from 1 to 6 (1 = best, 6 = worst) was used for evaluating overall image quality of 10 select pages from each vendor. Of the ten pages, some had photos only (n=6), some had text only (n=1), and some had a combination of text and photos or charts (n=3). Observers used a rating scale from 1 to 5 (1 = very low satisfaction, 5 = very high satisfaction) to judge overall image quality of the perfect bound books from each vendor. The final number of page sides evaluated in each book was reduced to forty pages plus two full-color covers due to removal of pages for other evaluations.

### *Experimental Details and Protocol*

Sixteen observers were recruited. The age range was from 18 to 63. Individual pages and books were evaluated in a controlled light booth (GTI EVS, D5000, 1800 lux). Observers rank ordered the individual pages on the table surface of the light booth. Most observers evaluated the perfect bound books while holding them in both hands, elbows bent. Viewing distance was unspecified. The experimental protocol was based on a Bartleson and Grum approach [16].

## Results and Analysis

### *Psychophysics*

Figure 1 contains the plots of the rank order overall image quality results for the individual page judgments. The averaged results of the ten pages for all sixteen observers are plotted in Figure 1a. Error bars in this paper are standard error values. The results show that the book from Vendor E is ranked the highest out of all six vendors while Vendor D's book is the lowest ranked. Observers commented that the pages from this latter book were grainy in appearance.

Figure 1b contains the averages of text pages rankings. The error bars in this plot are larger than those in Figure 1a due to the smaller number of pages used in the ranking. The rank order for the text image quality indicates that Vendor C has the highest text overall quality and Vendor A has the lowest. The text was written twice on a page. One copy was at 100% K and the other at 50% K. Observation indicated that the density of the 50% K in Vendor C's book is highest while the density for Vendor A's 50% K is low and somewhat blurred. This was likely due to the fact that printer A mixed CMY inks for the 50% K specification.

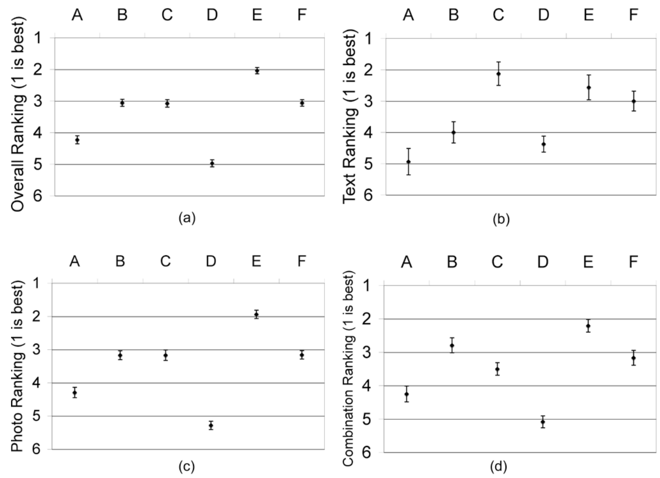


*__Figure 1.__ Rank order of overall image quality results for the individual page judgments (1 = best, 6 = worst). (a) The averaged results of pages for all sixteen observers (n=10). (b) The results for ranking the text pages (n=1). Large error bars are due to smaller sample number. (c) The results for the photo page rank order (n=6). (d) The results for the combination pages (n=3).*

The averages for the photo page rank order and combination pages appear in Figure 1c and Figure 1d, respectively. In Figure 1a, 1c and 1d, Vendor D appears to do the worst whereas for Figure 1b that does not seem to be the case. Also in Figure 1b, Vendor C appears to be among the best but in the others, this is not the case. This could indicate that overall quality response is strongly influenced by photo quality response. This question is worth future investigation.

The results for the rating scale evaluation of the perfect bound books appear in Figure 2. Here the books were evaluated as a whole versus individual pages reported above. Compared to the rank order of the averaged individual pages shown in Figure 1, the overall image quality results for the books are similar in distribution with the exception that Vendor F sees a large improvement relative to vendors B and C. These results place the Indigo vendors above the others in a way that was not clear-cut when the individual pages were evaluated.

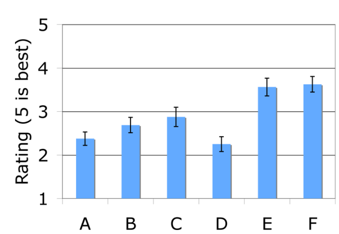


*__Figure 2.__ Rating scale evaluation of the perfect bound books (1 = very low satisfaction, 5 = very high satisfaction).*

### *Color Gamut*

Two untagged targets were incorporated into each book in order to assess the color gamut volumes. One target was a randomized version of the IT8.7/3 CMYK patches. The second target consisted of RGB values divided into 10 levels such that the target contained 10-cubed (1000) patches. The inclusion of both CMYK and RGB encoding was to compare the impact of image processing paths.

Table II contains the estimated gamut volume calculated using the alpha-shape techique [17]. It is interesting to note that Vendor F with the lowest RGB gamut had one of the highest overall subjective ratings. Unexpectedly, the CMYK gamut volumes for Vendors B and D *decrease* relative to their respective RGB volumes. These vendors are clearly not treating CMYK code as raw values and are applying an interpretation to CMYK prior to printing. For Vendor A, the nearly identical gamut volume results for both targets indicate a simple direct conversion of RGB to CMYK. The remaining vendors have the expected performance of a larger CMYK gamut volume.

**Table II. Color gamut volume summary (in cubic CIELab units) for six vendors. The last column indicates how the CMYK volume compares to the RGB volume.**

| Vendor Designation | RGB target | CMYK target | CMYK Volume % Increase |
|---|---|---|---|
| A | 307,433 | 309,056 | 0.53 |
| B | 429,179 | 313,516 | -36.89 |
| C | 372,807 | 448,792 | 16.93 |
| D | 253,074 | 215,801 | -17.27 |
| E | 401,549 | 448,567 | 10.48 |
| F | 224,045 | 273,149 | 17.98 |

### *Color Accuracy*

Color accuracy was assessed using the simulated Macbeth ColorChecker target with an embedded sRGB profile. Table III contains the CIEDE2000 results for each vendor compared to the aim CIELab values calculated from the sRGB-encoded values in the target. The color difference values indicate that Vendor B had the lowest average color errors.

**Table III. Simulated Macbeth Color Checker CIEDE2000 Values.**

| CIEDE2000 | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Mean | 4.35 | 3.92 | 5.09 | 5.36 | 6.11 | 5.95 |
| Min | 1.01 | 0.87 | 2.24 | 1.40 | 3.03 | 1.68 |
| Max | 7.70 | 7.58 | 9.84 | 10.59 | 9.39 | 8.93 |
| σ | 1.72 | 1.70 | 2.06 | 1.97 | 1.64 | 1.79 |

Notice that the two vendors with the highest overall image quality results, Vendors E and F, had the highest average color difference values. As is often the case, here preferred color and accurate color are not the same. Further analysis of Vendor E shows that all of the printed colors shift to darker L* values. Thus, the higher color difference numbers are driven by what seems to be a darker version of the book.

### *Overall Contrast*

Figure 3 shows how each vendor interpreted the neutral scale of the sRGB simulated Macbeth ColorChecker. The point associated with code value R=G=B=255 was added using measurements from the paper white for each vendor. Black points were added from a target which had a patch with R=G=B=0. The plot is an indication of the gamma (contrast appearance) of the system assuming that individual images or pages are not being processed with some type of localized tonescale modification software. Note that Vendor F has the lowest gamma whereas Vendor E has the highest gamma. Inspection of the prints reveals that the paper for Vendor E is coated and has a glossy component while Vendor F paper has a strong matte finish. Despite the differences in gamma, these two printers have the highest overall image quality ratings. This paradox indicates that high overall image quality can be obtained from vastly different color performance as long as the system is optimized.

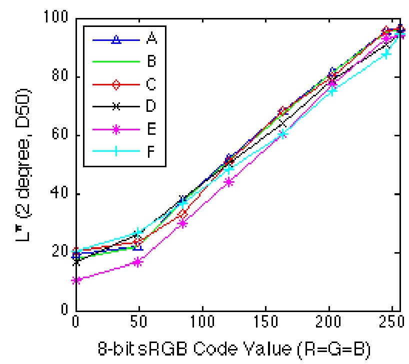


***Figure 3. L* (2 degree, D50) values of the neutral scale of the sRGB simulated Macbeth ColorChecker. Plot is an indication of the appearance of overall contrast of each vendor for sRGB encoding.***

### *Profiling Support*

Table IV contains the evaluation of the ICC profiling interpretation for each vendor based on how each vendor rendered the quadrant target. Vendors A and B failed the profiling probe, printing none of the four sections correctly. Inspection of the prints implies that the vendors are making an sRGB assumption regarding the RGB files passing through the image pipeline. Vendor D printed the version 4 profiles correctly, but not the version 2 profiles. Intuitively, this is surprising because the version 4 profile data structure choices are a superset of the version 2 profile data structure choices. Vendor E printed both version 2 profiles and one of the version 4 profiles correctly. It failed for a second version 4 profile, the sYCC profile. This profile utilizes the lutAtoBtype data structure, one that is not found in the version 2 specification. Thus, a processing package built to handle the version 2 data structures but that does not check the header to see if the profile is, in fact, version 2 will succeed in using the three other profiles but would not correctly handle the sYCC. Vendors C and F provided correct interpretation of all four embedded profiles.

**Table IV. Indication that the vendor used correct profile handling. * = Difficult to assess.**

| ICC Profile | ICC Version | A | B | C | D | E | F |
|---|---|---|---|---|---|---|---|
| e-sRGB | 4 | No | No | Yes | Yes | Yes | Yes |
| sYCC | | No | No | Yes | Yes | No | Yes |
| Adobe RGB (1998) | 2 | No* | No* | Yes | No | Yes | Yes |
| GBR | | No | No | Yes | No | Yes | Yes |

### *Cost*

Figure 4 contains a plot of the actual cost of books versus the overall image quality rating scale. Five of the six vendors exhibit a trend of increasing overall image quality with increased cost. There is one vendor that does not fall directly in this trend: Vendor B had a low price of $22 that indicates a disruptive business model in the marketplace. When a linear equation of the five most expensive books is fit, the resultant $R^2$ value is 0.92. Using this empirical model, Vendor B's price point is noted to be only 21% of the expected cost. Vendor B was left out of the model fit, but is placed in the chart for reference.

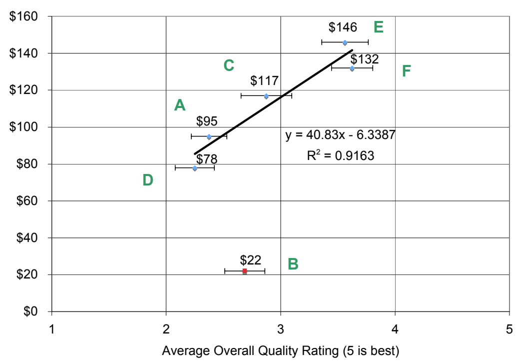


*Figure 4. Actual cost of book versus overall image quality rating scale. A linear fit of the 5 most expensive books resulted in $R^2$ = 0.92. The least expensive book (Vendor B) was left out of the fit, but is placed in the chart for reference.*

### *Spatial Analysis*

Scans of the neutral patches and their borders of the Macbeth ColorChecker were analyzed for sharpness and noise characteristics. For sharpness analysis, the transition between the neutral patch and its border was evaluated. An edge MTF was used to compute a feature of sharpness, CMT acutance [18], which includes a visual contrast sensitivity function (CSF). The CMT results were indicators that two aspects of the printed edge features can influence these results. The first is the shape and variation in location of colorant on the print. This could include ink spreading and dot separation, or toner clumping in electophotography. The second effect can be due to the spatial rendering, digital halftoning, that results in variations perpendicular to the edge.

For noise analysis, the scanned patch data were transformed to CIELab coordinates. The RMS deviates for the patches were then computed. In a procedure similar to that used to derive CMT acutance valued from the MTF, visually-weighted RMS L* values were computed by applying a spatial (convolution) filter to the L* image arrays and then computing the RMS fluctuations. Results indicate that the noise levels in the mid-density patches are more correlated to the overall image quality results ($R^2$=0.83) than the lightest or darkest patches ($R^2$=0.51 and 0.15, respectively).

## Conclusions

Six one-off print-on-demand vendors were assessed for overall image quality and cost. Rank order results indicate that photographic image quality on a page is more correlated to the overall quality of a book than the assessed quality of text. Because some publishers had different quality results for photos versus text, image reproduction may be the deciding factor for selection of one-off vendors of choice. Overall image quality ratings were highly correlated with actual cost when ignoring Vendor B's disruptive business model.

Analysis of the objective metrics indicated that high overall image quality could be obtained from measurably different performance. Also, the same printer hardware among different vendors did not guarantee similar image quality; software appears to have significant impact on image quality. In fact, color gamut comparisons revealed a paradox in that untagged CMYK gamuts are sometimes smaller than untagged RGB gamuts, which points to specific assumptions built into the vendors' software that can influence quality. Finally, use of an ICC profiling accuracy target revealed that ICC profile handling is still done inconsistently in the current one-off print-on-demand market.

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