Perceived Image Quality of Printed Images and Their Relation to Paper Properties

Ole Norberg, Mattias Andersson, Digital Printing Center, Mid Sweden University, Örnsköldsvik, Sweden

Abstract

In printing the final color image reproduction quality depends on the quality of the digital image as well as the properties of the printing system and the paper used. Although it is well known that the paper has a large influence on the print result it is seldom specified according to image quality attributes. Computer screens, digital cameras and printers are all technically specified with respect to resolution (number of pixels and dots per inch), gradation (bit depths) and primary color channels. The technical specification of paper on the other hand mainly includes properties of the unprinted paper that provide limited information about the appearance of the printed image. However, the characterization of paper is not as straight forward as the performance is not only related to the paper properties but also to a high extent to its interaction with the printing system. One way to indicate the color reproduction quality of images is to determine the modular transfer function (MTF). Several studies have derived the MTF of paper for certain printing situations (Bouzit 2002, Koopipat 2000 and Rogers 2000) and stated the influenced of not only the physical properties of the paper but also by the interaction between paper and ink. The most decisive properties found on paper MTF are ink penetration, ink spreading and the optical properties of the paper. Moreover, these paper properties can be associated to color rendering attribute associated with image quality such as color gradation, color gamut volume and image sharpness. In this study, these three attributes have been varied prior to printing in two sets of test images representing office paper and photo inkjet paper respectively. Color gamut volume, color gradation and sharpness were varied simultaneously according to a statistical experimental design thus producing a subset of modified versions for each image in the test set. Furthermore, a visual assessment study was carried out in order to study the effect of the modifications on the perceived impression of the printed images. Finally, the data from the visual assessment study was analyzed in order to reveal how the different attributes influenced the perceived color rendition. The results from the study showed that small changes in the varied attributes produces large response on the perceived color rendering quality and that the most important parameter is color gamut volume.

Introduction

The perceived quality of a printed image will depend on the physical properties of the substrate, the colorants used and the properties of the print engine, such as print resolution and adopted halftoning method. A widely established opinion regarding inkjet printing is that a large reproducible color gamut for the combination of a printer and a substrate automatically yields high perceived print quality. Furthermore, studies have shown that the volume of the reproducible color gamut for the combination of a printer and a substrate is one of the most important print quality attributes in high quality inkjet printing when relating objective print quality measurements to the visual appearance of a printed image (Gidlund 2005). On the other hand, other studies have shown that the visual appearance of a printed image is not only related to the volume of the gamut but also to a high extent to attributes such as color gradation, color accuracy and image sharpness (Hunt 2004, Keelan 2002). The influence of these parameters will, in turn, also be related to the actual composition of the image (the motif itself).

Background

It is widely known that the print quality in inkjet printing is heavily dependent of the properties of the substrate to be printed. The difference in print quality between an ordinary office paper and a high-quality inkjet paper is significant, but in turn, so is the difference in price. Furthermore, papermaking does in most cases imply compromising between different paper properties as well as production costs. Therefore, it is wise to find out what properties to give priority to when designing the paper. In a previous study the influence of different color rendition attributes on the perceived color rendition quality for office paper were determined (Andersson 2006). In this study, the objective was to compare these results to another quality space, specifically high quality photo paper. The objective was to get an understanding of what properties of an inkjet-printed image that would have the largest effect on the perceived color rendition for different paper grades. Therefore, different color rendition attributes were manipulated in test images prior to printing. The attributes that were varied in this study – color gradation, color gamut volume and sharpness are all attributes that can be associated with actual inkjet printing issues related to paper properties, such as ink penetration, ink spreading and light scattering which in turn can be related to the MTF of the paper. In paper production the optimization of certain properties might be contradictory. For example, improving the surface smoothness, and thus reducing ink spreading, often results in reduced light scattering and smaller color gamut. In a similar manner, the properties of coating layers and base paper must be balanced. Involving also the economical aspect the choice between spending money on surface treatment or pigments for light scattering will also influence the performance of the paper.

Method

This study was designed as a screening experiment aiming to explore the three attributes in order to reveal their influence on perceived color rendition quality. Moreover, the experiment was designed to identify the proper ranges of the attributes as well as to determine the relations between them. Multiple linear regression based on the principle of least squares analysis was used to analyze the data. The result was models consisting of regression coefficients. These local models performed as approximations of how the attributes affected the perceived color rendition quality of the printed images within the ranges specified by the confined experimental region.

Experimental Design

A full factor screening design with three factors in a symmetrical distribution of experimental points around a centre-point experiment was used. Experiments were carried out in all possible corners of the locally defined color rendition quality space. In the centre-point, three replicate experiments were carried out to investigate the experimental variation.

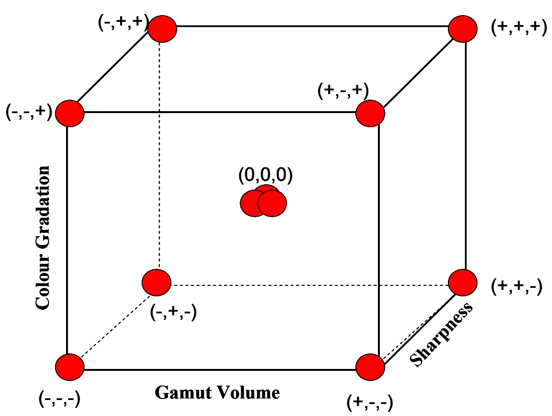

Figure 1: The three-factor full factorial design with eight corner-point experiments and three replicate experiments in the centre-point

The corner-experiments corresponded to eight images having different settings of the three varied color rendition attributes. The factor intervals were chosen on basis of experience reflecting variations among commercial papers. Along with these eight images, the centre-point-image was printed three times, thus resulting in a set of eleven printed images per motif. These image sets provided as the material for the visual assessments.

Table 1: Experimental design plan

ID	Sharpness	Gamut Volume	Gradation
1	low	low	low
2	low	low	high
3	low	high	low
4	low	high	high
5	high	low	low
6	high	low	high
7	high	high	low
8	high	high	high
9	Medium	Medium	Medium
10	Medium	Medium	Medium
11	Medium	Medium	Medium

Images

Three images, represented in 16-bit CIEXYZ-coordinates – "Pier", "Flowers" and "Threads" were chosen from the ISO 12640-2 image set. The ISO-images are well-documented and widely recognized images of high quality. Furthermore, the three images all have characteristics with the potential to reveal the influence of the varied attributes – color gradation, color gamut volume and sharpness.

Figure 2: ISO 12640-2 images Pier, Flowers and Threads used in the visual assessment study.

Paper and printing

A matte-coated inkjet office-paper (*Office paper*) and a photo-quality inkjet paper (*Photo paper*) were used in this study both having desirable properties representative to the target paper grades. All images and test targets were printed on a high-end inkjet printer. Prior to printing the test images in the experiment, ICC-profiles were calculated for the used printer-substrate combinations. An accompanying control strip was printed along with all images to verify the consistency of the printing process. Furthermore, all printed images were measured and compared to the digital data to assure that there were no color failures.

Simulating the printer-substrate combinations

Two paper grades with suitable properties were used to create experimental printer-substrate combinations, thus simulating an improved office paper and a high quality photo paper. With these simulated paper grades as a starting point, two sets of images for the visual assessment study were produced through the following steps:

1. The images were transformed from CIEXYZ-coordinates to CIELAB-coordinates using D50 illumination and 2° standard observer in the calculation.
2. The ICC-profiles generated for the utilized printer-paper combinations were used to convert the images defined in CIELAB-coordinates to device CMYK-coordinates using perceptual rendering intent.
3. The generated ICC-profiles were used to convert the CMYK-coordinates back to CIELAB-coordinates with relative colorimetric rendering intent, thus resulting in the starting-point image for the image manipulations.
4. Outgoing from the starting-point image, the different manipulations were applied, thus producing a set of nine images according to the experimental design plan.
5. Finally, the generated set of manipulated images was once again converted to device-space CMYK-coordinates using relative colorimetric rendering intent, and then printed thus resulting in eleven printed images.

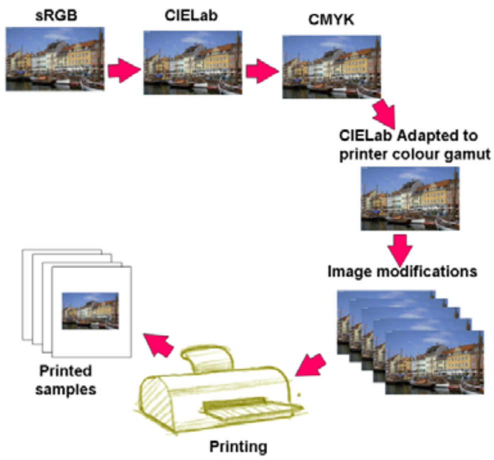

Figure 3: Producing the simulated printer-substrate combination.

Image manipulations

The image quality attributes were varied in a range representative for commercial papers for respectively paper grade based on long experience from print trials and print quality evaluations. For example, the gamut volume was varied by a scaling in the ab-plane of the starting-point image CIELAB coordinates as the L-axis, black ink channel, behaves differently from the other color channels and is less sensitive to variations in paper properties. A test image defining the sRGB gamut boundary was processed the same way as the other test images and the three scale-factors were applied. The printed samples were measured with a spectrophotometer and the color gamut volumes were calculated in the CIELAB space.

Table 2: Scale-factors and corresponding gamut volumes

Level	Scale-factor	Gamut Volume Office Paper	Gamut Volume Photo Paper
low	0.9	90,000 colors	350,000 colors
medium	0.95	101,000 colors	395,000 colors
high	1.0	113,000 colors	440,000 colors

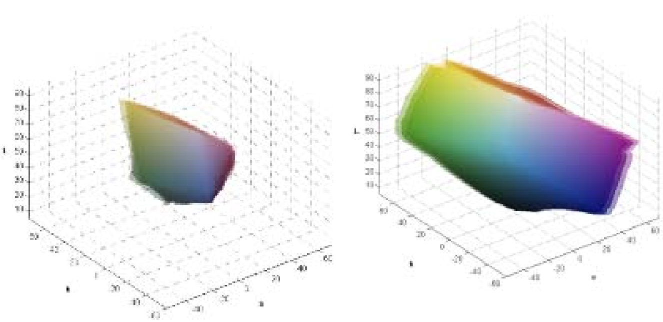

Figure 4: Color gamuts of the Office paper (left) and Photo paper (right) corresponding to the three scale-factors.

The images sharpness was varied by applying a Gaussian low-pass filter to the CIEXYZ-images. The highest sharpness was obtained for the original image, the medium level corresponded to the filter being applied once and to create the lowest level of sharpness, the filter was applied twice.

0.011	0.083	0.011
0.083	0.619	0.083
0.011	0.083	0.011

Figure 5: The Gaussian low-pass filter that was applied to vary the sharpness of the images.

The color gradation was varied by quantization the CIELAB-coordinates of the starting-point image prior to printing. For the *Office paper*, the quantization ranged from seven to nine bits. Since the results latter indicated that this range had a very small influence on the responses in the visual assessment study, the range was adjusted to span from six to eight bits in the *Photo paper* experiment.

Table 3: Color gradation and quantization of CIELAB-coordinates

Gradation level	Quantization (bits) Office Paper	Quantization (bits) Photo Paper
low	7	6
medium	8	7
high	9	8

Visual Assessment

The small differences between samples in the sets in combination with the relatively low number of samples made the paired-comparison method most suitable (Engeldrum, 2000). A separate study was carried out for each motif, each one consisting of eleven samples whereas three samples where identical. The visual assessment study was carried out in a perception lab at normal viewing distance in a viewing booth using D50 illumination without external light from surrounding light sources or windows. The printed images were mounted on white cardboard with a neutral grey frame mounted on top of the image as a surrounding mask, hence providing a constant visual reference. The observer panel consisted of sixteen persons mixed in age, sex and experience in judging printed samples. The observers were instructed to select the preferred sample with respect to the color reproduction quality. When the observer had completed the pair comparison they were asked to describe the most decisive areas in the image for their judgment. The paired-comparison index (PC-index) scales the samples from 0 to 200. High values correspond to samples perceived as having a good perceived color rendition, while low values correspond to samples perceived as having a poorer color rendition. The PC-index was calculated according to equation 1.

$$PC - index = \frac{\sum_{i=1}^{n} v_i}{2x(n-1)} * 200$$

where n is the number of observers and v_i is the value given by observer i.

Furthermore, a consistency coefficient was calculated for each observer and all observers with a coefficient of consistence lower than an acceptance level were excluded from the study.

Results of the visual assessment study

The results from the visual assessment differed between paper grades as well as between the tree motifs. An important finding was the small variation and centered positioning for the replicate centre-point samples. This variation was particularly small for the *Office paper* studies. With a variation in the three replicates much smaller than the total variation of the investigation series, the replicate error will not complicate the data analysis.

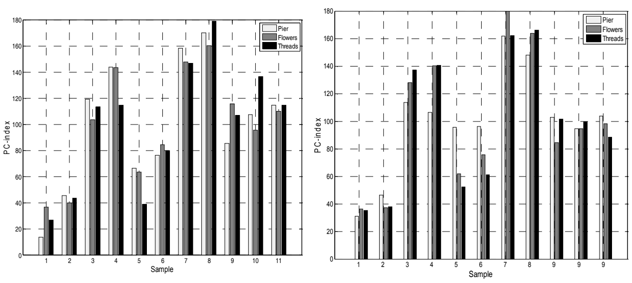

Figure 6: PC-index of the visual assessment of the "Pier", "Flowers" and "Threads" motif printed on Photo paper(left) and Office paper(right). Higher PC-index corresponds to a better color rendition. The sample characteristics are presented in table 1.

For the "Pier"-image as well as the "Flowers"-image, the observers had no trouble in agreeing on the critical areas. However, regarding the "Threads"-image, almost every observer had their own unique opinion on decisive areas and accordingly, the decisive areas differed widely.

Results Regression Model

The results from the regression were polynomial models which were used to interpret the influence of the factors. The objective was to find models using the same factors and interaction terms that fit to the responses from all three motifs. Singular value decomposition (SVD) was used to solve the system of equations. In the interpretation, the confidence intervals were used to estimate the uncertainty in coefficients and effects. *R2* is goodness of fit and describes how well the model fits the data. *Q2* is the goodness of prediction and estimates the predictive power of the model. Initially, all factors and their interactions were used in the regression. When analyzing the models for the *Office paper* case, high values of prediction ability and goodness of fit were obtained. The exception was the slightly lower prediction ability for the "Pier" image. When examining the regression coefficients, it was observed that the gamut volume and sharpness were the most influent factors while the color gradation had a very small effect on the responses. The only observed interaction of significance was the one between gradation and gamut volume for the "Threads" image, the contributions from other interactions could be regarded as noise. In order to improve the prediction ability for the "Pier" image model, the models were pruned, cleaned, from interaction terms insignificant in all models.

The result was considerably improved prediction ability for the "Pier" image and otherwise negligible impairments. For the initial models including all factors and interaction terms obtained in the *Photo paper* study, lower prediction abilities and goodness of fits were achieved. In similarity to the *Office paper* models, the regression coefficients indicated that the gamut volume and sharpness were the most influent factors. No significant interaction terms could be observed and consequently, they where excluded from the model. *Figure 7* shows the summary of fit and prediction ability for the six pruned models, one model for each motif printed on the two different paper grades respectively.

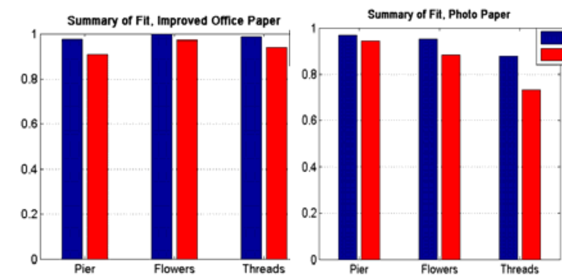

Figure 7: Summary of fit and prediction ability for pruned models

The regression coefficients for the pruned models are presented in *figure 8 and 9*. In this case of the *Photo paper*, a significant contribution from the color gradation could be observed.

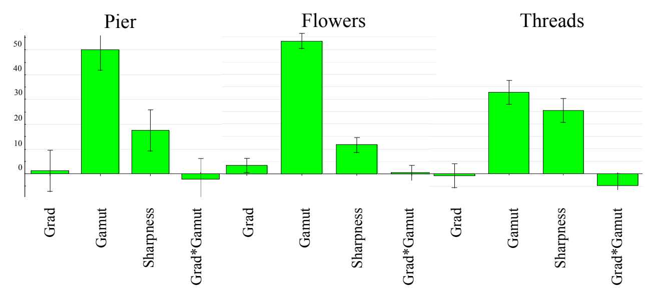

Figure 8: Regression coefficients in pruned Office paper model for "Pier", "Flowers" and "Threads" images.

Figure 9: Regression coefficients in pruned Photo paper model for "Pier", "Flowers" and "Threads" images.

Moreover, the model prediction plots indicate linear relationships between observed and predicted responses, *figure 10-15*. These results are in agreement with the high R2 and Q2 values obtained for the models.

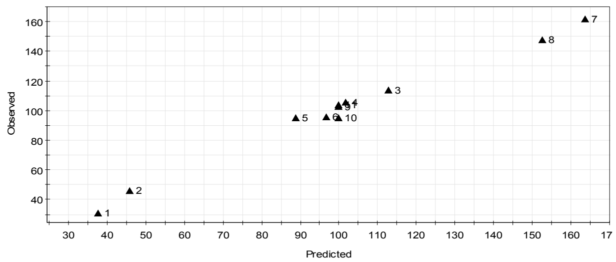

Figure 10: Predicted vs. observed response plot for "Threads" image and pruned Office paper model

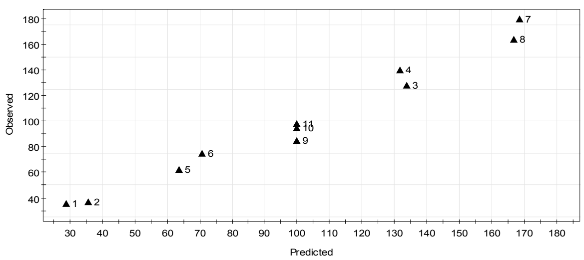

Figure 11: Predicted vs. observed response plot for "Pier" image and pruned Office paper model

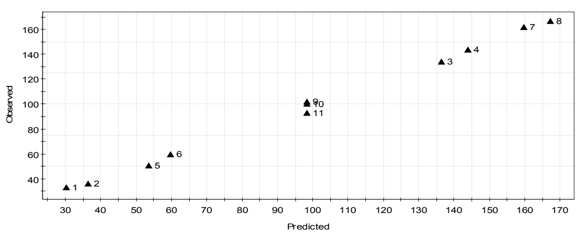

Figure 12: Predicted vs. observed response plot for "Flowers" image and pruned Office paper model

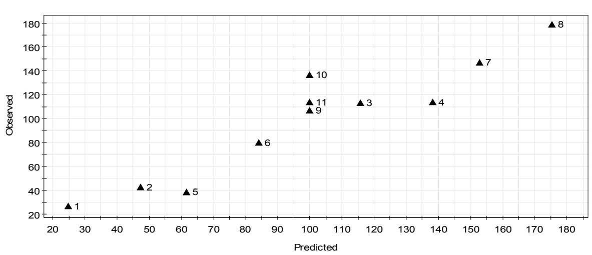

Figure 13: Predicted vs. observed response plot for "Threads" image and pruned Photo paper model

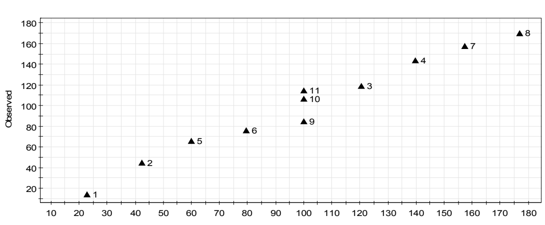

Figure 14: Predicted vs. observed response plot for "Pier" image and pruned Photo paper model.

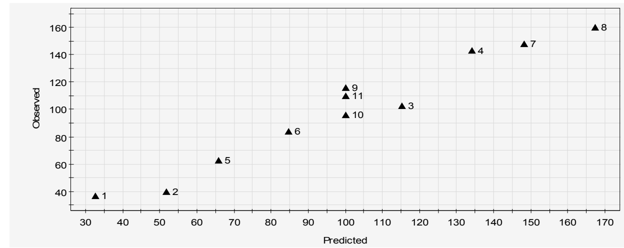

Figure 15: Predicted vs. observed response plot for "Flowers" image and pruned Photo paper model

Conclusions

The findings in this study show that relatively small differences in color gamut volume and sharpness can cause noticeable differences in the visual assessment of a printed image. Furthermore, the perceived color rendition quality was highly correlated with the color gamut volume. Therefore, the color gamut volume is arguably the single best objective parameter for quantization of color reproduction quality in inkjet printing. In addition, very large differences in color gamut volumes can be observed for different printer-substrate combinations, also illustrated in this study. Moreover, the influence of the sharpness was noticeable. Three different images were used and as expected, it could be observed that the visual assessments were influenced by the motif. For the color gradation, the findings indicate that as soon as the color gradation reaches a certain level it becomes a non-influential factor. In the study of the *Office paper*, the gradation was varied in a range where its effect on the perceived color rendition was negligible while in the study of the *Photo paper* it did influence the response. This confirms the relation between gamut volume and gradation. The *Photo paper* which is able to reproduce a very large color gamut also require more in-gamut levels than the *Office paper* with a smaller gamut to avoid gradation problems such as contouring and loss of close-color details.

Discussions

The developed models were sufficiently good and provide a good basis for further studies and the future design of inkjet papers. The actual relation to physical paper properties will vary depending on paper type and production set-up but this model can be used as a guide in the process of compromising between different properties. However, in a model covering several different substrates, differences in properties like gloss, whiteness, surface texture etc. might skew the study. A higher level of unexplained variation was observed for the *Photo paper* model compared to the *Office paper* model. This indicates that properties of the printed substrate other than the varied attributes influenced the visual assessment. One such property might be gloss. Another issue is whether the gradation could have been varied in another way than in this study, there are probably better ways to express gradation steps than in bit depth.

References

[1] Anderson M., Norberg O.2006 "Colour Gamut –Is Size The Only Thing That Matters?", TAGA 2006 Conference, Vancouver, Canada.

[2] Bouzit S. et al. 2002, Modelling the MTF of Various Imaging Devices, IS&T's 2002 PICS Conference

[3] Engeldrum P. G.2000 "Psychometric Scaling" (Imcotec Press, Winchester, MA)

[4] Fairchild M. D., 1998 "Color Appearance Models" (Addison Wesley Longman, Inc., Reading, MA)

[5] Gidlund Å. et al., 2005 "Quality Space of High-Quality Inkjet Prints" (2005 TAGA Proceedings, Toronto, Canada)

[6] Green P., 1999 "Understanding Digital Color 2nd Edition" (Pira International, Leatherhead, England)

[7] Green P., MacDonald L., 2002 "Color Engineering" (John Wiley & Sons Ltd, Chichester, England).

[8] Hunt R.W.G., 2004 "The Reproduction of Color 6th Edition" (John Wiley & Sons Ltd, Chichester, England).

[8] INCITS W1.1., 2005 "Update on the INCITS W1.1 Standard for Evaluating the Color Rendition of Printing Systems" Proceedings of the IQSP Conference of the 2005 EI Symposium

[9] ISO 12640-2, 2004 "Graphic Technology –Prepress digital data exchange", International Organisation for Standardisation

[10] ISO/DIS 3664, 1987 "Photography-Viewing Condition-Photographic Prints, Photomechanical Reproductions and Transparencies", International Organisation for Standardisation

[11] Koopipat C. et al., 2000, Image Evaluation and Analysis of Ink Jet Printing System (I) MTF Measurement and Analysis of Inkjet Images, IS&T's 2000 PICS Conference

[12] Keelan B.W., 2002, "Handbook of Image Quality", Marcel Dekker, New York, ISBN 0-8247-0770-2

[13] Lindberg S., 2004 "Perceptual Determinants of Print Quality" (Doctoral Dissertation, Royal Institute of Technology, Stockholm, Sweden)

[14] Montgomery D.C., 1991 "Design and Analysis of Experiments", John Wiley & Sons, New York, ISBN 0-471-52994-X

[15] Rogers G., "A Serie-Expansion Method for the Measurement of the MTF of Paper", IS&T's 2000 PICS Conference

[16] Sharma A.,2004 "Understanding Color Management" (Delmar Learning, Clifton Park, NY)

Biography

Ole Norberg received his MSc. in Physics from Umeå University, Sweden in 1996 and his Ph D in Media Technology from Linköping University, Sweden in 2006. Ole has long experience from R&D work in the paper Industry with special interest in paper optics, digital printing and color science. At present his is working as a Senior Research Scientist at Voxvil AB and part time at the Digital Printing Center at Mid Sweden University.