Modeling Local Print Density Variations in Rotogravure Print

Ulrich Hirn, Markus Lechthaler and Wolfgang Bauer

Graz University of Technology
Institute for Paper-, Pulp- and Fiber Technology
Kopernikusgasse 24
8010 Graz
Email: ulrich.hirn@tugraz.at

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1 Introduction

The paper related reasons for print unevenness are usually due to inhomogeneities in the paper structure. Instead of measuring overall paper parameters like e.g. PPS roughness or a formation index research has increasingly shifted towards high resolution measurement of local paper properties, which permits to analyze local defects and inhomogeneities of the paper structure. Linking local print density variations to high resolution measurements of local paper properties has been a promising approach to investigate print unevenness. Earlier studies focused on the effect of local grammage and/or topography on local print density variations (Kajanto 1989, Hansson and Johansson 1999, Dickson 2006, Mettänen et al. 2007).

In this paper the reasons for rotogravure print unevenness of SC papers is investigated. The key novelties of this work are summarized in three points.

1. Several variables in addition to formation and topography are analyzed. We are measuring seven paper properties as high resolution 2D maps. The measured paper properties are: Beta formation (local grammage), local brightness, local opacity, surface topography, paper thickness variations, local refractive index, local printing ink penetration. The effect of all these local paper properties on local print density variations are analyzed using statistical models.
2. We apply a modeling technique that permits to analyze the degree of redundancy (interrelation) between the model variables. This technique permits to identify key variables and to eliminate redundant variables. We are thus able to provide exact information which paper properties are responsible for print unevenness and, equally important, which are not.
3. Identical paper samples are printed on both, a laboratory printing press and an industrial printing press. We will demonstrate that industrial and laboratory print revealed similar, yet not identical results.

2 Materials and Methods

We analyzed three commercial SC papers from different European paper producers. The papers had a basis weight of 56g/m². Local paper properties were measured and linked to local print reflectance measurements of industrial and laboratory prints. Measurement of local paper properties and linking these data to local print reflectance is described in section 2.1. The analysis of industrial prints and laboratory prints has some important differences, hence they are described separately in section 2.2 and 2.3. Statisctical modeling and the interpretation of these results is explained in section 2.4.

2.1 Measurement and registration of local paper properties

Figure 1 illustrates the measurement and registration procedure by aligning the measurements of local basis weight (top, left) and the image of the paper after print, i.e. print reflectance (top, right). All other local paper property measurements are aligned in the same way. Each paper sample is marked with a hole pattern which defines the area of the paper to be analyzed (top images). The hole pattern is applied using a computer controlled CO_2 laser (Hirn et al. 2009b), the holes have a diameter of 200-500µm. The measurement maps are matched using a coordinate system defined by the hole pattern, as illustrated by the arrows in the top row images in Figure 1. Matching (also called registration) of two images consists of translation and rotation of the images, and rescaling if they have different pixel size, see Figure 1 (middle). The detailed procedure as well as an error estimate is described in (Hirn et al. 2008).

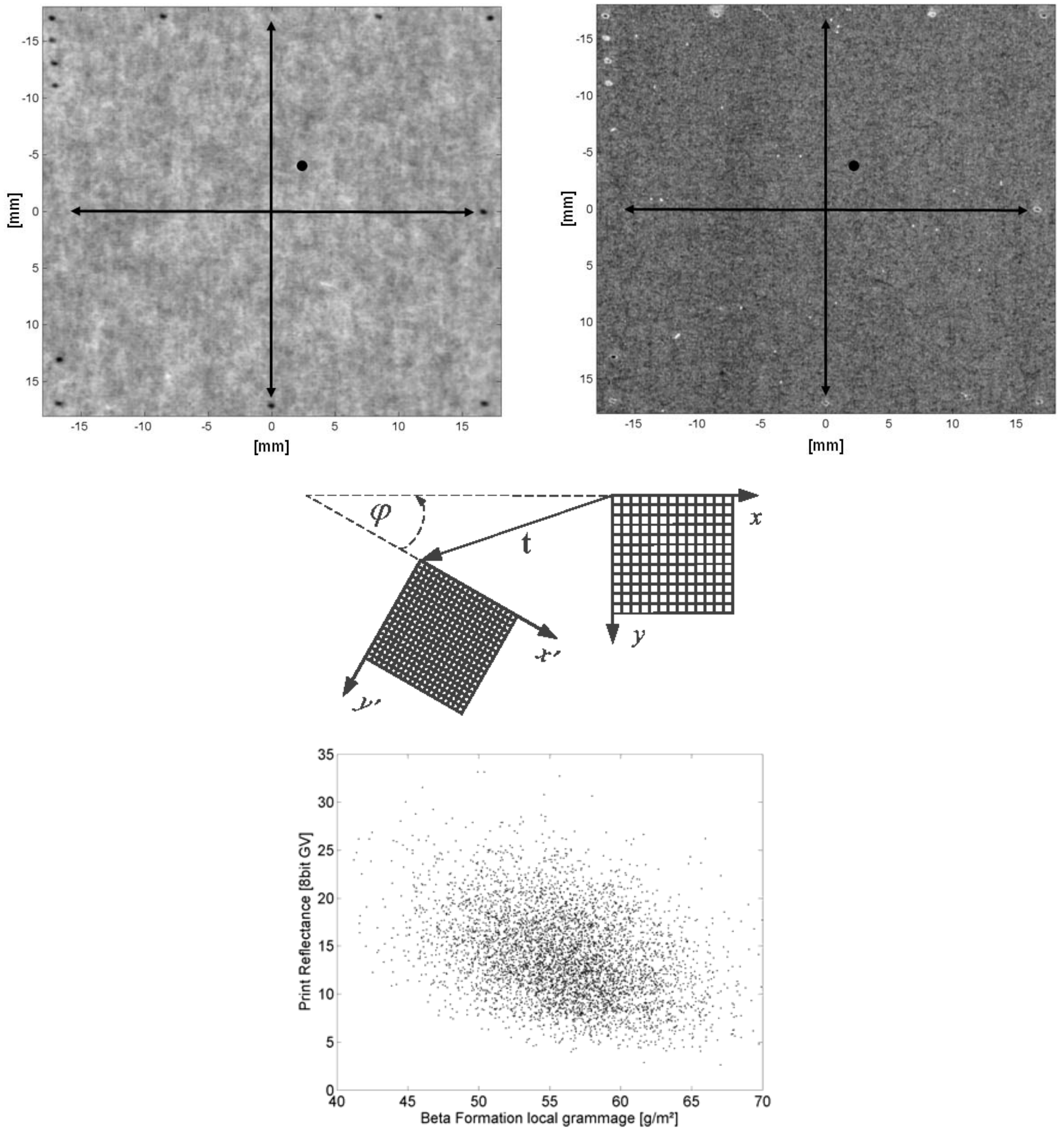

Figure 1. Laser holes (top) are used to define a coordinate system on the paper for all measurements. Registering two 2D measurement maps, i.e. images, consists of rotation and translation of the image coordinates (middle). After registration local grammage values are correlated to print reflectance after print (bottom), r²=0.12.

After image registration the coordinate systems in each image are congruent. So a point with specific coordinates in both images refers to the same position on the paper sample. Figure 1 (bottom) shows the data for local grammage before print and print reflectance after print extracted from the matched images. Each point in the scatter plot represents the values for local grammage and local print reflectance of a small area in a specific position on the paper. A relationship can be observed, regions with higher local grammage tend to be darker after printing ($r^2=0.12$).

In this work we were measuring seven local paper properties, the parameters of the measurements are given in Table 1. Additionally to seven paper properties local print reflectance of the printed paper has been measured. For data analysis all registered measurement maps are rescaled to the same pixel size of 250µm. For a viewing distance of 30cm under good illumination the human eye can resolve structures with a size between 125µm and 250µm (Olzak, Thomas 1986). Thus at a pixel size of 250µm we are preserving all structures visible to the human eye but deleting the invisible, smaller ones.

Table 1. Measurements of local paper properties and print reflectance.

Local Paper Property	**Measurement Method**	**Pixel Size of data map [µm/pix]**
Local Brightness [8 bit Image]	Flatbed scanner Epson Perfection 4990 Photo	21.17
Local Opacity [%]	Optical Microscope (Wanske et al. 2008)	6.42
Local Basis Weight [g/m²]	Beta Radiography (Keller et al. 2004)	50.00
Surface Topography [µm]	Chromatic White Light Sensor (Fries 2001)	20.00
Local Thickness Variation [µm]	Chromatic White Light Sensor (Fries 2001)	20.00
Local Effective Refractive Index [-]	Surfoptics System (Elton and Preston 2006)	200.00
Local Printing Ink Penetration [8 bit Image]	Flatbed Scanner Epson Perfection 4990 (Enzi et al. 2004)	21.17
Print Reflectance [8 bit Image]	Flatbed Scanner Epson Perfection 4990 Photo	21.17

2.2 Analysis of laboratory rotogravure prints

For analysis of laboratory prints the unprinted paper was first marked with holes. Then the six local paper properties were measured as described in Table 1: Local grammage (Keller et al. 2004), local brightness, local opacity, surface topography (Fries 2001), thickness variations and local refractive Index (Elton and Preston 2006). Subsequently black fields with 25%, 40%, 60% and 100% tone were printed in a rotogravure laboratory printing press, the LTG 20 Einlehner printability tester (Klein 2009). The LTG 20 is a sheet fed rotogravure press with one cylinder, it has an operation speed of 30 m/min. For each sheet 3 rotations of the cylinder are printed. The Einlehner press provides Electrostatic Printing Assist (ESA), however the prints were performed without ESA due to difficulties in finding a proper ESA setup. The resulting prints were scanned. Finally local printing ink penetration was measured (Enzi et al. 2004), this measurement is also described in the following section.

2.3 Analysis of industrial rotogravure prints

In rotogravure the paper is printed from the reel, thus it is impossible to measure local paper properties before printing. Thus we had to find a way to measure them afterwards, as a result the whole procedure was reversed. First the paper was printed, then the printing ink was removed and local paper properties were measured.

Printing was carried out on a commercial Cerruti 4-color rotogravure press with a web width of 650mm operated at a speed of about 40 m/min. It is a Double Ender gravure press, a machine layout which is also called ‘Pony’ concept, e.g. described by (Chung 2009). These machines are printing both sides of the web with only four printing cylinders by turning the web at the end of the machine, displacing it orthogonally to the printing direction and leading it back through the same cylinders. The same cylinder is used to print both sides of the paper web, these machines are thus often chosen for printing trials of paper producers because two sidedness in the print from a pony press always descends from the paper and not from the cylinder. We analyzed black fields printed with 30%, 50%, 60% and 100% tone value.

For the analysis of industrial rotogravure prints the printed paper sample is marked with laser holes *after printing*. Then the printing ink is removed from the surface of the paper using a mixture of a solvent (toluene) and black rotogravure printing ink (Enzi et al. 2004). Please note that this procedure not only removes the printing ink from the surface, it also reveals the structure of printing ink penetrated into the SC paper. The solvent used to remove the print contains black ink, thus the ink penetrates into all accessible regions of the paper. After removal of the print the local paper properties are measured.

It is easy to see, that after removal of the printing ink (Figure 2, right) local optical properties like local brightness and local opacity can not be measured any more. On the other hand it is quite straightforward to realize that local grammage (formation) does not change during the ink removal procedure and can thus be measured after print. Also local printing ink penetration is revealed with this technique (Enzi et al. 2004). However, for the three local paper properties surface topography, thickness variations and local refractive index it had to be verified that they can accurately be measured after ink removal. Verification has been performed using laboratory prints. Paper properties were measured *before* printing, then the paper was printed, the printing ink was removed and finally the paper properties were measured again. Comparing the local paper property maps measured on the unprinted paper and after ink removal yielded a correlation coefficient r² between 0.7 and 0.95. This result confirmed that surface topography, thickness variations and local refractive index measurements remain largely unaffected, they can be measured after removal of the printing ink. We have the hypothesis that toluene, which is a fully non-polar solvent, does not lead to any swelling of the fibers or dissolving of the fillers thus leaving paper properties unaffected by printing. Environmental SEM images of the paper surface, taken before print and after ink removal, are supporting this hypothesis. No changes are visible in the paper surface.

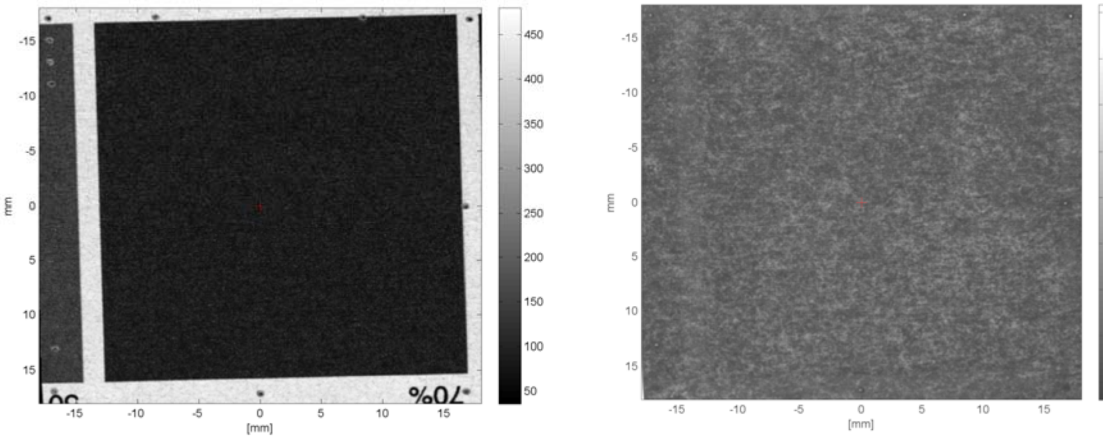

Figure. 2. Measurement procedure for industrial print of SC paper. The printed sample is marked with laser holes (left). Subsequently the ink on the surface is removed with a toluene based solvent (right). No more ink is on the surface, dark regions indicate penetration of the printing ink into the paper.

2.4 Modeling local print density from local paper properties

Applying the procedures described in section 2.1 to 2.3 we obtained congruent sets of data for local print density and local paper properties. One dataset comprises an area of 10cm², employing a pixel size of 250µm it contains roughly 15000 data points.

The key idea of our modeling approach is based on multiple linear regression. Modeling local print reflectance d by local paper properties p_1, p_2,…, p_7 (local grammage,…,local printing ink penetration) we employ the combined influence of all seven variables as a linear combination

$$d = \beta_0 + \beta_1 p_1 + \beta_2 p_2 + \beta_3 p_3 + \beta_4 p_4 + \beta_5 p_5 + \beta_6 p_6 + \beta_7 p_7$$

By applying differently configured linear models we analyze the influence of each predictor. The mathematical details of the method and the interpretation of the results are described by (Hirn et al. 2009a) and in more detail by (Lechthaler 2007).

The results of such a model are shown in Figure 3, the influence of the individual paper properties on print unevenness is represented as bars. Figure 3 gives the result for 30% tone value laboratory rotogravure print of one SC paper. A key feature of the modeling procedure is, that the r^2 value for each local paper property can be split into two parts. A redundant part (light gray part of the bar) consisting of information that is also provided by the other variables and an irredundant part (dark gray) of the information which is exclusively provided by this paper property. According to Figure 3Figure local brightness variation and formation have the strongest interrelation with local print density variations. Please note that most of the information provided by formation is redundant, i.e. it is also contained in the other variables. Interestingly local opacity is a significant influence factor, although the r^2 to local print density is low (r^2~0.17) it provides considerable *exclusive* (non-redundant) information to the model. Local refractive index and local ink penetration show little and mostly redundant r^2, thus these predictors are irrelevant. Furthermore the predictors local topography and local thickness variations are statistically not significant, this is indicated by the error bars of the predictors intersecting with the x-axis.

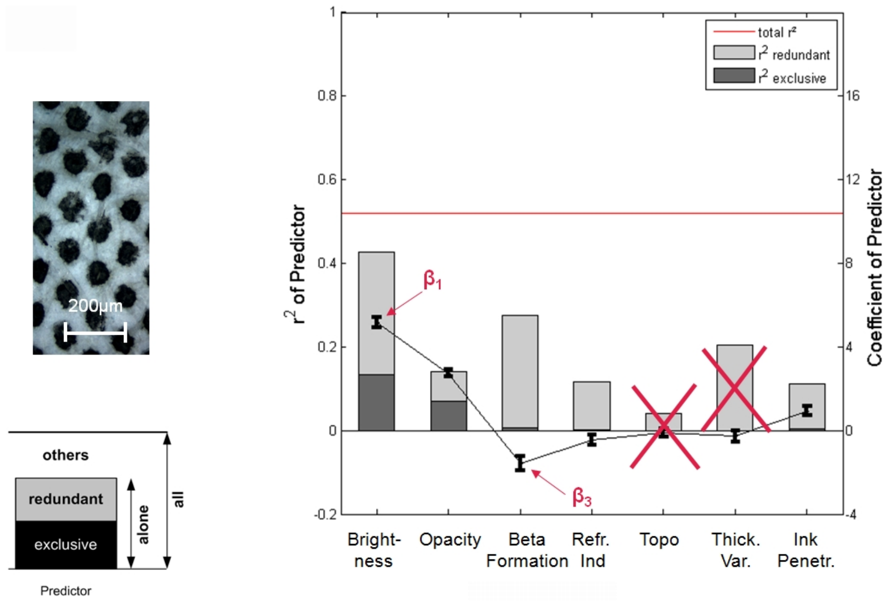

Figure 3. Model for the local print density as a function of local paper properties in 30% laboratory rotogravure print of SC paper.

In conclusion, the print density variations in 30% tone value of laboratory rotogravure print are controlled by variations of the optical properties local brightness and local opacity. This seems plausible, considering the fact, that more than 60% of the paper surface is unprinted, Figure 3 (left). It should be noted that roughly half of the information of the full model (horizontal line at r^2=0.53 in Figure 3) can be explained by formation. This leads to the conclusion that, while print unevenness is mainly related to variations of the optical properties, the *paper structural reason* for these optical variations can to a large part be attributed to formation.

3 Results

The highly compressed results of the industrial- and laboratory rotogravure prints are given in Figure 4 and Figure 5. The graphs give six bars for each predictor, in Figure 4 that is three papers with both, 30% and 50% tone industrial print (top) and the same three papers with 25% and 40% tone of lab print (bottom). Local brightness and formation are the strongest predictors for the lab print (bottom), these measurements are not available for the industrial print. It is interesting to see, that for industrial print (top) printing ink penetration is an important factor already in the low tone values. This can be explained by the lower viscosity of the industrial ink compared to the ink for the Einlehner lab press.

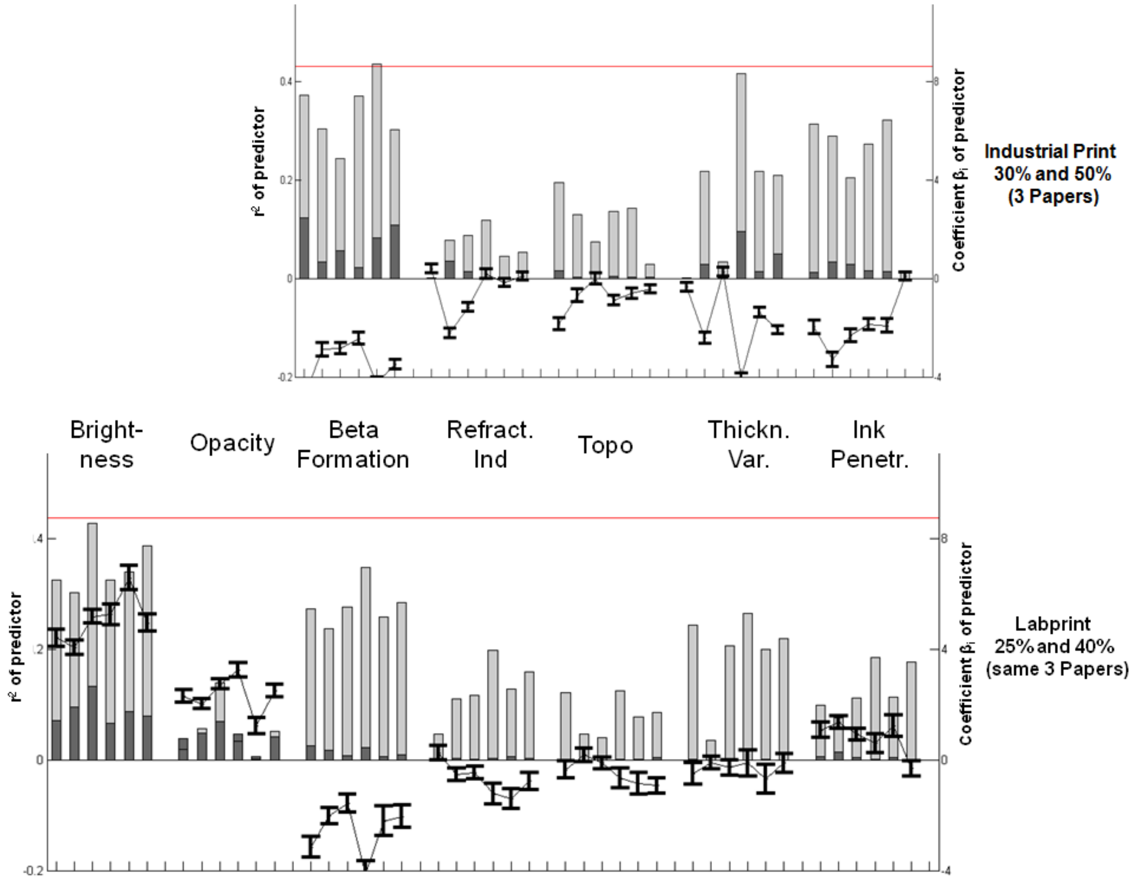

Figure 4. Analyzing the interrelation of local paper properties with print unevenness of rotogravure print in low tone values (25%-50%). The top graph shows the results for industrial print, the bottom graph for the lab print.

Local variations in refractive index of the paper did not yield an interrelation with local print density. Surprisingly topography did not come out as a critical factor either. We believe, this is due to the fact, that missing dots are the key criterion to guide paper calendaring and thus the smoothness of the paper. Our hypothesis is, that papers are calendared to the point, where surface topography is not playing an issue any more, i.e. no missing dots are occurring. It is interesting to see, that paper thickness variations are an important predictor, it is however highly redundant to other factors. Further analysis will be required to give a suitable interpretation for this result.

Figure 5 shows the results for high tone values. Again the same three papers were analyzed for lab print (60% and 100% tone) and industrial print (70% and 100% tone). Variations in printing ink penetration are clearly the dominant reason for print unevenness in high tones. Please note that the predictor printing ink penetration *alone* has nearly the same r^2 as the full model, this is evident from the small distance between the bars of ink penetration and the horizontal line giving the r^2 of the full model. Thickness variations and beta formation are also good predictors, however they are highly redundant (large light grey columns) to the other measurements. Interestingly local paper brightness is still somewhat relevant, even in the high tone values. Local variations in refractive index of the paper and surface topography again did not yield an interrelation with local print density.

3.1 Discussion

It has to be noted that the models reveal similar results for all papers. The groups of six bars, representing three papers with two high and two low tone values, have quite similar height for each predictor. This indicates that the results give stable and statistically representative models for the influence of local paper properties on rotogravure print unevenness. Repeatability and stability of the models from our analysis has also been examined in an earlier publication (Hirn et al. 2009a), the results were good.

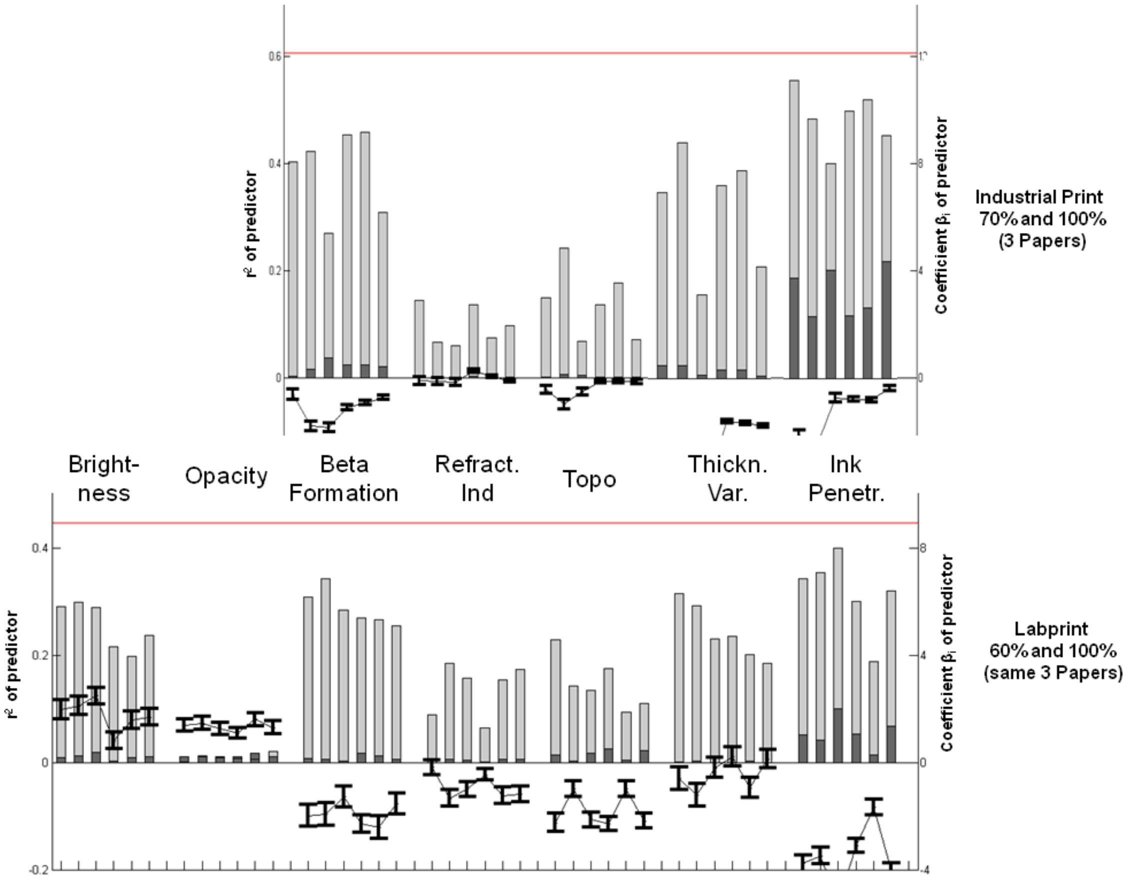

Figure 5. Analyzing the interrelation of local paper properties with print unevenness of rotogravure in high tone values (60%-100%). The top graph shows the results for industrial print, the bottom graph gives the results for the lab print.

The modeling results for both low and high tone values show that the measured local paper properties are highly inter-correlated. Some predictors like refractive index and topography are even entirely redundant to the other variables. That means that these measurements can be dropped from the models without a loss in overall r². This highlights the importance of using a modeling technique that quantifies and eliminates the inter-correlation between the local paper properties.

4 Conclusions and Outlook

A comprehensive methodology to examine the interrelation between print unevenness and local paper properties has been introduced. High resolution measurement of paper properties, subsequent linking local paper properties to local print density and finally statistical modeling of the interrelation is a powerful tool to investigate the paper related reasons for print unevenness. The ability of the modeling procedure to quantify redundant information from individual measurements has been shown to be a valuable tool to identify the key paper properties responsible for print unevenness.

Our analysis of rotogravure printed SC papers showed, that for both industrial and laboratory print three paper properties are the governing factors of print unevenness. These are local brightness variations, beta formation and local variations of printing ink penetration. All three are relevant in low and high tones, however local brightness variations are highly dominant in low tone values and local printing ink penetration is highly dominant in high tone values. The other parameters examined in this study (Surface topography, local opacity, local refractive index and local thickness variations) were of minor importance.

Analyzing print unevenness we obtain stable and reproducible models. The similarity of results between laboratory- and industrial print demonstrates that removing the printing ink after printing and then determining local paper properties is a valid procedure for rotogravure printed SC papers.

We want to point out that the presented methodology to analyze paper related reasons for print unevenness is also applicable to other paper grades and other printing technologies. Measurement of local paper properties and linking these data to local print density variations can also be applied to offset-, flexo- or digital printing. The analysis method is particularly well suited for sheet fed printing where it is easy to measure the local properties of a piece of paper *before* printing, e.g. digital printing and sheet fed web offset. For web fed printing either the printing ink has to be removed after the print or the method is limited to measuring local paper properties that remain unaffected by printing like e.g. formation. Also the method is applicable to all lab printing techniques. Thus our methodology could be applied to other research aimed to identify paper properties governing print unevenness in different printing technologies.

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