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Prediction of optical variations in paper from high resolution measurements of paper properties

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KEYWORDS: Paper properties, Variations, Filler content, Spatial, Grammage, Uncoated, Image registration, High resolution, Point-wise

SUMMARY: A method to predict optical variations from high resolution measurements of paper properties is evaluated in this work. The method combines the point-wise values of high resolution maps of filler content and grammage with an empirical model derived in an earlier study to predict the spatial optical variations in paper.

The method has been applied on two paper samples, a laboratory paper and a commercial 80 g/m² copy paper. The optical variations have been predicted at a scale of 1 mm². Validation has been made by using a high resolution spectrophotometric setup to measure the spatial reflectance variations in the paper. The results show that for the samples used, the influence of filler content variations and density variations on the optical variations is small compared to influence of the grammage variations.

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The optical properties of paper are important for the quality impression and for the resulting print quality. One important property is the homogeneity of the paper. Spatial small-scale variations in the paper structure can cause variations in the light scattering properties of the paper which in turn will impair the visual appearance. An understanding of the underlying causes to the optical variations in the paper is important in order to minimize such defects.

One approach is to predict the influence of different paper properties on the spatial optical variations in the paper.

Related research

In general, the qualitative relations between paper properties and the resulting optical response are well known for the large-scale properties of the paper (Fellers, Norman, 1998; Pauler, 2012; Alava, Niskanen 2006; Holik, 2006).

When analyzing high resolution variations in paper, one approach is to use 2D images of measurement values of paper properties and of optical variations in the paper. By aligning 2D images of different measurements, the values can be compared point-wise between the measurement maps. This has been used as parts of measurement methods, where several measurement maps are needed to

create a map of e.g. density values (Schulz-Eklund et al., 1992, Sung et al. 2005), or filler content (Hägglund et al., 2012b).

By combining 2D images of measurement values from different measurement devices, the point-wise interrelation between paper properties and resulting print quality or optical quality of the paper can be analyzed (Kajanto, 1989; Kajanto 1991; Hansson, Johansson, 1999; Chinga, Syverud, 2007; Mettänen et al. 2007).

There are different image registration methods used to align 2D maps of measurement values from different devices. Hirn et al. (2008) discuss the difference between different registration methods used for paper applications, and present a method to combine 2D paper measurement maps with different resolutions.

When analyzing the relation between optical response and the underlying variations in paper properties, one approach that has been shown in several works is to quantify the paper formation with light transmission measurements (Bernié, Douglas, 1996; Dooley, Sampson, 2002). While this may be a fast and useable method for on-line measurements, it is not possible to accurately relate optical variations with grammage variations only. Variations in local scattering coefficient and differences in optical properties of components will also affect the optical response of the paper.

By using a multivariate model based on a set of samples produced according to an experimental design, the simultaneous interrelation between paper properties and the resulting optical response can be taken into account when predicting the optical variations from variations in material properties of the paper. The optical response should then be quantified with parameters related to the paper material. The optical properties of paper can be quantified by using optical models such as the Kubelka-Munk theory (ISO 9416, 1998), or the radiative transfer model, DORT2002 (Edström, 2005), which model the optical response in paper from the light scattering and light absorption properties of the paper.

Aim of the present study

The aim of this work is to present and evaluate a method that predicts the optical variations in paper at a scale of 1 mm² from high resolution measurements of grammage and filler content. The method will be valuable in the work to analyze the underlying causes to optical variations in paper.

Materials and Methods

Overview

In an earlier work (Hägglund et al., 2012a), an empirical model was derived with a partial least squares (PLS) method that predicts a light scattering coefficient, s , from measured values of filler content and density of an uncoated paper. In this work, the PLS model was applied on high resolution values of filler content, and the mean

Fig 1. Schematic overview over the procedure to calculate estimated values of R_0' from high resolution measured values of filler content and grammage, and mean values of density and light absorption coefficient, k , assessed with standard methods.

density of the paper. The resulting light scattering coefficient, s' , was combined with a light absorption coefficient, k_{mean} , calculated with the Kubelka-Munk equations from $d/0^\circ$ measurements of the paper, and high resolution values of the grammage variations, in order to calculate a predicted reflectance value, R_0' (Fig 1).

In order to validate the predictions of optical variations with optical measurements on the paper samples, a high resolution spectrophotometer setup, described below, was used.

Materials

The method presented in this study was applied on two paper samples: a laboratory paper produced on a small experimental paper machine (XPM), and a commercial 80 g/m² copy paper. For both papers the pulp mixture consisted of two chemical pulps with 70% hardwood and 30% softwood, refined to 26°SR. In order to make the XPM paper comparable to the commercial paper, the target grammage of the XPM paper was set to 80 g/m². Calcium carbonate was used as filler in both of the paper samples used. The filler content of the commercial copy paper was 23.4 % and the filler content of the XPM paper was 22.4%. Contrary to the commercial paper, the XPM paper did not contain any fluorescent whitening agent or dye.

Measurements

The model used to predict optical variations is based on measurements of density, grammage and filler content in the paper. In order to predict the optical variations at a scale of 1 mm², high resolution maps of grammage and filler content were combined with a mean value of the density of the paper to estimate a local light scattering coefficient, s' , at high resolution. A $d/0^\circ$ measurement was made according to (ISO 2469 2007) with a Lorenzten & Wettre Elrepho instrument in order to assess the mean light absorption coefficient, k_{mean} , of the whole paper. From the light scattering coefficient, s' , the light absorption coefficient, k_{mean} , and the local grammage, the estimated reflectance, R_0' , was calculated using the Kubelka-Munk equations (ISO 9416 1998).

High resolution grammage measurements – beta formation

For measurements of grammage variations, a beta-radiation based measurement method with fluorescent imaging plates was used (NSP 5, 2009). In order to minimize the noise level, two measurements were made on the same sample and were combined with the image registration method presented in (Hägglund et al., 2012b).

Fig 2. Schematic overview of the high resolution spectrophotometric setup.

The method gives a 2D image of the grammage distribution over the sample. The spatial resolution of the measurement images chosen for this work was 0.2 mm x 0.2 mm.

Density variations

The model derived in (Hägglund et al., 2012a) predicts light scattering variations from density variations and filler content variations in an uncoated paper. The influence of grammage on the light scattering intensity showed to be negligible. However, when regarding the spatial variations of paper properties, a dependency between density variations and grammage variations can be expected. In order to determine if spatial density variations could be neglected or described as a function of grammage variations in the paper, the thickness and grammage was measured along a line of the paper sample and compared point-wise at a resolution of 1 mm. A STFI thickness tester was used to assess the thickness variations, and beta formation was used to measure the grammage variations in the paper. From the two measurements, the density could be calculated and compared with grammage.

High resolution filler content

The calcium atoms in the filler of the paper were measured with an X-ray fluorescence setup, and with the help of a stepper table a 2D map with a resolution of 0.2 mm x 0.2 mm of calcium detections in the paper could be assessed. The measurement setup is described in (Hägglund et al., 2012b). In the same work, a method to calculate filler content from calcium detections and grammage measurements is described. The method uses image registration to combine the two maps, generating a filler content map with a resolution of 1 mm².

Optical measurements

For the optical measurements, a high-resolution 45°/0° spectrophotometric setup was used. The setup is illustrated in Fig 2. In the setup, the light from a halogen lamp is connected via an optical fiber to a measuring head, giving a ring illumination with an incident angle of 45 degrees to the normal direction of the sample. The measuring head is placed on a stepper table, giving the possibility to create a 2D map of spectral measurements of the sample.

The reflected light is collected in the measuring head at the normal from the sample with the help of lenses, allowing a small focus point with a diameter of 0.5 mm for the measurements. The collected light is connected

Fig 3. Mean spectral values over the surface of analysis of the XPM paper (black, dashed) and the copy paper (blue, solid), together with the mathematical Y_{C12° filter (magenta, dotted).

via a second optical fiber to a Zeiss MCS621VIS II spectrophotometer.

A black trap and a white sodium sulphate tile are measured before each set of measurements in order to calibrate the measured point-wise intensity values of the sample to reflectance values.

This measurement setup enables spectrophotometric measurements with a spatial resolution of 0.5 mm x 0.5 mm. The spectrophotometer has a spectral resolution of 3 nm, with the spectral interval 300 nm to 1145 nm. For this application only wavelengths within the visible range (400 nm-700 nm) were used.

In order to reduce noise and minimize the influence of UV fluorescence in the copy paper, the spectral values were filtered with a mathematical Y_{C12° filter (CIE 15, 2004). In Fig 3, the mean spectral reflectance values from measurements on the XPM paper and on the copy paper are shown, together with an illustration of the mathematical Y_{C12° filter. The samples were measured on both sides.

Calculations

Prediction of optical response

The optical response was predicted by using an empirical model that estimates the light scattering coefficient, s' , derived from the Kubelka-Munk equations (ISO 9416, 1998), from variations in paper properties.

Hägglund et al, (2012a), presented a model that predicts the spectral mean value of the light scattering coefficient, s'_{mean} , from paper properties. In this work, a similar model was used, but the predicted light scattering coefficient, s' , was based on spectral data filtered with a mathematical Y_{C12° filter (CIE 15, 2004) instead of a spectral mean value. The light scattering coefficient, s' , was calculated as:

$$s'_{XPM} = 1.32 \times f - 3.55 \cdot 10^{-2} \times \rho + 53.2 \quad [1]$$

$$s'_{Copy} = 1.25 \times f - 4.70 \cdot 10^{-2} \times \rho + 68.7 \quad [2]$$

where f is filler content in percent and ρ is density in kg/m³.

In order to calculate an estimation of the reflectance, R_0' , the light scattering coefficient, s' , was combined with a light absorption coefficient, k , derived from Elrepho

Fig 4. Point-wise density plotted against grammage for the XPM paper (blue) and the copy paper (black), measured with a resolution of 0.2 mm.

measurements made on the sample and the mean value of the grammage values assessed with the beta radiogram method. With the help of the Kubelka-Munk equations, the light scattering coefficient, s' , the light scattering coefficient, k , and the point-wise grammage, w , could be transformed to point-wise reflectance, R_0' .

Effect of paper parameters on the optical variations

The influence of the paper properties included in the model on the optical response was extracted by removing the variations in the chosen property before calculating the predicted reflectance, R_0' , for each paper property.

The correlation coefficient between the predicted reflectance, R_0' , and the measured reflectance, R_0 , was calculated for each case.

Results

High resolution measurements of grammage and filler content

Table 1 shows the measured values of grammage and filler content for the two samples.

Density

In Fig 4, the point-wise density values are plotted versus grammage, assessed at a resolution of 0.2 mm, for the two paper samples. The copy paper shows a higher mean density. The relation between density and grammage is approximately linear. A linear regression gives the following linear coefficients for the two papers:

$$\rho_{XPM} = 5.48 \times w_{XPM} + 220 \quad [3]$$

$$\rho_{Copy} = 6.54 \times w_{Copy} + 268 \quad [4]$$

where w_{XPM} and w_{Copy} are the pointwise grammage values measured in the XPM paper and the copy paper respectively, and ρ_{XPM} and ρ_{Copy} are the corresponding density values calculated from linear regression.

Table 1. Mean grammage (*Mean w*), standard deviation of grammage (σw), mean number of calcium detections (*Mean N_{Ca}*), and standard deviation of number of calcium detections (σN_{Ca}) for the XPM paper and the copy paper.

Sample	Mean w	σw	Mean N_{Ca}	σN_{Ca}
XPM	75.6 g/m ²	4.2 g/m ²	2220	41
Copy	77.3 g/m ²	3.8 g/m ²	2190	93

Optical measurements

The copy paper showed a lower mean R_0 than the XPM paper, which is probably due to the shading dyes that are apparent in the copy paper. The results are shown in Table 2. The two samples showed no significant difference between the two sides when comparing the mean values of R_0 .

Effect of paper parameters on the optical variations

In Fig 5, the predicted reflectance, R_0' , is plotted against the measured reflectance, R_0 , for the two paper samples. The subfigures show the result when each paper property was held constant when predicting the optical response. The two paper grades show different sensitivity to the variations in paper properties.

The calculated correlation coefficients for each case are shown in Table 3. A high correlation coefficient indicates a better prediction of R_0' . The grammage variations show

the highest impact on the optical variations, with a significant decrease in correlation coefficient for both paper grades when it is excluded. On the other hand, when excluding density from the model the correlation coefficient increases for both the XPM paper and the copy paper. Excluding the filler content shows only a negligible effect in the correlation coefficient.

Table 2. Mean and standard deviation of R_0 measurements made on the two paper samples.

Sample	Mean R_0	σR_0
XPM front side	85.4	0.7
XPM back side	85.5	0.7
Copy front side	81.1	0.8
Copy back side	80.9	0.8

a) All parameters included.

b) Filler content constant.

c) Density constant.

d) Grammage constant.

Fig 5. Predicted reflectance, R_0' , vs. measured reflectance, R_0 , for the XPM paper (black) and for the copy paper (blue). Predictions are made with all parameters included in the model (a), filler content held constant (b), density held constant (c) or with grammage held constant (d). The two paper grades show different sensitivity to the variations in each paper property, especially filler content (b) and grammage (d).

Table 3. The correlation coefficient between measured R_0 and predicted R_0' when the contributions from selected paper properties are excluded from the model. The correlation coefficient decreases for both paper grades when grammage variations are excluded from the calculations, while the change is negligible when filler content variations are excluded.

Sample	All included	Filler excluded	Density excluded	Grammage excluded
XPM	0.905	0.906	0.915	0.632
Copy	0.920	0.912	0.939	0.885

Discussion

The model showed a slightly better predictability for the copy paper than for the XPM paper. The difference in predictability may be due to the difference in production process of the commercial copy paper and the XPM laboratory paper sample.

The model was most influenced by grammage, which is natural because of the influence of the local grammage on the local filler content and on the local density. The local grammage is also used in the Kubelka-Munk calculations when estimating R_0' from the predicted light scattering coefficient, s' .

The approximation of density by assuming a linear relation between density and grammage adds a noise which would be reduced by including local thickness measurements.

Including density in the model gave a decrease in the correlation between predicted and measured values. This is most probable due to a difference between how the density relates to fiber weight in the formette paper samples that the PLS model is based on, and how local density relates to local grammage in the XPM paper.

The negligible effect of filler content on the optical variations in the samples used may be due to the strong correlation between local filler weight and local basis weight for both samples. For a more complex paper structure, e.g. coated paper, the distribution of PCC particles may have a stronger influence on the optical variations.

The offset between the measured and the predicted reflectance values (Fig 5) can be due to the difference in geometry between the Elrepho and the high resolution spectrophotometric setup. The model used to predict the reflectance is based on optical measurements made on an Elrepho, which apply a $d/0^\circ$ geometry, while the high resolution measurements made here have been performed on a different instrument, with a $45/0^\circ$ geometry. It has been shown that the measurement geometry affects the measurement result (Edström et al., 2010). Some of the deviations between predicted and measured values can be explained by possible light absorption variations in the paper, which are not accounted for in the model.

There was a difference between the mean reflectance values of the two samples used in this study, in both measurements and predictions. The copy paper had a lower light scattering, which probably was mostly due to the sizing and the calendering of that sample. The copy paper also contained shading dyes, which adds to the light absorption in the green band of the spectrum.

The empirical model used filler content, grammage and density as paper properties. By measuring local thickness, the density variations in a calandered paper can be included in the calculations. The model could also be extended to include measurements of other optical properties, such as gloss variations, brightness variations, etc. Other future applications could be to analyze the effect on coated paper and on paper with printed surfaces.

Conclusion

A model to predict optical variations from high resolution measurements of variations in paper properties has been presented and evaluated in this work. The model produces a 2D map of the optical response that is comparable with visible optical response.

The model will be a useful tool when analyzing the causes to optical variations in paper.

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