Efficient Characterisation of Printing Systems for the Packaging Industry

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Abstract

To print accurate colours, every printing system needs to be characterised. Nowadays, this characterisation is performed by printing and measuring a colour target and creating an ICC profile. Every time the substrate or the ink changes, this procedure has to be repeated. In frequently changing environments, like the packaging industry, the standard colour characterisation procedure is too demanding in resources to be of any practical use.

In this work, we present a novel technique that characterises the printing system without reprinting a colour target at each substrate or ink change. It requires the printing of a target only once per printer system and can handle an ink or a substrate change with an off-line spectral measurement of the new ink or substrate. This results in a substantial progress in terms of resource allocation and costs.

To achieve our goal, we developed a new physical model of a printer. In addition, we needed an algorithm for modifying an existing ICC profile based on this model.

Keywords

Color management, packaging, physical printer model, Neugebauer model.

1. Introduction

In the packaging industry, it is common to use custom inks. For each job, the ink set changes. With traditional colour management, we would have to print a target for each job. This would lead to unacceptable costs and delays. Therefore, we propose a method that enables to handle an ink (or a substrate) change, without reprinting a target. We assume that we can print once a target on the press.

The model used for characterisation has to describe the interaction between the light, the ink and the paper. It has to distinguish the influence of each of these components in order to allow any component of the model to be exchanged. Traditional models, like the Neugebauer [1], Yule Nielsen [2] or Clapper-Yule [3] models did not provide sufficient accuracy for our needs. We found that more elaborate models, for which [4] gives an overview, are either too complex or require parameters that cannot be simply extracted from printed data with a spectrophotometer. We finally adapted a model proposed by Hoffman and Schmelzer [5] to fullfill our needs.

The paper starts by deriving, in Section 2, the adapted Hoffman-Schmelzer model. In Section 3, it shows the performance of the model on single ink halftone gradients, on 2 inks overprints and on the whole color space. Finally, in section 4, it presents an heuristic correction that improves the model performance.

2. The reflectance model

Let us first describe the model of a full tone patch on a coated paper by ignoring any whitener agents in the paper. The spectrophotometer illuminates the paper with an incident angle $\theta_1 = 45^\circ$ and measures all the light coming back from the paper with an angle smaller than α_1. As illustrated in figure 1, light that enters the ink gets diffused by the paper and undergoes multiple reflections before reaching the measurement device. Some light does not even reach the device. The measured spectrum is computed using:

- The surface reflection R_{sf}, due to specular reflection on ink non-uniformities.
- The light attenuation I_i when entering the paper the first time.
- The light attenuation $R_p I_C$ due to an internal reflection cycle.
- The light attenuation I_O by leaving the paper, combined with the ratio of light that reaches the measurement device.

As the incoming light ray enters the paper, if gets refracted and makes an angle θ with the vertical. The angle variation is given by Snell law [6, chap. 1]

$$n_1 \cdot \sin(\theta_1) = n_2 \cdot \sin(\theta),$$

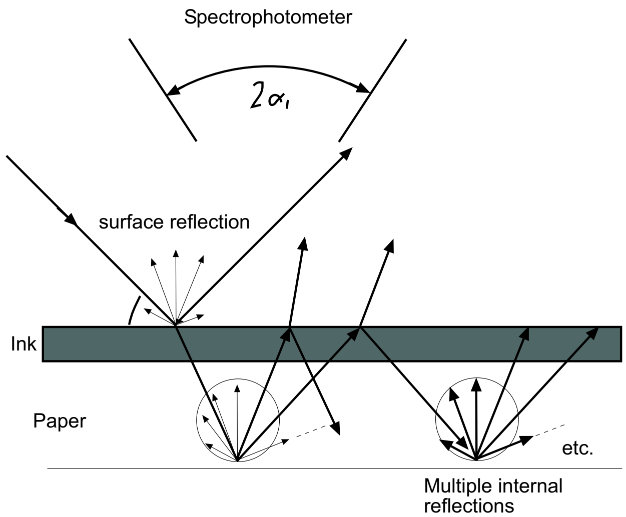


Figure 1: Illustration of the light, paper and ink interaction. The lights enters the ink with a 45° angle and gets reflected multiple times before leaving the ink and reaching the measurement device. Only the rays making an angle smaller than α_1 with the vertical reach the measurement device.

where n_1 is the refraction index of air ($n_1 = 1$), n_2 is the refraction index of paper and ink ($n_2 = 1.5$) and θ_1 is the incident angle of the ray in the air ($\theta_1 = 45°$). The ray travels a distance $d/\cos(\theta)$ across the ink before reaching the paper, where d is the thickness of the ink layer (fig. 2). It gets attenuated by a factor I_i:

$$I_i = (1 - r_0)\, e^{k_\lambda d/\cos(\theta)},$$

where r_0 is the specular reflectance or the ink layer surface, k_λ the attenuation coefficient rate of the ink layer, λ is the wavelength and d is the thickness of the ink layer.

Then, the ray gets scattered by paper, which is assumed to be a perfect diffuser. In other words, the intensity scattered by the paper follows Lambert law:

$$I(\theta) = I_0 \cos(\theta).$$

In figure 3(a), the light flux traversing surface S_2 is equal to the light flux traversing surface S_1 and can be expressed as

$$\partial\phi_{S_1} = 2\pi \sin(\theta) I(\theta) \partial\theta.$$

Because we are interested in the ratio of incoming versus outgoing light, we set I_0 such that the intensity integrates to 1 over the hemisphere:

$$\int_0^{\pi/2} 2\pi \sin(\theta) I_0 \cos(\theta) d\theta = 1. \qquad (1)$$

This gives:

$$I_0 = 1/\pi.$$

When the light is in the ink, it either leaves the ink, or gets reflected internally. This internal reflection process can be repeated indefinitely, as illustrated in figure 3(b). To compute the reflectance, we must sum the amount of light that leaves the ink at each reflection cycle. For a given ray making an angle θ with the ink layer, the amount of internal reflection r_{21} is governed by Fresnel law [6, sec. 6.2],

$$r_{fr}(n_1, n_2, \theta_1) := \sqrt{\left(\frac{n_1\cos(\theta_1) - n_2\cos(\theta)}{n_1\cos(\theta_1) + n_2\cos(\theta)}\right)^2 + \left(\frac{n_2\cos(\theta_1) - n_1\cos(\theta)}{n_2\cos(\theta_1) + n_1\cos(\theta)}\right)^2}$$

$$r_{21} = r_{fr}(n_2, n_1, \theta)$$

which sets the ratio between the incoming and reflected light flux. The reflected ray traverses the ink over a distance $2d/\cos(\theta)$ and gets attenuated by a factor $e^{\frac{-k_\lambda \cdot 2d}{\cos(\theta)}}$.

By synthesising all previous equations, we can compute the percentage of light I_C that get reflected internally:

$$I_C = \int_0^{\pi/2} r_{21} 2\pi \sin(\theta)\cos(\theta) I_0 \cdot e^{-2k_\lambda d/\cos(\theta)} d\theta \qquad (2)$$

$$= \int_0^{\pi/2} r_{21} \sin(2\theta) e^{-2k_\lambda d/\cos(\theta)} d\theta. \qquad (3)$$

By leaving the paper, a ray of light traverses a distance in the ink layer equal to $d/\cos(\theta)$ and gets attenuated by a factor $e^{-k_\lambda d/\cos(\theta)}$. Only the rays that leave the ink with an angle smaller than α_1 reach the measuring device, i.e. the amount of light reaching the instrument is given by I_O:

$$I_O = \int_0^{\alpha_2} (1 - r_{21}) e^{-k_\lambda d/\cos(\theta)} \sin(2\theta) d\theta, \qquad (4)$$

where α_2 is the angle of the light ray (measured in the ink) that exists the ink with angle α_1.

Finally, the reflectance R of an inked patch, measured with the $45°/0°$ spectrophotometer is given by

$$\mathrm{R}\,(\mathrm{k}_\lambda, d) = \mathrm{R}_{sf} + \frac{I_i\, R_p\, I_O}{\sin^2(\alpha_1) \cdot (1 - R_p I_C)} \qquad (5)$$

where R_{sf} is a surface reflectance parameter, I_i is the input attenuation, R_p the paper inner reflectance, I_O the output attenuation and $R_p I_C$ the attenuation of an inner reflection cycle.

Since the spectrophotometer only sees light that deviates less than α_1 degrees from the vertical, the measured

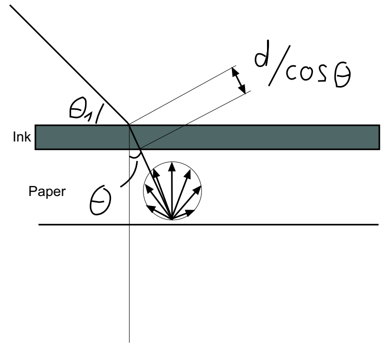


Figure 2: *Illustration of the incoming light through the ink layer.*

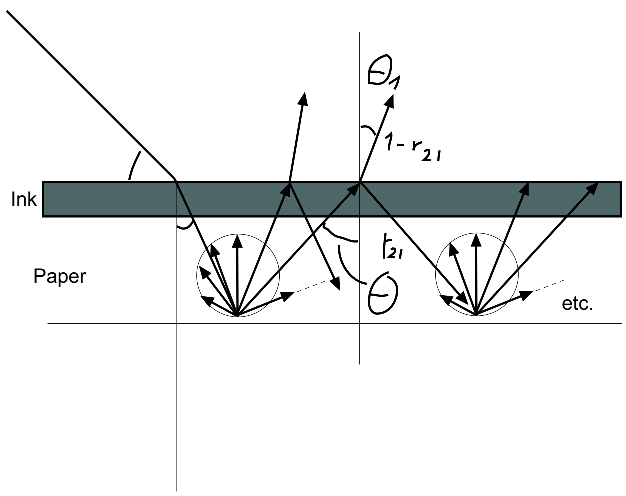


Figure 3: *Illustration of the internal reflections in the ink and the exiting light path toward the measurement device.*

value is divided by $\sin^2(\alpha_1)$ to get an equivalent diffuse reflectance measured over the whole hemisphere.

R_p is computed by setting $k_\lambda = 0$ and by using a spectral measurement of the paper. R_{sf} depends on the paper roughness.

2.1. Superimposing 2 inks

Ideally, if we superimpose 2 inks, we should get a reflectance

$$\mathrm{R} = \mathrm{R}\left(k_\lambda^{(1)} d + k_\lambda^{(2)} d\right). \tag{6}$$

Because the ink amount that an offset printer[1] can put on already printed paper is less than the amount on pure paper, the reflectance becomes

$$\mathrm{R} = \mathrm{R}\left(k_\lambda^{(1)} d + k_\lambda^{(2)} \cdot \mu \cdot d\right), \tag{7}$$

[1]We use an offset print in our test, but this could also be gravure or flexo, but not inkjet.

where μ is a thickness reduction ratio, or *trapping* parameter. By fitting this formula on a 2 inks patch, we can compute the trapping μ for various combinations of inks.

2.2. Extension to halftone

Let a be the area coverage of the ink on the paper. We will assume that a light ray hitting the printed surface will have a probability a to fall on an area covered by ink. From (5) the reflectance of a single ink halftone gradient becomes

$$\mathrm{R}(k_\lambda, d, a) = \mathrm{R}_{sf} + \frac{A_i R_p A_O}{\sin^2(\alpha_1) \cdot (1 - A_C)} \tag{8}$$

$$A_i = (1 - r_0)\left[a \cdot e^{k_\lambda d/\cos(\theta)} + (1 - a)\right]$$

$$A_O = [a \cdot I_{Ok} + (1 - a) \cdot I_{Op}]$$

$$A_C = R_p\,[a \cdot I_{Ck} + (1 - a) \cdot I_{Cp}],$$

where k is an index to denote inK and p an index to denote Paper. A_i is the light attenuation at the input, A_O the attenuation at the Output and A_C the attenuation during a reflection Cycle. Paper is assumed to have $k_\lambda = 0$.

More generally, the spectrum of a halftone patch composed of n inks can be expressed as

$$\mathrm{R}(\mathbf{k}_\lambda \mathbf{d}) = \mathrm{R}_{sf} + \frac{A_i R_p A_O}{\sin^2(\alpha_1) \cdot (1 - A_C)} \tag{9}$$

$$A_i = \int \mathrm{P}(\mathbf{d}) \cdot I_i\,(\mathbf{k}_\lambda \mathbf{d})\,\partial \mathbf{d}$$

$$A_O = \int \mathrm{P}(\mathbf{d}) \cdot I_O\,(\mathbf{k}_\lambda \mathbf{d})\,\partial \mathbf{d}$$

$$A_C = R_p \cdot \left[\int \mathrm{P}(\mathbf{d}) \cdot I_C\,(\mathbf{k}_\lambda \mathbf{d})\,\partial \mathbf{d}\right]$$

where A_i is the light attenuation at the input, A_O the attenuation at the output and A_C the attenuation during a reflection cycle. $\mathbf{k}_\lambda \mathbf{d}$ is the light attenuation rate at each wavelength:

$$\mathbf{k}_\lambda \mathbf{d} = \sum_{i=1}^{n} k_\lambda^{(i)} d_i \tag{10}$$

$\mathbf{d}$ is a vector that expresses the relative thickness of each ink layer contained in the colour patch.

$$\mathbf{d} = [d_0, d_1, ..., d_n]^T.$$

The thickness is expressed relative to the thickness of the full tone patch of the same ink. For example if $d_2 = 1$ the ink layer 2 in the colour patch is as thick as the ink layer of the patch printed only with ink 2 and with 100% coverage. d_0 is equal to 0 and represents a virtual ink of thickness 0 used to account for the paper.

$P(\mathbf{d})$ is the probability to find the combination of ink thickness described by $\mathbf{d}$ in the colour patch at a microscopic level. By assuming independence of the colour layers, we get

$$P(\mathbf{d}) = P_0(d_0) \cdot P_1(d_1) \cdot \ldots \cdot P_n(d_n)$$

Since each ink assumes a given thickness d_i, the probability density function of the ink thickness translates to

$$P_i(D = d_i) = a_i \cdot \delta(D - d_i) + (1 - a_i) \cdot \delta(D)$$
$$P_0(D) = \delta(D)$$

where $\delta(\cdot)$ is the dirac distribution and a_i the area coverage of ink i.

This formulation of halftoning assumes full scattering, i.e. the position where a light ray exits the paper is independent of the its incoming location.

3. Experiments

3.1. Fitting criterium

To fit our model to the measured spectra, we minimise the log of the error between the measurements and the computed spectra, weighted by a sensitivity function $W(\lambda)$:

$$\Theta = \arg\min \left(\sum_{\lambda=380}^{730} W(\lambda) \cdot \log^2 \left[R_\Theta(\lambda) / R_{meas}(\lambda) \right] \right)$$

where Θ is a vector containing every model parameters, like for example the area coverage or the trapping parameter. The sensitivity $W(\lambda)$ is the maximum of the three CIE 1931 Standard 2° Colorimetric Observer matching functions [7, Chap. 2]. In this way, we get a compromise between a perceptual and a spectral optimisation.

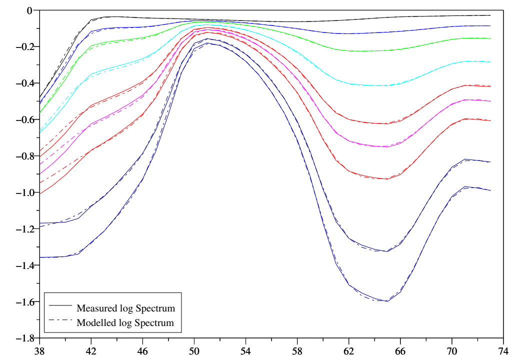
3.2. Fitting a halftone gradient

We will use equation (8) to fit a halftone gradient of each single colour used in printer. Each patch is measured with a GretagMacbeth Spectrolino with polarisation filter. Since the polarisation filter annihilates the surface effect, we set $R_{sf} = 0$.

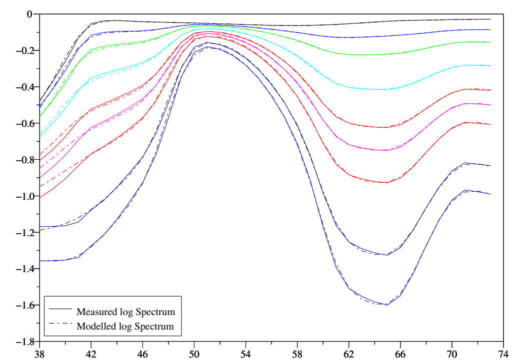
We allow to vary the thickness and the area coverage parameter to do the fit. The thickness and the area coverage parameter are estimated independently for each patches, regardless of the associated input device value **D**. The results are shown in figure 4. The fit is excellent, the maximum ΔE_{94} is around 1. As shown in Figure 4(c), the area coverage parameters as well as the thickness parameter are very irregular when plotted against the input **D** value.

By modelling the area and thickness variations with a smooth parametric curve $A(\Theta)$ and $T(\Theta)^2$ we get to the

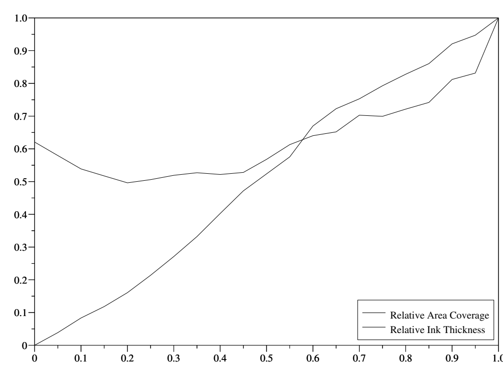
[2] We left out the descriptions of these functions, because of space constraints.



(a)



(b)



(c)

Figure 4: Comparison between modelled and measured halftone patches, for individual inks. (a) Cyan (b) Green (c) Relative Area coverage and thickness parameters used to fit the data in (a)

results of Figure 5. The fitting is still below 1 ΔE_{94} except for the black ink where it gets to 1.4 ΔE_{94}.

3.3. Fitting the superposition of 2 inks

By performing an optimisation on the trapping parameter μ of equation (7), we can fit the spectrum of a patch composed of 2 inks, printed at full coverage. The results are depicted in Figure 6. The fitting performance lies around 1-2 ΔE_{94}. The fit is not perfect, because every ink shows some scattering behaviours, which we neglected in our formulation. Indeed, some light gets scattered by the top layer and does not reach the lower layer. We can recognise this behaviour in the small overshoot at about 500nm-550nm in Figure 6(c).

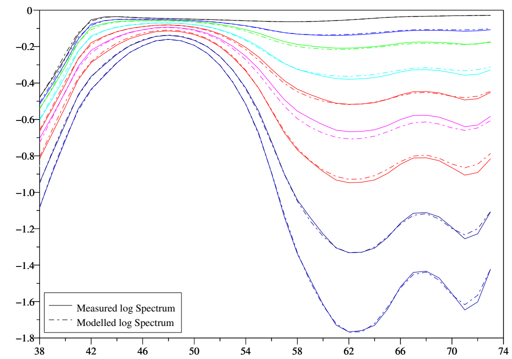
3.4. Fit on the whole colour space

By using the halftone gradient fits for each colour, we can compute an area coverage and a thickness parameter for each device input for every ink separately. By fitting every ink combination pair and knowing the laydown order of the colorants on the paper, we can compute a trapping parameter matrix μ_{ij}. From the area, thickness and trapping, and by multiplying the thickness with the trapping, we can compute the spectrum for any device input **D** by applying equation (9). The overall fit, performed on offset and flexo data, with 4 different datasets, is around 4-5 ΔE_{94} with a peak of 15 ΔE_{94}. This fit is poor, probably for two reasons: We neglected scattering and, besides trapping, we did not consider any interactions between the inks in a halftone. Nevertheless, the fit is good enough to be used as a differential model (See Section 4). We should keep in mind that our goal is not to fit the data, but to be able to explain the data using 'real' parameters. The fit of the data with 'wrong' parameter, i.e. parameters that do not correspond to a physical reality, can be performed quite easily, but will break as soon as we try to model an ink change.

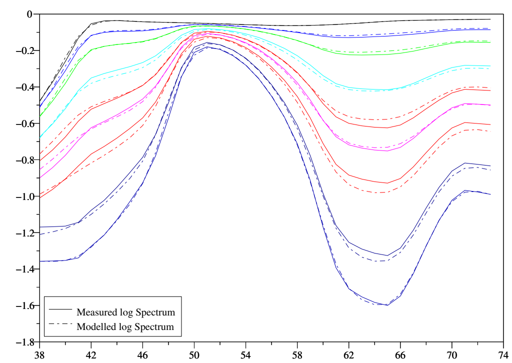
3.5. Replacing an ink

When an ink gets replaced in the press, the reflectance of the new ink layer can be computed with a spectral measurement of the ink patch and a spectral measurement of the substrate. In other words, we compute a new $k_\lambda^{(i)}$ to be used in equations (9) and (10). This patch can be printed off-line on another printer. We assume the new ink behaves like the old one, since it is used by the same element in the press. We also assume that the off-line printed patch has an ink layer thickness comparable to the one coming out of the press.

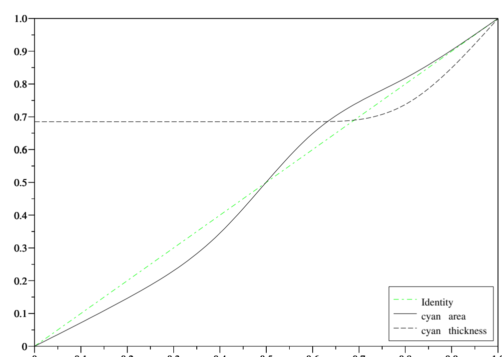
For our tests, we print a large set of colour patches using ink set 1 and another large set of colour patches using ink set 2. We take the first measurement set and fit the



(a)

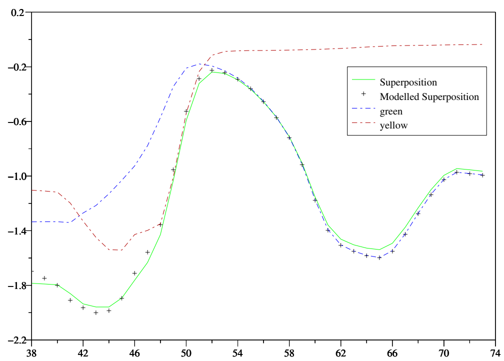


(b)

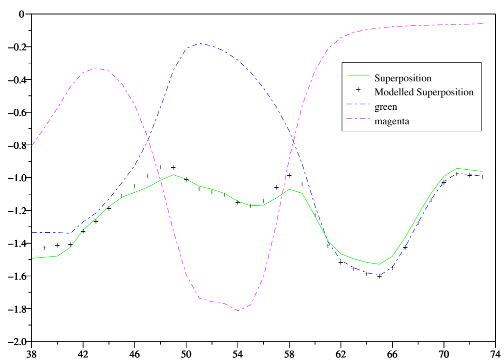


(c)

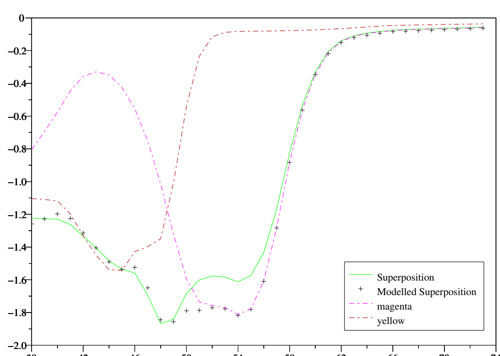
Figure 5: Same experiment as in Figure 4, using smooth parametric functions to model the area coverage and thickness variations (a) Cyan (b) Green (c) Relative Area coverage $A(\Theta)$ and thickness $T(\Theta)$ functions used to fit the data in (a)



(a)



(b)



(c)

Figure 6: *Fitting a patch composed of* 2 *inks. (a) Green-Yellow patch (b) Green-Magenta patch (c) Magenta-Yellow patch. The fitting error is about* 0.5-2 ΔE_{94}.

model, as described in section 3.4. Then, we take a single measurement of each ink of set 2 and by using the area coverage and the trapping characteristics of the old inks, we can recompute a spectrum for any $\mathbf{D}$ input. We then compare it to the appropriate patch printed with ink set 2. The fitting performance is the same as in section 3.4, thus confirming the validity of the physical model. We performed small changes, like a red-to-orange replacement, as well as big changes like a brown to blue replacement.

4. Differential modelling

Because there is still a lot of work left to completely describe the paper, ink and light interaction for halftone prints, we will apply a heuristic correction to our results.

Let $C_r(\mathbf{D})$ the colour associated to input value $\mathbf{D}$. The function $C_r(\mathbf{D})$ is found by interpolating between a set of about 1000 measurements[3]. Let $C_1(\mathbf{D})$ be the colour delivered by the model of section 2 and $C_2(\mathbf{D})$ the colour delivered by the same model after replacing one or more inks in the set.

Now, we use $C_1(\mathbf{D})$ and $C_2(\mathbf{D})$ to modify our traditional function $C_r(\mathbf{D})$. Let the difference e between the modelling before and after the ink change be

$$e = \Delta E_{94} \left(C_1(\mathbf{D}), C_2(\mathbf{D}) \right).$$

Following the principle that if e is small, the change in colour due to the ink change is small, thus the 'real' colour C($\mathbf{D}$) should be similar to $C_r(\mathbf{D})$, we get:

$$C(\mathbf{D}) = C_2(\mathbf{D}) + \alpha \cdot (C_r(\mathbf{D}) - C_1(\mathbf{D})) \qquad (11)$$

$$\alpha = \begin{cases} 1 - 1/\xi \cdot e, & e < \xi \\ 0, & \text{else} \end{cases} \qquad (12)$$

With this correction, the difference dropped to 2-3 ΔE_{94} in the mean and 8-10 ΔE_{94} in the max.

The choice of ΔE_{94} as an error criterion, as well as the value ξ have been found by trial and error.

5. Conclusions

We presented an algorithm that enable the characterisation of a press in a environment with frequently changing inks. The algorithm only needs a single print of a target and a spectral measurement of the new ink set for the future print job. The performance of the system lies at about 2-3 ΔE_{94} from the measurements in the mean.

The present algorithm is implemented in the profiling package ProfileMaker Packaging Pro® version 5 that also contains a proper handling of the optical brightener in the paper. This last topic was left out of this presentation for space reasons.

[3] $C_r(\mathbf{D})$ is an ICC profile

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