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Comparing quality attributes of coated cardboards for inkjet printing by using different methods

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Abstract

The reproduction of fine details is an important aspect in print quality and influences both the legibility and thus readability of texts and the decodability of 1D and 2D codes. Technical standards related to digital printing, such as ISO/IEC 24790:2017, predominantly evaluate printing systems. In this study, the focus is on media as the object of analysis. The evaluation of character and line image quality attributes was used to analyze the reproduction on different media comprising seven primed and non-primed cardboards printed with dye and pigment based inks. The tests were compared with the resolution of Siemens stars, line reflection and dot gain values. This study demonstrates the applicability of ISO/IEC 24790:2017 for inkjet media evaluation and shows a proper correlation between different methods of print evaluation.

Keywords: print media evaluation, ISO/IEC 24790:2017, ISO/TS 15311-2:2018, dot gain, Siemens star

1. Introduction

Inkjet printing requires three substantial components to be compatible with each other: ink, printer (or, more precisely, printhead) and media, i.e., printing substrates. These three components are usually predetermined from the printer manufacturer. The development of a printing system is based on the characteristics of a particular media, such as plastic, ceramic or plain paper or based on an application such as packaging or books (Pond, 2000, p. 65).

As a basic principle, an ink is developed for a particular printhead. The ink parameters such as viscosity, amount and size of solid particles and surface energy influence the drop formation and the size of the ink droplets. The ink will be properly ejected when these ink parameters fit the ejection parameters of the printhead (voltage, frequency and pulse for particular drop size and shape). The droplets are placed on the media correctly when the relative movement and the speed of the printhead and media are compatible.

The media should have morphological (porosity, roughness, leveling) and physicochemical characteristics (pH, surface energy) compatible with the ink. Incompatibility between media and ink causes defects in the image reproduction and results in problems like irregular spreading, sorption (too high or too low), wicking, inefficient wetting, adhesion and/or drying. Coated cardboards printed with water based inkjet inks can suffer all of these drawbacks.

In order to enable inkjet printing of coated cardboards with water based inkjet inks (pigment and dye based) using industrial inkjet printing systems, a printer concept with priming and drying units was developed and presented in a previous paper (Rosalen and Backhaus, 2018). The cardboards were pretreated with a polyvinyl alcohol (PVOH) bonding agent/primer (PVOH solution) that increases the wetting and the adhesion by means of high amount of OH-groups available for ink bonding. After printing, the boards are post treated with infrared (IR) radiation that accelerates water evaporation. After the radiation the ink is held close to the paper surface, but protected by the primer, avoiding ink smearing. Primers and IR radiation can influence the ink flow behavior and other drawbacks of print quality can occur. Too strong ink spreading or sorption can reduce the decodability of 1D or 2D codes and the legibility and thus readability of a text due to, for example, poor edge contrast, imperfect edge determination, inadequate modulation or erroneous unused error correction. In composite images these factors can cause incorrect color reproduction. When an object can be visually well defined, it is – said in common words – sharp. For experts it means, in case of very small dot spacing, that the image has a high resolution.

According to the standard ISO/TS 15311-1:2016 (International Organization for Standardization, 2016) sharpness and resolution are different qualities. Sharpness is capability of a printer to produce distinct edges. Resolution is the ability to reproduce fine details. Sharpness and resolution are thereby interdependent and it can be assumed that "the more details a printing system is able to reproduce the higher the print quality of the resulting image will be" (Cisarova, et al., 2013). During the last decades, specific technical standards for digital printing provided procedures for measurement and reference values for print quality evaluation. Particularly for 8 bit or 1 bit images there are three standards related with the aim of this present study.

The third part of DIN 53131 (Deutsche Institut für Normung, 2010) suggests procedures to measure optical resolution, optical density and image point disturbances as ink spreading and fraying. This standard was developed to evaluate inkjet media. To use it, specially designed software for the evaluation of image point disturbances and optical resolution is necessary, but according to the DIN institute this software is no longer available.

The standards ISO/TS 15311-1:2016 and ISO/TS 15311-2:2018 (International Organization for Standardization, 2016; 2018), also called digital printing production standards, reference ISO/IEC 24790:2017 (International Organization for Standardization / International Electrotechnical Commission, 2017) to measure detail rendition capabilities that can be also called reproduction of fine details. This standard was developed to evaluate monochrome office equipment. In comparison with a long list of published articles (Briggs, et al., 1999) about the previous version, ISO/IEC 13660:2001, which was later revised by ISO/IEC 24790:2017, to the best of our knowledge, no studies with application and experiences were published about the current version/standard until now.

With aspects similar to ISO/IEC 24790:2017, ISO/IEC TS 29112:2012 (International Organization for Standardization / International Electrotechnical Commission, 2012) is used to evaluate monochrome office printers and also includes measurement of addressability that is not relevant for this study.

The objectives of this study were to understand:

- Whether the standard ISO/IEC 24790:2017 can be used to classify media for inkjet printing (for inkjet printed coated cardboards there are no guidelines available to evaluate the print quality).
- How the measurements obtained by means of ISO/IEC 24790:2017 correlate with other measurements of print reproduction quality.
- How the developed primer/bonding agent (Rosalen and Backhaus, 2018) influences the reproduction of fine details.

As in the previous study dealing with coated cardboards printed with water based inkjet inks cyan, magenta and yellow had no drawbacks, this study is focused on black inks, both pigment and dye based.

2. Materials and equipment

Tested materials, equipment for production and spectrophotometric measurement of the samples as well as further information about laboratory equipment and software used for testing are listed in Table 1 to Table 6.

Table 1: Materials used in the tests

Materials	Identification	Data
Cardboard	"B-01" to "B-07"	Commercial cardboard (see Table 2) folding box board (FBB) and solid bleached board (SBB)
Ink	"K"	Dye based black ink (Canon dye ink: CLI-551)
	"PBK"	Pigment based black ink (Canon pigment ink: PGI-550)
Primer	"Primer"	PVOH 20-98 (a mass fraction of 4 %) and high-performance liquid chromatography (HPLC) water (a mass fraction of 96 %) prepared by means of magnetic stirrer with constant temperature until the mixtures became homogenous

Table 2: Properties of cardboards

Cardboard [ID]	Grammage [g/cm²]	Thickness [µm]	Moisture [%]	Roughness (Top) [µm]	Layers [-]	Type [-]
B-01	300 ± 5 %	365 ± 5 %	5.5 ± 1	1.8 ± 6 %	2	SBB
B-02	300 ± 4 %	474 ± 5 %	8.2 ± 1	< 1.3	2	FBB
B-03	295 ± 2 %	505 ± 3 %	8.1 ± 1	1.0 (max. 1.3)	1	FBB
B-04	300 ± 2 %	345 ± 3 %	N/A	1.0	1	SBB
B-05	300 ± 4 %	365 ± 4 %	6.5 ± 1	0.9 (max. 1.4)	2	SBB
B-06	300 ± 4 %	395 ± 4 %	6.0 ± 1	0.9 (≤ 1.4)	3	SBB
B-07	295 + 3 % / – 5 %	505 ± 5 %	8.2 ± 1	1.0 (max. 1.7)	3	FBB

Table 3: Surface energy (total, disperse and polar components) and contact angle (CA) with different liquids for unprimed and primed substrates

Cardboard [ID]	B-01	B-02	B-03	B-04	B-05	B-06	B-07
Unprimed substrates							
Total [mJ/m²]	42.67	39.60	35.33	27.97	32.99	38.84	35.65
Disperse [mJ/m²]	27.89	32.50	28.52	23.43	24.81	23.61	29.93
Polar [mJ/m²]	14.78	7.10	6.81	4.54	8.17	15.22	5.71
CA – Diiodomethan [°]	50.56	50.04	51.64	55.38	52.72	57.16	49.76
CA – Water [°]	62.66	74.90	77.42	87.24	77.36	65.32	79.08
CA – Ethylene glycol [°]	44.46	56.04	56.34	72.34	63.58	52.98	56.04
Primed substrates with PVOH-primer							
Total [mJ/m²]	56.52	42.43	49.67	28.04	41.47	54.92	44.30
Disperse [mJ/m²]	31.90	23.56	29.80	22.94	30.98	27.68	30.62
Polar [mJ/m²]	24.62	18.87	20.18	5.10	10.48	27.24	13.68
CA – Diiodomethan [°]	40.56	51.98	54.90	51.68	58.70	50.76	54.86
CA – Water [°]	42.92	63.68	53.56	83.40	71.24	42.62	63.68
CA – Ethylene glycol [°]	15.96	23.88	15.02	71.52	20.02	17.08	26.52

Ink surface tension [mN/m] for K = 37.18 and for PBK = 38.29

Table 4: Spectrophotometric measurements

Equipment Manufacturer / Model	Measurements [number of measurements / samples]*	Measurement data
Spectrophotometer Techkon / SpectroDens	Dot gain [16 / ink coverage, ink, cardboard, treatment]	Geometry: 0°/45°, Illuminant: D50, Observer: 2°, Measurement illumination condition: M1
	Maximal reflectance of cardboard surfaces [25 / cardboard, treatment] Minimal reflectance of printed surfaces [25 / cardboard, ink, treatment]	Geometry: 0°/45°, Illuminant: D50, Observer: 2°, Measurement illumination condition: M1, Pol-Filter: No, White Calibration: Absolute, Wavelength: 550 nm (to avoid optical brightening and fluorescent whitening agents influence)

*Ink coverage: 10 % to 100 %, ink: K and PBK, cardboard: B-01 to B-07, treatment: primed and unprimed

Table 5: Production equipment

Equipment Manufacturer / Model	Data
Printer Canon / PIXMA iX6850	Thermal printhead technology – 1200 dpi Quality printing mode: Standard Media quality: Standard
Mayer rod	Wire wound rod – primer transferred weight 1.2 ± 0.1 g/m^2
Infrared dryer Elstein / HTS	Panel radiators wavelength 2–10 μm, panel temperature 500 ± 5 °C, distance panel to cardboards 38 ± 1 mm

Table 6: Laboratory equipment and software used for testing

Equipment and test charts	Data
Scan conformance test chart ISO/IEC 24790:2017	Developed by the Japanese committee for ISO/IEC with patches for determination of: banding, graininess, mottle, mark, void, haze, line width and halftone tints
Scanner Epson / Perfection 4990 Photo	Flatbed scanner – Optical resolution: 4 800 × 9 600 dpi, Color depth: 16 bits/pixel, Optical density: 4.0
Print test charts	Self-developed in Photoshop and Illustrator CS3 Output file: PDF without embedded profile
Image processing software	ImageJ (for image cropping)
Evaluation program for target: Siemens star	Programmed in Matlab R2017b
Evaluation software for target: fine details reproduction	Package Tool TS24790_Tool_vers.1.5.1., default configuration
Surface energy / contact angle	Data Physics OCA 30, Fluids: water, diiodomethane and ethylene glycol (15 measurements each fluid), calculations by means of Owens, Wendt, Kaelble and Rabel method with three fluids (Deutsche Institut für Normung, 2011)
Bubble pressure tensiometer	SITA T60, measured points 5 to 50 s (interval 5 s), 10 measurements

3. Method

3.1 Test chart based on ISO/IEC 24790:2017

For the analysis with the standard ISO/IEC 24790:2017 the Package Tool, a quality analysis system, developed by ISO/IEC JTC 1/SC 28, Work Group 4, was used. The measurements were made in conformance with the procedures described in ISO/IEC 24790:2017, Sections B.1 to B.4.5, B.4.6.1 and B.4.6.2. The printed test chart is illustrated in Figure 1.

The test chart was developed based on the specifications of ISO/TS 15311-2:2018 (International Organization for Standardization, 2018, p. 26). The standard suggests a chart with vertical and horizontal lines. The test chart was created with 1200 ppi (pixel ≈ 21.16 μm × 21.16 μm) 8 bits and saved as uncompressed TIFF file. For each line width, 5 and 6 pixels (px in Figure 1), respectively, there are 10 lines parallel and 10 lines perpendicular to the printing direction (length 400 pixels).

For the reflectance R measurement from lower and upper limits (R_{max} and R_{min} in Figure 1, respectively) there are 10 squares (500 μm × 500 μm), five of them printed with 100 % black for the measurement of the lower reflectance limit R_{min} (printed areas) and five defined areas for the measurement of the upper reflectance limit R_{max} (background). For the measurements, 5 test charts were printed on unprimed cardboard, 5 on primed cardboard, and 5 on primed cardboard with IR drying assistance. For each parameter, for example, line width of a 5 px-line in horizontal print direction, the final result is the average of 50 measurements. The region of interest (cropped image area) has around 3 mm × 9 mm.

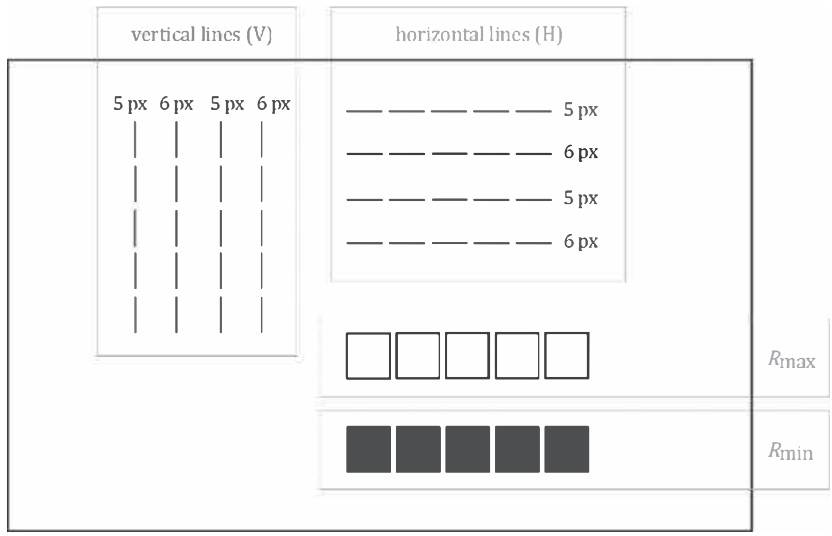


Figure 1: Test chart for measurement of reflectance and line image quality attributes

3.2 Line reflection

The reproduction of fine details is determined by means of the reflectance grade ϱ from Equation [1] (Kipphan, 2001, p. 465). As explained in Section 3.1 the maximal and minimal reflectance are measured to define the limits for the calculations. Each substrate background (maximal reflectance) and each printed patch (minimal reflectance), depending on ink type, has different reflectance grades. These data are used in the description of the different reflectance zones for the calculation of, for example, blurriness (Equation [2] from ISO/IEC 24790:2017, p. 19) and line and character darkness (Equation [3] from ISO/IEC 24790:2017, p. 19). Line width is the average width of the stroke line (printed line). The measurements are made along the line from edge to edge (ISO/IEC 24790:2017, p. 18). The line raggedness calculations (Equation [4] from ISO/IEC 24790:2017, p. 20) are based on residuals along the printed line (Figure 2).

$$\varrho = \frac{\Phi_R}{\Phi} = \frac{reflected\ light\ flux}{incident\ light\ flux} \quad [1]$$

$$Line\ blurriness = \frac{Dis_{70-10}}{\sqrt{LID}} \quad [2]$$

where Dis_{70-10} is the distance between $\varrho 70$ and $\varrho 10$ in [mm] and LID is the line image density [dimensionless].

$$Line\ and\ character\ darkness = LID \times \sqrt{LW} \quad [3]$$

where LW is the line width [mm].

$$Line\ raggedness = \frac{1}{N}\sum_{j=1}^{N}\sqrt{\frac{1}{k-1}\sum_{i=1}^{k}(RFL)} \quad [4]$$

where N is the count of edges, left and right edge in case of measuring the single line, and k is the pixel-row within an region of interest (ROI) that delivers a local edge postition which is repeated across the height of the ROI, and RFL are residuals from a line [mm].

The Figure 2 illustrates the different reflectance zones, definitions and how the distances in relation to reflectance areas are read to calculate the results.

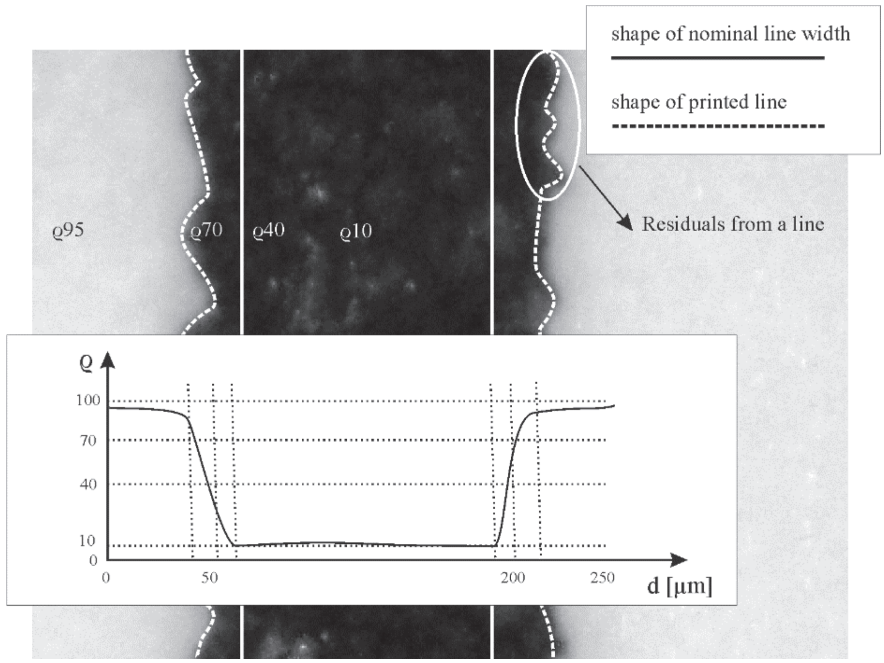


Figure 2: Reflectance areas of a printed line, based on ISO/IEC 24790:2017, p. 58

3.3 Siemens star

Siemens stars or sine wave stars are used to measure the spatial frequency response (SFR) of scanners or digital cameras. According to ISO 12233:2017 (International Organization for Standardization, 2017) resolution and SFR are related metrics and "generally, contrast decreases as a function of spatial frequency to a level where detail is no longer visually resolved." This is illustrated in Figure 3.

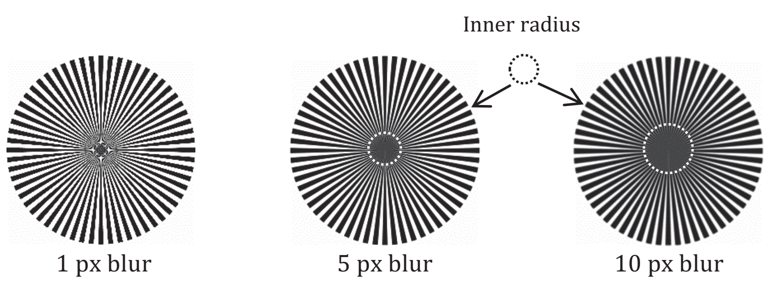


Figure 3: Loss of resolution in function of blur increase

The three stars were generated in Matlab with the same cycle numbers, diameter and three different levels of blur: 1, 5 and 10 pixels. They were exported with the same output resolution (1 200 dpi). When loss of resolution occurs, the center of the star tends to lose contrast and becomes predominantly black, forming an inner radius. The larger this inner radius, the lower the resolution. This will be illustrated in detail in Section 4.2.

In the tests, a Siemens star with 13.5 mm outer radius, and 60 spokes in black and white (60 cycles) was designed in Matlab. The image was saved in TIFF format without compression, dot gain or anti-alias with 1200 dpi, 8 bits. The stars were cropped with ImageJ and imported into Matlab Evaluation program, where the center of each star, focal point, radius, Siemens star diameter, and number of cycles were calculated. The final resolution is calculated by means of Equation [5] (Prinzmeier, 2009).

$$Resolution\ [\mathrm{dpi}] = \frac{Cycles\ [\mathrm{dimesionless}] \times scan\ resolution\ [\mathrm{dpi}]}{\pi \times radius\ [\mathrm{px}]} \qquad [5]$$

3.4 Print dot gain

Since digital printing systems do not use either a film or other image carrier, the difference between real tone values of digital data (file) and measured tone values of a print can be defined as dot gain. Figure 4 shows the test chart design for dot gain measurement. For the calculation of dot gain, 16 test charts were printed on unprimed cardboards, 16 on primed cardboards and 16 on primed cardboards using IR drying assistance. The printed charts were read with a spectrophotometer using the Murray-Davies dot gain calculation.

Figure 4: Test chart for dot gain measurement

4. Results and main observations

The measurements were performed in three groups:
- printed charts on unprimed cardboards (called "unprimed")
- printed charts on primed cardboards (called "primed"), and
- printed charts on primed cardboards and dried with IR drier (called "primed-IR").

The results of primed and primed-IR do not differ significantly. Therefore, only the measurements of unprimed and primed will be shown and discussed in the following.

4.1 Line width, blurriness, raggedness and darkness (ISO/IEC 24790:2017)

Figures 5 and 6 present the line width measurements. These data are the difference between the lines on unprimed vs. the lines on primed cardboards. This calculation method was also used to present the line blurriness, raggedness and darkness measurements. All lines printed on unprimed and primed cardboards have widths greater than the nominal line widths. Table 7 compares, based on measurements, the line width on unprimed and primed cardboards.

Table 7: Visual assessment – line width on primed cardboards (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively)

Ink	Dye				Pigment			
Line	5 px H	5 px V	6 px H	6 px V	5 px H	5 px V	6 px H	6 px V
On primed cardboards the lines become:	wider	thinner	thinner	thinner	wider	thinner	wider	wider

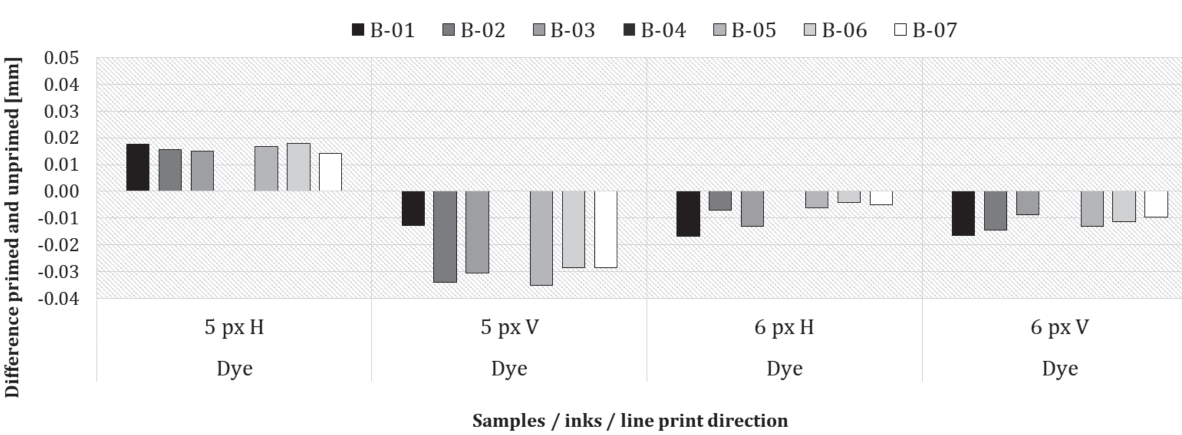


Figure 5: Measurements – line width – 5 px and 6 px – dye based ink (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively), for B-04 the measurements are not presented

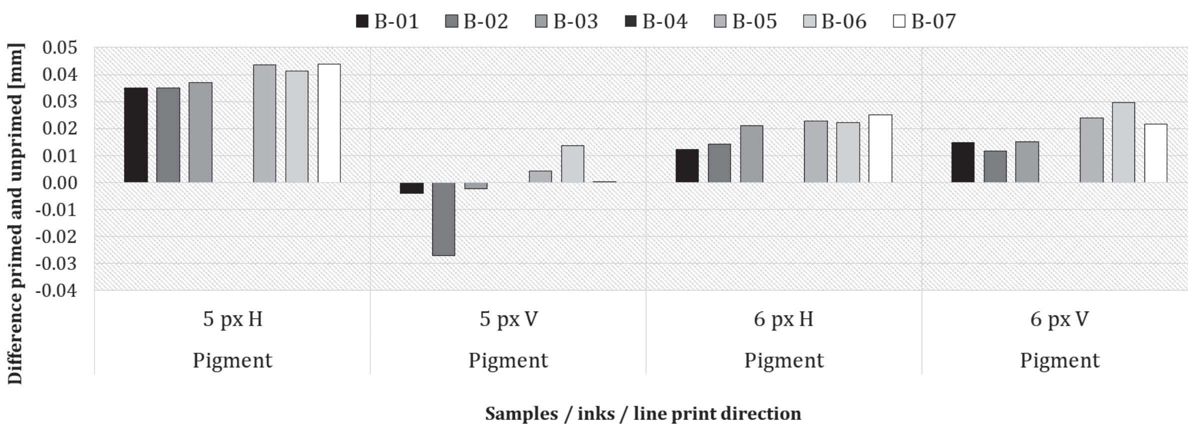


Figure 6: Measurements – line width – 5 px and 6 px – pigment based ink (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively), for B-04 the measurements are not presented

Considering surface energy only, it might have been expected that the lines on primed surfaces might be wider than lines printed on unprimed surfaces, because the primer increases the surface energy of the media and reduces the contact angle between ink and media causing more ink spreading (Rosalen and Backhaus, 2018). The measurements show different trends that will be discussed in Section 5. For B-04 the measurements could not be presented. This cardboard is cast coated and particularly pigment inks have serious wetting drawbacks on unprimed cardboards. The measurements show large standard deviation (over 10 %) and more than 70 % of the samples could not be read in the Package Tool.

For 5 px lines the measurements show a traceable course: horizontal-lines (see Figure 1) on primed cardboard printed both with pigment and dye based ink became wider than lines on unprimed cardboards. The vertical-lines (see Figure 1) on primed cardboard became thinner due to mechanical limitations of home/office printers to reproduce vertical lines as they are in the literature already known and can affect this kind of measurement (Briggs, et al., 1999; Guiping, et al., 2010).

For 6 px line the measurements show another traceable course. The difference of results were not related with the print direction, but with the ink type. Lines printed with dye ink became thinner and lines printed with pigment became wider. As this deviation happens by all cardboards, which were printed and scanned independently, a measurement error is unlikely.

Blurriness and raggedness of both sides of the line are calculated in the Package Tool; LR stands for lower or right and UL stands for upper or left (Figure 7). This is relevant for printer quality evaluation, but not for the evaluation of media or primer. Both reading directions presented the same trend. In Figure 8 to Figure 11 the measurements of line blurriness and line raggedness, respectively, are presented.

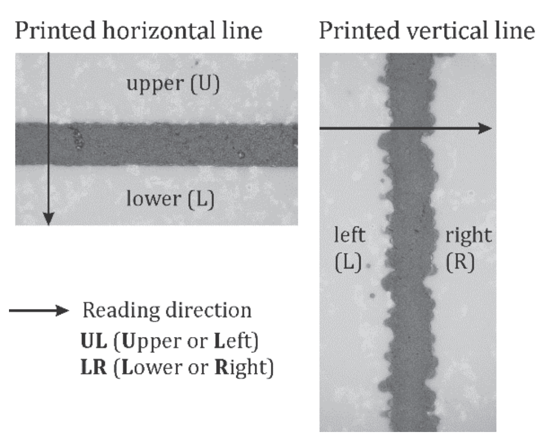


Figure 7: Reading directions for blurriness and raggedness calculations

Overall the primer increased blurriness in all samples printed with dye based ink and in all 5 px and 6 px horizontal lines printed with pigment based ink. Probably this happens also with the 5 px and 6 px vertical lines, if the standard deviation is considered. It is important to indicate that the absolute measurement values vary predominantly between 0.010 mm and 0.013 mm which in 1200 dpi resolution means between around 1 pixel and the standard deviation is below 1 pixel. In this amplitude it is probable that some measurements cannot be correctly calculated, since little alterations will be rounded, causing distortions in the result, but it is possible to observe a trend.

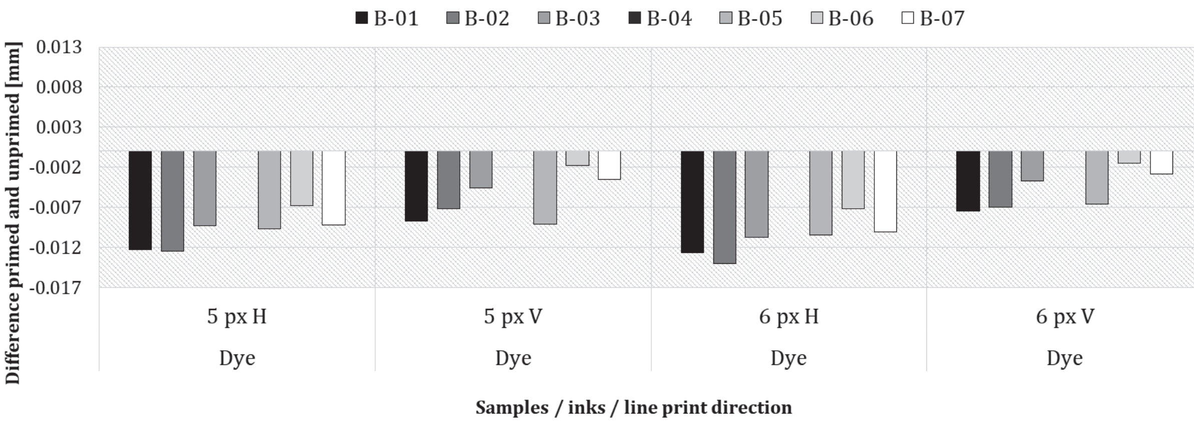


Figure 8: Measurements – line blurriness 5 px and 6 px – dye based ink (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively), for B-04 the measurements are not presented

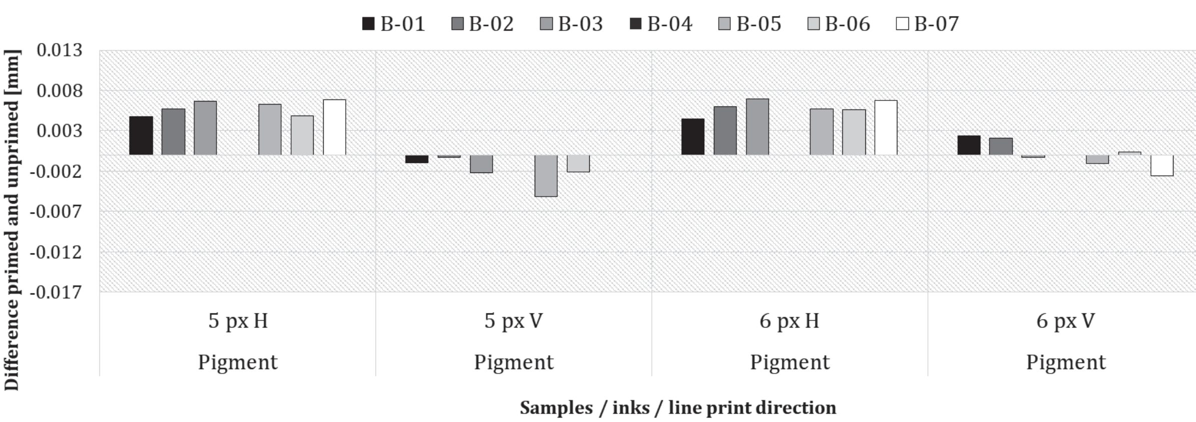


Figure 9: Measurements – line blurriness 5 px and 6 px – pigment ink (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively), for B-04 the measurements are not presented

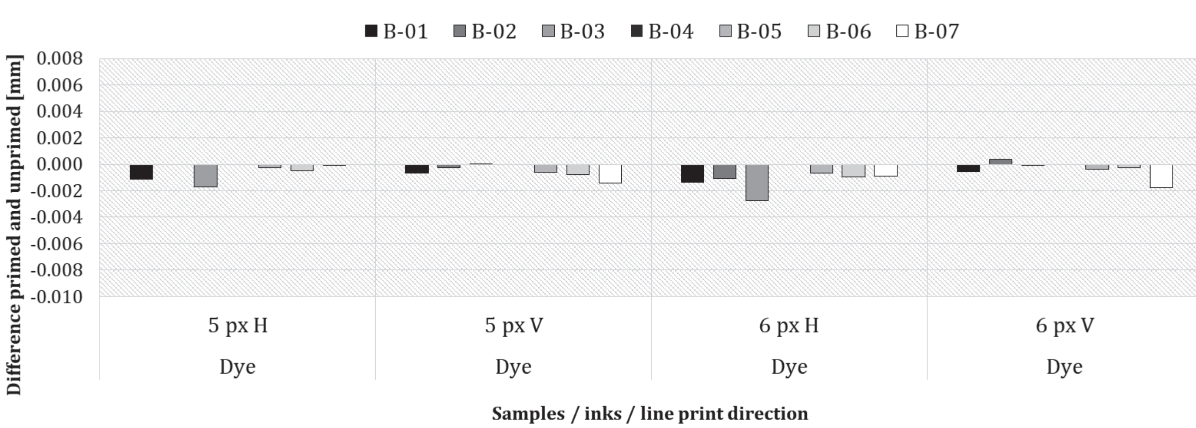


Figure 10: Measurements – line raggedness 5 px and 6 px – dye based ink (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively), for B-04 the measurements are not presented

The measurements of line raggedness with dye based ink do not show any relevant difference between primed and unprimed cardboards (Figure 10). From the measurements of the samples printed with pigment ink it is possible to observe a clear difference between horizontal and vertical lines (Figure 11).

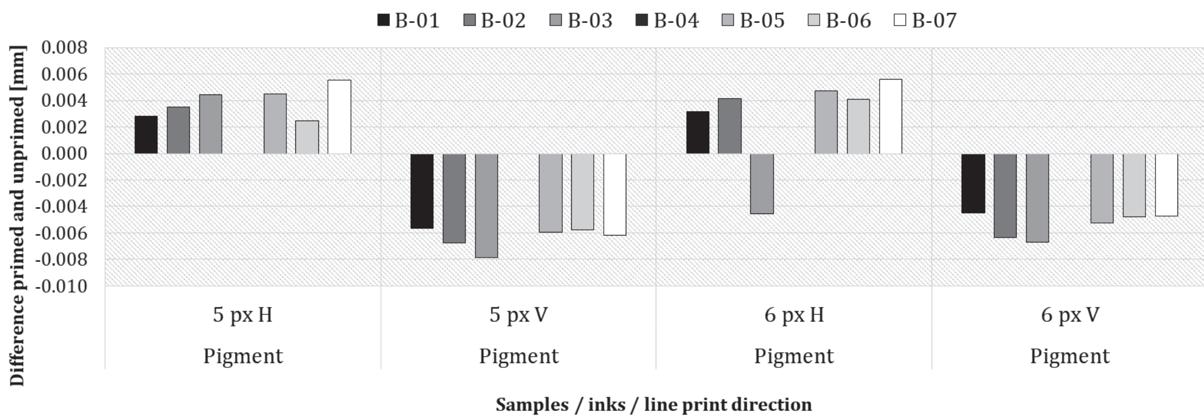


Figure 11: Measurements – line raggedness 5 px and 6 px – pigment based ink (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively), for B-04 the measurements are not presented

The measurements of line/character darkness (ISO/TS 15311-2:2018 calls this attribute line darkness, ISO/IEC 24790:2017 calls it character darkness and it is a dimensionless parameter) show that lines printed on primed cardboards are darker than the lines printed on unprimed cardboards, but with an outlier: 5 px-vertical line printed with both pigment and dye based ink (Figures 12 and 13).

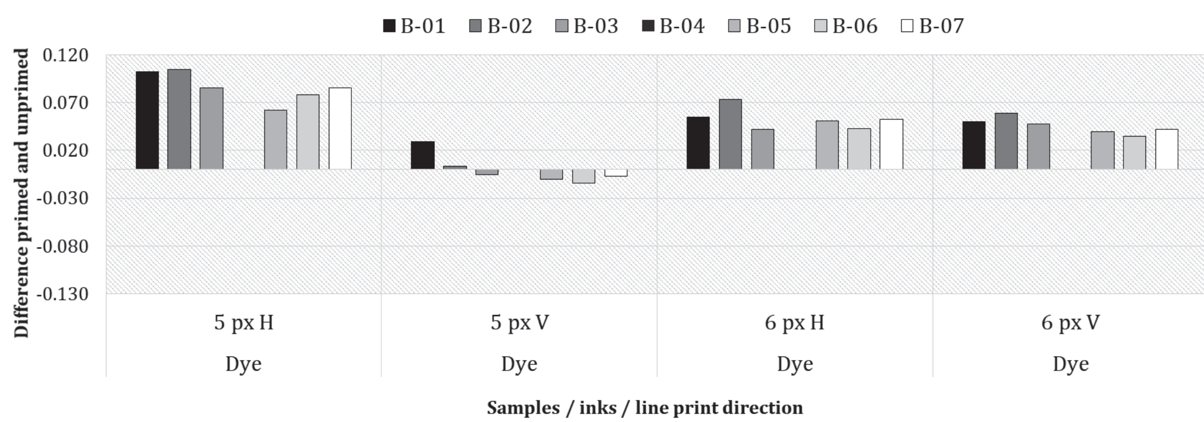


Figure 12: Measurements – line/character darkness 5 px and 6 px – dye based ink (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively), for B-04 the measurements are not presented

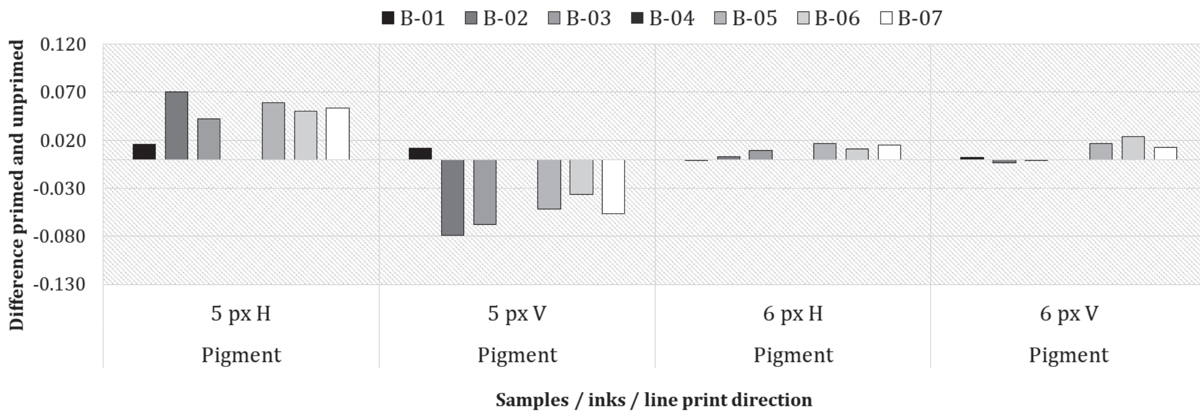


Figure 13: Measurements – line/character darkness 5 px and 6 px – pigment based ink (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively), or B-04 the measurements are not presented

It is observed that there is no direct correlation between measured line width (Table 8) and darkness. This supports the fact that darkness is not related to print area but related to print density, which, in turn, is proportional to the amount of dye or pigment present per unit area, and so less spreading will lead to a darker image provided there is sufficient spreading to provide surface coverage by the inkjet droplets.

Table 8: Comparison between line width and line darkness measurements (H and V means horizontal and vertical or parallel and perpendicular to the printing orientation, respectively)

Ink	**Dye based**				**Pigment based**			
Line	5 px H	5 px V	6 px H	6 px V	5 px H	5 px V	6 px H	6 px V
On primed cardboards the lines become:	wider	thinner	thinner	thinner	wider	wider and thinner	wider	wider
On primed cardboards the lines become:	darker	lighter	darker	darker	darker	lighter	darker	darker

Table 9: Reflectance measurements and difference Δ between unprimed and primed patches, by equation

$$(\Delta = \frac{unprimed}{primed} - 1) \cdot 100\ [\%]$$

Patches (see Figure 2)	R_{max}		**Dye (K) –** R_{max}		**Pigment (PBK) –** R_{max}	
Media	Unprimed	Primed	Unprimed	Primed	Unprimed	Primed
B-01	0.8687	0.8624	0.1003	0.0298	0.0116	0.0134
Δ		1 %		237 %		−13 %
B-02	0.8768	0.8673	0.0917	0.0244	0.0134	0.0151
Δ		1 %		275 %		−12 %
B-03	0.9048	0.8955	0.0837	0.0247	0.0128	0.0196
Δ		1 %		238 %		−34 %
B-04	0.8990	0.9049	0.1553	0.1204	-	-
Δ		0 %		29 %		-
B-05	0.9100	0.9046	0.0804	0.0213	0.0116	0.0174
Δ		1 %		277 %		−33 %
B-06	0.9141	0.9048	0.0538	0.0183	0.0120	0.0174
Δ		1 %		194 %		−31 %
B-07	0.8776	0.8648	0.0982	0.0253	0.0135	0.0241
Δ		1 %		288 %		−44 %

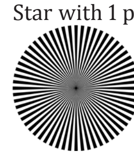
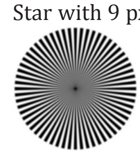
The measurements of line/character darkness were compared also with the reflectance measurements (Table 9). Dye inks printed on primed cardboards show less reflectance, i.e. they are darker than inks printed on unprimed cardboards. The opposite happens with pigment inks on primed cardboards were the reflectance is higher than without primer.

4.2 Siemens star

The inner radius is a core component to measure the resolution using Siemens stars. It is the distance between the geometric center of the star until the white and black segments can be differentiated. That is, the larger the inner radius, the poorer the resolution. The challenge of printing fine spokes in the center of the star may be a limitation of the printer, but also of the media.

For better understanding of the results, ten Siemens stars with 2 400 dpi – 13.5 mm outer radius, 60 cycles (black/white segments) with different grades of blur were created and measured in Matlab Evaluation Program. The results are listed in Table 10. A star without blur obtained a resolution close to the image output resolution itself, 2 378 dpi (blur = 0). As the center of the image loses focus, the resolution decreases.

Table 10: Exemplary resolutions of Siemens stars with different grades of blur

Applied blur [px]	Measured resolution [dpi]	Examples
0	2 378	Star with 1 px blur
1	**2 083**	
2	1 554	
3	996	
4	777	
5	720	Star with 9 px blur
6	655	
7	566	
8	443	
9	**365**	

The measurements of Siemens stars (Table 11), printed with 1200 dpi – 13.5 mm outer radius, 60 cycles (black/white segments) show that stars printed with dye ink on primed cardboards show higher resolution than stars printed on unprimed cardboards. This result was not expected, because, as mentioned above, considering surface energy only, the primer increases the media surface energy and reduces the contact angle between ink and substrate causing more ink spreading and decreasing the resolution (Rosalen and Backhaus, 2018). Stars printed with pigment inks show the inverse result, that is, on primed cardboard, the resolution decreased. This will be discussed further in section 5.

Table 11: Siemens star resolution measurements with standard deviation σ

	Unprimed K Resolution [dpi]	***σ***	**Primed K Resolution [dpi]**	***σ***	**Unprimed PBK Resolution [dpi]**	***σ***	**Primed PBK Resolution [dpi]**	***σ***
B-01	377	3 %	596	2 %	584	4 %	474	8 %
B-02	574	5 %	607	2 %	585	4 %	530	6 %
B-03	473	8 %	564	8 %	581	5 %	500	7 %
B-04	-	-	606	2 %	-	-	641	17 %
B-05	508	6 %	587	5 %	588	4 %	471	10 %
B-06	593	3 %	595	5 %	585	4 %	449	9 %
B-07	510	8 %	605	3 %	588	5 %	502	10 %

4.3 Print dot gain

The dot gain curves for B-01 to B-07, except B-04, are presented in Figure 14. All curves, for K and PBK on primed and unprimed cardboards, have similar profiles. The patches of 70 % and 80 % are marked in the graphics as areas where in average, due to dot gain, dot area increases to 90–95%. The dot gain analysis in this section is relevant for this study, because they are read in the Package Tool as solid areas (lines). In this patches the dot gain of K ink is almost identical for primed and unprimed cardboards and for PBK ink the primed cardboards have more dot gain than unprimed.

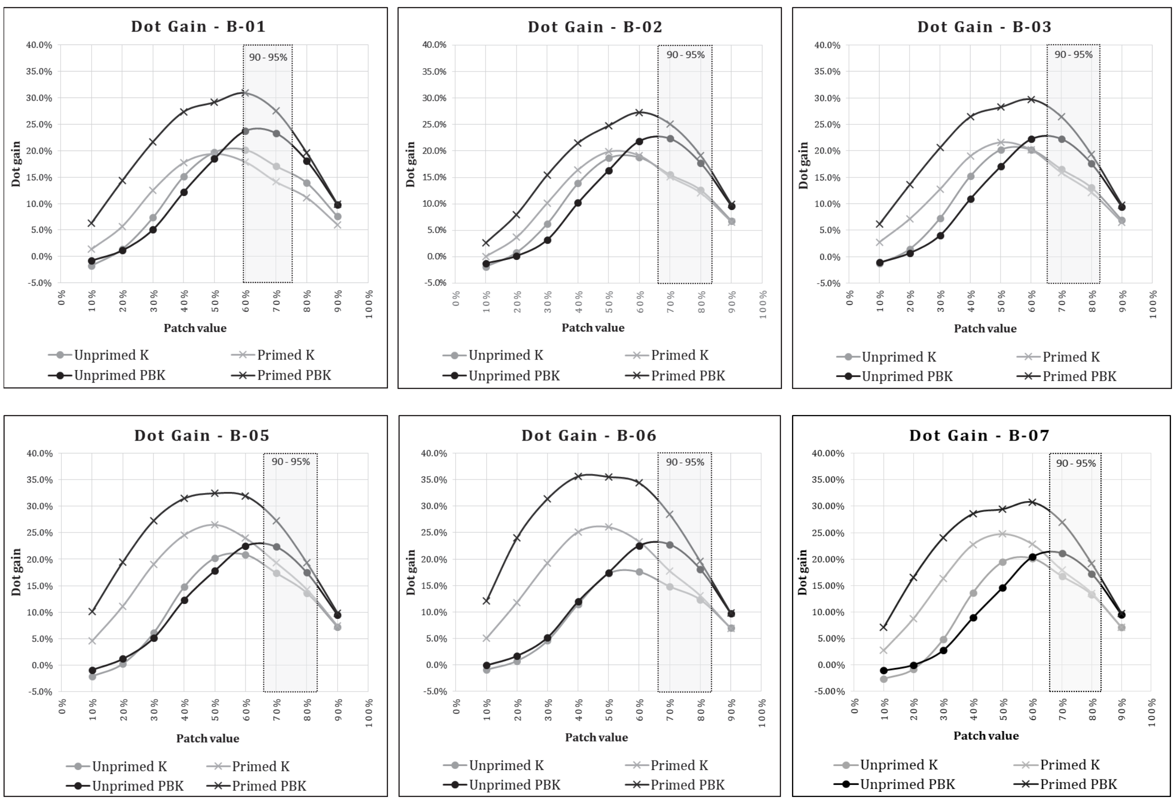


Figure 14: Dot gain of B-01, B-02, B-03, B-05, B-06 and B-07

It is not considered here that the measured dot gain refers only to ink spread. Part of the value refers to optical dot gain. In addition, the primed surface is more transparent and glossy, which affects the dot gain measurements. What is relevant here is that in relation to both treated and untreated surfaces the areas with the higher dot gain in the region of interest are related to the fact it is printed with pigment based ink.

Dot gain measurements of B-04, a cast coated cardboard not suitable for inkjet, are not displayed here. The charts present severe drawbacks of homogeneity (Figure 15), particularly for PBK on unprimed cardboard.

a) *b)*

Figure 15: Printed charts B-04 (60–100 %) with PBK on primed surface (a) and on unprimed surface (b)

5. Discussion

The ISO/IEC 24790:2017 standard was developed to evaluate printing systems. To understand if this standard can be used to classify media for inkjet print, a correlation with other well-known measurements was used. In Table 12 all measurements are summarized. Because one objective of this study is to understand the effect of the primer on the reproduction of fine details, this comparison shows what tendentially occurs with the printed objects on primed cardboards vs. unprimed cardboards.

Table 12: Overview – Comparison primed vs. unprimed cardboard

	Line width		Blurriness		Raggedness		Darkness	
	K	**PBK**	**K**	**PBK**	**K**	**PBK**	**K**	**PBK**
5 px H	wider	wider	more	less	more	less	darker	darker
5 px V	thinner	thinner	more	more	more	more	lighter	lighter
6 px H	thinner	wider	more	less	more	less	darker	darker
6 Px V	thinner	wider	more	more	more	more	darker	darker

Siemens star (resolution)		Reflectance		Dot gain (70–80 %)	
K	**PBK**	**K**	**PBK**	**K**	**PBK**
Resolution increases	Resolution decreases	darker	lighter	no difference	more dot gain

Regarding the effect of PVOH primer there was expected: more dot gain, the resolution decreases and lines becomes wider in comparison with printed lines on unprimed cardboards. These hypotheses were fulfilled by pigment based inks. Although exactly the opposite happened with dye based black inks, the logical correlation between line widths, resolution of the Siemens stars and dot gain is in overall correct. The main finding is that the primer can influence both dye and pigment based inks in opposite ways.

According to Lamminmäki, Kettle and Gane (2011) the time and amount of absorption of a liquid is dependent on the surface structure defined as network pore structure, surface chemistry and diffusion effects. In this work, it was demonstrated that the use of PVOH in pigment coatings helps to keep dyes on the cardboard surface what increases the color density and darkness. In Ridgway, Kukkamo and Gane (2011) it has been shown that PVOH in anionic dispersed coatings formulations can increase absorption/adsorption from dyes. However, PVOH used in the experiments demonstrated here is non-anionic. In this case, the authors assume that the diffusion of ink water molecules, an effect known as swelling, opens the PVOH polymer chain and the dye enters the amorphous part of the polymer.

Despite the hydrophilic character of PVOH it was also demonstrated that the absorption properties depend on the concentration of PVOH in the pigment coating. This is based on the assumption, that PVOH can also reduce media permeability by connecting previously opened pores and cavities. This effect is observed in both modified calcium carbonate and precipitated calcium carbonate, usual pigments in cardboard coatings. The higher the amount of PVOH the lower the permeability. Authors further demonstrate that bleeding increases with increasing PVOH fraction in the coating formulation. It is indicated that dye based inks "locate more uniformly in the coating structure because PVOH covers the pigment coating surfaces and masks any surface cationicity of the pigment" coating. (Ridgway, Kukkamo and Gane, 2011; Lamminmäki, et al., 2009)

Another study (Lamminmäki, et al., 2011) demonstrates interesting effects of PVOH through tests performed by means of thin layer chromatography. On the one hand PVOH reduces the available surface for dyes absorption but on the other hand the water molecules present in the ink (vehicle) open the PVOH polymer chain allowing anchoring of the dye, i.e. the same effect explained before.

In Lamminmäki, et al. (2010) the liquid uptake is analyzed as a function of time. It has been shown that up to 2 seconds after water application in pigment coatings with PVOH and different calcium carbonate the rate of absorption reduces compared to pure calcium carbonate coating. They claim that in this short timescale the rate and velocity of ink vehicle imbibition is predominantly controlled for the smallest pores. Because of the swelling effect the capillarity and absorption rate reduces. At longer timescale the dominant force controlling the rate of liquid imbibition is the permeability flow in the porosity of the coating.

It can be assumed that this effect also occurs by pigment based ink but not in the same order, because pigments exist as particles in the order of nanometers in the ink vehicle. Cross-section micrographs in Svanholm (2007) showed that both types of inks penetrate between the particles voids of pigment in coatings produced with silica and PVOH. It was shown that dye based inks penetrate the pores of the pigment coating, whereas pigment based inks stay on the surface. Since these observations were made on silica coatings, a correlation with what can happen on not microporous surfaces is only an assumption.

It is therefore possible that the IR-radiation absorbed by the assembly (media, ink and primer) changes the polymer chain either by rapid evaporation of water or by heating the PVOH above the glass-transition temperature (about 75–85 °C). Thus, both dyes and pigments are enveloped by the flexible and amorphous part of the polymer. After returning to environment temperature the colorant components are fixed and protected in the PVOH.

With respect to the correlation between the measurements it is possible to observe a proper numerical correlation among them, but with outliers. The measurements of lines with line thickness around 100 µm in vertical orientation can be also questionable for home office printers. This can explain the trend differences between measurements in vertical and horizontal 5 px lines. Albeit a lab printer (Dimatix) could have been used to minimize the print direction influence, the printing speed of this printer is not compatible with the print speed of commercial printers, which would be adverse for a correct analysis.

It is also necessary to verify if the measured values of the lines are within an acceptable range. In the Annex C (Informative) of ISO/TS 15311-2:2018 representative FOGRA print quality measurements results are listed. For full-page color advertisements, large-format professional studio photos (fine art) the typical measured differences from goal (digital image) are: for line width ≤ 100 µm, for line blurriness ≤ 100 µm and for line raggedness ≤ 50 µm. All results from K and PBK on primed cardboards fit this range.

6. Conclusion and outlook

This study demonstrates the use of the standard ISO/IEC 24790:2017 (detail rendition reproduction part) to compare quality attributes of inkjet media, exemplary here, between coated cardboards with and without pretreatement and post treatment. Other qualitative parameters to analyze print quality as resolution by means of Siemens stars, reflectance and dot gain were compared with generally accepted correlations between the parameters with the expectations of some outliers. The effect of a primer/bonding agent to coated cardboards could be also numerically analyzed.

However, the reference values are for other types of substrates. Reference values for packaging, to the best of our knowledge, do not exist. The correct reproduction of fine details, as explained before, is relevant to the legibility and thus readability of texts and decodability of codes. Standards with open parameters that can be measured in the graphics industry still need to be developed.

Lastly, the differences of the results between dye and pigment based inks are relevant and should be the next variable to be analyzed by means of ink flow behavior and dependence of the ink volume on spreading.

Acronyms

1D codes	One-dimensional data representation as code 39 or UPC-A
2D codes	Two-dimensional data representation as dataMatrix or QR-Code
dpi	Dots per inch
FBB	Folding box board
HPLC	High-performance liquid chromatography
PVOH	Polyvinyl alcohol
R_{max}	Maximal reflectance
R_{min}	Minimal reflectance
SBB	Solid bleached board
σ	Standard deviation
Φ	Light flux

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