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Journal of Print and Media Technology Research

Scientific contributions

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To meet the need for a high quality scientific publishing platform in its field, the International Association of Research Organizations for the Information, Media and Graphic Arts Industries is publishing a quarterly peer-reviewed research journal.

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A letter from the Editor

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The latest issue of the Journal in 2020 rounds off the time when the lives of all of us have changed, but the authors, reviewers, editors, and users have enabled its smooth publication by their contribution.

This time, four interesting papers have been published in scientific content. The overview begins with the first original scientific paper dealing with a 3D-printed spectral verification system for colorimetric biosensors, based on gold nanoparticles aggregation that changes their colour when cysteine analyte is added, which affects the spectral transmission of the sensor. In another original scientific paper, the optimization of the milling process for water-based printing inks is discussed based on the determination and optimization of parameters influencing the optimal specific energy consumption and the size of the dispersed pigment particles in the printing ink.

Two more research papers follow. The first is a report on an extensive survey of paper metrics as predictors of the quality of inkjet printers, and the second discusses the competencies and tools of higher education graphic communications programs. The content of both is non-conventional, as in the first case a large number of samples and several equipment manufacturers are included in the research, while in educational programs the emphasis is on the expectations and requirements of industrial partners and not primarily on the educational institutions.

The Topicalities are shorter for two pages of Events affected by pandemic situation and measures, however, Markéta Držková (marketa.drzkova@jpmtr.org) collected and edited some interesting information for us. Update on CIE publications and most important Fogra activities in the last year are presented in News & more section. In the overview of the Bookshelf, the books are listed from the fields of printed electronics, 3D printing materials, media, colour science, typography, design, and history.

The overview of three interesting doctoral dissertations begins with the thesis defended by Titas Braukyla at the Kaunas University of Technology. The author investigated functional Tröger molecules for optoelectronic applications including perovskite solar cells and light-emitting materials. The second thesis was defended by Aditya Suneel Sole at the Norwegian University of Science and Technology in Gjøvik. The author investigated a self-designed image-based measurement setup for flexible packaging print materials with complex optical properties. The third thesis is based on the research of roll-to-roll reverse offset printed millimeter-wave antennas on flexible substrates, presenting their fabrication, methods for quantification of radiation performance, efficiency and stability of the chosen printing method, and materials used. The author Jianfang Zheng defended his thesis at Aalto University in Espoo.

The list of events is shorter than usual due to many conferences, seminars, and fairs canceled or postponed for a few months or even a year. Even the events which will be held in the next months are at least partly planned as online events. An overview of changes in the announcement of new dates or form of the events is added together with some information for attendees. Some new dates are considering the optimistic scenario, however, any further changes due to the pandemic situation cannot be excluded.

With 14 scientific contributions and one technical paper published in Volume 9 (2020), we achieved the main goal of the Journal, the well-established channel dedicated to the dissemination of the knowledge and research results in the field known as print and media technology. We are optimistic also at the beginning of the new year. In the name of the editorial team, I wish you a healthy and happy new year 2021, with successfully fulfilled research and academic goals.

Ljubljana, December 2020

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Development and validation of a 3D-printed spectral verification system for colorimetric-based biosensors

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Abstract

We propose a method to transfer colorimetric assays based on gold nanoparticle aggregation from the laboratory to clinics, practices, or even to an application at home, by creating printed biosensors. While colorimetric assays need laboratory equipment and trained personnel, our printed biosensors (through manual pipetting) are storable, portable and usable from anyone anywhere. The method is verified using a model system for detection of the analyte amino acid cysteine (cys) and a spectral experimental setup in transmission. The model system consists of dispersed gold nanoparticles, which aggregate after cys addition. The biosensor is created by pipetting droplets of a gold nanoparticle solution onto the carrier Hostaphan GN 4600. Its functionality is sustained during the drying process through an addition of glucose, which preserves the gold nanoparticles from aggregation through its amorphous state. The glucose mixture can be kept amorphous over a long time by controlling the surrounding humidity with silica gel beads in an airtight container. The sample mount for the experimental setup is 3D-printed and designed to measure the spectral transmittance of the biosensor before and after analyte addition. The characterization of the setup suggests to expect coefficients of variation below 1 %, which validates its use. The biosensor and transmission spectrometer are tested with analyte concentrations between 10 mM and 50 mM. After a successful verification the printed biosensor would be ready to be evaluated without special equipment, meaning visually or with commercially available imaging techniques. Keeping in mind the possible application at home, the most obvious solution is using your own eyes or smartphone. These methods are discussed in the outlook.

Keywords: spectrometer, gold nanoparticle aggregation, color change, ready to use, printed biosensor

1. Introduction and background

There is a growing need to easily and rapidly detect specific molecules in a sample and biosensors are on the rise to fulfil it. The best-known example is the detection of the blood sugar level of diabetics, but there are many more applications in healthcare, consumer goods, or environmental protection. For instance, pathogens are being detected to stop the spread of illnesses (Ecker, et al., 2008), residues of antibiotics in food are being monitored to avoid antibiotic resistance (Wegener, 2003), contaminations of water and air are examined to protect the environment (Justino, Duarte and Rocha-Santos, 2017), and many more. We have picked a specific kind of colorimetric biosensor, which before only existed as a laboratory assay, to upgrade it into a ready-to-use biosensor. After giving the definition of a biosensor and introducing these colorimetric biosensor assays, we will state the specific aim of our research.

1.1 Biosensors

The International Union of Pure and Applied Chemistry (IUPAC) defined in Thévenot, et al. (2001) that a biosensor is a device that transforms chemical information, e.g. concentration of a specific analyte in a sample, into an analytically useful signal. To be more precise, a biosensor consists of several parts working together, as visualized in Figure 1. It represents what we plan to achieve in the future. In this paper we only analyze the transducer part. The recognition element works with a biochemical mechanism and is coupled via an interface to the transducer, which transforms the output from the recognition element into a measurable signal that is usually amplified.

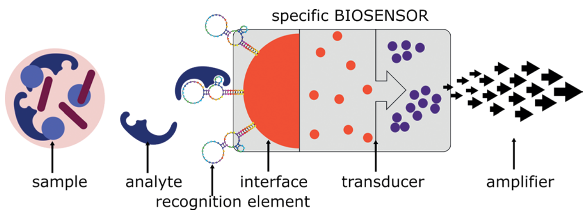


Figure 1: Schematic representation of a specific colorimetric biosensor based on gold nanoparticles

1.2 Biosensor assays using gold nanoparticle aggregation

One way to realize colorimetric biosensors is by using gold nanoparticles (AuNP) and their color change through aggregation as transducer element. The physical phenomenon that enables the intense colors of AuNP ranging from red over purple to blue is called the localized surface plasmon resonance (LSPR). Details on the LSPR can be obtained in the review from Petryayeva and Krull (2011) amongst others. The essence is that the colors are caused by specific absorption spectra that are linked to the particle agglomeration size.

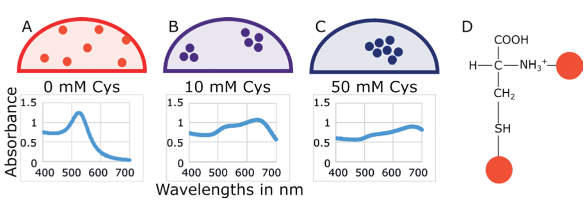


Figure 2: Absorption spectra of gold nanoparticles dispersed (A) and aggregated after cys addition (B, C), measured in liquid state with a well plate reader, where (D) visualizes schematically the aggregation by cys; altered from Zhong, et al. (2004)

Figure 2 depicts the general idea: a well distributed solution of AuNPs in buffer solution absorbs wavelengths in the green region and appears red (A). If the particles get agglomerated or linked to bigger clusters, the absorption peak broadens and shifts to higher wavelengths; accordingly, the color shifts to purple (B) or blue (C). This so-called aggregation can be brought about in different ways, which can be categorized into specific and unspecific aggregation. Examples for unspecific aggregation are destabilization mechanisms or unspecific linkers, e.g. the amino acid cysteine (cys). Cys binds to the surface of AuNP with the NH_3^+ and SH end groups (D) and creates links that form clusters.

If AuNP are used as a transducer in biosensors, only aggregation as a reaction to the specific analyte is wanted. This is called specific aggregation and can be realized by functionalizing the AuNP surface with recognition elements. A good overview on the possible detector designs of AuNP based colorimetric biosensors is given by Zhao, Brook and Li (2008). One recognition element with high affinity and selectivity that is often used in this context are aptamers. They are single stranded DNA or RNA nucleic acids that bind through their complex 3D structure. Biosensors with aptamers as recognition element are called aptasensors. To give some examples on AuNP based aptasensors: Shi, et al. (2013) measured acetamiprid in soil samples, Song, et al. (2011) sensed the antibiotic kanamycin, Wei, et al. (2007) detected the protein thrombin, and Zheng, Wang and Yang (2011) determined dopamine levels. All of these biosensors have in common, that they are evaluated in liquid form using test tubes or micro plates and are dependent on the laboratory equipment and personnel. The absorption curves of the liquids are measured and presented as intensity ratios over analyte concentration and show either a linear or logarithmic behavior. Therefore, we refer to these kinds of biosensors as assays.

1.3 Printing biosensors

Generally, printing techniques can be divided into conventional and digital printing. Conventional printing always needs a printing plate, while digital printing has the advantage of easily adjustable layout and usually smaller dead-beat volumes (Rech, 2000). The different digital printing techniques differ in amount of transferred ink. Inkjet transfers droplets with volumes of several pico liters (Hoath, 2016), pipetting and spotting are in the range of micro liters (Zhao, et al., 2008) and pneumatic dispensing works by depositing lines or dots of micro liter volumes with a controlled, pressurized air source (Komuro, et al., 2013). Printing of biomaterials often means pipetting or dispensing. Here we use Eppendorf Research plus pipettes for manual pipetting to deposit the model system, but in future research this step can be automated.

1.4 Aim of research

The ultimate goal of our research is to bring biosensor assays based on gold nanoparticle aggregation from the laboratory into small clinics and homes by printing portable biosensor test strips. The difficulty of printing these kinds of biosensors lies in preserving the dispersed status of the AuNP during the drying and storing process. Without additives the water within the deposited AuNP droplets will evaporate and leave aggregated AuNP behind. In order to prevent premature nanoparticle aggregation additives are required. In the literature, different types of sugars have successfully been applied for this task, e.g. in paper-based biosensors (Zhao, et al., 2008) or the conjugate pads of lateral flow tests (Choi, et al., 2010). Thus, the applicability of different sugars as additives were tested within this study.

The research described in this paper represents the first step: a printed unspecific biosensor, which can detect cys and a spectral measuring setup to verify its functionality. The idea is to start with an unspecific platform technology and later transfer it to a specific AuNP biosensor. In previous work we have been successful with a similar transfer. In Jaeger, et al. (2019) we printed a biosensor onto filter paper detecting the antibiotic ciprofloxacin based on fluorescence. The work was based on printing DNA and DNA dyes as an unspecific biosensor, which was presented at the IARIGAI conference in 2018 and published in the JPMTR one year later (Stamm, et al., 2019).

2. Materials and methods

2.1 Construction of the transmission spectrometer

To verify the functionality of the printed biosensor we needed an experimental setup to measure the absorption spectra. In the liquid state AuNP absorption spectra are usually measured by absorbance microplate readers. For this we used the CLARIOstar Plus microplate reader from BMG LABTECH. It works by sending a light beam with intensity I_0 through the probe and measuring the intensity I afterwards. The transmittance *T* is then calculated by the ratio of the two intensities and the absorbance *A* by the logarithm of *T*:

$$T = \frac{I}{I_0}, \qquad A = -log_{10}T \qquad [1]$$

The printed biosensor could not be evaluated using a microplate reader, because it is only built for homogeneous liquids. We needed a setup that will average over the whole sample by using one bigger light beam. For this purpose, we created a transmission spectrometer with a 3D-printed mount and a Nanocalc 2000 UV-Vis-NIR spectrometer. The spectrometer measures light intensities in counts over wavelengths. Over and underexposure can be adjusted by varying the integration time. The wavelengths are covered in 1 nm steps between 201 nm and 890 nm. To operate it in transmission mode another UV-Vis-NIR optical fiber was needed (30–1100 nm from Ocean Optics) and a 74-UV collimator lens (*Φ* 5 mm; 185–2 500 nm from Ocean Optics). A mount was 3D-printed to hold everything together and specimen holders were also 3D-printed to enclose the sample and position it in the light beam. All parts were created with the 3D printer Prusa i3 MK3 and the material polylactic acid (PLA) through Fused Filament Fabrication.

2.2 Characterization of the transmission spectrometer

To validate the measurements with the transmission spectrometer it needed to be characterized. The warm-up phase could be derived from the average coefficients of variation (CV) between the light source spectra of increasing time. Crosstalk could be examined by using a laser diode from Laser Components, type: FP-D-450-1-C-C, with a peak at 450 nm and a peak width at half-height of 1–2 nm. The repeatability of transmission measurements could be validated by comparing the CVs of several measurements from fixed scenarios. For this purpose, we used the green optical cast plastic color filter from Edmund optics with the stock number 43-935. A time dependency was examined by 19 measurements of the same filter with the same specimen holder, without removing it, and without calibration in between. This series was compared to a well plate reader measurement. The repositioning accuracy was tested for one and for different specimen holders, by reinserting it 19 times. Finally, a recalibration was made in between measurements to test its effect on the CVs.

2.3 Biosensor fabrication

The model system used in this research was the well-known AuNP aggregation by addition of the analyte cys, as introduced in Figure 2. The biosensor consisted of 3 μl printed ink droplets on a carrier material. The ink was a mixture of AuNP and additives. The pretreated side of polyethylene terephthalate (PET) foil Hostaphan GN 4600 from Mitsubishi Polyester Film GmbH was selected as carrier for the sensor system. The biosensor was evaluated by pipetting the analyte solution onto the dried AuNP droplets.

2.4 Ink and analyte fabrication

The ink was prepared by blending AuNPs and additives by the mixing ratios of 1:1, 2:1 or 2:3 to reduce the original concentrations. The additives were needed to prevent premature aggregation of the AuNP during drying and storing. The AuNP were concentrated as follows:

- The store bought AuNP (Sigma Aldrich, prod. no.: 777137, USA) solution came in citrate buffer and had a concentration of 1.64×10^{12} particles per ml which equals 2.72 nM. The 10× and 20× solutions were produced by centrifugation and removal of the supernatant; 10× equals 90 % removal and 20× equals 95 % removal.

- The concentrations of the additives sucrose (Sucrose, Sigma Aldrich, prod. no.: S7903 USA), glucose (D(+)-Glucose, Carl Roth, prod.no.: X997.2, Germany), fructose (D(-)-Fructose, VWR, prod. no.: 24282.290, Germany), agarose (Agarose, low gelling temperature, Sigma Aldrich, prod. no.: A9414-100G, USA) and alginate (Alginic acid sodium salt from brown algae, Sigma Aldrich, prod. no.: 71238-250G, USA) were prepared in weight percentages, by being dissolved in osmose water. Isopropanol (Böttcherin IPA, Felix Böttcher, prod. no.: 10501, Germany) was used as delivered.

- The analyte solutions were prepared by creating a stock solution and diluting it to the desired molar concentrations. A 1 M stock solution was prepared by dissolving 1.2116 g of cys (L-Cysteine, Sigma Aldrich, prod. no.: W326305, USA) in 10 ml of osmose water. Dilutions between 5 mM and 50 mM were used.

2.5 Drying and storage of biosensors

The phenomenon of amorph sugars crystallizing has been observed by papers on related research topics. Labuza and Labuza (2004) studied the stability of cotton candy, which consists of sucrose. They found that by storing it at room temperature with reduced humidity between zero and 11 % the cotton candy stayed amorphous for up to 2 years. As the humidity increases the time until crystallization decreases. The explanation is that to stay amorphous the sugar has to stay at or above the glass transition temperature, which is related to the given relative humidity. Leinen and Labuza (2006) explored the possibility to add a small percent of another sugar to an amorphous sucrose system to increase its stability.

The drying behavior and storage over 4 weeks were investigated at the example of the additive sucrose. The ink was prepared by using 10× AuNP and 30 % sucrose at a mixing ratio of 2:1. There were four conditions used to dry 3 µl droplets of the ink on the Hostaphan foil: open, in the oven, in the fridge and dehumidified. The open samples were exposed to 25 °C and 45 % air relative humidity. The oven samples were dried for 1.5 hours in a 60 °C oven and then stored in the open. The fridge samples were immediately put in a box and stored at 4 °C. The dehumidified samples were stored in airtight containers with silica gel beads (Carl Roth, prod. no.: 2440, Germany). The beads have an incorporated indicator, which changes the beads' color from dark blue to pink at saturation. The humidity in the box was measured to be lower than 20 %, by the digital Thermo-Hygrometer (VWR, prod. no.: 620-0915, Germany). But the humidity could be considerably lower, as the color of the beads stayed blue for months when the box stayed unopened.

3. Results and discussion

The present study describes the development and validation of a 3D-printed spectral verification system for colorimetric-based biosensors focusing on two objectives. First, the suitability of different sugars and polysaccharides as nanoparticle aggregation preventing additives were tested on an unspecific biosensor. Second, the development of a spectral setup to validate the functionality of the printed biosensor is presented.

3.1 Experimentally optimizing the biosensor fabrication

We evaluated the suitability of the different additives qualitatively by observation with the human eye. The additives and the AuNP solutions were prepared as explained in Section 2. The ink was prepared by mixing both solutions in the stated mixing ratio. The suitability experiment consisted of two steps.

First several 3 µl droplets of each ink were pipetted onto the foil and let dry for approximately one hour. The color is supposed to stay red. In a second step different concentrations of the aggregation analyte were pipetted on top. Only after the second step the color is supposed to change. In our experiments the first step was successful with sucrose, glucose, fructose and alginate. Nearly homogeneous droplets were formed during the drying process. However, in the second step the biosensor with alginate did not change its color after analyte addition.

Between the suitable analytes glucose was chosen for transmission measurements of the biosensor, because it yielded the fastest color change after analyte addition. Additionally, other additives and compositions were tested, which did not yield promising results. All results are summarized in Table 1.

While strong colors could be observed in reflection with 20× AuNP and mixing ratios of 1:1 with glucose, the absorption is too high for the transmission spectrometer to yield good results. This is why the mixing ratio was reduced to 2:3. The color change of the biosensor used for transmission measurements is shown in Figure 3. The pictures before aggregation were obtained after a 24-hour drying period and the after-aggregation pictures were obtained 40 minutes after cys addition.

Table 1: Suitability of different additives

Additive	Concentration AuNP : additive	Mixing ratios	Results	Suitable?
Sucrose	10× : 30 %	2:1	Slow aggregation. Nearly homogeneous droplets.	Yes
Sucrose	20× : 50 %	1:1	Slow aggregation. Nearly homogeneous droplets, preferable to 30 %.	Yes
Glucose	20× : 50 %	1:1	Quick aggregation with cys. Nearly homogeneous droplets.	Yes
Fructose	20× : 50 %	1:1	Slow aggregation. Nearly homogeneous droplets.	Yes
Agarose	10× : 0.5 %	2:1	Highly irregular aggregation and color distribution.	No
Agarose	10× : 0.25 %	2:1	Highly irregular aggregation and color distribution.	No
Alginate	10× : 0.5 %	2:1	No aggregation of AuNP.	No
Sucrose & Isopropanol	10×: 30 % : 99.9 %	2:1:1	Disintegration and running and reduced aggregation.	No
Sucrose & Agarose	10× : 30 % : 0.5 %	2:1:1	Less homogeneous than agarose alone.	Moderately

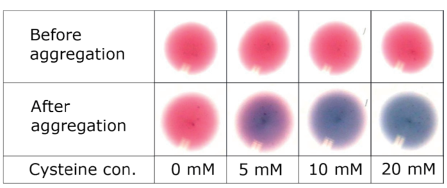


Figure 3: Photograph of four pipetted unspecific biosensors: the droplets consist of 2:3 AuNP (20×) and glucose (50 %), they were captured under D65 lighting panel before and after aggregation with 3 µl of different cys solutions

The results of the drying and storing experiment for four weeks are shown in Figure 4. If the drops were left in the open, they aggregated (blue dots) or crystallized (lighter dots). At high temperatures even more drops crystallized. Storage at low temperatures lead to no visible change compared to the open. The best solution was storing the biosensors in airtight containers with silica gel beads. This way they could be stored at least four weeks and stay functional (red color).

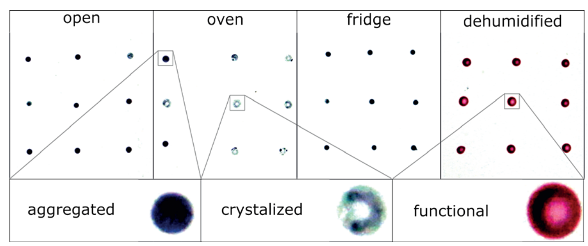
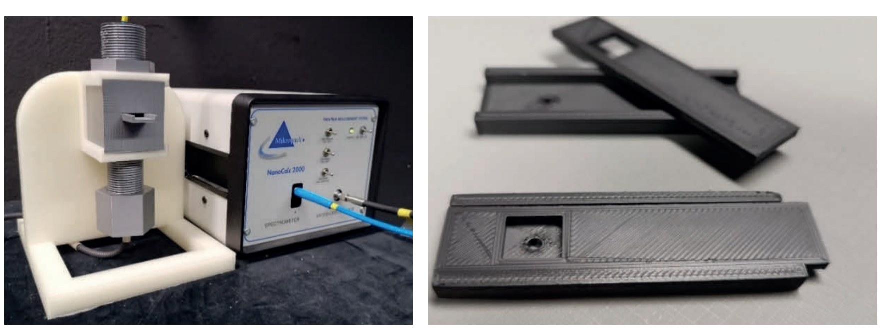


Figure 4: Photographs of the results of the drying and storing experiment with 3 µl drops of 2:1 10× AuNP and 30 % sucrose after four weeks; nine samples are shown for each condition: open, oven, fridge and dehumidified, which are either aggregated, crystallized or functional; one exemplary sample of each state is magnified

3.2 Buildup and characterization of a transmission spectrometer

The measuring setup and specimen holders are shown in Figure 5; the construction and light path are illustrated in Figure 6. The mount was constructed to meet



a) b)

Figure 5: Measuring setup including (a) the NanoCalc 2000 spectrometer and the 3D-printed mount, and (b) the specimen holders, which enclose the biosensor and are inserted into the measuring setup

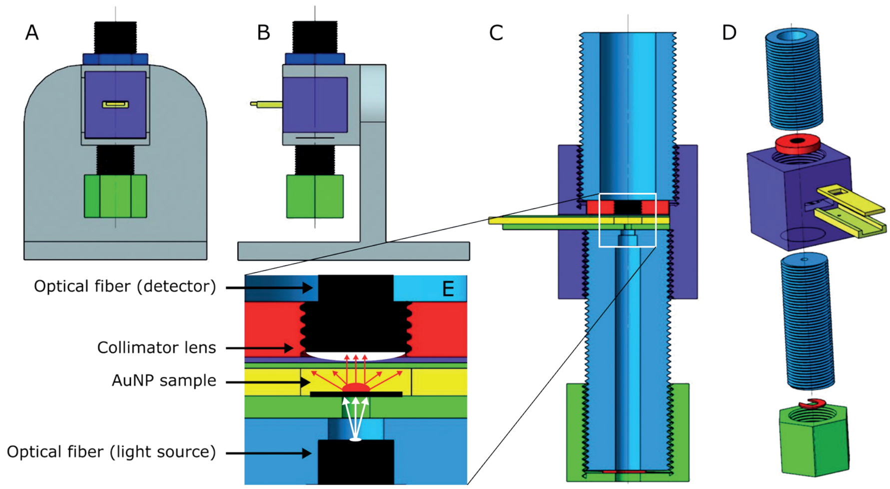


Figure 6: Schematic of the 3D-printed mount; A: front view, B: side view, C: cross section view, D: exploded view and E: optical light path

several requirements, which are that the samples can be placed precisely at the same location, while the distance between light source and sample as well as sample and detector can be adapted. The conic light beam illuminated the entire hole with 2.5 mm diameter in the specimen holder and therefore the whole sample.

Furthermore, the samples were placed horizontally to enable measurements in the liquid state with the light path perpendicular to the sample. All components can be dismounted through screw connections, exterior light is shielded and it is possible to easily convert back to reflective mode. The whole setup will be called transmission spectrometer.

To validate the measurements with the newly created transmission spectrometer, a thorough characterization was carried out. A needed warm-up phase of 10 minutes was derived from the average CVs between the light source spectra of increasing time. The first measurement differs from the others with an average CV of 0.027. But, after 10 minutes the CV is below 0.0021. Crosstalk is examined by using a laser diode with a peak at 450 nm and a peak width at half-height of 1–2 nm. The measured spectrum exhibited a peak at 451 nm with 7 nm width. This shows that the precision of the detector is indeed 1 nm, but the crosstalk is bigger. Finally, transmittance measurements of the green plastic color filter were carried out to test the repeatability with five different test series.

The first test series measured the time dependency after the warm up phase. The filter was measured 19 times without removing it and without calibrations in between. The average transmittance spectrum is shown in Figure 7. The average CV and percental standard deviation can be found in Table 2, test series 1. The CV is the highest for transmittance values below 470 nm, which are close to zero. Still the deviations are very small, with a maximal CV of 0.075. For each test series the average CV is given for all wavelengths and for wavelengths longer than 470 nm. The later excludes transmittance values close to zero and is called “zero excluded”. For the first test series the average CVs are 0.014 over all wavelengths, and 0.005 for zero excluded.

Table 2: Average CV results from dividing the standard deviation by the transmittance values given from all values (overall) and excluding transmittance values close to 0 (zero excluded) for five test series conducted measuring the green color filter

	Coefficient of variation	
Test series	**Average overall**	**Average zero excluded**
1: Time dependent variation, the sample is not moved (Figure 7)	0.014	0.005
2: Comparing the results of first series with well plate reader measurements (Figure 8)	0.138	0.045
3: Repositioning accuracy by using the same specimen holder, the sample removing and reinserting between measurements	0.019	0.009
4: Repositioning accuracy by using different specimen holders	0.024	0.013
5: Recalibration between measurements of fourth series	0.020	0.008

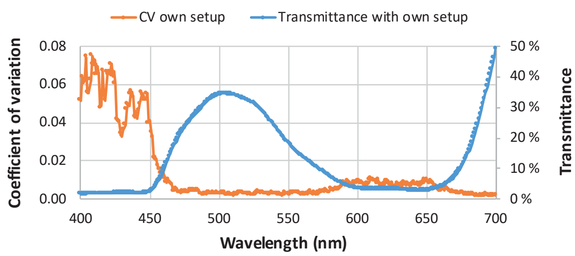


Figure 7: First test series: average transmittance (blue) and CV (orange) of 19 measurements with the same specimen holder, same green color filter and no removal; the errors given by standard deviation are too small to be visible as error bars.

In the second test series the measured spectra with the transmission spectrometer were compared to the average transmittance measurement with the well plate reader CLARIOstar Plus of the same filter. Both average transmittance spectra are shown in Figure 8, including the CVs of the CLARIOstar measurements and the CVs of both average transmittance spectra to give a comparison between them. The CLARIOstar measurements consisted of two data sets, which each consisted of 22 averaged data points taken. The average CVs over all wavelengths of the CLARIOstar measurement are 0.035 and with zero excluded 0.004, although the maximal CV reaches a value of 0.85. These high CV values are rare and do not matter since they only occur for values close to zero. In a next step the average spectra of both measurement methods were compared. The average CVs between the two average spectra are overall 0.138 and with zero excluded 0.045. Both values show an increase of more than the power of ten compared to the other test series. In Section 3.3 these values magnitudes will be compared to the magnitudes of measured biosensor samples.

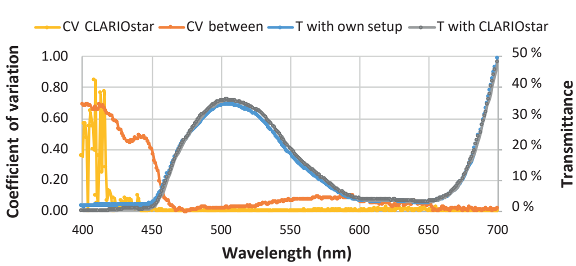


Figure 8: Second test series: average transmittance of the green color filter from own setup (blue) and from well plate reader CLARIOstar (grey); the CVs are given for the CLARIOstar measurements (yellow) and for the deviation between the average transmission spectra of both measurements (orange)

In Table 2 the results are summarized, including three additional test series. Later when measuring the transmittance spectra of the biosensors will be removing and reinserting samples (test series 3) with different specimen holders (test series 4). This will increase the errors, while a new calibration in between these measurements (test series 5) will reduce the error. The maximal CV, excluding test series 2, resulted while using different specimen holders and without calibration between measurements. It amounts to 0.024 over all wavelengths.

3.3 Biosensor measurements

Finally, the transmission spectrometer was tested with the biosensor. For the following experiment a new calibration was made in between different samples. As these transmittance spectra do not get close to zero an average CV of 0.008 is expected resulting from the measuring setup. Forty biosensors with the properties described in Section 2 were created. Here we use 20× AuNP and 50 % glucose in a mixing ratio of 2:3. Twenty samples were measured after drying for 1 hour and the other 20 samples after drying for 24 hours. Figure 9 shows the average transmittance spectrum and corresponding CVs at the example of the AuNP measurement after 24 hours. Additionally, the spectra of the two samples with minimal and maximal transmittance are included. At smaller wavelengths below 500 nm the CV is around 0.13, it increases and reaches a maximum at 560 nm with 0.16. Afterwards the CV decreases constantly and reaches 0.06 at 650 nm. This shows that the crucial region, where most of the spectral change happens is below 650 nm. For the other samples the CV is more constant over the whole spectrum.

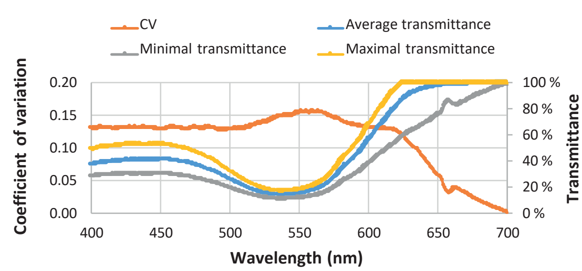


Figure 9: The average transmittance of the AuNP-after-24-hours measurement including the corresponding CVs and the transmittance spectra of two samples with minimal and maximal transmittance

After the measurement of samples dried for 24-hours, the analyte was added: 3 µl of four different analyte solutions were pipetted onto the dried AuNP droplets. The concentrations of the analyte solutions were 10 mM, 25 mM and 50 mM cys in water, as a reference only water was used. This way, 10 identical biosensors for each analyte concentration were tested. One hour after analyte addition the color change was complete and the transmittance of the biosensors was measured again. Figure 10 shows the average transmittance spectra of all different measurements. The absorption peak becomes a transmittance valley in this representation. The higher the analyte concentration the broader the valley and the greater the shift to bigger wavelengths. At the same time the slope connecting the transmittance valley and higher wavelengths gets less steep.

Only considering concentrations higher than 25 mM another phenomenon can be observed: the overall transmittance increases, making the sample more and more translucent. The transmittance curve of the AuNPs without any analyte also shifts to higher wavelength while being stored for one day and the water addition increases the transmittance a little bit, while the slope gets a little less steep. These three transformations are signs that a little bit of aggregation was already taking place, without analyte addition. The average CVs of the AuNP spectra are: 0.125 (1 hour), 0.113 (24 hours), 0.111 (10 mM cys), 0.115 (25 mM cys) and 0.096 (50 mM cys). These values should be compared to the CVs with zero excluded from Table 2, because here we have no values close to zero.

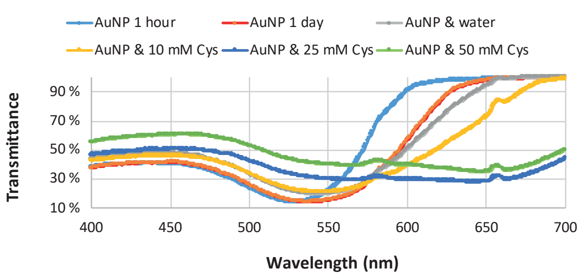


Figure 10: The transmittance curves of AuNP after drying for one hour and for one day, after the addition of osmose water, 10 mM cys, 25 mM cys and 50 mM cys

To conclude the analyte concentration from measured transmittance spectra of unknown samples, a simpler relation is needed. In literature usually a ratio between two points of the transmittance or absorption spectrum is formed and plotted over the analyte concentration. One point describes the red fraction, the other the blue fraction. The exact wavelengths are chosen according to the sample.

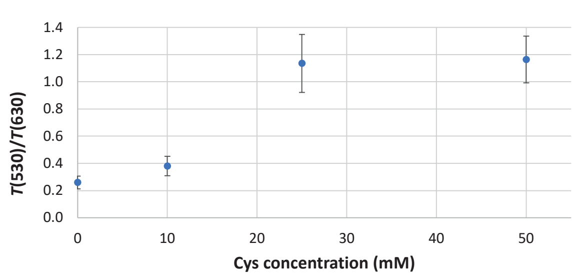


Figure 11: Ratio of the transmissions from 530 nm (red) to 630 nm (blue) over cys concentration taken from the transmission spectra shown in Figure 9

In Figure 11 we used the transmittance at 530 nm for the red value and the transmittance at 630 nm for the blue value. As this was a proof-of-concept experiment, we did not measure enough different analyte concentrations to precisely describe the course of the transmittance ratio over cys concentration. But, from these values it is possible to derive the region of interest. In future research we will focus on the region between 10 mM and 25 mM.

Usually the light source spectrum should be cancelled out in the transmittance spectrum, which is calculated by dividing the light intensity after and before passing through the probe (see Equation [1]). But this is only true if the detector counts are linear with increasing intensity. The linearity of the spectrometer detector was examined by measuring a series of spectra with increasing integration time. For exemplary wavelengths the counts were plotted over the integration time and it was found that its course was only linear up to 2 500 counts from maximal 4 096 counts. This means that measurements should only be carried out in the lower 61 % region of the maximal counts and not up to 80 % as the producer states.

4. Conclusions and outlook

With this research we showed that it is possible to print and dry AuNP biosensor assays when using glucose or sucrose as additives, to store the printed biosensors and to spectrally evaluate the analyte concentration based on a model system consisting of dispersed gold nanoparticles, which aggregate after cys addition.

One disadvantage of this method is the crystallization which can occur if the biosensors are stored at high humidity. We chose to use silica gel beads in an air-tight storing box to decrease the humidity and slow down the crystallization process. Another solution could be using additional sugars such as trehalose and raffinose or vacuum-packing the biosensors individually, but the latter would need a mechanical protection around the AuNP droplets. Another disadvantage is that after analyte addition the droplets are in liquid form and prone to running while handling the biosensor. This could be solved by creating depressions in the carrier material which hold the liquid at its original position. We experimented with this, which yielded good results for visual and imaging processes, but not for the spectral measurements, because the depressions enhance the lens effect of the droplets. Moreover, we analyzed the occurring bumps in the transmittance spectra at 656 nm and 580 nm. We found that the linearity of the detector is only given in the lower 61 % region of the maximal counts. Future research should consider this and receive no bumps in the spectra.

As an outlook we have some ideas how a biosensor created based on our method could be evaluated after analyte addition in a home application. A user-friendly method would include either visually evaluating the changed color or using a smartphone as measuring equipment. The later could use the built-in camera to take a picture. Research would be needed on if the automatic picture enhancements are hindering or helpful. The RGB values of the droplets could be compared to a data base with pictures of known analyte concentrations or an algorithm could be found to directly calculate the concentrations. Either way a camera calibration will be needed at some point to make up for varying environmental conditions and different types of installed cameras. The visual analysis as well as the smartphone based one would need a reference color chart for comparison, which could be printed on a reference piece from the same material as the carrier material of the biosensor.

Another idea for visual analysis includes printing several droplets on one biosensor that have increasing sensibility for the analyte. The user would only have to judge for each droplet if it had changed color or not and the analyte concentration would lie between the last droplet which had changed color and the first which had not.

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Standardizing milling process parameters for the narrowest pigment particle size distribution with optimum energy consumption

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Abstract

Water-based ink, used in production of a new type of green packaging material has an efficient application in the flexible packaging industry to resolve the environmental issues related to volatile organic compound. To get the best possible application properties of dispersed pigment whose performance is mainly measured by the particle size distribution, it is essential to reduce the size of agglomerates. Concentrated dispersed material is manufactured by using a stirred bead mill, which is an energy-intensive process. The process of dispersion must be done efficiently and in the shortest possible time to draw out of the pigment its maximum color properties at the minimum cost. The grinding-energy efficiency is a significant parameter in bead milling as that affects the amount of energy used during grinding of pigment particles. The milling process needs to be optimized to reduce energy consumption. The objective of this study is to determine optimum dispersion process parameters to optimize energy consumption to achieve the narrowest pigment particle size distribution of rubine red pigments used in water-based ink. Experiments were conducted for fine grinding of organic rubine red pigment using a vertical bead mill. The experiments were conducted for varying sizes of grinding media from 0.5 mm to 1.0 mm, for two pigment loadings of 30 % and 37 %, and by extending milling time from 4 h to 6 h. The pigment particle size distribution and power consumption during each trial were measured to optimize process parameters with minimum energy consumption. Response surface design was performed to analyze data. Analysis of variance (ANOVA) techniques were used to check the significance of factors and the interaction of factors. The regression model for specific energy consumption was developed and tested; validation trial for dispersion process parameters concludes that 30 % pigment loading and mixed grinding media size provides narrowest pigment particle size distribution of 128 nm with minimum energy consumption of 1.67 kWh/t.

Keywords: pigment dispersion, bead milling, grinding efficiency, transparency, regression analysis

1. Introduction

The dispersion process of ink involves complete wetting of the pigment surface and then their uniform distribution in the application vehicle. Thus, the dispersion process includes the breakdown of pigment particles, agglomerates (with primary particles touching each other at the corner), and aggregates (with primary particles having surface to surface contact), into smaller particles and their distribution in a vehicle, leading to a colloidal suspension. A colloidal suspension is characterized by the behavior that the finely divided particles do not settle under their gravitational forces.

The dispersion of pigments in printing inks is important for several reasons as it improves the color strength of pigment, increases the transparency of pigment, affects rheological behavior and flow properties of the ink, provides more gloss and finally, it provides stability to ink throughout its shelf life (Pal and Fleming, 2006; Simpson, et al., 2015). For getting maximum benefits of pigment, it is recommended to get the maximum reduction of pigment size as possible to its primary particle size. The color strength of pigment depends on its exposed surface area, so the smaller the particles, the higher the surface area and thus stronger the color (Herbst and Hunger, 2007; Klein, 2010).

Concentrated dispersed material is manufactured by using a stirred bead mill. Stirred bead milling is however an energy-intensive process. Along with this, the high prices of raw materials make it essential to look the efficiency of the dispersion process (Weber and Langlois, 2010). The process of dispersion must be done efficiently and in the shortest possible time to draw out of the pigment its maximum color properties at the least cost (Klein, 2010).

Pigment dispersion process by using a bead mill is the major energy-consuming process during the manufacturing of water-based ink. Milling process parameters like milling time, size and density of grinding media (GM), pigment loading, and speed of machine are majorly affecting the pigment particle size distribution and energy consumption during the milling operation. Therefore, the milling process parameters need to be optimized to increase the milling efficiency to achieve the desired particle size distribution with minimum energy consumption. (Zheng, Harris and Somasundaran, 1996; Hamey, 2005; McDowell, 2006; Choi, Lee and Kim, 2009; Weber and Langlois, 2010; Inam, Ouattara and Frances, 2011; Schmidt, et al., 2012; Ohenoja, Illikainen and Niinimäki, 2013; Senthilkumar and Akilamudhan, 2014; Simpson, et al., 2015)

The researchers highlighted that the use of chemical additives during wet dispersion improves the surface and mechanical properties of individual particles such as surface energy and flow of medium which improves the efficiency of the grinding process. (Farrokhpay, 2004, p. 147; McDowell, 2006; Nsib, Ayed and Chevalier, 2006; Choi, Lee and Kim, 2009)

Kwade's model (Kwade, 2004) summarized that the milling efficiency of a stirred media mill is a product of stress intensity and stress frequency. The best milling efficiency is obtained by selecting GM size, the density of GM, and mill speed as these parameters approach to an optimum stress intensity and the maximum stress number (Choi, Lee and Kim, 2009; Weber and Langlois, 2010; Simpson, et al., 2015). During the pigment dispersion, specific energy is the amount of energy or work required to grind a pigment agglomerate to a desired particle size. The most common units of specific energy are J/kg or kWh/t of slurry. The amount of specific energy required to grind a particular solid to a desired particle size is a fixed value, only dependent on the efficiency of the equipment, milling time, density of GM, and mill base (McDowell, 2006). Various studies were conducted to analyze the influence of materials of GM of different specific weights, sizes of GM, stirred tip speeds, milling times, and solid concentrations on particle size and particle size distribution with optimum energy consumption. (Weber and Langlois, 2010; Ohenoja, Illikainen and Niinimäki, 2013; Simpson, et al., 2015)

Weber's rule predicts that when the particles are of 0.4 μm to 0.7 μm in size they provide the maximum scattering for wavelengths between 400 nm and 700 nm. Thus maximum scattering from pigment particles is observed if the size of the pigment is equal to its wavelength. Exactly opposite to this for maximum transparency is that the pigment particle should be as small as possible. (Herbst and Hunger, 2007)

Therefore to achieve maximum transparency and maximum color strength it is important to obtain the narrowest pigment particle size distribution during dispersion.

The milling process needs to be optimized to reduce energy consumption. Energy consumption can be different as per the mill base properties. Energy consumption during the resin-free dispersion of the pigment to achieve narrow particle size distribution as well as the effect of the pigment particle size distribution on transparency are relatively unexplored.

In this study process parameters like milling time, GM size and pigment loading were optimized to achieve target pigment particle size distribution. During each trial, power consumption was measured to optimize process parameters with minimum energy consumption. The optimum value for the GM size, milling time, and pigment loading were determined to obtain the narrowest particle size distribution with the optimum stress intensity and lowest specific energy consumption.

2. Experimental procedure

2.1 Materials

Rubine red pigment (PR 57:1) manufactured by Sudarshan Chemical Industries Ltd. was used for the pigment dispersion process. Dispersing additive, polydimethylsiloxane based antifoaming agent, was provided by BYK. Constant percentages of a dispersing agent, and antifoaming agent were used during the resin-free dispersion process. De-ionized water was used as a solvent in the grinding experiments and used to adjust the pigment loading of the mill base. Grinding media of different size ranges were used, purchased from M/s Jyoti ceramics.

2.2 Premixing of material

To prepare a premixture, initially, a mixture of deionized water, dispersing agent, and the antifoaming agent was prepared and later slow addition of pigment was allowed under low shear rate by using a stirrer (make-REMI). Prepared premixture was allowed to soak for 24 h. The formulation used for mill base is provided in Table 1.

Table 1: Formulation of a mill base used during a resin-free dispersion of PR 57:1

Ingredient	Specification	Amount (%)	Purpose of ingredient
Pigment	PR 57:1	25 to 30	Coloring agent
Dispersing agent	Disperse BYK	7 to 8	Dispersion of pigment
Antifoaming agent	BYK 019	0.35 to 4	Rupture of the foam
Deionized water	DI Water	60 to 68	Acting as a vehicle

2.3 Variables for experiment

Experiments were conducted to fix the levels of few parameters such as the speed of the stirrer, the density of GM, range of GM size, and pigment loading. The significant parameters and their levels for the pigment particle size distribution were screened and considered as input parameters to optimize the energy consumption. Higher density of GM as 6.2 g·cm^{-3}, speed of the machine as 2 600 rpm, and GM size as 0.5 mm to 1 mm were determined to be the more efficient values for the reduction of the pigment particle size. Response surface design of experiments (DOE) was generated to evaluate the energy consumption for narrow particle size distribution. The experimental design consists of three factors, namely GM size, milling time, and pigment loading, and different values of each factor (called levels of the factors). In the design it includes three groups of sizes of GM (zirconox beads): 0.4–0.6 mm (named as 0.5 mm), 0.8–1.0 mm (named as 1 mm) and 50 : 50 ratio of both 0.4–0.6 mm and 0.8–1.0 mm (named as 0.75 mm), two pigment loading percentages: 30 % and 37 %, and three milling times: 4 h, 5 h and 6 h. Thus, the total trials in the design were 18. The detailed experimental design along with input parameters and their levels are indicated in Table 2.

2.4 Equipment

Most of the mills used for grinding of pigments are vertical and horizontal bead mills due to their high efficiencies, low energy consumption, and high unit output. The lab-scale vertical bead mill equipped with a stationary grinding chamber, a high-speed stirrer with cowl blade fixed on a drive shaft which rotates at 2 600 rpm (tip speed is 6 m·s^{-1}) was used for pigment dispersion. The capacity of the grinding chamber is 1.5 liter. After dispersion 600 mesh was used to separate GM from the dispersed material. For lab scale 500 g of premixture was prepared. To maintain the constant temperature of mill base as 25 °C to 27 °C during dispersion, the grinding vessel is equipped with a water jacket. The particle size distribution of dispersed samples was measured by Malvern particle size analyser (Zetasizer Nano s90 model) at M/s Sudarshan Chemical Industries. Two watt meters were connected to the power supply to measure active power during the dispersion of the material.

Initially power consumption for the unloaded mill (empty mill) is measured from reading observed in two watt meters W1 and W2. It was measured ten times for every ten minutes. The average value of active power provides the value of N_0. Active power was measured throughout the dispersion process and for each trial power consumption was calculated.

2.5 Calculations

Width of particle size distribution (WPSD), transparency, specific energy consumption (SEC) and stress intensity (SI) were calculated by using Equations [1] to [5].

Width of particle size distribution, which provides a size range of pigment particles which occupies a total 80 % volume of the dispersed material, was calculated by using Equation [1].

$$\text{WPSD} = D_{90} - D_{10} \qquad [1]$$

where D_{90} and D_{10} are the particle sizes in nanometres representing the 90 % and 10 % values in the cumulative volumetric size distribution (Ding, et al., 2013; Barth, Schilde and Kwade, 2013).

Transparency was determined by ASTM D344-11(2016) method for visual assessment (ASTM, 2016), and instrumental ASTM D2805-11(2018) standard method (ASTM, 2018) used to calculate opacity. The BYK opacity chart (Figure 1) was used to calculate opacity by using Equation [2]. A uniform ink drawdown by using bar coater no. 1 was applied on a black/white contrast chart. After air-drying the drawdown, a spectropho-

Table 2: Variables and their levels used during optimization of resin-free dispersion process for PR 57:1

Variables	Level 1	Level 2	Level 3
Zirconox beads	0.4 mm to 0.6 mm (0.5 mm)	0.8 mm to 1.0 mm (1 mm)	Mixture of both (50 : 50), (0.75 mm)
Pigment loading	30 %	37 %	–
Milling time	4 h	5 h	6 h

tometer (make: Gretag Macbeth, model: Eye-One Pro) was used to measure Y (tristimulus value) against white and Y against black of contrast chart. Transparency was calculated by using Equation [3].

Figure 1: Byko-chart Opacity 3B (BYK, n.d.)

$$\text{Opacity (\%)} = \left[\frac{Y\,(\text{against black})}{Y\,(\text{against white})}\right] \times 100 \qquad [2]$$

where Y is a tristimulus value.

$$\text{Transparency (\%)} = 100 - \text{Opacity (\%)} \qquad [3]$$

where opacity is calculated from Equation [2].

Specific energy consumption was determined by using two wattmeter method, which was used to measure the power throughout the dispersion process time. Power data was measured after every 10 min from both wattmeters to calculate power consumption for each design of the experiment. The power was recorded during grinding and SEC was calculated (Equation [4]) as the power input integrated over the grinding time t_G and divided by the mass of slurry (m),

$$\text{SEC} = \int (N - N_0) \cdot dt_G \ / \ m \qquad [4]$$

where SEC (kWh/t) is specific energy consumption, N (kW) is necessary electrical power running the filled mill with beads and slurry, N_0 (kW) is necessary electrical power running the empty mill, $(N - N_0)$ (kW) is active electrical power, and m (t) is a mass of slurry.

The stress-energy or stress intensity of GM describes the maximum kinetic energy of two colliding grinding beads. Optimum stress intensity and maximum energy utilization will happen when the stress intensity is just sufficient to break the particle. The stress intensity of the GM (SI_{GM}) *was* calculated using Equation [5].

$$SI_{GM} = d_{GM}^3 \cdot \rho_{GM} \cdot v_T^2 \qquad [5]$$

where SI_{GM} (Nm) is stress intensity of the GM, d (m) is bead diameter, ρ (kg/m^3) is specific weight of GM, and v_T (m/s) is stirrer tip speed.

2.6 Analysis of the impact of WPSD on transparency of water-based ink

The effect of WPSD on the transparency of water-based ink was analyzed. When there is one categorical independent variable and one quantitative dependent variable, one-way analysis of variance (ANOVA) is preferred statistical technique. It tells us if the dependent variable changes according to the level of the independent variable (Vik, 2014).

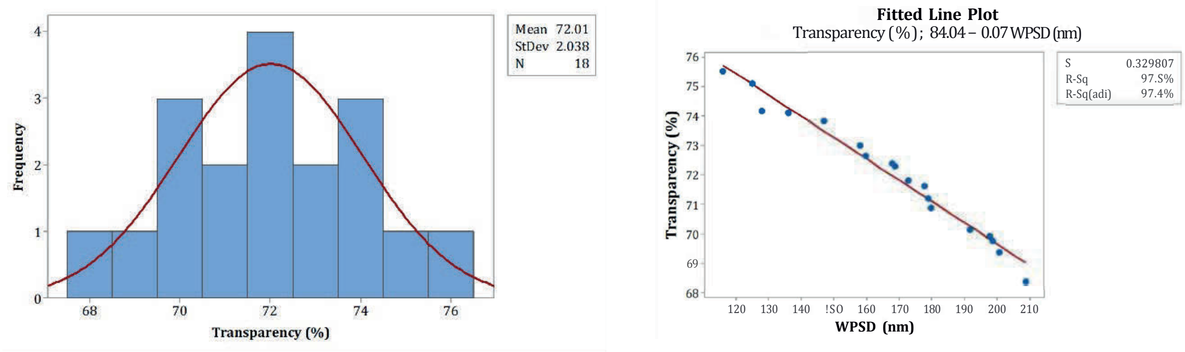
In this experiment WPSD is considered as independent variable and transparency is dependent variable. For the analysis, WPSD is the only factor considered; so, one-way ANOVA is used to predict the effect of WPSD on transparency of water-based ink. Above model with one predictor is referred to as simple linear regression model.

3. Results and discussion

3.1 Effect of WPSD on transparency of water-based ink

Dispersion experiment based on different pigment loading, GM size, and milling time provides varying widths of WPSD, which were measured by using particle size analyzer. Figure 2a presents the normal distribution of data measured for transparency of various formulations. Figure 2b describes the negative linear relation between WPSD and transparency of water-based ink. Narrower WPSD provides higher transparency. This is attributed to the fact that narrowest WPSD provides more surface area to interact with light and improves the absorbency of pigment. The amount of light scattering which influences the transparency depends strongly on the particle size of the pigment. Very small particle scatters very little light. Scattering increases with increasing particle size until the particles are about the same size of the wavelength of light and then it decreases for still larger particles. Thus, less scattering power of smaller particles, results in a higher degree of transparency, which is very important in four color conventional printing processes to achieve the higher strength of colors.

The regression result (Table 3) tells that particle size is significant for transparency because of their low p-values. Particle size distribution account for 97.5 % of the variance of transparency. For each 1 % increase in the amount of transparency, the percentage of WPSD is expected to decrease by 0.07 %.



a) b)

Figure 2: (a) Histogram of transparency, and (b) negative linear relation between transparency and WPSD

Table 3: ANOVA, regression analysis and regression equation for transparency
Regression analysis: transparency (%) versus WPSD (nm)
Analysis of variance for transparency

Source	DF	Adj. SS	Adj. MS	*F*-value	*p*-value
Model	1	68.9	68.9	633.4	0
Pure error	16	1.7	0.1		
Total	17	70.6			

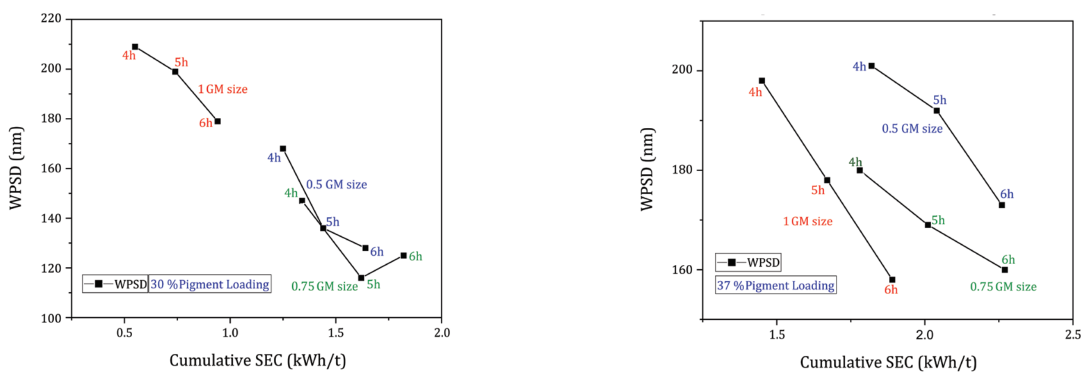
R-sq = 97.5 % *R*-sq(adj.) = 97.4 %
Regression equation:
Transparency (%) = 84.04 – 0.07 WPSD (nm)

3.2 Effect of GM sizes on WPSD and SEC

The effect of three different GM sizes on WPSD and cumulative SEC were analyzed. The GM used for the experiment was zirconium oxide with different levels of varying bead diameter named as 0.5 mm, 1 mm, and 0.75 mm.

Figure 3 indicates the effect of GM sizes on WPSD and cumulative SEC for two different pigment loading percentages. It is seen from Figure 3a larger GM size provides wider WPSD than smaller GM size. It is also observed that with longer milling time the WPSD is reduced.

Referring to Figure 2b narrow WPSD provides maximum transparency. Hence narrow WPSD is recommended which will provide higher strength for dispersed pigment. The pigment dispersion process to achieve narrow WPSD is least expensive when the grinding process works for 37 % (Figure 3b) it is for largest GM at the minimum of the SEC. It is observed from Table 4 that minimum specific energy was consumed to achieve narrowest WPSD for 30 % pigment



a) b)

Figure 3: Effect of GM size on WPSD and cumulative SEC for three different milling times at two different pigment loadings: (a) for 30 % pigment loading, and (b) for 37 % pigment loading

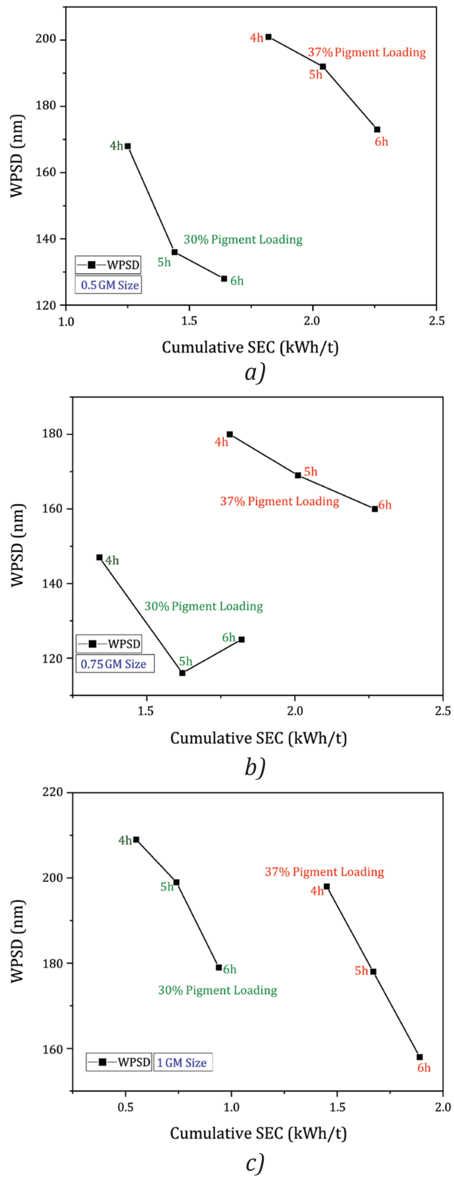
loading and when milling continued up to 5 h with 0.75 mm GM size. But if milling extended for 6 h it increases the WPSD with increased SEC. The 0.5 mm GM size also provides moderately narrow WPSD but is slightly higher than 0.75 mm GM size with low energy consumption. Higher GM size consumes less energy but provides wider WPSD which reduces the overall performance of pigment. Smaller GM size of the same density as larger GM size dramatically increases the number of grinding beads per liter of the mill working volume. Along with this the kinetic energy of the grinding beads is increased by the ratio of the specific weight of the bead material by equal stirrer tip speed in the mill. Both parameters, reduction in bead size and using beads with higher specific weight, improve the milling efficiency because the increased surface area of beads achieves more contact points where impact, shear and compression forces takes place between the beads and pigment particles; along with this higher kinetic energy generated helps to reduce particle size effectively. Due to increased surface area of GM, utilization of free material was observed, which increases the viscosity of mill base and needs more energy at a specified tip speed for the momentum of the mill base.

Large-sized grinding beads have different motion paths and speeds compared to a smaller one due to their mass difference. Single GM size provides monotonous movement among the material. The 0.75 mm GM size, as it is the mixture of both 0.4–0.6 mm and 0.8–1.0 mm, provides rise to two different momentums as a result of the different mass of the beads, which breaks the monotonous movement between them and increases the irregular movements. This will help to break more effectively the pigment particles and provides higher rate for reduction of WPSD value in comparison with a single size of GM, hence it reduces the dispersion time and indirectly reduces the energy consumption. Thus the 0.75 mm GM size optimized the energy consumption to provide narrowest WPSD.

3.3 Effect of pigment loading on WPSD and SEC

The effect of different pigment loading for three different GM sizes on the WPSD is presented as a function of a cumulative SEC as shown in Figure 4.

Narrow WPSD is observed for the lowest solid concentration i.e. 30 % with minimum energy consumption. This result is applicable for 0.5 mm and 0.75 mm GM size when used for dispersion. But for the 1 mm GM size (Figure 4c), narrow WPSD is observed at higher pigment loading (37 %) with moderately less energy consumption. This is attributed to the fact that 1 mm GM size i.e. higher GM size reduces the number of grinding beads required in a specified volume.



a)

b)

c)

Figure 4: Effect of two different pigment loadings on WPSD and cumulative SEC at three different milling times with constant GM size: (a) for 0.5 mm GM size, (b) for 0.75 mm GM size, and (c) for 1 mm GM size

Along with this it also reduces the surface area of grinding beads, which reduces the ratio of the surface area with material volume. More free moving material is present, which provides unused collisions of the grinding beads inside the mill. When pigment loading is increased it consumes the free moving material and provides the required viscosity to mill base which utilizes the maximum collisions of grinding beads to reduce the particle size. Thus, when 1 mm GM size i.e higher GM size and 37 % i.e. high solid percentage are used for dispersion it provides narrow WPSD with moderately less energy consumption. For the 0.5 mm GM size (smaller GM size) as well as the 0.75 mm GM size (mixed GM size), ratio of surface area to the material is very high, which reduces free-flowing material; so when pigment loading is 30 % it provides sufficient viscosity to mill base to utilize the maximum collision of GM, which helps to reduce the particle size distribution. But for higher pigment loading (37 %) viscosity gain is observed, which restricts the free motion of grinding beads and ultimately reduces the frequency of collisions; hence wider WPSD is observed even though high energy is consumed during dispersion. The 0.75 mm GM size provides narrowest WPSD after 5 h of milling time with minimum energy consumption.

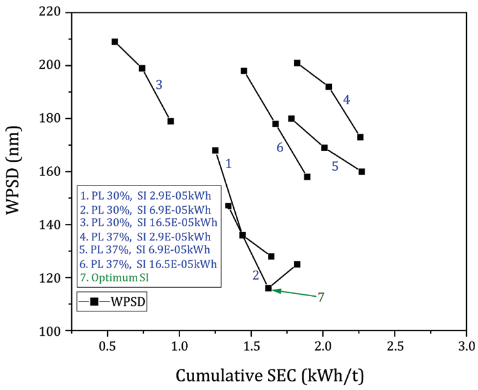


Figure 5: Stress intensity with optimum (marked by the green arrow) of GM with respect to WPSD and cumulative SEC

The stress intensity of GM corresponds to the maximum kinetic energy of two colliding grinding beads at the stress events. When the maximum utilization of kinetic energy takes place at stress events to break the pigment particles then it is an optimum stress intensity. Stress intensity for different solid percentages of dispersion remains constant as it is assumed that the velocity of the mill base is equivalent to a tip speed of stirrer. Figure 5 shows the WPSD at different SEC as a function of stress intensity. It can be seen from Figure 5 that the lower the stress-energy, the lower the particle size. When energy consumption is considered, the optimal stress-energy is seen to be around $6.9 \cdot 10^{-5}$ kWh (written as 6.9E-05 kWh in the legend in Figure 5) to the low energy consumption with narrowest WPSD. The stress-energy $2.9 \cdot 10^{-5}$ kWh (2.9E-05 kWh) can also be considered as optimal stress energy as it also provides moderately narrow WPSD with slightly higher energy consumption than $6.9 \cdot 10^{-5}$ kWh stress intensity. Thus, the most efficient grinding is observed at the smallest GM size, but the optimum condition is observed at mixed GM size.

3.4 Statistical analysis of SEC

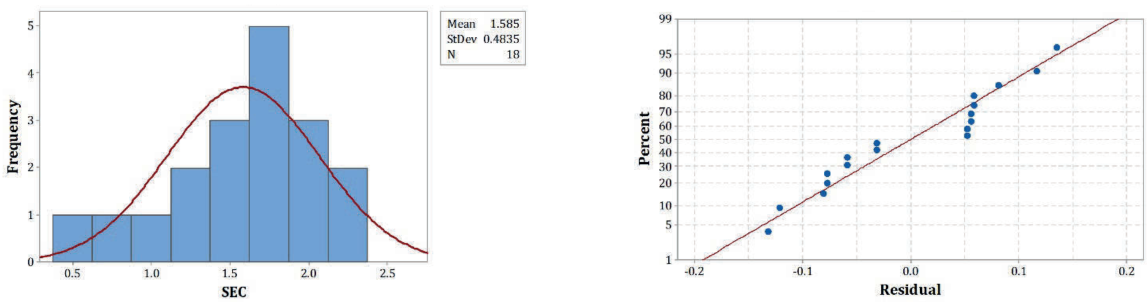
Histogram of the residuals (Figure 6a) is an exploratory tool to show general characteristics of the residuals including typical values, spread, and shape. It shows the normal distribution of samples. Normal probability plot (Figure 6b) of residuals shows that the points in this plot form a straight line, which means that the residuals are normally distributed.

3.5 Main effect plot and interaction plot

Main effect plot (Figure 7a) explains the significance of GM size, milling time, and pigment loading on specific energy consumption. The 0.75 mm GM size, higher pigment loading i.e. 37 % and higher milling time provide higher specific energy.

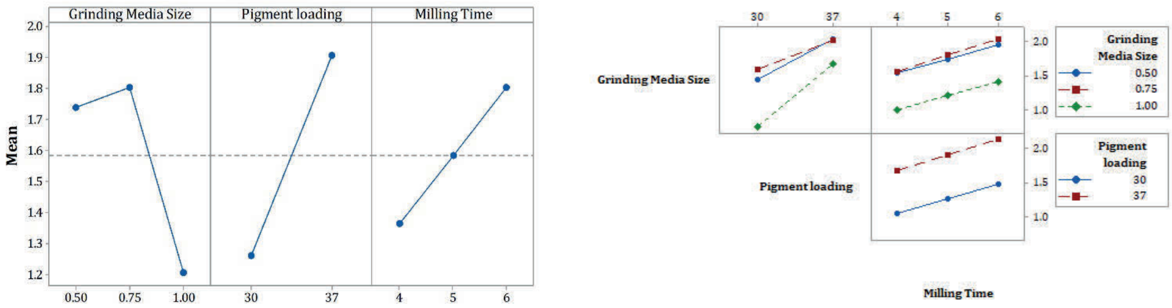
In the interaction plots (Figure 7b), the upper-left one consists of non-parallel lines representing there is an interaction between GM size and pigment loading.

The ANOVA table (Table 4) summarizes the linear terms, the squared term and the interaction. Higher *F*-value of linear terms compared to square term and interaction term, indicates that the model is majorly explained by the linear terms. The *p*-values from the ANOVA table, which are below α value of 0.05, indicate that all the main factors such as GM size, pigment loading and milling time are significant for energy consumption. The higher *F*-statistics values for pigment loading, GM size and milling time indicate these are the most significant factors that influence energy consumption. The inter-



a) *b)*

Figure 6: (a) Histogram of SEC residuals, and (b) normal probability plot of residuals for SEC response



a) *b)*

Figure 7: (a) Main effect plot of SEC and (b) interaction plot of SEC, both for different GM sizes (in mm), pigment loadings (in %) and milling times (in h)

Table 4: Response surface regression model for energy consumption
Response surface regression: energy consumption versus GM size, pigment load, milling time
Stepwise selection of terms α to enter = 0.15, α to remove = 0.15
ANOVA for energy consumption

Source	**DF**	**Adj. SS**	**Adj. MS**	***F*-value**	***p*-value**
Model	5	3.86	0.77	79.56	0.00
Linear	3	3.33	1.11	114.57	0.00
GM size	1	0.86	0.86	88.68	0.00
Pigment loading	1	1.90	1.90	195.50	0.00
Milling time	1	0.58	0.58	59.53	0.00
Square					
GM size * GM size	1	0.44	0.44	45.69	0.00
2-way interaction					
GM size * Pigment loading	1	0.08	0.08	8.39	0.01
Pure error	12	0.12	0.01		
Total	17	3.97			

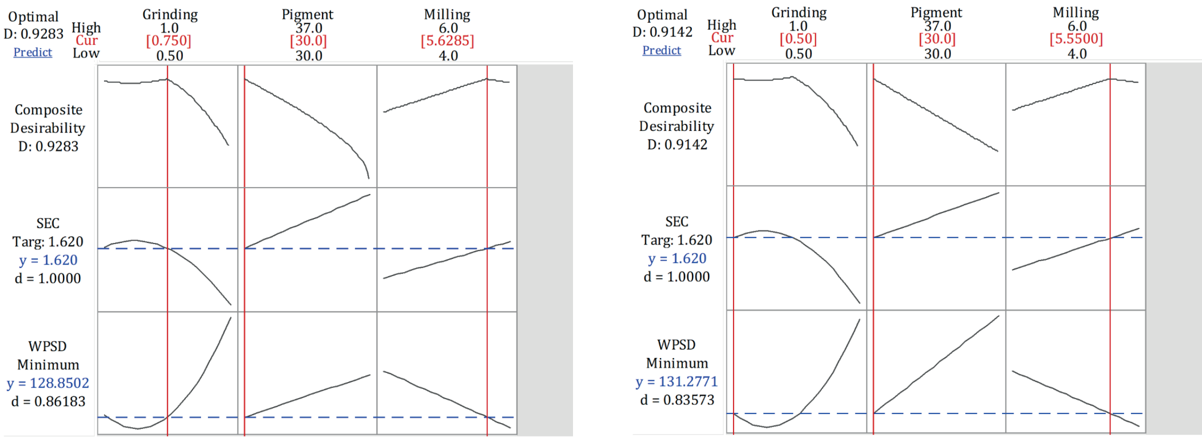
R-sq = 97.07 % *R*-sq(pred.) = 95.85 % *R*-sq(adj.) = 93.87 %
Estimated regression coefficients for energy consumption:
Energy consumption = −2.22 + 3.76 GM Size + 0.02 Pigment loading + 0.21 Milling time − 5.33 GM Size * GM size + 0.09 GM size * Pigment loading

action of GM size and pigment loading is significant for energy consumption at a 95 % confidence level. Table 4 shows a higher percentage of *R*-sq., indicating that 97.07 % of the variability could be explained by the model at a 95 % confidence level. The adjusted *R*-sq of 93.87 % indicates a significant improvement of the model by using three parameters. The predicted *R*-sq of 95.85 % indicates that the model predicts new observations nearly as well as it fits the existing data. The regression equation describes the statistical relationship between dispersion process factors and energy consumption. Table 4 provides the regression equation that helps to predict new observations for desired particle size distribution with energy consumption.

3.6 Optimization from regression model

The optimization plot (Figure 8) shows the effect of each factor ie. GM size, pigment loading, and milling time on the cumulative energy consumption to achieve the desired particle size. The vertical red lines on the graph represent the current factor settings. The numbers displayed at the top of a column in a square bracket show the current factor level settings. The horizontal dash lines and numbers represent the responses of WPSD and energy consumption for the current factor level. Minitab software calculates the narrowest WPSD and minimum energy consumption for two hold values of GM size, namely 0.75 mm and 0.5 mm.

Figure 8 explains that when the same amount of energy consumption is considered it is observed that 0.75 mm GM size will provide narrowest WPSD compared to 0.5 mm GM size. Hence 0.75 mm GM size, 30 % pigment loading, and milling time of 5.63 h are the optimized parameters which will provide narrowest WPSD with minimum energy consumption as shown in the Figure 8.



a) *b)*

Figure 8: Optimization plot from the regression model for the smallest WPSD and minimum SEC: (a) hold value 0.75 mm GM size, and (b) hold value 0.5 mm GM size

Table 5: Multiple response prediction for 0.75 mm hold value of GM size
Response optimization: SEC, WPSD

Optimized value

Variable	**Setting**
GM size	0.75 mm
Pigment loading	30 %
Milling time	5.63 h

Solution

Solution	**GM size**	**Pigment loading**	**Milling time**	**WPSD fit**	**Energy consumption fit**	**Composite desrability**
1	0.75 mm	30 %	5.63 h	1.62	128.85	0.93

Solution

Response	**Fit**	**SE fit**	**95 % CI**	**95 % PI**
SEC (kWh/t)	1.62	0.0497	(1.51, 1.73)	(1.38, 1.86)
WPSD (nm)	128.85	5.2600	(117.39, 140.31)	(103.44, 154.26)

Additionally, as presented in Table 5, summarizing the optimization results the confidence interval (CI) indicates the 95 % confidence that the mean of the WPSD at these settings is between 117.39 nm and 140.31 nm, and the SEC is between 1.51 kWh/t and 1.73 kWh/t. The prediction interval (PI) indicates 95 % confidence that WPSD of a single new observation will fall between 103.44 nm and 154.26 nm and SEC will be between 1.37 kWh/t and 1.86 kWh/t.

Table 6: Response predicted values for optimum energy consumption

Variable	**Setting**	**WPSD (nm)**	**SEC (kWh/t)**
GM size (mm)	0.75		
Pigment loading (%)	30.00	128	1.67
Milling time (h)	5.63		

3.7 Validation trial

A validation trial was conducted for the optimized setting (Table 6). The WPSD of 128 nm was achieved with 1.67 kWh/t SEC. These values are close to those estimated using the model (see Table 5).

4. Conclusion

Width of particle size distribution (WPSD) shows negative linear relation with transparency of water-based ink. Narrower WPSD provides higher transparency. In the bead milling process size of grinding media (GM), the pigment–binder ratio, and milling time have a significant effect on the milling rate and efficiency of the milling process. Smaller GM size provides narrow WPSD with minimum energy consumption. Mixed GM size provides a slightly higher rate of WPSD reduction with the lowest energy consumption. Percentage of pigment loading should be sufficient enough for the maximum utilization of collisions of grinding beads which affects the rate of particle size reduction and energy consumption. The model showed more than 96.57 % predictability. Validation trial for dispersion process parameters concludes that 30 % pigment loading, mixed GM in wide range of sizes (named 0.75 mm, and milling time of 5.63 h) provide narrowest pigment particle size distribution of 128 nm with minimum energy consumption of 1.67 kWh/t.

In this research the regression model was developed for a specific type of pigment. Research can be continued in a direction that would include energy efficiency and optimization of pigment particle size distribution for the grinding of other process colors as well as special color pigments. Also, the optimization of percentage of dispersing additive for resin-free dispersion for all process color pigments is recommended to develop cost-competitive stable pigment dispersion for water-based ink.

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Assessment of paper metrics as predictors of quality for inkjet printing

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Abstract

Recent developments in inkjet technology have enabled the development of high-speed inkjet presses with similar quality and performance to conventional printing presses. These inkjet presses can print on a wide range of papers. Prints made on some papers are of high quality whereas on others are unacceptable. These print results vary from one digital press to another. The focus of this publication is the development of techniques to predict print quality from measurements of papers. Two studies were conducted. In the first, a set of around 250 papers were measured, prints were made on a single digital press and the print quality assessed. In the second, a set of 20 papers were measured, prints were made on three digital presses from different manufacturers and the print quality assessed for each. The studies were unable to identify or develop a single metric that can be used to predict print quality, however, a set of techniques is presented that have been found to be effective predictors of print quality where multiple metrics are used in combination and these methods and results are presented. Both studies adopted a 'black box' approach where only the paper measurements and the result of assessment were used to make predictions.

Keywords: inkjet press, print quality, paper property, logistic regression, quality prediction model

1. Introduction

For traditional printing where ink is pressed onto paper, we have observed as an industry that some physical behaviour of paper such as its ability to absorb ink quickly or the smoothness of its surface correlate well with print image quality. Paper properties have been identified that correlate with this physical behaviour, for example porosity (air permeability) and gloss. Paper manufacturers make measurements of these paper properties as part of the production process and use these to communicate with printers to help with paper selection.

For inkjet printing where ink is jetted onto paper, it has been observed that these conventional paper properties do not predict print image quality well. Understanding the physical interaction between ink and paper continues to be very important, and there are many scientific approaches in order to understand the physical interactions and their mechanism, for example Blohm and Åslund (2004), Kettle, Lamminmäki and Gane (2010), and Gigac, et al. (2014). The effect of calcium carbonate coating is explored in Možina and Franken (2018) and surface chemistry in general in Moutinho, Ferreira and Figueiredo (2010); the effects documented by these projects may be related to the surface measures in this paper. Krainer, Saes and Hirn (2020) explored the relationship between contact angle and ink spreading. These research projects have established some general principles that can be applied to the design of paper, however, the relationship between image quality and paper properties cannot yet be clearly described.

High-speed inkjet presses generally include two stages. In the first stage the paper is coated and in the second stage ink is jetted onto the coated surface. The first stage (precoating) modifies the characteristics of the paper surface to widen the window of paper properties that produce good print image quality. This is not intended to make the surface condition the same for all papers and the original paper properties still have a substantial influence following precoating. The time between precoating and inking is very small and usually the precoating does not completely dry before inking, therefore precoating and inking are continuous and dynamic processes and should not be considered separately. In addition, the method of precoating varies from one press to another as it is specific to the way in which ink is jetted onto the paper surface. For this reason, all measurements of the papers in this study were made before any precoating. From a practical perspective, it may be sufficient to find a direct correlation between measured properties (before any precoating step) and print acceptability based on print image quality.

The research described in this publication is one of the outcomes from a summit meeting held in April 2018 in conjunction with an ISO/TC 130 meeting where a range of industry experts discussed how the process of paper selection for high-speed inkjet presses might be improved. Attendees included representatives from paper manufacturers and from inkjet press manufacturers. In that meeting it was reported that considerable work had been done to try to find a simple metric that can be used to predict print image quality for inkjet presses without any success. At that meeting a group of industry experts including representatives from a number of inkjet press manufacturers (an ad-hoc group) agreed to work together to work on this problem. One inkjet press manufacturer, Fujifilm, conducted the research reported herein.

As this publication will show, while a single metric that predicts print image quality has not been identified, combinations of a relatively small number of metrics have been identified that enable prediction of print image quality with a high degree of confidence.

A study was conducted on a large set of papers printed on a single inkjet press (referred to as 'large study') to establish principles and methods of prediction. A second study was conducted on a small set of papers printed on three different inkjet presses (referred to as 'multi-press pilot study'). The results show that in all cases, a small set of predictor metrics produces high confidence in the prediction of print image quality. The best set of metrics for one press may not be the best set for another although there is significant overlap between these sets.

2. Methods

2.1 Paper selection

For the large study, a range of 250 commercially available papers were used, including cardboard, decorative and glossy papers. In a few cases, papers from different production lots were treated as different paper types.

For the multi-press pilot study, a set of 20 papers were selected by 7 inkjet press manufacturers. Each manufacturer selected at least one paper that produced good results and at least one that produced poor results using the best known press settings for that paper. The method of assessment in each case was the manufacturer's quality assurance process which was not disclosed and probably different for each manufacturer.

Papers were stored and measured in environments having temperature of 23 °C ± 1 °C and relative humidity of 50 % ± 2 %.

2.2 Measurement of paper properties

For the large study, all measurements were made by Fujifilm. For the multi-press pilot study, paper properties were measured in different laboratories that were made available to the project based on the capability of each laboratory. The set of paper properties measured for the large study and the set used by the multi-pres pilot study were slightly different from each other and the two sets of measurements made are described in Annex A.

2.3 Printing and visual assessment

For the large study, papers were printed on the Fujifilm Jet Press 720 which was optimised for each paper to produce the best reproduction possible in each case using Fujifilm's standard method. The overall print image quality was assessed using Fujifilm's standard quality assurance method. This was assessed from various perspectives such as image quality, quality of text, quality of solid areas and then each paper was classified as 'Accepted' or was assigned another category. The second category included a range from those that are never acceptable to those that may be acceptable for some uses. For the purpose of analysis, this second range of papers were combined into a single category.

For the multi-press pilot study, each paper in the set of papers was printed by three press manufacturers. In each case, the manufacturers applied their standard procedure for identifying the most suitable press setup for each. The way in which these presses were configured are not disclosed and this is likely to have been different for each manufacturer.

2.4 Prediction of print image quality

2.4.1 Background

The first step was to use a traditional approach and to look for a simple correlation between one of the paper metrics and print image quality assessment for each set of papers. When no such correlation could be identified, two possible options were considered.

The first option considered was to develop a new paper metric that provides a better correlation with print image quality. To date, it has not been possible to identify any existing metric or to develop any new metric of this kind that predicts print image quality. Steps to explore this option continue and may be fruitful in the longer term.

The second option was to look for correlation between print image quality and a combination of paper metrics. The initial investigation of this seemed to be promising but it was clear that at least three metrics are required to obtain a satisfactory prediction.

2.4.2 Model construction and prediction accuracy assessment

Logistic regression, a standard statistical method using linear regression for dimensionality reduction, was used as the method of prediction for this work. KNIME (see KNIME, 2020) was used as the platform to perform this analysis. Details of the use of logistic regression are described in Annex B.

For both studies, the method involves using a subset of papers to build a prediction model (the training set) and then testing the accuracy of this model using the remaining papers (the test set).

For the large study this was straightforward as it was possible to select 80 % of the papers at random as the training set used to build the model and then used the remaining 20 % of the papers as the test set to estimate the prediction accuracy of the model.

The technique used for the multi-press pilot study was different because of the small number of papers used. In this case, all of the papers except one were used as the training set to build the model and then the single paper was used as the test set to estimate prediction accuracy. This process was repeated for each paper in turn and so produced 20 predictions (one for each paper). This entire set of predictions was used when considering the overall accuracy of the model. This is a variant of k-fold cross-validation known as 'leave one out cross-validation' (LOOCV).

When considering logistic regression with more than three parameters, the method used to construct the model involved finding the minimum value of a multi-dimensional function and this can produce slightly different results each time and so it was also important to repeat each set of predictions to ensure consistent results.

2.4.3 Deciding which paper metrics to use

Since there are 16 paper metrics to choose from and if (for example) 4 metrics are selected for the model, there are almost 2 000 choices and it is not always practical to test every combination. It is therefore desirable to reduce the set of options and one way to do this is to identify the parameters that are independent from other parameters.

To do this the variance inflation factor (VIF) was calculated for the set of parameters and the parameter with the strongest correlation with other parameters was removed from the set. In this way the set of parameters was reduced to a more manageable set. The remaining metrics were then tested individually to determine their influence and the least important metric was removed.

3. Results

3.1 Traditional approach

When simple 2D plots were made, such as shown in Figure 1, in order to explore the relationship between the physical parameters of paper and parameters of image quality no clear correlation was apparent. Figure 1 shows an example of a 2D plot for a set of papers from the large study between a physical parameter of paper (the ink to paper contact angle recorded in 300 ms after the landing of ink) and a parameter of image quality (the maximum optical density of cyan). The dashed lines have been added to show slight trends in the data, for example there is a slight trend for a smaller contact angle to produce a higher maximum optical density, but these do not model the mechanism for ink–paper interaction.

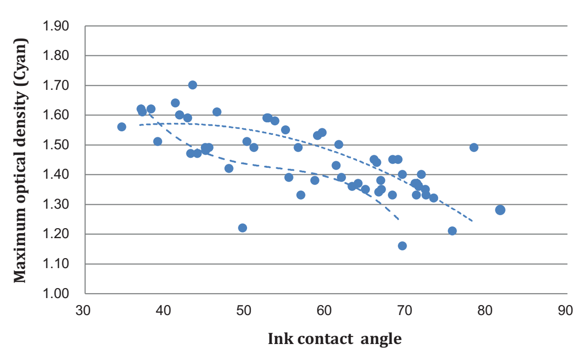

Figure 1: The 2D plot of cyan maximum optical density against ink contact angle

There may be a way to analyse such a relationship between the simple physical interaction between paper and ink, but as yet no satisfactory theory has been established.

Statistical approaches were also tested, an example of which is shown in Figure 2 for the same measured parameter, namely ink contact angle. In this case, each dot represents assessment of print image quality for a single paper, being given a value of either 1 for accepted and 0 for not accepted. The green line shows the logistic regression curve in respect to ink contact angle after 300 ms after landing of ink, and it can be seen that many points would have been incorrectly classified based on this single parameter. Across all such parameters, no single parameter was found which could give a reliable prediction for the acceptability of print image quality.

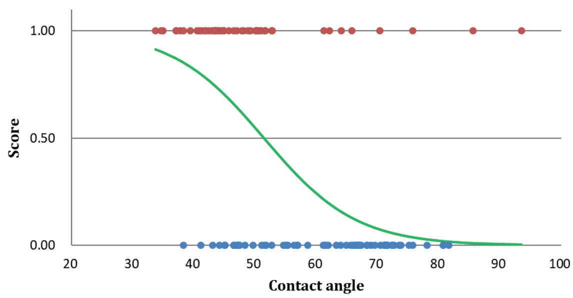

Figure 2: Example of logistic regression for the ink contact angle 300 ms after the landing of ink

3.2 Use of multidimensional linear methods

3.2.1 General approach

Since a simple relationship between parameters such as shown in Figure 1 could not be found an alternative approach was needed and multidimensional analysis was explored to determine whether this shows such a relationship.

Instead of looking for a relationship between physical parameters and image quality parameters a high-level approach was adopted. In this case it was assumed that the details of printing and assessment are unknown and that all that is known are the paper metrics and the result of assessment of print image quality. It was assumed that care has been taken to establish the best printing conditions for each paper and that a consistent process has been established for the assessment of print image quality. These assumptions mirror what happens in practice when manufacturers assess a new paper type for their press.

3.2.2 Prediction using all data sets and parameters

Logistic regression analysis was applied to the data. For the large study, predictions were calculated for 200 combinations randomly selected from the data set as the training set. An average accuracy of 0.80 and Cohen's kappa of 0.54 (Cohen, 1960) were obtained using the metrics shown in the first column of Table 1.

The first and second row of the table shows a good accuracy value, but a low value for Cohen's kappa. This difference indicates that the set of papers used to make predictions included more papers from one assessment category than the other. Since the selection process was random this was to be expected.

3.2.3 Removal of correlated parameters

In order to reduce the set of parameters used by the prediction model their independence was checked by calculating their VIF with all other parameters. The test results are shown in Table 2.

Table 1: Improvement in prediction accuracy and Cohen's kappa for each step

Condition	All metrics	VIF test	Test 1	Test 2	Test 3	Remove two papers (58 and 63)
Accuracy	0.803	0.808	0,827	0.833	0.840	0.869
Cohen's kappa	0.537	0.554	0.602	0.616	0.629	0.690
Contact angle (ink, 300 ms)	✓	✓	✓	✓	×	×
Contact angle (ink, 10 000 ms)	✓	✓	✓	✓	✓	✓
Contact angle (ink, 30 000 ms)	✓	×	×	×	×	×
Contact angle (H_2O, 300 ms)	✓	✓	✓	✓	✓	✓
Contact angle (H_2O, 10 000 ms)	✓	✓	✓	✓	✓	✓
Contact angle (H_2O, 30 000 ms)	✓	×	×	×	×	×
Surface pH	✓	✓	✓	×	×	×
Roughness	✓	✓	✓	✓	✓	✓
Thickness of coating layer	✓	✓	×	×	×	×
Si component	✓	✓	✓	✓	✓	✓
Al component	✓	×	×	×	×	×
Ca component	✓	✓	✓	✓	✓	✓
Ti component	✓	✓	✓	✓	✓	✓

Table 2: Variance inflation factors (the values above 2, 5 and 10 marked in green, yellow and red, respectively)

	Contact angle (ink, 300 ms)	Contact angle (ink, 10 000 ms)	Contact angle (ink, 30 000 ms)	Contact angle (H_2O, 300 ms)	Contact angle (H_2O, 10 000 ms)	Contact angle (H_2O, 30 000 ms)	Surface pH	Roughness	Thickness of coating layer	Si component	Al component	Ca component	Ti component
Contact angle (ink, 300 ms)	–												
Contact angle (ink, 10 000 ms)	4.034	–											
Contact angle (ink, 30 000 ms)	10.692	4.049	–										
Contact angle (H_2O, 300 ms)	1.367	1.269	1.300	–									
Contact angle (H_2O, 10 000 ms)	2.833	1.918	2.070	1.401	–								
Contact angle (H_2O, 30 000 ms)	2.861	1.996	2.257	1.407	23.454	–							
Surface pH	1.122	1.085	1.125	1.050	1.128	1.129	–						
Roughness	1.173	1.148	1.212	1.480	1.209	1.222	1.092	–					
Thickness of coating layer	1.031	1.015	1.038	1.013	1.004	1.004	1.037	1.003	–				
Si component	1.016	1.019	1.004	1.057	1.052	1.041	1.232	1.063	1.001	–			
Al component	1.012	1.016	1.003	1.044	1.039	1.030	1.373	1.052	1.011	5.953	–		
Ca component	1.006	1.001	1.012	1.000	1.005	1.007	1.872	1.039	1.007	2.063	2.170	–	–
Ti component	1.007	1.001	1.002	1.034	1.033	1.028	1.642	1.018	1.085	1.262	1.575	1.613	1.000

Strong correlations (VIF > 5) can be found between ink contact angles (300 ms and 30 000 ms), between water contact angles (10 000 ms and 30 000 ms) and between metal components (Si and Al). Based on this analysis, contact angle (ink, 30 000 ms), contact angle (H_2O, 30 000 ms) and Al component were removed from the model.

The results of predictions following the removal of these parameters are shown in the third column of Table 1. There is no dramatic change to the accuracy but the value of Cohen's kappa is improved. Following this step, the average of accuracy was 0.81 and the average Cohen's kappa was 0.55.

3.2.4 Removal of additional metrics using *k*-fold cross-validation

A method based on LOOCV was used to identify metrics with a low or negative effect on the model. For each LOOCV iteration, a single paper was used as the test set and all other papers used to build a logistic regression model. The prediction was recorded for each paper and this prediction compared with visual assessment. An LOOCV accuracy score was assigned for the set of metrics tested in this way as the ratio of correct predictions to the total number of papers.

This test was repeated multiple times, and each time one of the metrics was removed. The set of metrics with the highest LOOCV score was identified. This test was repeated three times (Test 1, Test 2 and Test 3 of Table 1) and each time the set of metrics with the best score was selected. Test 1 showed that removing the thickness of coating metric improved the accuracy and Cohen's kappa to 0.83 and 0.60, respectively. Test 2 showed that removing the surface pH metric improved the Cohen's kappa to 0.62. Test 3 showed that removing the contact angle (ink, 300 ms) metric the accuracy and Cohen's kappa improved to 0.84 and 0.63, respectively.

It was further observed that two papers seemed to be substantially different from the others in the set (papers 58 and 63). When these two papers were removed from the assessment, the accuracy and Cohen's kappa increased substantially to 0.87 and 0.69, respectively, as shown in the last column of Table 1. The reason for this is not completely clear and further investigation of this aspect is needed. It is possible that the visual assessment was incorrect or that there is some fundamental difference in these papers compared to the others.

4. Discussion

4.1 Prediction

These values for accuracy and Cohen's kappa seem to indicate that this provides a good basis for a prediction method for print image quality.

The studies considered only measurement values of physical paper properties when making predictions, but when data directly relating to image quality such as whiteness and gloss are also used in the prediction a different direction may be found.

Further investigation of this aspect is necessary including other measures such as those included in the ad-hoc data sets.

4.2 Verification of this prediction method

In order to confirm that this prediction method works well with data and assessments other than Fujifilm (the large study), predictions were also made using the data measured by the ad-hoc group. These predictions were done using 20 types of paper collected by the group. In this case, the number of data sets is very small and it is therefore necessary to reduce the set of parameters used for prediction.

Although VIF analysis is one direction to remove the parameters, only four parameters were eliminated from these data sets. Since *k*-fold cross-validation reduces the size of data sets, it is not an effective method for this prediction with small data sets. In the Equation [B.1] of logistic regression explained in Annex B, the coefficient β_i determines the extent to which the variable x_i contributes to the prediction. Therefore, if the coefficient β_i is close to zero, the variable x_i does not contribute to the prediction, and those parameters can be eliminated from the prediction. Table 3 shows the list of coefficients β_i for the printers by three different manufacturers.

Table 3: Coefficients obtained for each printer

No.	Parameters	Coefficient β_i Printer A	Printer B	Printer C
1.	Whiteness	−2.016	1.758	−0.454
2.	Gloss	−8.953	−8.100	−7.439
3.	Opacity	−2.722	5.899	−7.317
4.	Surface pH	1.688	−14.573	−2.134
5.	Liquid penetration	5.067	−3.184	0.662
6.	Setting homogeneity	−0.931	0.065	−2.976
7.	Surface roughness	7.060	1.348	3.220
8.	Mercury porosity	−3.187	0.507	−0.768
9.	Al component	2.659	6.619	0.944
10.	Si component	−0.425	9.345	0.988
11.	Ca component	7.976	1.905	−2.339
12.	Ti component	4.744	0.466	0.388
13.	Hygroexpansivity	−0.707	−7.721	4.507
14.	Contact angle 300 ms	5.967	0.862	1.943
15.	Contact angle 1100 ms	4.749	1.830	2.760
16.	Contact angle 3100 ms	6.315	0.853	3.399
17.	Constant	−3.845	7.415	2.193

Even with the same parameter, the coefficients are different depending on the printer. Here, the parameters with coefficients less than 1.0 were eliminated from the prediction. Tables 4 to 6 shows the results of the prediction using a small data set that has undergone the processes reducing the parameters used.

Table 4: The results of predictions for small-size data for printerA

	Results of assessment	P (Acc)	P (NA)	Prediction
1	Acceptable	0.6492	0.3508	Acceptable
2	Not acceptable	1.0000	0.0000	Acceptable
3	Acceptable	0.9984	0.0016	Acceptable
4	Acceptable	1.0000	0.0000	Acceptable
5	Acceptable	1.0000	0.0000	Acceptable
6	Acceptable	1.0000	0.0000	Acceptable
7	Not acceptable	1.0000	0.0000	Acceptable
8	Not acceptable	0.0000	1.0000	Not acceptable
9	Acceptable	0.6347	0.3653	Acceptable
10	Acceptable	1.0000	0.0000	Acceptable
11	Not acceptable	0.0041	0.9959	Not acceptable
12	Acceptable	1.0000	0.0000	Acceptable
13	Acceptable	1.0000	0.0000	Acceptable
14	Not acceptable	0.0000	1.0000	Not acceptable
15	Not acceptable	0.9999	0.0001	Acceptable
16	Acceptable	0.0000	1.0000	Not acceptable
17	Not acceptable	0.0000	1.0000	Not acceptable
18	–	–	–	–
19	–	–	–	–
20	Acceptable	0.6181	0.3819	Acceptable

Table 5: The results of predictions for small size data for printer B

	Results of assessment	P (Acc)	P (NA)	Prediction
1	Acceptable	1.0000	0.0000	Acceptable
2	Acceptable	0.9998	0.0002	Acceptable
3	Acceptable	0.9999	0.0001	Acceptable
4	Acceptable	1.0000	0.0000	Acceptable
5	Not acceptable	0.4306	0.5694	Not acceptable
6	Not acceptable	0.0000	1.0000	Not acceptable
7	Not acceptable	0.0000	1.0000	Not acceptable
8	Not acceptable	0.0000	1.0000	Not acceptable
9	Not acceptable	0.0038	0.9962	Not acceptable
10	Not acceptable	0.0000	1.0000	Not acceptable
11	Not acceptable	1.0000	0.0000	Acceptable
12	Acceptable	1.0000	0.0000	Acceptable
13	Not acceptable	0.3097	0.6903	Not acceptable
14	Not acceptable	0.0000	1.0000	Not acceptable
15	Acceptable	0.0389	0.9611	Not acceptable
16	Not acceptable	0.0513	0.9487	Not acceptable
17	Acceptable	0.5966	0.4034	Acceptable
18	Acceptable	1.0000	0.0000	Acceptable
19	Not acceptable	1.0000	0.0000	Acceptable
20	Not acceptable	0.0717	0.9283	Not acceptable

Table 6: The results of predictions for small size data for printer C

	Results of assessment	P (Acc)	P (NA)	Prediction
1	Acceptable	1.0000	0.0000	Acceptable
2	Acceptable	1.0000	0.0000	Acceptable
3	Acceptable	0.9994	0.0006	Acceptable
4	Acceptable	0.9999	0.0001	Acceptable
5	Acceptable	1.0000	0.0000	Acceptable
6	Acceptable	1.0000	0.0000	Acceptable
7	Not acceptable	0.0000	1.0000	Not acceptable
8	Not acceptable	0.0000	1.0000	Not acceptable
9	Acceptable	1.0000	0.0000	Acceptable
10	Acceptable	0.9809	0.0191	Acceptable
11	Not acceptable	0.1736	0.8264	Not acceptable
12	Not acceptable	0.0007	0.9993	Not acceptable
13	Not acceptable	0.0289	0.9711	Not acceptable
14	Not acceptable	0.0712	0.9288	Not acceptable
15	Not acceptable	0.0001	0.9999	Not acceptable
16	Not acceptable	0.0000	1.0000	Not acceptable
17	Not acceptable	0.0000	1.0000	Not acceptable
18	Acceptable	0.9285	0.0715	Acceptable
19	Not acceptable	0.0000	1.0000	Not acceptable
20	Acceptable	0.9999	0.0001	Acceptable

All the predictions (P (Acc) for acceptable and P (NA) for not acceptable) have high accuracy, particularly, all predictions are correct for printer C.

According to these results, the method provides a good prediction of visual assessment. On the other hand, it is unlikely that a set of 20 papers is sufficient to provide an accurate prediction for all papers. For users of digital presses, however, even a lower level of prediction would be beneficial.

4.3 Extending the multi-press study

In an ideal world, a very large number of papers would be printed on a large number of digital presses and the result of printing carefully assessed by multiple experts. In practice this is difficult, as configuring the presses and assessing the result for a single paper can be quite time consuming. Different formats of printing presses, for example sheet sizes or roll versus sheet differences also need to be considered.

It has been helpful to hold the multi-printer pilot study with a small number of digital presses and papers in order to establish working methods that can be developed and where necessary modified for use in a larger study. Building on the experience gained from this study should inform future projects.

5. Conclusions

These studies have been able to demonstrate that a model can be developed where a relatively small number of paper metrics when combined produces a good prediction for print image quality. They have only demonstrated this for a limited number of digital presses and papers and further testing is necessary to ensure reliable application of this model.

Acknowledgment

The authors wish to acknowledge the guidance and helpful input and discussions with members of high-speed inkjet papers ad-hoc group related to ISO/TC 130/WG 4. We also wish to thank those who contributed by identifying papers that should be used and by making measurements of these papers. In particular we would like to acknowledge the leadership of Uwe Bertholdt of Fogra in this activity.

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Annex A: Measurements and measurement methods

Table A.1 shows the set of paper measurements made by Fujifilm for use in the large study. This set of metrics was selected from a larger set of measurements made by Fujifilm and represents the set that has the most significant effect for the Fujifilm press used in present study.
Table A.2 shows measurements used for the multi-press pilot study made by members of the ad-hoc group. In some cases, the measurement methods differ slightly even where the same name is used.

Table A.1: Description of measurements used for the large study

Measurement name	Description
Contact angle (ink, 300 ms) Contact angle (10 000 ms) Contact angle (ink, 30 000 ms) Contact angle (H_2O, 300 ms) Contact angle (H_2O, 10 000 ms) Contact angle (H_2O, 30 000 ms)	Measured by an automated contact angle tester for ink and water, at intervals of 300 ms, 10 000 ms and 30 000 ms after the ink or water landed on the surface. See IEC 62899-201:2016 Amendment 1 (summary) and TAPPI/ANSI T 558 om-15 (full description).
Surface pH	Measured by pH meter with flat-head electrode. See IEC 62899-201:2016+AMD1:2018, Amendment 1.
Roughness	Surface roughness was measured by Parker-Print-surf (PPS) method. See ISO 8791-4:2007.
Thickness of coating layer	Evaluated by observation from a scanning electron microscope (SEM). The details including the preparation of cross-sections are specified in IEC 62899-201:2016+AMD1:2018, Amendment 1.
Si component Al component Ca component Ti component	The composition was analysed by X-ray fluorescence spectrometry (XRF) and the amounts of Al, Si, Ca and Ti were measured. Units are kilo count per second (kcps) according to the Kα ray of each metal. See IEC 62899-201:2016+AMD1:2018, Amendment 1.

Citations Table A.1

International Electrotechnical Commission, 2018.
Technical Association for the Pulp and Paper Industry, 2015.
International Organization for Standardization, 2007.

Table A.2: Description of measurements used for the multi-press pilot study

Measurement name	Description
Whiteness	Based on adopted Hunter Whiteness Index calculated from CIELAB: $$Whiteness = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad [A.1]$$ where L^*, a^* and b^* are the components of CIELAB (see Whetzel, 2014).
Gloss	The 60° gloss measurement using Byk micro-TRI gloss meter. See ISO 2813:2014
Opacity	Measured by the diffuse reflectance method using L&W Elrepho 070. The illuminant/observer was C/2°. See ISO 2471:2008.
Surface pH	Measured by the pH meter with flat-head electrode. See IEC 62899-201:2016+AMD1:2018.
Liquid penetration	Automatic scanning liquid absorptometer based on Bristow's method (see Bristow, 1967) was used.
Setting homogeneity	The surface of tested papers was coated entirely with purple ink in a thick layer. The two minutes later all excess ink was wiped off and its uniformity assessed by a group of experts from Fogra and ISO/TC 130. Ink used: 'wipe test ink' from Flint Group Germany.
Surface roughness	Surface roughness was measured by Parker-Print-surf (PPS) method. See ISO 8791-4:2007.
Mercury porosity	Measured by Mercury porosimetry; the mercury pressure was up to 345 MPa (50 000 psi). See ISO 15901-1:2016.
Al component Si component Ca component Ti component	The composition was analysed by X-ray fluorescence spectrometry (XRF) and the amounts of Al, Si, Ca and Ti were measured. Units are kilo count per second (kcps) according to the Kα ray of each metal. See IEC 62899-201:2016+AMD1:2018.
Hygroexpansivity	Dimensional stability for moisture is measured as hygroexpansivity. See ISO 8226-1:1994.
Contact angle 300 ms Contact angle 1100 ms Contact angle 3100 ms	Measured by an automated contact angle tester for water at intervals of 300 ms, 1100 ms and 3100 ms after the water landed on the surface. See IEC 62899-201:2016+AMD1:2018, Amendment 1 (summary) and TAPPI/ANSI T 558 om-15 (full description).

Citations Table A.2

International Electrotechnical Commission, 2018.

International Organization for Standardization, 1994; 2007; 2008; 2014; 2016.

Technical Association of the Pulp and Paper Industry, 2015.

Annex B: Summary of the use of logistic regression

B.1 General

The general equation for a logistic regression model is shown in Equation [B.1].

$$p = \frac{1}{1 + b^{-(\beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_i x_i)}} \quad [B.1]$$

where in this case,
p is the probability of prints made on the paper having good print image quality,
β_i are the parameters of the model,
x_i are the predictors of the model, in this case the selected paper property measurements,
b is a base which in this case is the base of the natural logarithm (e).

This equation can be thought of as having two steps: a dimensionality reduction step which maps the multiple dimensions x_i to a single dimension (y), and a mapping step which maps y which has range ($\pm\infty$) to the range [0 1].

These two steps can be written as shown in Equations [B.2] and [B.3].

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_i x_i \quad [B.2]$$

$$p = \frac{1}{1 + e^{-y}} \quad [B.3]$$

Consider the case of two paper properties, x_1 = Contact angle and x_2 = Ca content. Each paper can be plotted as shown in Figure B.1 according to the measurement of each of these two properties. In this case, green circles indicate papers that produce good print image quality and red crosses those that do not.

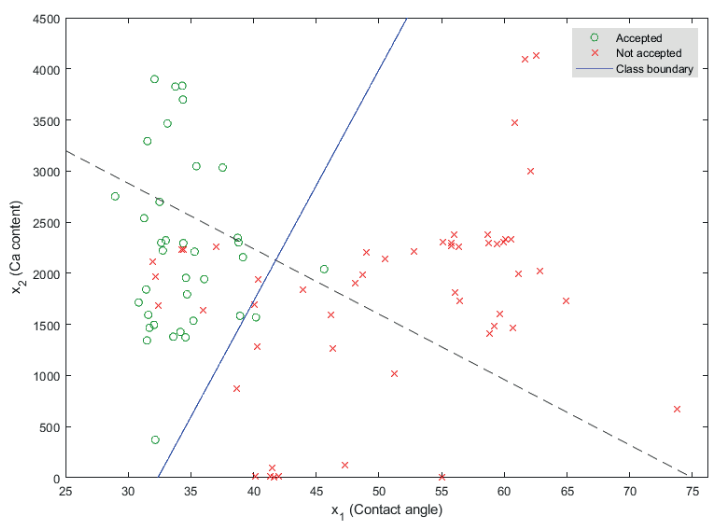

Figure B.1: Assessment relative to two paper metrics

The set of values corresponding to y = 0 for the first step of the equation is illustrated by the blue line. The region to the left of the line is predicted by the model as **Acceptable** and the region to the right is predicted as **Not acceptable**.

Each circle or cross has a y value corresponding to its distance from this line. The result of this mapping is shown in Figure B.2 which shows the values of y on a number line and Figure B.3 which shows the corresponding probability p.

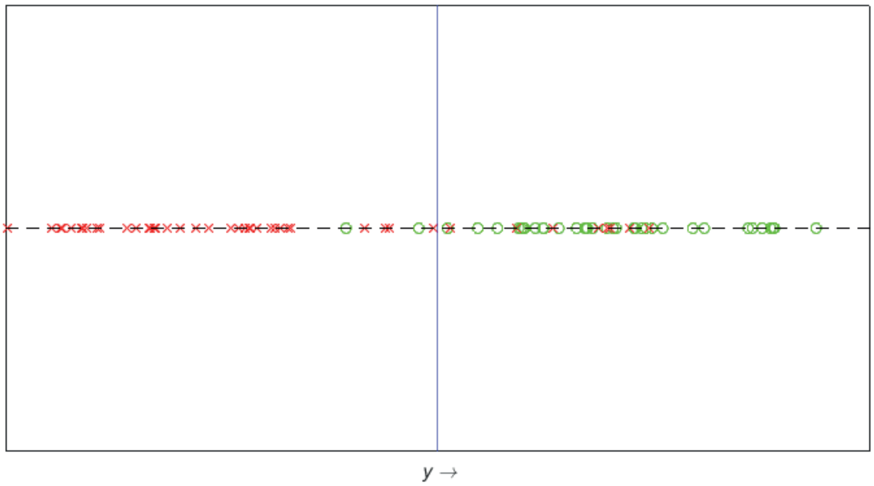

Figure B.2: Distance (y) from class boundary for each paper

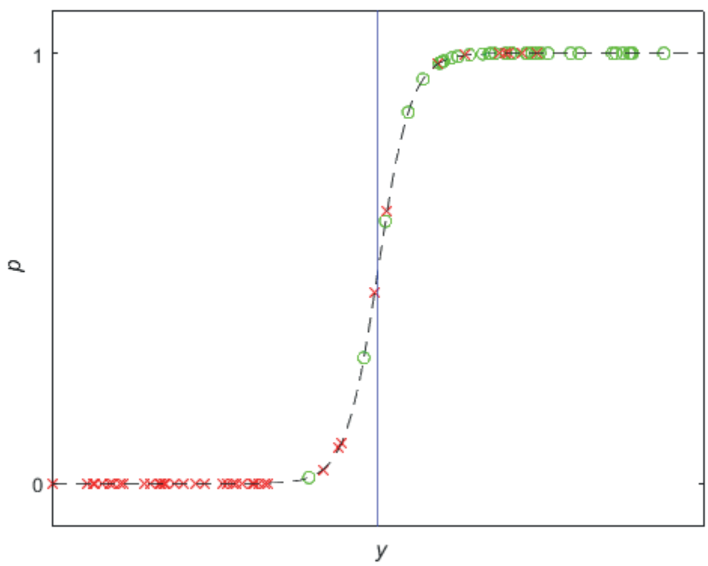

Figure B.3: Relationship between logistic regression probability and distance

As can be seen, the results for these two paper properties are quite good but can be improved. For example, visual inspection shows that eight papers that were classified as **Not acceptable** have been predicted by the model as being **Acceptable** (the red crosses to the left of the model class boundary in Figure B.1) and similarly two papers that were classified as being **Acceptable** have been predicted by the model as being **Not acceptable** (green circles to the right of the model class boundary in Figure B.1).

B.2 Measuring the performance of the model

A confusion matrix, also known as an error matrix, is a specific table layout that allows visualization of the performance of statistical algorithms. In this case the confusion matrix for Figure B.1 is shown below in a more usual form.

Table B.1: Confusion matrix for example of Figure B.1

		Predicted print quality	
Confusion matrix		**Acceptable**	**Not acceptable**
Assessed print quality	Acceptable	34	2
	Not acceptable	8	44

One way to measure the performance of the model is by the percentage of correct predictions (p_0) which is calculated as shown in Equation [B.4].

$$p_0 = \frac{(34 + 44)}{(34 + 8 + 2 + 44)} = 88.6\ \% \qquad [B.4]$$

This is an important measure but, in this case, there are 36 papers which are **Acceptable** and 52 which are **Not Acceptable** and so the results are likely to be biased. In order to avoid this problem, Cohen's kappa (κ) was used which takes into account the probability of chance agreement. This is done by measuring the probability that either the print is assessed or predicted as **Acceptable** (p_A) and the probability that the print is assessed or predicted as **Not acceptable** (p_N) and taking their sum (p_e) as shown in Equations [B.5], [B.6] and [B.7].

$$p_A = \frac{34 + 8}{34 + 8 + 2 + 44} \times \frac{34 + 2}{34 + 8 + 2 + 44} = 0.477 \times 0.409 = 0.195 \qquad [B.5]$$

$$p_N = \frac{2 + 44}{34 + 8 + 2 + 44} \times \frac{8 + 44}{34 + 8 + 2 + 44} = 0.523 \times 0.591 = 0.309 \qquad [B.6]$$

$$p_e = 0.195 + 0.309 = 0.504 \qquad [B.7]$$

Cohen's kappa is then defined as shown in Equation B.8.

$$\kappa = \frac{p_0 - p_e}{1 - p_e} = \frac{0.886 - 0.504}{1 - 0.504} = 0.770 \qquad \text{or } 77\ \% \qquad [B.8]$$

B.3 Extending to higher dimensions

The studies have found that the model can be significantly improved when four paper properties were used in combination. It is not possible to show a plot in this case but these same metrics can be used to measure the performance of the model for any number of paper properties.

B.4 Testing the model for large and small data sets

The discussion so far has assumed that the model is built and tested using the same data set but this is not generally useful when the objective is to predict the result for other papers. To do that, it is usual to split the data set into two and use one part to build the model and the other part to test it.

For the large data set this can be done relatively successfully and (for example) 80 % of the samples (in this case 70 samples) can be used to build the model and the remaining 20 % (in this case 18 samples) to test the model's performance.

For the smaller data set, which has just 20 samples, this is not possible and the approach must be modified somehow and, in this case, *k*-fold cross-validation was used. The data set was partitioned into (say) 19 samples and 1 sample and this is done in all possible ways – there are 20 ways to do this. A model is built for each of these cases using 19 samples and then tested using 1 sample and the result recorded. The average value of the results for all 20 tests is then taken as the overall result.

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Competencies and tools of higher education graphic communications programs

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Abstract

In this study, I sought to identify skills, content knowledge, and tools needed in higher education graphic communications programs. Currently a lack of research on the topic of graphic communications competencies exists. The industry is also experiencing a widening scope as well as rapid advancements in technology. The research study utilized a modified Delphi Technique as its method and included participants consisting of full-time graphic communications educators and industry professionals located in the southeast United States. One goal of the study was to gain a consensus among experts regarding what students are expected to know when entering the industry. The purpose of the research was to utilize what experts find to be the most important skills, content knowledge, and tools as a framework for developing and evaluating current higher education graphic communications curriculum. Participants of the study overwhelmingly identified soft skills as being the most needed skills, while software applications were identified as the most needed tools. The results of the project will allow educators to determine whether the current curriculum is preparing students to enter the field.

Keywords: curriculum, employment, evaluation, soft skills, software, tools

1. Introduction

In the year 2012, I conducted a research study on the Identification of 21st Century Skills, Content Knowledge, and Tools Needed in a Successful University-level Graphic Design Program (Bridges, 2016). At that time, I served as the sole graphic design professor in a small liberal arts university. The program lacked the number of students to qualify for accreditation by the national accrediting body; therefore, my role was to determine whether my students were receiving the necessary skills to be successful in the graphic design industry. I successfuly conducted a study utilizing educators and industry professionals as participants, which identified competencies and tools most needed in higher education graphic design programs. The information I obtained in my research study proved to be valuable in the evaluation and continued development of the program's current graphic design curriculum. The results also led to new course offerings as well as modifications to the focus of some existing courses. At the conclusion of the study, I determined that similar types of studies would also be useful in other higher education disciplines, especially those where educators and industry professionals may differ in terms of expectations of students entering the workforce. Today, as a graphic communications educator at a large public university, I have the same desire to ensure that students are being adequately prepared with the graphic communications skills and content knowledge areas needed to be successful.

Due to rapid technological advancements and the wide range of services offered, the graphic communications industry now encompasses much more than simply printing services (Print and Graphic Scholarship Foundation, 2015). According to the Introduction to Print and Graphics Scholarship Foundation (2015), "Companies in the business have expanded services to include creative design, retail display design, e-commerce, web page design and hosting, mailing, fulfillment, and a host of services that provide horizontal marketing well beyond the core printing model." With that in mind, one must wonder if current higher education graphic communications programs are adequately preparing students with the skills and content knowledge to enter a workforce undergoing such a tremendous industry shift. In addition, as technology continues to evolve, expectations may have also changed regarding what tools (hardware and software) students should be proficient in. These questions led to the present research study. The results of the study will aid educators in the development and evaluation of graphic communications curriculum based on what participants find to be most important. The study utilized a modified Delphi Technique to examine views from experts in the graphic communications field including educators and industry professionals in order to gain a consensus. My research sought to answer the following questions: 1) What are the skills and content knowledge areas most needed in higher education graphic communication programs as identified by experts? 2) What are the tools most needed in higher education graphic communication programs as identified by experts?

1.1 Previous research

There is a dearth of recent research on graphic communications competencies. This lack of research could be due to insufficient survey research in general, survey length causing participants to drop out or leave surveys incomplete, low participant rates, and challenges related to the identification of participants, particularly industry professionals. Smith (2014, p. 3) sought to identify "what impact will technical and business process trends in the graphic communications industry have on the required competencies of its future personnel". Among others, the research questions Smith sought to answer included identifying technical skills and soft skills needed for future personnel over the next 10 years. Participants in the study included graphic communications industry professionals throughout the United States. Smith (2014) found that industry professionals showed a clear preference for soft skills over technical skills. Some desired soft skills included attitude, good communication, teamwork, good work ethic, listening skills, problem solving, project management, and the ability to adapt and be flexible. Smith (2014) recommended that future researchers include studies utilizing other participants such as graduates and educators from graphic communications programs. Finally, she recommended educators use the results as a starting point for discussion with industry professionals regarding the status of related educational programs. Building on this work, my study requested input from both educators and industry professionals in order to reach a consensus regarding the most needed competencies for students when entering the graphic communications workforce.

2. Methods

The Rand Corporation first introduced the traditional Delphi research method in the 1950's (Goodman, 1987). Since its development, the Delphi has been useful in gathering a consensus among experts regarding future trends. Yousuf (2007, p. 1) defined the Delphi technique as a "group process involving an interaction between the researcher and a group of identified experts on a specified topic, usually through a series of questionnaires. The method has been used in several disciplines including education, health care, engineering, information systems, and transportation, to name a few (Rowe and Wright, 1999). The Delphi is particularly useful in educational research. In his article Use of Delphi Methods in Higher Education, Judd (1972) discussed the ways in which the Delphi research method can be useful. Delphi's benefits include identification of educational goals and objectives, curriculum planning and development, and assessment and evaluation.

The traditional Delphi technique is a qualitative research method generally consisting of seven rounds of questioning (Andrews and Allen, 2002). However, based on previous research, the method appears to be relatively flexible in terms of how the process is conducted. Thus, there have been several modifications to the Delphi method over the years (Riggs, 1983). Many of those modifications incorporate a mixed methods approach, where both quantitative and qualitative components are collected.

My research study utilized a mixed method modified Delphi technique as proposed by Haughey (2010). Haughey's model consists of seven steps, beginning with the selection of a facilitator, which in most cases is the researcher. The second and third steps include the identification of a panel of experts willing to participate in the research as well as the identification of the research problem. Step four is to begin to gather the opinions of the participants, most often by a questionnaire. Once the initial questionnaire is completed, the researcher collates the data, eliminating outliers, in order to begin to gain a consensus. The fifth recommended step is to create the second-round questionnaire, based on results from the first. The second round is, again, distributed to participants and results are collated and summarized. Step six is to create and distribute the third questionnaire. The final round questionnaire, step seven, is intended to sharpen focus on the particular areas participants agreed on.

2.1 Participants

The Delphi method requires careful selection of experts in order to participate in a study (Stitt-Gohdes and Crews, 2004). Gibbs, Graves, and Bernas (2001) identified specific criteria regarding the selection of participants for a Delphi study. The criteria include participants who had previously published research in that area in the past five years, industry professionals currently employed in the specific area of interest, and educators teaching in the area of interest.

In addition to careful selection of experts, sample size is also important in the successful completion of a Delphi study. Based on previous research, Delphi studies have been conducted with as few as 15 participants and as many as 60. Obviously, the latter is more desirable.

My study requested participation from approximately 300 experts located throughout the southeastern United States. I utilized independent data collection to locate full-time educators currently teaching in 2-year and 4-year graphic communication programs. For industry professionals, I used an up-to-date intern employer database from my current teaching institution. All experts were sent an email invitation with an attached informed consent requesting their participation in the study. Of the 300 requested, 13 educators and 21 industry professionals committed to the research project, an acceptable number of participants (n) for a Delphi study. Table 1 shows the response rates from each round of questioning. It should be noted that rounds three and four were conducted during the COVID-19 pandemic, which could have contributed to the lower response rates.

Table 1: Participant response rates from the four rounds of questionnaires (n = 34)

Questionnaire	Responses	Response rate
Round one	33	97 %
Round two	33	97 %
Round three	31	91 %
Round four	28	82 %

2.2 Procedures

For my current study, I developed the first-round questionnaire based on the results of a previous research study (Smith, 2014). According to Stitt-Gohdes and Crews (2004, paragraph 27), the Delphi is intended to give experts the "opportunity for initial feedback, collation of feedback, and distribution of collated feedback back to participants for further review." Therefore, I opted to use the graphic communications technical and soft skills identified by Smith (2014) as an initial starting point for the round one questionnaire. The decision was made to combine soft skills and technical skills into the round one questionnaire in order to stay true to the modified Delphi technique being used to conduct the study.

The first-round questionnaire consisted of a web-based questionnaire created using the Qualtrics software package. The questionnaire was distributed to participants via email link. Round one requested participants to rate each competency using a Likert scale ranging from one to seven, one being extremely undesirable and seven being extremely desirable. Participants also had the option to leave positive or negative comments related to each competency. The final two questions of the round-one questionnaire prompted participants to list additional skills or content knowledge areas not appearing on the questionnaire, and to list required tools (hardware, software, other devices) needed in higher education graphic communications programs. Round two was based on results from the first round and, again, asked participants to rank competencies on a scale from one to seven. Experts were also asked to list additional competencies and tools not appearing on the questionnaire. In order to move participants to a consensus, the round three questionnaire was completely quantitative and prompted participants to rank from one to seven each previously identified competency based on results from round two. Finally, round four prompted experts to rank the top twenty skills and content knowledge areas and the top twenty tools needed in higher education graphic communications programs. Round three was intended to identify the importance of each competency and tool, while round four was designed to obtain a clearer consensus among experts. Descriptive statistics, specifically mean and standard deviation, were used to analyze the quantitative data and coding was used to analyze the qualitative data.

3. Results

3.1 Round one results

The ranking of the most needed competences in graphic communications is shown in Table 2.

Statements with the highest mean scores, or those closest to seven, are considered most important.

The five statements receiving the highest mean scores were critical thinking skills, teamwork, business ethics, customer service skills, and supervisory techniques such as managing people and systems. Some expert comments related to critical thinking included "… this is essential across all technology, methods, and time" and "… absolutely necessary no matter what career a student aims to work in." Teamwork comments provided by experts included "Understanding that there are multiple segments within the production process and how each segment impacts the final outcome is key. It takes a team to get to the finish line" and "When people go into the workforce, they have to be able to work in groups. If they cannot do that, it doesn't matter what their skills are." Comments related to business ethics included "… critical for long-term success" and "Ethics are very important because they can raise a company up or they can bring it down. These kinds of

Table 2: Round one descriptive statistics for the most needed graphic communications competencies (n = 33)

Competency	Mean score	Std. deviation
1. Critical thinking skills	6.85	0.43
2. Teamwork	6.85	0.43
3. Business ethics	6.64	0.59
4. Customer service skills	6.30	0.97
5. Supervisory techniques such as managing people and systems	6.06	0.81
6. Project management concepts and software	6.00	1.10
7. Spot color and process builds	5.85	1.26
8. Color management	5.85	1.08
9. Job estimating, planning, and scheduling	5.79	1.20
10. Variable data marketing	5.75	1.12
11. Quality control systems and devices	5.73	1.58
12. Trends in digital communication	5.73	1.14
13. Sales in graphic communications	5.58	1.23
14. Plant organization, management, and workflow	5.52	1.54
15. Printing industry standards such as SWOP, GRACoL, and G7	5.33	1.59
16. Social media marketing	5.30	1.22
17. Publishing for mobile devices	5.15	1.26
18. Understanding the concept of imposition	5.03	1.67
19. Content management and repurposing	5.03	1.27
20. Interactive PDF’s	5.03	1.40
21. Computer programming	5.03	1.70
22. Performing imposition with software applications	4.91	1.33
23. Product fulfillment – understand the logistics and physical distribution	4.84	1.58
24. PURL’s, QR codes, and email blasts	4.48	1.52
25. Binding – understand the terminology and processes that are used	4.48	1.67
26. History of printing	3.88	1.63

ethics are not taught in the home. So we have to prepare students for the real world.” Comments regarding customer service skills were “… sell yourself and sell the product” and “We routinely train for soft skills. Graduates are not using salutations, closings in emails. They often send shortened replies that look like texts and avoid calling clients directly.” Finally, comments related to the fifth highest-ranking skill, supervisory techniques, included “Everyone should have an insight how to manage people, positive and negative feedback, conflict resolution, performance reviews” and “We are not educating operators, we are educating higher level employees. These skills are very needed.” Interestingly, all of the top five competencies are considered to be soft skills. The lowest-ranking competency was the history of printing, which is considered a content knowledge area. Comments related to the history of printing included “history gives perspective to the current trends and helps students identify their historical reference and repurposing” and “Good to know. It creates appreciation for what we do. In the end, it is probably not going to get someone a job though.”

Round one requested participants to list any additional competencies not appearing on the questionnaire. As a result, experts added 33 new statements. Participants were also given the opportunity to provide feedback regarding the wording of statements, therefore some statements were modified to provide clarification for the round two questionnaire. For example, color management changed to color management – including creating curves and profiles. All statements receiving a mean score of at least 4.0 or better were included in the round two questionnaire. This affected only one statement, the history of printing. However, based on comments from participants, the history of printing was modified to “basic knowledge of the history of printing,” thus the modified statement was included in the subsequent round. Most statements, specifically those that ranked at or near the top, had standard deviations close to 1.0, indicating a normal distribution. In addition, round one prompted participants to list all tools and equipment needed in higher education graphic communications programs. Experts listed a total of 28 tools.

3.2 Round two results

Statements with the highest mean scores, or those closest to seven, are considered most important.

Statements with mean scores below 4.0 were not included in the subsequent round.

Table 3: Round two descriptive statistics for the most needed graphic communications competencies (n = 33)

Competency	Mean score	Std. deviation
1. Critical thinking skills	6.79	0.48
2. Problem solving and analytical skills	6.72	0.58
3. Teamwork	6.62	0.55
4. Communication skills – oral, written (including technical writing) and business	6.62	0.55
5. Business and personal ethics	6.52	0.68
6. Adaptability and flexibility	6.52	0.72
7. Organization skills	6.14	0.82
8. Spot color and process builds for design and/or production	6.11	0.94
9. Customer service skills	6.10	0.99
10. Prepress and printing workflow	6.03	1.03
11. Knowledge of trends in digital communication	6.03	0.72
12. Presentation skills	5.97	0.93
13. Digital literacy skills	5.97	1.10
14. Networking skills	5.97	1.10
15. Leadership skills and supervisory techniques such as managing people, systems, and supply chains	5.90	0.71
16. Quality control systems and devices for color and production	5.76	1.07
17. Knowledge of brand communications and brand security related to printing	5.68	1.04
18. Knowledge of inkjet hybrid printing technology	5.66	1.35
19. Basic knowledge of job estimating, planning, and scheduling	5.62	1.00
20. Knowledge of design principles	5.59	1.54
21. Packaging and package (structure) design	5.55	1.10
22. Color management – including creating curves and profiles	5.52	1.22
23. Ability to develop and tell a story	5.48	1.52
24. Business administration skills	5.45	1.00
25. Preflighting skills	5.45	1.54
26. Research and data analysis skills	5.41	1.07
27. Knowledge of safety skills	5.41	1.47
28. Project management concepts and software	5.38	1.30
29. Sales in graphic communications	5.34	1.15
30. Plant organization, management, workflow, and facility planning	5.31	1.25
31. Graphic design skills	5.31	1.46
32. Basic knowledge and understanding of printing industry standards such as SWOP, GRACoL, and G7	5.28	1.65
33. File naming/versioning skills	5.28	1.55
34. Variable data printing process and application	5.17	1.37
35. Content management and repurposing	5.14	1.36
36. User experience and interface design	5.11	1.32
37. Variable data marketing (promoting and selling products or services)	5.10	1.35
38. Basic knowledge of social media marketing	5.10	1.37
39. Machine optimization and calibration	5.10	1.63
40. Basic knowledge of PURL's, QR codes, and email blasts	5.07	1.11
41. Product fulfillment – understand the logistics and physical distribution	5.03	1.83
42. Publishing for mobile devices	5.03	1.61
43. Information technology skills	5.03	1.00
44. Interactive PDF's	5.00	1.14
45. Knowledge of offset printing technology	4.97	1.56
46. Web design skills	4.93	1.72
47. Basic knowledge of computer programming – HTML and CSS coding	4.90	1.30
48. Understanding and performing imposition with software applications	4.89	1.17
49. Knowledge of advanced screening and platemaking technologies	4.79	1.27
50. Digital photography skills	4.66	1.51
51. Binding – understand the terminology and processes that are used	4.62	1.45
52. Six Sigma/Lean practices	4.59	1.45

Table 3 – continued

Competency	Mean score	Std. deviation
53. Videography and video production skills	4.41	1.69
54. Cyber security knowledge	4.41	1.75
55. Anti-counterfeiting technology	4.41	1.47
56. Basic knowledge of the history of printing	4.24	1.30
57. Custom ink mixing	4.18	1.67
58. Animation and motion graphics	4.14	1.74
59. Advanced knowledge of computer programming – C++, Python, etc.	3.52	1.61

Due to the large number of statements included in the round two questionnaire (Table 3), the statements were divided into categories consisting of content knowledge areas, soft skills, and technical skills. Content knowledge refers to an understanding of those areas at the core of the discipline, including metacognition, empathy, holding a perspective, application, interpretation, and explanation (Davis, 2010). According to Rego (2017, p. 11) soft skills "are intangible, nontechnical and are the personal character traits or qualities you need to succeed in any profession". Technical skills refer to "knowledge or training that you have gained through any life experience, including in your career or education" (indeed.com, 2020).

The highest-ranking statements from round two are considered to be soft skills, which include critical thinking skills, problem solving and analytical skills, teamwork, communication skills, and business and personal ethics. Two of the five statements were newly added based on comments from round two, problem solving and analytical skills and communication skills. Comments provided by experts related to problem solving and analytical skills were "essential" and "…this is critical for success." Some comments related to communication included "…this is something our college grads have difficulty with" and "It is shocking how many technical types avoid sending an email to a client because they lack confidence in their written communication skills. Employers are blaming social media and texting on poor writing skills but it's really a coach-able issue." The lowest ranking competency, advanced knowledge of computer programming, was a newly added statement. Some comments related to this competency included "role specific," "this is outside of our industry," and "these jobs most often go to computer science or computer programming grads." All statements receiving a mean score of 4.0 or better were included in the round three questionnaire. Only one statement, advanced knowledge of computer programming, received a mean score below 4.0, therefore it was not included in the round three questionnaire. It is interesting to note that with change in wording regarding the history of printing, its mean score increased to 4.14 in round two. As with round one, most competencies had a standard deviation at or close to 1.0, which indicated a normal distribution. As with the round one questionnaire, participants were given the opportunity to provide positive and negative comments related to each statement as well as add any new statements not appearing on the questionnaire.

Table 4: Round two results for the most needed graphic communications tools with percentage of participants selecting tool/equipment (n = 33)

Tool/equipment	Percentage
1. Adobe Illustrator	85 %
2. Adobe Photoshop	82 %
3. Apple Computers	70 %
4. Adobe InDesign	70 %
5. Email tools (Outlook, Gmail)	67 %
6. Microsoft Excel	64 %
7. RIP systems	64 %
8. Color measurement tools	64 %
9. Digital printing press (roll and sheet fed)	64 %
10. All Adobe software	61 %
11. Wide format printing press (roll and sheet fed)	61 %
12. Project management tools	61 %
13. Online management and communication tools (Slack)	58 %
14. Esko	55 %
15. Packaging design prototyping software	55 %
16. Variable data printing software	52 %
17. Cameras with HD video capability	48 %
18. Cutting tables	48 %
19. DSLR cameras and accessories	45 %
20. MIS software (Management Information Systems)	42 %
21. CRM tools (Customer Relationship Management)	39 %
22. Photo studio equipment (lighting, backdrops, light meter)	39 %
23. Imposition software	39 %
24. Sales tool experience (Salesforce)	36 %
25. Flexography printing press	36 %
26. Social media tools	36 %
27. Content Management System software (Wordpress, etc.)	36 %
28. Basic code editing software (Brackets, Text Wrangler, Sublime, etc.)	36 %

Round two requested participants to select from a list, generated based on feedback from round one, of the most needed graphic communications tools (Table 4). Software applications dominated the most top-ranking tools, with Adobe Illustrator and Photoshop ranking number one and two. The five lowest ranking tools were selected by 36 % of participants and included sales tool experience, flexography printing press, social media tools, content management system software, and basic code editing software. Participants were given the opportunity to list any additional tools and equipment not appearing on the current list. Five additional tools were added.

3.3 Round three results

Statements with the highest mean scores, or those closest to seven, are considered most important.

Statements with mean scores below 4.0 were not included in the subsequent round.

Round three, again, requested that participants rank statements based on a scale from one to seven, with seven being the highest. Participants were given the opportunity to leave positive and negative comments related to each statement, however no new statements could be added in this round. The results of round three questionnaire are shown in Table 5. This is consistent with the purpose of the Delphi method, which is to encourage a consensus among experts regarding the most needed competencies and tools. Critical thinking skills were, again, the highest-ranking competency in round three. This was followed by problem solving and analytical skills, adaptability and flexibility, business and personal ethics, and communication skills. Adaptability and flexibility replaced teamwork in the top five highest ranking statements. However, teamwork did come in at number six. The lowest ranking statements were anti-counterfeiting technology, basic knowledge of the history of printing, and custom ink mixing. The latter two had mean scores below 4.0, thus they were not included in the subsequent round.

Table 5: Round three descriptive statistics for the most needed graphic communications competencies (n = 31)

Competency	Mean score	Std. deviation
1. Critical thinking skills	6.76	0.51
2. Problem solving and analytical skills	6.72	0.54
3. Adaptability and flexibility	6.56	0.73
4. Business and personal ethics	6.56	0.63
5. Communication skills – oral, written (including technical writing) and business	6.56	0.49
6. Teamwork	6.44	0.62
7. Current digital literacy skills (ability to find, evaluate, communicate, and share online content)	6.20	0.69
8. Emotional Intelligence (managing people objectively and respectfully)	6.04	1.25
9. Knowledge of trends in digital communication	6.00	0.73
10. Organization skills	5.96	1.00
11. Customer service skills	5.88	0.91
12. Networking skills	5.84	0.95
13. Presentation skills	5.76	0.99
14. Prepress and printing workflow	5.64	1.45
15. Leadership skills and supervisory techniques such as managing people, systems, and supply chains	5.60	1.01
16. Spot color and process builds for design and/or production	5.58	1.11
17. Packaging and package (structure) design	5.56	1.37
18. Ability to develop and tell a story	5.56	1.40
19. Knowledge of inkjet hybrid printing technology	5.56	1.47
20. Knowledge of design principles	5.52	1.24
21. Research and data analysis skills	5.52	1.54
22. Business administration skills	5.40	0.79
23. File naming/versioning skills	5.38	1.40
24. Quality control systems and devices for color and production	5.36	1.19
25. Basic knowledge of job estimating, planning, and scheduling	5.36	1.01
26. Knowledge of brand communications and brand security related to printing	5.36	1.04
27. Knowledge of safety skills	5.36	1.40
28. Basic knowledge of social media marketing and the ability to stay current with practices and trends	5.32	1.27
29. Project management concepts and software	5.32	1.26

Tble 5 – continued

Competency	Mean score	Std. deviation
30. Graphic design skills	5.32	1.57
31. Variable data printing process and application	5.20	1.06
32. Preflighting skills	5.16	1.61
33. Color management – including creating curves and profiles	5.13	1.19
34. Publishing for mobile devices, including but not limited to mobile websites, apps, social media, videos	5.12	1.40
35. Content management and repurposing	5.08	1.21
36. Variable data marketing (promoting and selling products or services)	5.00	1.31
37. Knowledge of user experience and interface design	5.00	1.06
38. Basic knowledge and understanding of printing industry standards such as SWOP, GRACoL, and G7	4.84	1.60
39. Web design skills	4.84	1.48
40. Information technology skills	4.80	1.58
41. Machine optimization and calibration	4.80	1.70
42. Product fulfillment – understand the logistics and physical distribution	4.76	1.56
43. Knowledge of offset printing technology	4.76	1.39
44. Plant organization, management, and workflow	4.72	1.33
45. Sales in graphic communications	4.68	1.22
46. Interactive PDF's	4.64	1.38
47. Basic knowledge of computer programming – HTML and CSS coding	4.60	1.55
48. Digital photography skills	4.60	1.37
49. Videography and video production skills	4.60	1.62
50. Basic knowledge of PURL's, QR codes, and email blasts	4.56	1.36
51. Six Sigma/Lean practices	4.56	1.71
52. Cyber security knowledge	4.48	1.73
53. Understanding and performing imposition	4.42	1.66
54. Binding – understand the terminology and processes that are used	4.32	1.69
55. Understanding and performing imposition with software applications	4.32	1.49
56. Knowledge of advanced screening and platemaking technologies	4.32	1.42
57. Animation and motion graphics	4.32	1.41
58. Anti-counterfeiting technology	4.04	1.88
59. Basic knowledge of the history of printing	3.92	1.46
60. Custom ink mixing	3.72	1.61

As with previous rounds, most standard deviations remained near or below 1.0.

Table 6: Round three results for the most needed graphic communications tools (n = 31)

Tool/equipment*	Percentage**
1. Platemaking devices	39 %
2. 3D printers	32 %
3. Screen printing presses	29 %
4. Lightroom	29 %
5. 3D visualization software (zBrush, Cinema 4D)	23 %

*Only newly added tools were included in this round.
**Percentage of participants selecting tool/equipment.

In round three, it was determined that rather than giving participants the full list of tools and equipment again, only newly added tools would be included (Table 6). The highest-ranking tool was platemaking devices, with 39 % of participants selecting it. None of the newly added tools are considered the most important as all came in below 50 %. Participants were not given the opportunity in this round to list additional tools.

3.4 Round four results

The final round requested participants to rank the top twenty competencies, thus statements with mean scores closest to one are considered most important.

In order to gain a clearer understanding regarding the most needed graphic communications competencies and tools, round four differed from previous rounds in that it requested participants rank the top twenty competencies in order of importance (Table 7). Participants were given a list of the top twenty statements from round three. There were 21 statements on the list

Table 7: Round four mean results for the top twenty most needed graphic communications competencies (n = 28)

Competency	Mean score
1. Critical thinking skills	3.82
2. Communication skills – oral, written (including technical writing) and business	4.79
3. Teamwork	5.61
4. Problem solving and analytical thinking skills	6.11
5. Business and personal ethics	8.11
6. Organization skills	8.29
7. Adaptability and flexibility	8.50
8. Customer service skills	9.64
9. Emotional intelligence (managing people objectively and respectfully)	9.68
10. Leadership skills and supervisory techniques such as managing people, systems, and supply chains	9.86
11. Research and data analysis skills	11.50
12. Spot color and process builds for design and/or production	11.93
13. Presentation skills	12.11
14. Knowledge of design principles	13.75
15. Knowledge of trends in digital communication	13.96
16. Prepress and printing workflow	14.25
17. Ability to develop and tell a story	14.32
18. Packaging and package (structure) design	15.11
19. Networking skills	15.29
20. Current digital literacy skills (ability to find, evaluate, communicate, and share online content)	15.89
21. Knowledge of inkjet hybrid printing technology	18.50

because two statements had equal mean scores. It was determined that results could best be interpreted by showing mean scores rather than frequencies thus, those statements with mean scores closest to 1.0 are considered most important. In round four the top five competencies remained relatively the same however, the order of importance shifted once again, as with previous rounds. Critical thinking skills remained at the top with a mean score of 3.82. It was followed by communication skills, which came in at number two for the first time.

Teamwork went back up in round four and was considered by experts to be the third most important graphic communications competency followed by problem solving and analytical skills and business and personal ethics. It should be noted that of the 11 soft skills listed in round three, only one, business administration skills, was not selected to be included in the top 20 most needed competencies. Knowledge of inkjet hybrid printing technology was the lowest ranking competency in round four.

Round four also requested participants to rank the top 20 most needed tools in graphic communications higher education programs, thus tools with mean scores closest to one are considered most important (Table 8). As with the top 20 competencies, mean scores were used to best interpret the results. Adobe Illustrator remained at the top as the most needed tool followed by Microsoft Excel, Adobe Photoshop, all Adobe software, and Adobe InDesign. All top five tools are software applications. The lowest ranking tools were cutting tables and cameras with HD video capability.

Table 8: Round four mean results for the top twenty most needed graphic communications tools (n = 28)

Tool/equipment	Mean score
1. Adobe Illustrator	5.39
2. Microsoft Excel	6.46
3. Adobe Photoshop	6.68
4. Email tools (Outlook, Gmail)	6.71
5. All Adobe software	7.57
6. Adobe InDesign	8.71
7. Esko	8.86
8. Online management and communication tools (such as Slack)	9.25
9. Apple computers	9.89
10. Project management tools	10.64
11. Color measurement tools	10.75
12. RIP systems	11.46
13. Packaging design prototyping	11.54
14. Digital printing press (roll and sheet fed)	12.32
15. MIS software (Management Information Systems)	12.57
16. Variable data printing software	13.11
17. Wide format printing press (roll and sheet fed)	13.61
18. DSLR cameras and accessories	14.01
19. Cutting tables	14.64
20. Cameras with HD video capability	15.79

4. Discussion

This study addressed the following research questions: 1) What are the skills and content knowledge areas most needed in higher education graphic communication programs as identified by experts? 2) What are the tools most needed in higher education graphic communication programs as identified by experts? Based on the results of the data collected, out of the 21 top ranking skills and content knowledge areas, three statements are considered to be content knowledge areas; those are: 1) Current digital literacy skills, 2) Knowledge of trends in digital communication, and 3) Knowledge of design principles. Six statements are technical skills: 1) Emotional intelligence, 2) Research and data analysis skills, 3) Spot color and process builds for design and/or production, 4) Prepress and printing workflow, 5) Packaging and package (structure) design, and 6) Knowledge of inkjet hybrid printing technology. The remaining twelve statements are soft skills: 1) Critical thinking skills, 2) Communication skills, 3) Teamwork, 4) Problem solving and analytical thinking skills, 5) Business and personal ethics, 6) Organization skills, 7) Adaptability and flexibility, 8) Customer service skills, 9) Leadership skills and supervisory techniques, 10) Presentation skills, 11) Ability to develop and tell a story, and 12) Networking skills. Soft skills were not only in the majority in terms of most needed skills, but were also consistently the highest ranking skills in all of the rounds of questioning. Regarding research question 2, the most needed tools, many of the tools and equipment identified by experts are software applications and/or digital-based tools. Software applications were among the highest-ranking tools. Some hardware and equipment also ranked in the top 20 most needed tools however, they were ranked closer to the bottom.

The main findings of this study were consistent with results from a previous study conducted by Smith (2014). As previously mentioned, Smith found that industry professionals showed a clear preference for soft skills over technical skills. Experts in the Smith's (2014) study identified attitude, good communication, teamwork, good work ethic, listening skills, problem solving, project management, and the ability to adapt and be flexible as the most needed soft skills for students entering the graphic communications industry. Five out of eight soft skills identified in Smith's study were also identified in this study.

4.1 Limitations/delimitations

One notable limitation of this current study relates to the Delphi method itself. The traditional Delphi study is very time intensive due to the sheer number of rounds of questioning (Powell, 2003). However, utilizing a modified approach with fewer rounds helps to expedite the process, as well as provides participants with an existing questionnaire in round one rather than requesting they generate the list themselves. As previously mentioned, low participant rates are a limitation of Delphi studies. In Smith's (2014) study, low participation was also an issue. Smith (2014) questioned whether this may be isolated to graphic communications particularly, or if participants are simply already overloaded with other information. Exploring low participant rates in the field of graphic communications would be an area worthy of future research. In this study, participant rates declined as the project progressed, which is a common issue in Delphi studies.

Other limitations relate to quantitative and qualitative studies in general, such as protecting participant anonymity, obtaining appropriate permissions, and avoiding researcher bias. Careful consideration was given in order to avoid these potential issues. Finally, limitations related to the data collection instrument can also be a concern. Web-based questionnaires, specifically, can encounter issues including low response rates, emails being sent to junk folders, and other technology issues such as web pages timing out, etc. Delimitations of the study include limiting the participant location to the southeast and narrowing the participant group to only full-time educators in higher education programs and full-time industry professionals currently working in the graphic communications field.

4.2 Future research

It would be beneficial to conduct this study in other geographic locations as well as in other graphic communications-related markets. For example, would the results of this study be consistent in other regions of the United States and in other areas of the world? This would be important, not because all higher education programs need to have the same program offerings, but rather because of the synergy that exists among academics and industry. Consistency in findings ensures that expectations from both organizations align with each other leading to better relationships and, more importantly, a better prepared workforce. This research could also be applicable in other markets aside from academics. For example, it would be interesting to note whether the results of this study would be similar if conducted in a large flexography packaging company or in a large information technology center.

One of the important aspects of the project was to encourage participants, both educators and industry professionals, to arrive at a consensus regarding the most needed competencies and tools, however, separating the two participant groups and then comparing the results could also yield some important findings. As mentioned previously, conducting the study with more participants would also provide additional data, potentially giving the research more statistical significance and validity. In addition, this study could be conducted using a different research method, such as a case study where more qualitative data can be collected. Nonetheless, it will be essential to repeat this research frequently because industry practices and expectations will continue to evolve and new technology will be developed.

4.3 Significance & practical application

The purpose of this study was to identify the most needed skills, content knowledge areas, and tools needed in higher education graphic communications programs. Changing trends in technology as well as a lack of research on the topic were the driving factors regarding the need for this study. As educators, it is important that we are providing students with the knowledge and skills to be productive graphic communications industry professionals. It is also vitally important that educators and current industry professionals have similar expectations regarding what students need to know. In addition, as technology continues to evolve and new equipment and capabilities emerge, higher education graphic communications programs should evaluate the current curriculum as well as tools and equipment to ensure that they are up-to-date, in-line with industry expectations, and most importantly, meeting the needs of the students.

The results of this study can provide higher education educators with a framework for evaluating the existing curriculum, especially for those programs that are not overseen by an accrediting body. The most obvious means for doing so would be to conduct a program evaluation. For those institutions with current graphic communications programs, a summative evaluation would be most appropriate. Grayson (2011) proposed an evaluation comprised of seven steps: identify the context of the program being studied; define the program's theory; identify all stakeholders; explain the purpose of the evaluation; identify evaluative questions and criteria; locate, collect, and analyze the data; and finally report findings. The findings from this study would be applicable in step five of the process, identifying questions and criteria. For example, evaluating which particular courses emphasize critical thinking and assessing how current course assignments and projects measure students' ability to critically think through a problem.

This research can also serve as a checklist of sorts for inventorying current tools and equipment that are being used to teach students specific skills, and determining if some are lacking or simply obsolete. For example, it was interesting to note that several types of printing presses were not identified as being essential tools. Screen printing presses and flexography printing processes were two of the lowest-ranking tools identified, and offset printing was not identified at all. Also, platemaking devices scored quite low. This indicates that the industry continues to shift away from some of the traditional types of hands-on presses and production. However, digital printing presses and wide format presses scored in the top 20 most needed tools. These findings can, again, be applicable in evaluating course content and determining how and if particular print production processes should be taught and what equipment should be used. This would also give faculty the opportunity to identify how to integrate new types of tools, specifically those that are software-based, into existing courses or possibly creating new courses to aid in the instruction of these tools.

Finally, this study revealed that educators and industry professionals overwhelmingly placed the most importance on soft skills. This leads to the question "Can soft skills be taught?" Currently there is a wide range of educational research regarding soft skills. Researchers argue that soft skills can in fact be taught. Shuman, Besterfield-Sacre, and McGourty (2005) argue that skills such as, communication and ethics can easily be incorporated into a variety of projects. They also point out that many colleges and universities offer entire courses on the subjects. Rego (2017) stated that oftentimes students who communicate effectively also work well with a team. It can be assumed then that if communication skills can be taught, teamwork can as well. Professionalism is another soft skill that can be incorporated into courses by educators when he or she exhibits those qualities in the classroom by "… taking responsibility, being accountable, having integrity, and presenting an overall positive image" (Rego, 2017, p. 11). It is evident that the inclusion of soft skills into the graphic communications curriculum is not only possible, but essential in the success of students in the field. The challenge and duty of educators is to determine how best to do that. It is imperative that educators be innovative, creative, and purposeful in the creation of course content and assessment in order to ensure that students are not only building on the technical skills and content knowledge areas the industry requires, but more importantly, the soft skills that experts have deemed vital for students entering the workforce.

5. Conclusions

The results of this research will add to the existing body of research on the topic of graphic communications competencies, and the conclusions drawn from this study align with previous research. This study, along with the study conducted by Smith (2014), found that experts overwhelmingly determined that soft skills are the most needed graphic communications competencies. In addition, this research revealed that the majority of most needed tools are software applications or digital-based tools. The results from this study provide higher education graphic communications programs with an instrument to evaluate current curriculum offerings as well as determine which tools and equipment may be obsolete and/or what new tools may now be necessary. It is the obligation and responsibility of graphic communications educators to apply these findings in order to ensure that students are being adequately prepared to enter the industry, and are also prepared to adapt to the continuously evolving technological advancements inherent to the graphic communications field. In closing, the importance of this study can be summarized by a request for participation response I received from an industry participant stating, "We are very much in need of a qualified pipeline of full-time employees in this field."

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TOPICALITIES

Edited by Markéta Držková

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News & more

A yearly update on CIE publications

Among the publications from the International Commission on Illumination (CIE) issued since the previous overview provided in JPMTR 8(2019)4, the full papers of the presentations from the three-day technical conference held in June 2019 in Washington, DC, USA are collected in Volume 1 of the Proceedings of the 29th Session of the CIE (CIE x046:2019), comprising the majority of over 1 900 pages the proceedings have in total. Volume 2 with the quadrennial officers' and technical reports, as well as the reports on workshops, is freely available on the CIE website.

The new technical reports include CIE 236:2019, published at the end of 2019 and providing a summary of empirical data on lighting for pedestrians as a basis for future revisions to lighting design standards, CIE 238:2020 dealing with optical measurement methods, instrumentation and procedures to reproducibly characterise AC-driven light-emitting diodes for solid-state lighting applications thanks to accurately set and controlled junction temperature, and CIE 241:2020, which provides CIE recommended reference solar spectra for industrial applications (this document cancels and replaces CIE 085-1989). To facilitate systematic investigations of responses to light influenced by ipRGC (intrinsically-photosensitive retinal ganglion cells), CIE prepared freely available technical note CIE TN011:2020 with the guidance what to document and report in studies on this topic.

In reaction to COVID-19 pandemic, CIE made temporarily available for free two of its relevant documents: CIE 155:2003 Ultraviolet air disinfection and CIE 187:2010 UV-C photocarcinogenesis risks from germicidal lamps, downloaded by more than 14 thousand users. Also, the Russian translation of the latter publication was issued. Now, the content of these publications is summarised in the new CIE Position Statement on the use of ultraviolet radiation to manage the risk of COVID-19 transmission, explaining the most important aspects of the use of UV-C radiation (100–280 nm). While UV-C is highly effective in disinfection and sterilisation, it can be very hazardous to humans and animals as well as to cause photodegradation of the exposed materials. On the other hand, UV-C products that are safe for general use may not be effective in reducing the risk of virus transmission.

In cooperation with the International Organization for Standardization, namely with its technical committee ISO/TC 274 Light and lighting, CIE works on the revision of ISO 11664-2:2007 (CIE S 014-2:2006) to be released as the first edition of ISO/CIE 11664-2 Colorimetry – Part 2: CIE standard illuminants. The document defines the CIE standard illuminants A, D65 and D50 along with the sources for realizing these three illuminants. It also provides the appropriate theoretical and experimental basis and correlated colour temperatures for both daylight illuminants. The illuminants' relative spectral power distributions are included in Annex, with values at 1 nm intervals from 300 nm to 830 nm.

The sections on the next page present the publications that are more of interest to the field of print and media technology.

Research and other activities of Fogra in 2020

From the areas covered by Fogra, almost half of projects in the 2020 research programme were concerned with prepress technology. The project investigating the possibilities for improving the readability of barcodes and matrix codes with regard to high-speed inkjet printing ended in spring. According to the results, the best performance was achieved with the barcodes aligned parallel to the print head and output in true black; the quality was also influenced by the bar width reduction. A tool developed for the corresponding PDF data verification is available free of charge within Callas software pdfToolbox. The agreement between the reading devices decreased with lower-quality codes. Recently has been finished the project focused on a colour-accurate soft proof for 3D objects, which involved characterisation of the process to acquire the material data, development of the rendering algorithm and integration of both into the iccMAX- framework.

The area of full-colour 3D printing is further explored in an ongoing project aiming to significantly streamline the characterisation and profiling processes thanks to the optical characterisation of the components produced by Polyjet and Multijet fusion technology. Another ongoing prepress project deals with colour communication in multi-primary printing. The new project running since June 2020 in cooperation with the Institute of Imaging & Computer Vision at the Aachen University aims to utilise machine learning for dynamic evaluation of image style, helping to select images suitable for a given purpose. The second project that started this year is also related to prepress technology; its goal is to design a standardisation concept to improve colour communication in digital textile printing.

In other areas of research, the topics currently studied at Fogra cover the classification of papers for high-speed inkjet printing, modelling of changes in colour appearance due to both matt and gloss coatings of known thickness, and improved bending analysis of smart cards for better predictability of their service life. Among the recently finished Fogra projects, three comprised the research on characterisation and testing. The two lasting till spring 2020 include further development of the laboratory method for the determination of the residual strength of papers for heat-set web-offset printing, in order to meet the current conditions of print production, and the new test system for the evaluation of wettability and surface purity, which is based on two ink sets intended for surfaces that are predominantly either polar or non-polar and a so-called master ink to determine which set to use. This project also involved the development of a standardised method for ink application and software-supported evaluation procedure. The third one, finished this autumn, aimed to develop a method for characterisation of metallic prints. To establish objective parameters that correlate with their visual appearance, the work included the colour and gloss measurements of metallised print samples together with the development of a viewing technique allowing a clear assessment of the metallic effect. The last project that ended in the past months was carried at the Materials & Environment department of Fogra. It was dealing with a printable primer system for direct printing on glass, in particular on reusable beverage bottles, with the aim to achieve optimum adhesion both to the substrate and the UV-curing inks, and thus sufficient durability of the print.

During the past year, Fogra has also started the new one-year Fogra Web Academy as an additional option to the established on-site training courses. The one-hour online webinars in English are offered on Mondays since September 2020 and include 15 sessions, with each of them covering one fundamental topic and one special topic.

CIE S 017/E:2020 – ILV: International Lighting Vocabulary

This is the 2nd edition of the International Lighting Vocabulary published as a CIE standard. This version cancels and replaces CIE S 017/E:2011 and CIE S 017-SP1/E:2015. The vocabulary, which was first published in 1938, provides the definitions and essential explanations for radiation, quantities and units, vision, colour rendering, colorimetry, emission, optical properties of materials, physical detectors for radiometric, photometric and colorimetric measurements, actinic effects of optical radiation, light sources, components of electric light sources and auxiliary apparatus, lighting technology and daylighting, luminaires and their components, visual signalling, and imaging. The online version of the vocabulary is available on the CIE website. Since 2015, all activities regarding the ILV are coordinated by CIE JTC 8. That includes maintaining and updating the terms and definitions by CIE Divisions 1–6 and 8, as well as their harmonisation with IEC 60050-845 International Electrotechnical Vocabulary – Lighting and ISO 80000-7 Quantities and units – Part 7: Light and radiation. The new ILV from December 2020 comprises 248 pages and presents the definitions of 1 347 terms.

CIE 237:2020 – Non-linearity of optical detector systems

This technical report prepared under Division 2, Physical Measurement of Light and Radiation, reviews the reasons for non-linearity of detectors, their operating circuits, measurement conditions, detector signal measurement modes and preamplifier output measurements. It also covers the non-linearity of detector arrays and avalanche photodiodes. The last part discusses the methods and approaches for the determination of linearity.

CIE 239:2020 – Goniospectroradiometry of optical radiation sources

Another technical report elaborated under Division 2 deals with the measurement of the spectral distribution as a function of the emission angle of the source. It describes conditions, equipment and methods for goniospectroradiometric measurement, calculation of radiometric, photometric and colorimetric quantities, calibration, and measurement uncertainties.

CIE 240:2020 – Enhancement of images for colour-deficient observers

Prepared by the appointed committee under Division 1, Vision and Colour, this technical report summarises on over 60 pages the methods used to enhance images to be easily recognised by colour-deficient observers. The document presents use cases and their requirements for image enhancement for colour-deficient observers and details the enhancement techniques based on recolouring, edge enhancement and pattern superposition, along with their comparison. It also provides three types of images (a natural image, a scientific visualisation and an office document) for testing of the enhancement techniques and describes different evaluation methods. The annexes include assessment and groups of colour-deficient observers, colour-difference metric and a glossary with the relevant terms.

CIE 242:2020 – Photometry of curved and flexible OLED and LED sources

This technical report from Division 2 reflects the progress in the field of flexible products and describes the methods of measuring photometric and colorimetric quantities for curved sources, including luminance, luminous flux, colour, reflectance and viewing angle.

Bookshelf

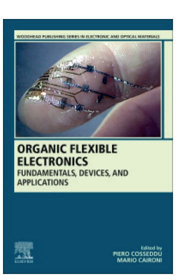
Organic Flexible Electronics
Fundamentals, Devices, and Applications

This new book with 70 contributors aims to bring a comprehensive and timely review in the field, from basic concepts of organic electronics to novel approaches to the design and fabrication of different electronic devices making use of new materials, technologies and architectures. The volume also presents a number of innovative and promising applications of flexible organic electronics.

The first chapter introduces the fundamentals of organic electronic devices, such as the charge-carrier transport and metal–semiconductor interfaces, and presents the main differences between organic and inorganic electronics. The next eight chapters deal with the materials for flexible organic electronics and their properties, detailing the development of conjugated polymers, electronic and ionic transport, chemical doping, interface energetics in organic electronic devices, thermoelectric and mechanical properties, as well as the encapsulation of flexible devices employing suitable barrier structures to ensure the long-term stability.

The next part explores the advances in flexible organic devices, namely the most significant achievements in the inkjet-printed organic and perovskite solar cells together with the remaining challenges for inkjet fabrication of active layers and electrodes, the thermoelectric generators for the energy harvesting of waste heat, the materials and designs of flexible alkali-ion batteries, the progress in 3D integration of organic printed transistors and circuits with a focus on modelling and simulations for their development, the amplifier topologies employing organic thin-film transistors including both unipolar and complementary solutions, the ultra-conformable organic devices for different purposes, and the stretchable electrodes for highly flexible electronics.

Finally, among the novel applications, one chapter discusses the organic biosensors and bioelectronics, especially the biosensors based on electrolyte-gated organic transistors, their mechanism and specific applications such as the detection of proteins. Another one presents the use of flexible organic electronics for the development of neuromorphic computing systems, mimicking and implementing essential concepts of the brain in hardware. Also here, in a future outlook, a particular focus is on interfacing with biological environments. The next chapter is dedicated to the emerging technology of flexible and large-area imagers using solution-processed organic photodetectors, including the recent developments towards the curved X-ray detectors and biometric scanners. The last chapter reviews the progress in the area of organic, flexible and wearable monitoring systems for biomedical applications, presenting the most interesting devices and systems in biomechanics, clinical electrophysiology and bioelectronics, which can be more easily and possibly imperceptibly integrated directly onto a human body.



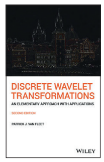
Editors: Piero Cosseddu, Mario Caironi

Publisher: Woodhead Publishing
1st ed., October 2020
ISBN: 978-0-12-818890-3
664 pages
Softcover
Available also as an eBook

Discrete Wavelet Transformations
An Elementary Approach with Applications

Author: Patrick J. Van Fleet

Publisher: Wiley
2nd ed., April 2019
ISBN: 978-1118979273
624 pages
Hardcover
Also as an eBook

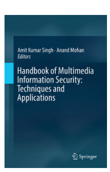


The changes in the second edition of this textbook are based on the feedback received for the original one. After introducing wavelets and providing the basics of vectors, matrices and digital images, the text explains the Haar and Daubechies wavelet transformations, wavelet shrinkage and its application to signal denoising, biorthogonal wavelet transformations, complex numbers and Fourier series, filter construction in the Fourier domain, wavelet packets, lifting, and the JPEG2000 image compression standard. The book includes numerous exercises and basic statistics in the appendix.

Handbook of Multimedia Information Security
Techniques and Applications

Editors: Amit Kumar Singh, Anand Mohan

Publisher: Springer
1st ed., August 2019
ISBN: 978-3030158866
808 pages, 369 images
Hardcover
Also as an eBook



The content of this book is organised into three parts that review the topics in multimedia security, processing and applications. Several chapters deal with biometrics, encryption and watermarking methods, image processing techniques for various purposes and the use of multimedia in medicine and the Internet-of-Things. The book also presents the face identification system, analysis of streaming data, digital image forensics with the methods for forgery detection, and more.

Pioneers of Color Science

This book presents the history of colour science through brief descriptions of lives and scientific work of almost hundred pioneering figures in the field, having background mainly in physics or psychology, but also in chemistry, mathematics, optical engineering, physiology and art. The content is organised chronologically into five parts, dedicated to the era of antiquity, the Islamic Golden Age, the Middle Ages and the Renaissance, the Age of Enlightenment, and the period from the 19th century to present. The last part comprises about two-thirds of all essays. The span illustrates the collage by the first author, beginning with a part of the painting 'School of Athens' by Raphael depicting the antique philosophers with Plato and Aristotle at the centre, and ending with the photograph of David L. MacAdam and Gunter Wyszecki (with Ernst Ganz and Alan R. Robertson who are not presented in the book) taken by Fred W. Billmeyer at a CIE Meeting, which is merged with the CIE chromaticity diagram. The text includes several contributions from other authors, which were modified for this book after being published in the first edition of the Encyclopedia of Color Science and Technology, see this section in JPMTR 5(2016)3, or which are planned to appear in the second edition of the encyclopedia.

Authors: Renzo Shamey, Rolf Kuehni

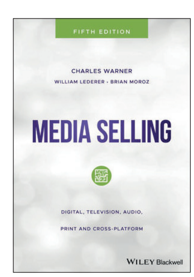
Publisher: Springer
1st ed., November 2020
ISBN: 978-3-319-30809-8
431 pages, 198 images
Hardcover
Available also as an eBook

Media Selling
Digital, Television, Audio, Print and Cross-Platform

The current edition of this classic textbook on media selling by Ch. Warner has been thoroughly updated to reflect the vast changes in the media and advertising that took place since the fourth edition published a decade ago. The fifth edition includes the chapters 'Researching insights and solutions' and 'Google and search' by B. Moroz and the chapters 'Programmatic marketing and advertising' and 'Measuring advertising' by W. Lederer. It also covers cross-platform selling, Facebook and other social media, podcasting, etc. Overall, the book focuses on personal selling and the changes in approaches and skills it requires, while emphasising sales ethics. The book includes a glossary for digital advertising and links to materials available on the accompanying website; also, instead of future outlook, it provides links to the sources where readers can follow the news relevant to the topic.

Authors: Charles Warner, William A. Lederer, Brian Moroz

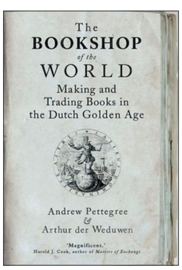
Publisher: Wiley-Blackwell
5th ed., August 2020
ISBN: 978-1-119-47739-6
576 pages
Softcover
Available also as an eBook



The Bookshop of the World
Making and Trading Books in the Dutch Golden Age

The authors of this volume on Dutch book history provide rich information about the topic over the course of 150 years, building on comprehensive research and detailed analysis that allowed to show the interesting points and reveal new insights. The content documents the importance of print and the Dutch bookselling industry in early modern Europe. In the 17th century, the most books per capita were published in the Dutch Republic; the book industry products were bought by its citizens, contributing to a literate and well-informed population, and also constituted one of the major exports. It was possible thanks to the important innovations in print marketing and selling, which included newspaper advertising and book auctions, where millions of books were traded. Besides the books produced by the Dutch, their international book trade also involved large numbers of imported and re-exported books.

While many of the books published in this Dutch era belong to the masterpieces, the authors pay attention to all kinds of printed matter of that time to get a complete picture and better understand the evolution of the society. The survey includes the newspapers, different non-commercial prints, such as official ordinances or student dissertations, as well as the books intended for practical use, most of which had worn out and become forgotten. The text is complemented by carefully selected illustrations. The softcover edition of the book is available since September 2020.



Authors: Andrew Pettegree, Arthur der Weduwen

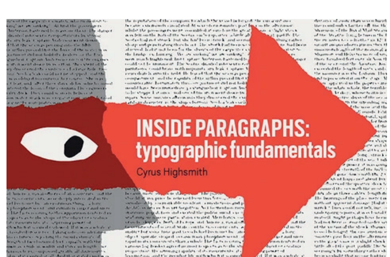
Publisher: Yale University Press
1st ed., April 2019
ISBN: 978-0-300-23007-9
496 pages, 70 images
Hardcover

Inside Paragraphs
Typographic Fundamentals

This book demonstrates the role of space within a letter, a word, a line and a paragraph through lucid descriptions and illustrated examples, generously presented on page spreads in a landscape format. The author explains the essential typographic concepts and terms in relation to readers' experience in an effective and engaging manner. After several translated editions issued since its first publication in 2012, the book is now available in the updated English edition and with a new preface.

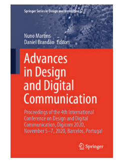
Author: Cyrus Highsmith

Publisher: Princeton Architectural Press
2nd ed., August 2020
ISBN: 978-1-61689-941-7
104 pages, 62 images
Softcover



Advances in Design and Digital Communication

Editors: Nuno Martins, Daniel Brandão

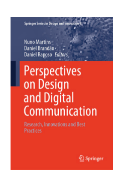


Publisher: Springer
1st ed., November 2020
ISBN: 978-3030616700
617 pages, 276 images
Hardcover
Also as an eBook

The contributions in the Proceedings of Digicom 2020, the 4th International Conference on Design and Digital Communication held this November as an online event, are divided into four parts focused on digital and interaction design, design strategies and methodologies, pedagogy, society and communication in design practice, and graphic design and branding. The topics include, among others, the display issues with the Indian typefaces in digital platforms, a new tool for type design education, the future of film posters, the marketing and design perspectives on brands and rebranding, the soft skills developed in the transnational graphic design education in Sri Lanka, the benefits of visual representation of design process, and also the effect of visual communication in COVID-19 prevention and risk mitigation.

Perspectives on Design and Digital Communication
Research, Innovations and Best Practices

Editors: Nuno Martins, Daniel Brandão, Daniel Raposo



Publisher: Springer
1st ed., July 2020
ISBN: 978-3030496463
238 pages, 87 images
Hardcover
Also as an eBook

This volume includes 15 chapters from the authors of the best papers presented at the 3rd edition of Digicom, the conference mentioned above, held in November 2019 in Barcelos, Portugal. They discuss, for example, the intersections between printed and digital media and the design of interactive narratives.

Plastics
Microstructure and Engineering Applications

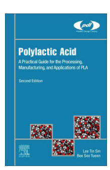
Authors: Nigel Mills, Mike Jenkins, Stephen Kukureka

Publisher: Butterworth-Heinemann
4th ed., February 2020
ISBN: 978-0081024997
336 pages, Softcover
Also as an eBook

The current edition of this classic textbook on the properties and engineering of plastics, emphasising the specific aspects of mechanical design, has been substantially revised to reflect the progress in the fields relevant for plastic materials, including new insights into their microstructure and electrical properties, 3D printing, ageing, sustainability, life-cycle analysis and waste disposal considerations.

Polylactic Acid
A Practical Guide for the Processing, Manufacturing, and Applications of PLA

Authors: Lee Tin Sin, Bee Soo Tueen



Publisher: William Andrew
2nd ed., June 2019
ISBN: 978-0128144725
422 pages, Hardcover
Also as an eBook

This guide begins with the overview of biodegradable polymers; then, it details the synthesis and production of poly(lactic acid), followed by its thermal, chemical, mechanical and rheological properties, as well as degradation and stability. The second edition also covers the use of additives and processing methods for poly(lactic acid), including their recycling requirements. One chapter is dedicated to injection moulding and 3D printing, which is further discussed among the applications of poly(lactic acid) in the next chapter. The last one then reviews the environmental assessment and international standards of polymer biodegradation.

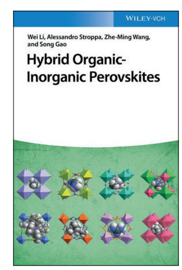
Hybrid Organic-Inorganic Perovskites

The authors of this timely book review the recent developments of hybrid perovskites enabled by the homogeneous integration of organic and inorganic components at an atomic level. The opening chapter provides the background on perovskite oxides and the incorporation of organic components resulting in hybrid organic-inorganic perovskites, along with their classification and chemical variations. This chapter also outlines the structure, crystal symmetry, tolerance factor and physical properties of different hybrid perovskites, dependent on their composition, and explains the processes involved in their phase transitions.

The main content is clearly organised into eight chapters describing the individual types of hybrid perovskites – their synthesis, structures, phase transitions and specific physical properties. These include five chapters dedicated to hybrid halide, formate, azide, dicyanamide and cyanide perovskites, a joint chapter on hybrid dicyanometallate and borohydride perovskites, another one on hypophosphite perovskites, and the last one, which reviews other perovskite-like hybrid materials, namely the hybrid organic-inorganic perchlorates and tetrafluoroborates, and metal-free perovskites. Finally, the last chapter discusses the future research directions, challenges and opportunities in the field.

Authors: Wei Li, Alessandro Stroppa, Zhe-Ming Wang, Song Gao

Publisher: Wiley-VCH
1st ed., October 2020
ISBN: 978-3-527-34431-4
292 pages
Hardcover
Available also as an eBook

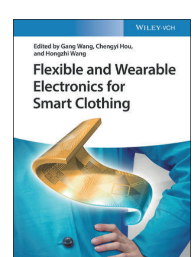


Flexible and Wearable Electronics for Smart Clothing

The first two parts of this book review the applications in sensing, presenting wearable organic nano-sensors, stimuli-responsive electronic skins and flexible thermoelectrics, and the applications for energy harvesting and storage, which include triboelectric nanogenerators, solar cells and supercapacitors, and lithium-ion batteries. The third part deals with the interaction of smart clothes with the human body, discussing thermal and humidity management, functionalisation of fibre materials, and flexible microfluidics for wearable electronics. The last part begins with a chapter on piezoelectric flexible bio-integrated electronics and then explores various processes and materials for fabrication of flexible and printed electronics for smart clothes, including the strategies of production upscaling.

Editors: Gang Wang, Chengyi Hou, Hongzhi Wang

Publisher: Wiley-VCH
1st ed., June 2020
ISBN: 978-3-527-34534-2
360 pages
Hardcover
Available also as an eBook



Bookshelf

Academic dissertations

Synthesis and Investigation of Functional Tröger's Base Molecules for Optoelectronic Applications

This thesis contributes to the research on organic compounds applicable in optoelectronic devices. Namely, it deals with tetracyclic Tröger's base molecules with two tertiary amine groups, exhibiting a specific rigid V-shaped chiral structure. The aim of the thesis was to synthesise and investigate novel functional Tröger's base compounds to be used as charge-generating double-acceptor dyes for dye-sensitised solar cells, solid-state light-emitting materials for organic light-emitting diodes, and well-performing amorphous hole-transporting materials for perovskite solar cells. The dissertation reviews the synthesis of Tröger's base, its reactions and analogues along with their use. The main part describes the series of experiments comprising the synthesis and characterisation of novel Tröger's base compounds. Four chapters explore their application as hole-transporting materials. Here, Tröger's base core was combined either with triphenylamine moieties that could be further extended by phenylethenyl moieties, or with TPD (N,N′-bis(3-methylphenyl)-N,N′-diphenylbenzidine) moieties, or with enamine-linked diphenyl branches. For all types, derivatives having methyl- or methoxy-substituents were prepared as well. The work presents thermal, optical and photoelectrical properties of all synthesised compounds. Except for the first type with the smallest molecules, their performance in perovskite solar cells was also successfully tested. Next, two chapters deal with metal-free sensitisers for dye-sensitised solar cells based on Tröger's base scaffold with triphenylamine and rhodanine-3-acetic acid moieties and their improvement by phenyl-branched hydrazone units. Then, the light-emitting materials containing tetraphenylethenyl moieties and Tröger's base core are presented. All measurements and materials are detailed before the conclusions.

Doctoral thesis – Summary

Author:
Titas Braukyla

Speciality field:
Chemistry

Supervisor:
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Defended:
20 September 2019,
Kaunas University of Technology,
Faculty of Chemical Technology,
Department of Organic Chemistry
Kaunas, Lithuania

Contact:
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Image-Based Bidirectional Reflectance Measurement of Non-Diffuse and Gonio-Chromatic Materials

The general focus of this thesis was on a time- and cost-efficient way for optical characterisation of flexible packaging print materials that require bidirectional measurements. The aim was to investigate the possibility to use an image-based measurement setup to perform bidirectional reflectance measurements of flexible and homogeneous packaging print materials with complex optical properties. The thesis was also concerned with an analytical estimation of the bidirectional reflectance distribution function (BRDF) of materials using different reflectance models and a representation of material appearance from the data obtained using this measurement setup.

The dissertation provides the background on visual appearance and packaging print materials, bidirectional reflectance measurements and representation of BRDF, with an emphasis on the analytical BRDF models, and then presents the research work. The image-based measurement setup employed a halogen tungsten lamp of a film projector as a uniform point light source, illuminating the sample fixed on a cylinder of known radius, and a commercially available digital single-lens reflex camera as a detector. The positions of the light source, the detector and the sample were fixed, with

Doctoral thesis – Summary

Author:
Aditya Suneel Sole

Speciality field:
Colour Imaging

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Ivar Farup

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5 December 2019, Norwegian University of Science and Technology, Faculty of Information Technology and Electrical Engineering, Department of Computer Science
Gjøvik, Norway

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every point on the curved material surface making the corresponding incident and viewing directions with respect to the normal at that point. Each pixel in the image captured by the camera corresponds to a point on the curved sample surface. The BRDF of the measured sample was calculated from the captured image using the determined spectral sensitivity of the camera sensor. The measurement accuracy of this setup applied for flexible, homogeneous and isotropic packaging print materials was estimated by comparing it with two commercially available gonio-spectrophotometers. The uncertainty in estimating the incident and viewing directions, which was large due to the error in performing physical measurements, and the error in calculating the conversion matrix using the measured camera spectral sensitivities were identified as two main sources of error of the tested image-based measurement setup. Further studies investigated the applicability of the image-based measurement setup for packaging print materials with different reflectance properties ranging from diffuse to non-diffuse and gonio-chromatic. The highly non-diffuse materials required multiple-exposure captures to obtain an image with high dynamic range. The BRDF of the materials was estimated using different analytical reflectance models and parameters optimised using an appropriate cost function. The non-diffuse and gonio-chromatic reflectance properties were then visualised using BRDF estimated with optimal measurement dataset.

Doctoral thesis – Summary

Author:
Jianfang Zheng

Speciality field:
Electrical Engineering

Supervisors:
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Zachary D. Taylor

Defended:
10 February 2020, Aalto University, School of Electrical Engineering, Department of Electronics and Nanoengineering
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Millimeter-Wave Antennas on Flexible Substrates: Roll-to-Roll Reverse-Offset Printing and Probe Station-Based Characterization

The research within this thesis dealing with the next-generation communication systems operating at millimetre-wave frequencies addressed the challenges related to the requirements on manufacturing and characterisation of the antenna. The chosen approach to low-cost and high-resolution fabrication of millimetre-wave antennas on flexible substrates employs roll-to-roll reverse-offset printing. The thesis also systematically studies the methods to quantify radiation performance in terms of gain and radiation pattern for the on-wafer antennas in a probe station environment. The dissertation introduces the topic and the roll-to-roll reverse-offset printing technique capable of producing micron-sized features, discussing the suitable printing substrates and conductive inks as well as the need for supporting pillars when printing large conductive areas in order to avoid pattern distortion caused by the elasticity of the polydimethylsiloxane blanket. The design simulations accounted for the holes resulting from the use of tiny supporting pillar structures. The results for W band (75–110 GHz) indicated a strong positive correlation between the loss and the number of holes. The design comprised microstrip patch antenna structures fed with coplanar waveguide transmission lines. The samples were produced by roll-to-roll reverse-offset printing of silver nanoparticle ink dispersed in ethanol on polyethylene naphthalate substrate, with the ground on the backside evaporated separately. The measurements in an on-wafer probe station confirmed sufficient conductivity of the printed ink layers for millimetre-wave antennas. The measured magnitude of broadside realised gain reached 4.5 dBi. The second part of the work presents the method of antenna gain measurement using a specular conductor plate as a reflector instead of the second antenna to reduce the complexity of the measurement system. The considerations included the influence of reflector size on measurement accuracy estimated using physical optics and simulations of both ideally and imperfectly aligned reflector. By adding a rotator in the setup, the one-antenna method also allows the measurement of antenna radiation patterns. The proposed method was applied to antennas with different beam directions.

Events

EI 2021 – IS&T International Symposium on Electronic Imaging

electronic IMAGING 2021

https://www.imaging.org
18–21 & 25–28 January 2021

The schedule of the 2021 online edition combines the sessions of 18 technical conferences, featuring about 30 keynotes and four plenary speakers. In the first week, participants can hear from Michal Irani, presenting deep internal learning without any prior examples or training data, and Kenneth A. Parulski, reviewing the development of integral colour image sensors from the early beginning to opportunities for the future. The second week opens the plenary by Ramesh Raskar sharing highlights of femto-photography, which enables unique imaging and computer vision applications. The last plenary speaker is Luca Verre presenting the principle of event-based vision and its application in new bio-inspired machine vision systems.

The conference is preceded by a five-day short-course programme in the week of 11 January, which this year offers 23 short courses. These include two new courses, one presenting hardware of 3D imaging systems and its calibration and the other introducing the event detection camera, and several updated courses, dealing with the resolution in mobile imaging devices, compact camera modules for augmented and virtual reality, automotive and machine vision applications with a focus on colour, optics and calibration, and sources of camera noise and its characterisation. All recordings of short courses and technical sessions can be then accessed until 30 April 2021.

FLEX 2021

FLEX 2021 VIRTUAL EVENT FEB 22-26 | 20 YEARS of Driving Innovation to Make the World Safer

https://flex.semi.org/
22–26 February 2021

The agenda of the 20th anniversary of the FLEX conference and exhibition includes four session days dedicated to flexible hybrid electronics systems, materials processing, sensors and micro-electro-mechanical systems, and sustainability and power, which are followed by a day with virtual tours and demonstrations. Participants can preview the presentations during the preceding week (15–21 February) and prepare their questions for the live event that each day combines keynotes, panel discussions, short talks from expert speakers, student posters, and more. The approved content then remains available for on-demand access until 26 March 2021.

The keynote topics announced so far include the approaches to safe and responsible development and deployment of advanced nanomaterials needed to identify and mitigate potential health and environmental hazards presented by Charles Geraci, Jr., recent advances in the interfacing of electronics with the human brain reviewed by George Malliaras, the progress in safe and high-performance power sources with respect to their chemistry, device architecture, manufacturing and integration explored by Christine Ho, as well as additive manufacturing of flexible printed circuit boards by Masaaki Sugimoto and the MicroLED display technology by Falcon Liu.

Changes in the calendar of events continue in 2021

The Color 2021 conference hosted by the PRINTING United Alliance was at first postponed to June and then fully cancelled. The next edition is scheduled for January 2022. The sessions of the PRINTING United Digital Experience successful autumn event are freely available on-demand through the end of January 2021.

Similarly, the TAGA Annual Technical Conference has been rescheduled to March 2022. However, the Technical Association of the Graphic Arts will publish the 2021 Proceedings and the call for papers is still open, so as for the 2021 TAGA Student Competitions. This time, groups compete with the electronic journals of student research instead of the traditional printed ones, which is an opportunity to engage more institutions worldwide. The Levenson Undergraduate Student Paper and Rhodes Graduate Student Paper competitions for individuals are open to all students in higher education, regardless of TAGA chapter membership.

The PrintPack India 2021 Exhibition has been postponed from February, with new dates yet to be announced. The next edition of Graphispag in Barcelona, Spain is moved from 2021 to May 2022. The FESPA Brasil show in São Paulo is still announced for 24–27 March 2021. The Labelexpo Americas 2021 show to be held in Rosemont, Illinois, USA, and previously planned for March, is now scheduled for 8–10 June 2021. The other events moved from March to June 2021 include Packaging Innovations and Empack Birmingham (announced for 17–18 June) and the 5th International Exhibition of Print Technology for Industrial Manufacturing held in Germany, InPrint Munich (22–24 June). The latter one is co-located with the 12th International Converting Exhibition and the 5th International

Exhibition for the Corrugated and Folding Carton Industry. Similarly, the London Book Fair is currently rescheduled from March to summer (29 June to 1 July 2021). Considering the ongoing pandemic situation, all dates listed above are tentative.

Last but not least, the drupa trade fair has been cancelled also for 2021, with a four-day digital event, virtual.drupa, announced within the period originally planned for drupa 2021, from 20 to 23 April.

Other online events held in the first months of 2021

The 24th edition of SGI Dubai 2021, the Sign & Graphic Imaging show, takes place online on 18–20 January (https://www.signmiddleeast.com). Among the Jakajima events, the 8th 3D Printing Electronics Conference is held on 21 January (https://www.3dprintingelectronicsconference.com); later, on 9 March, the 6th edition of the 4D Printing & Meta Materials Conference can be joined (https://www.4dpmmconference.com). The courses of the IMI Europe Inkjet Winter Workshop 2021 (https://imieurope.com), as well as the EFI Engage Virtual Conference sessions (https://www.efi.com), are offered between 25 January and 5 February.

The Digital Document Security conference is held on 3–4 February (https://digitaldocumentsecurity.com), followed by the 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications, VISIGRAPP 2021 on 8–10 February (http://www.visigrapp.org), the World Congress on Textile Coating on 11–12 and 18–19 February (https://www.technical-textiles.net), and the Digiday Publishing Summit Worldwide LIVE on 24–26 February (https://digiday.com). Next month, the Digital Media India 2021 takes place on 2–4 March (https://events.wan-ifra.org), the trade fair and conference LOPEC 2021 on 23–25 March (https://www.lopec.com), and the Intergraf Currency+Identity Conference and Exhibition on 24–26 March (https://intergrafconference.com).

innoLAE 2021
Innovations in Large-Area Electronics

http://innolae.org
22–25 February 2021

The 7th annual innoLAE event is organised by IMI Europe and held online. Its programme begins with two half-day courses covering the wet and dry processing technologies for large-area electronics and the industry networking day. The conference on the next two days offers both oral and poster presentations, with a dozen invited talks confirmed up to now. The schedule features the keynotes on ‘Skin-inspired electronics and sensors’ by Zhenan Bao, ‘Novel bio-electronics for ICU-grade monitoring in premature neonates’ by Steve Xu, and ‘Enabled textiles that transform human connectedness in a socially distant world’ by Tony Chahine.

SPIE Events

Photonics West 2021

https://spie.org
6–11 March 2021

The 2021 edition of this event that belongs to the main ones organised by SPIE is also transformed into the Digital Forum. A free online series of photonics webinars, Photonics West Preview, can be joined on 25–28 January. During the Photonics West in March, only Digital Marketplace and industry sessions can be attended for free.

Across individual conferences of the Photonics West Digital Forum, numerous contributions present the research involving printing. These include the keynote presentation on high-speed polymer 3D printing and several other papers within the 8th Laser 3D Manufacturing conference, invited talks on 3D micro-printing, micro-transfer printing and micro-solid printing processes and their applications, presentations dealing with printed polymer optical waveguides, polarising beam-splitter, resonant nanocones for THz field-driven photoemission, and more.

Smart Structures / Nondestructive Evaluation 2021

https://spie.org
7–10 March 2021

This SPIE Digital Forum organised in the same period also features many applications of printing technology. The topics cover the inkjet printing of mm-scale electrostatic actuators, electrical and mechanical characterisation of medical-grade silicones in dielectric elastomers produced by aerosol-jet printing, performance evaluation of 3D-printed magnetorheological elastomers, 3D-printed polypyrrole biosensors with integrated pH-activated drug delivery, and the non-contact health monitoring system for gears manufactured by printing conductive ink, for example. The programme also includes the invited talk discussing printed skin-conformal bioelectronics for wireless continuous stress monitoring and management, and the session on 3D Printing and Novel Materials presenting, among others, the method that enables 3D printing with the high-concentration nanocellulose ink.

Journal of Print and Media Technology Research
A PEER-REVIEWED QUARTERLY

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ISSN 2223-8905 (Print)
CODEN JPMTBI
UDC 665

Call for papers

The Journal of Print and Media Technology Research is a peer-reviewed periodical, published quarterly by iarigai, the International Association of Research Organizations for the Information, Media and Graphic Arts Industries.

JPMTR is listed in Emerging Sources Citation Index, Scopus, Index Copernicus International, PiraBase (by Smithers Pira), Paperbase (by Innventia and Centre Technique du Papier), NSD – Norwegian Register for Scientific Journals, Series and Publishers.

Authors are invited to prepare and submit complete, previously unpublished and original works, which are not under review in any other journals and/or conferences.

The journal will consider for publication papers on fundamental and applied aspects of at least, but not limited to, the following topics:

- **Printing technology and related processes**
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- **Premedia technology and processes**
  Colour reproduction and colour management; Image and reproduction quality; Image carriers (physical and virtual); Workflow and management

- **Emerging media and future trends**
  Media industry developments; Developing media communications value systems; Online and mobile media development; Cross-media publishing

- **Social impact**
  Environmental issues and sustainability; Consumer perception and media use; Social trends and their impact on media

Submissions for the journal are accepted at any time. If meeting the general criteria and ethic standards of scientific publishing, they will be rapidly forwarded to peer-review by experts of relevant scientific competence, carefully evaluated, selected and edited. Once accepted and edited, the papers will be published as soon as possible.

There is no entry or publishing fee for authors. Authors of accepted contributions will be asked to sign a copyright transfer agreement.

Authors are asked to strictly follow the guidelines for preparation of a paper (see the abbreviated version on inside back cover of the journal).

Complete guidelines can be downloaded from: <http://iarigai.com/publications/journals/guidelines-for-authors/>
Papers not complying with the guidelines will be returned to authors for revision.

Submissions and queries should be directed to: journal@iarigai.org

Journal of
Print and Media Technology Research
A PEER-REVIEWED QUARTERLY

Vol. 10, 2021

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The text should be cohesive, logically organized, and thus easy to follow by someone with common knowledge in the field. Do not include information that is not relevant to your research question(s) stated in the introduction.

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