COMPARATIVE ANALYSIS OF COLOR REPRODUCTION IN DIGITAL AND FLEXOGRAPHIC PRINTING OF PACKAGING MATERIAL

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Abstract

The study sought to answer the question of how a given digital printing technology reproduces colours on a typically frequently used packaging material (20µ thick transparent polypropylene) as a printing substrate, and how the colour reproduction characteristics of digital and flexographic (flexo) printing compare. The study revealed the impact of prepress (printing plate production technology) on colour reproduction in flexographic printing. The research focused on 10 flexographic printing samples produced using different printing plate production processes and/or different printing machines. Similarly, a sample was produced using a digital printing process on an HP Indigo 20000 printing machine. The print sample used for the CMYK colour space tests was a GMG Flexo chart.
By measuring, comparing, and evaluating the colour profiles of the 11 print samples, it was found that both digital and flexographic printing technologies can cover approximately half of the Lab colour spectrum. Both the technology and type of printing plate production and the screen structure used on the printing plate have a clear impact on the colour gamut reproduction capability of flexographic printing.

Keywords: *Packaging material printing, flexography, digital printing, scene reproduction.*

1. PRINTING PROCESSES IN PACKAGING PRODUCTION

All major printing processes are employed in the production of packaging materials [1]. The principal processes include flexography, offset lithography, screen printing, and digital printing [1, 2]. For many years, flexography has been one of the most significant and frequently applied printing technologies within the packaging industry [3]. When compared to other printing methods, flexography offers several considerable advantages [4]. Consequently, it has become one of the most widely used printing processes in packaging production across North America, Latin America, and Europe (HP Inc., 2016). According to Henry [5], the flexible packaging segment represents a broad market in which flexography dominates, accounting for approximately 75% of total market share, while digital printing holds only about 1%. Bates et al. [6] identified both flexographic and digital printing as the most dynamically developing printing technologies. Typically, digital printing is applied for products with lower print volumes; as print quantities increase, flexographic printing assumes a more dominant role. According to Hohmann [7], the United States is the market leader in extended-gamut flexographic printing, although the number of practical implementations remains relatively low.

2. COLOUR MANAGEMENT IN THE PRINTING INDUSTRY

Colour is the perceptual appearance of a stimulus resulting from the visual response of the human eye to light [8]. Measurable physical properties trigger physiological and psychological processes of human colour perception, resulting in the subjective impression that an object appears to possess a certain colour. The stimulus is referred to as the colour stimulus, while the human perceptual response—mediated through visual and cognitive processes—is termed the colour perception [9]. The range of light visible to the normal human eye extends approximately from 400 nm to 700 nm [10,11] or roughly 380–780 nm [12]. There are two fundamental methods of producing colours from primary hues: additive and subtractive colour mixing. Primary colours are defined as those that cannot be generated by mixing other colours, yet all other colours can be derived from them [13]. Subtractive colour mixing occurs in printing when inks containing the primary pigments—cyan, magenta, and yellow (CMY)—are combined in varying proportions.

Theoretically, a perfect combination of cyan, magenta, and yellow should yield black; however, in practice, the inks differ from ideal pigments, producing a less than perfect black [2]. For this reason, a separate black ("K" for "Key") ink is introduced in the printing process. According to Dharavath and Kokil [14], colour can be regarded as a quantitatively analysable and measurable science. Nevertheless, for the human eye, colour perception remains a subjective phenomenon, which presents challenges in the printing industry. The visual evaluation of colour is subjective and influenced by numerous factors simultaneously [15]). One of the principal objectives of the printing industry is to produce accurate and consistent colours for customers [16], even when packaging materials are printed at different locations, using different printing processes, or on diverse substrates. Colour management serves as a means of regulating colour throughout these processes. As graphics are reproduced across various devices and substrates [17], process calibration and ICC profiling ensure reliable and verifiable colour data conversion between colour spaces [18]. Without colour management, an identical input colour value (RGB or CMYK) may appear differently across devices or substrates. To enable precise colour transformations between devices, eight industry leaders established the International Color Consortium (ICC) in 1993. The ICC Profile Format Specification defines the open ICC profile format, enabling colour conversion between devices and colour spaces via a device-independent reference colour space [19]. In flexographic printing, colour appearance is always device dependent. This means that every printing process produces slightly different visual results, even when using identical inks. When a specific process colour composition (CMYK) is defined, the outcome will still vary between printing machines [11]. The printing and reproduction processes must therefore be evaluated and profiled, so that calibrated proofs can accurately simulate the expected print appearance [15]. Each configuration and printing setup must be measured individually. It is recommended to follow relevant ISO standards, such as ISO 12647-7:2016, during measurement and calibration [15]. Process colour assessment is conducted through colour gamut fingerprinting, the implementation of which may vary.

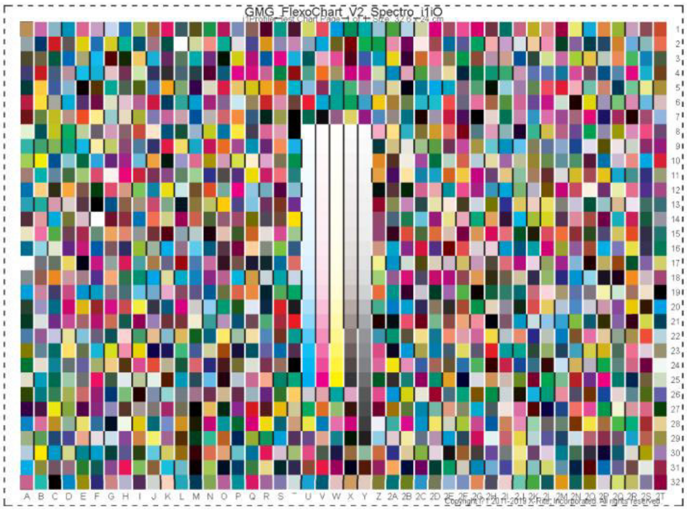

Figure 1: illustrates an example of a test chart suitable for evaluating the colour gamut of a printing process.

3. AIM OF THE RESEARCH

Colour gamut reproduction remains a continually relevant topic within the field of printing technology. The primary objective of every printing process is to reproduce the widest possible colour gamut, although this gamut will always represent only a portion of the spectrum perceptible to the human eye. During the course of our research, representatives of the flexographic printing industry acknowledged the potential of digital printing as a complementary or even competing technology in the future development of print production. Digital printing may gradually become a competitor to flexography as the technology continues to evolve and improve in terms of print quality and colour accuracy.
The research was therefore designed to address the following key questions:

- What is the colour gamut reproduction capability of digital printing?
- How does the colour reproduction performance of digital printing compare with that of flexographic printing?
- What is the impact of prepress processes, specifically the plate-making technology, on the colour gamut reproduction in flexographic printing?

4. IMPLEMENTATION OF THE PRINTING TESTS

Our research began with the mapping of digital printing capabilities. The printing tests were conducted using an HP Indigo 20000 digital press. This press has a web width of 762 mm and a printing speed of 101 ft/min (30.78 m/min) in four-colour mode, 82 ft/min (25 m/min) in five-colour mode, and 137 ft/min (41 m/min) in EPM mode (Hewlett Packard, 2013).
Utilizing the full potential of this printing system, a test form was designed to cover the entire web width. The test included multiple photographic elements, flexographic test patterns, and a measurement chart consisting of 1,472 colour patches, from which an ICC profile could be generated. The substrate used for the test was a 20 μm transparent polypropylene film. Upon completion of the printing test, the ICC profile was measured using the GMG colour management system and an i1iO automatic scanning spectrophotometer. These tools provided precise colour measurement and profiling to evaluate the gamut reproduction capabilities of the HP Indigo 20000. To extend the scope of the study, additional colour profiles were required. For this purpose, a set of flexographic colour gamut tests conducted over the past two to two and a half years was selected. The samples represented multiple printing companies, covering both solvent-based and UV-curable ink systems, and included several plate-making technologies. Thus, a broad cross-section of the flexographic industry was incorporated. In total, ten flexographic ICC profiles were selected for inclusion in this stage of the research.

Table 1: Color profiles and their manufacturing parameters involved in the study (Source: author)

Nr.	Printed substrate	Type of the printing plate	Platemaking technology	Type of the ink
1.	PP TR	MacDermid Lux® ITP™ 60	Bellissima DMS	UV
2.	PP TR	MacDermid Lux® ITP™ 60	Bellissima DMS	UV
3.	PP TR	Kodak Flexcel FNXH	Kodak NX A	UV
4.	PP TR	DuPont™ Cyrel® ESXR	Digital Flat Pixel A	UV
5.	PP TR	DuPont™ Cyrel® DPN	Classic Digital	solvent
6.	PP TR	MacDermid Lux® ITP™ 60	Bellissima DMS	solvent
7.	PP TR	Kodak Flexcel FNXH	Kodak NX A	solvent
8.	PP TR	DuPont™ Cyrel® ESXR	Digital Flat Pixel A	solvent
9.	PP TR	MacDermid Lux® ITP™ 60	Bellissima DMS	solvent
10.	PP TR	Kodak Flexcel FNXH	Kodak NX A	solvent

All profiles were measured using the same GMG software and i1iO measurement device, ensuring consistency and comparability. As a result, a total of eleven ICC profiles (one digital and ten flexographic) were available for analysis. The comparison was carried out using the Gamutvision software, which allows visual and numerical comparison of ICC profiles. The software can display two colour gamut's in three-dimensional space and quantify the gamut volume, thereby expressing the extent of the reproducible colour range. The outcomes of these comparative analyses are presented in the following section.

5. PRESENTATION OF THE EXPERIMENTAL RESULTS

The first stage of the analysis examined the colour gamut reproducible by the HP Indigo 20000 digital press using the Gamut vision software. The reference colour space for comparison was the D50 Lab colour space. The visual representation of the result is shown in *Figure 2*.

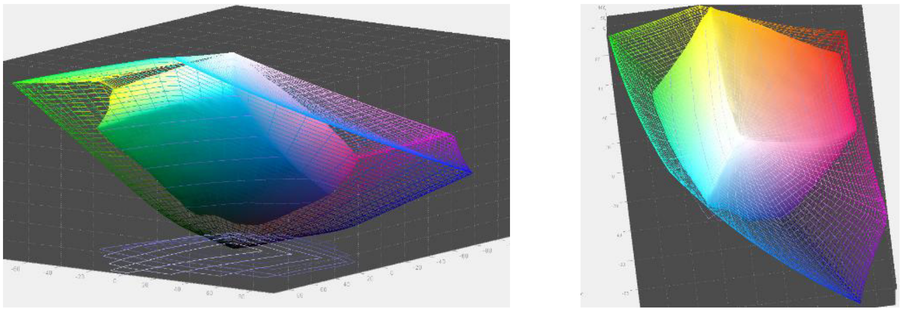

Figure 2: Comparison of the HP Indigo 20000 and D50 Lab colour spaces (Source: author)

The analysis revealed that the gamut volume of the D50 Lab colour space was 840,064, while that of the HP Indigo 20000 was 460,722. As illustrated in the figure and confirmed by the numerical data, the digital print sample was capable of reproducing approximately half of the D50 Lab colour gamut. The next comparison was made between the HP Indigo 20000 and the first flexographic print sample. This flexo print used UV-curable inks, a MacDermid Lux® ITP™ 60 plate, and Bellissima DMS screening technology, printed on a transparent polypropylene substrate. The visual comparison can be shown in *Figure 3*.

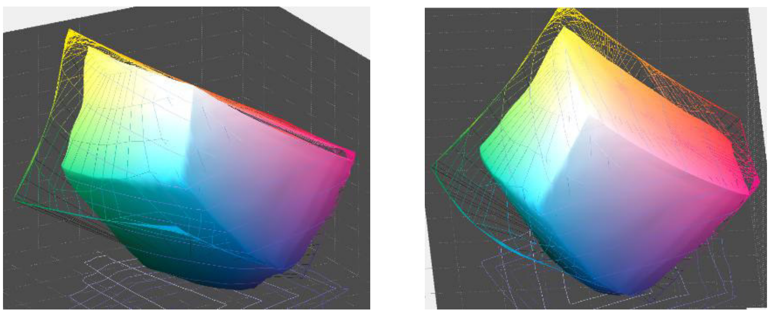

Figure 3: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 1 (Source: author)

In this case, the gamut values were as follows: the HP Indigo 20000 remained at 460,722, while the flexographic sample yielded a gamut volume of 348,449. It can therefore be concluded that digital print exhibits a wider colour gamut. The colour gamut reproduction relative to the D50 Lab space was 41.47%, and relative to the HP Indigo 20000, 75.63%. The second flexographic sample was produced using the same plate material and substrate as the first but printed in a different printing plant.

Interestingly, the printing presses and anilox rollers were identical, while the ink manufacturer differed. The results are illustrated in *Figure 4*.

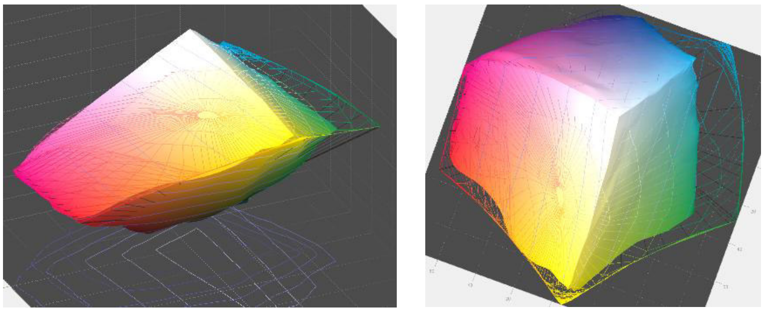

Figure 4: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 2 (Source: author)

The second flexographic sample shows better colour gamut reproduction than the first. Although the digital print still displays a broader gamut, this flexo sample approaches it more closely. In the yellowish, reddish, and purplish tones, the match is very good — in some areas, the flexo print even outperforms the digital sample. However, the bluish and greenish hues are more accurately rendered by digital print. The gamut value of this flexo sample is 407,321, compared to Indigo's 460,722. Thus, the colour gamut reproduction relative to D50 Lab was 48.48%, and relative to HP Indigo 20000, 88.40%. The third sample was again a UV-curable flexographic print on transparent polypropylene film. The printing plate was made using Kodak Flexcel NXH technology, which employs flat-top dots via a semi-digital plate-making process.The visual comparison is shown in *Figure 5*.

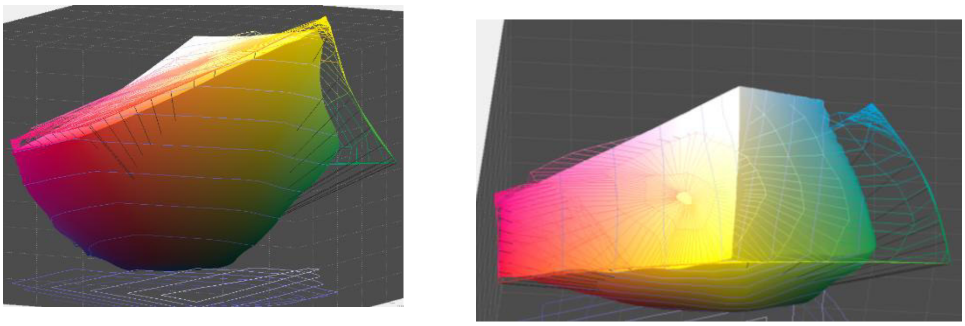

Figure 5: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 3 (Source: author)

From the visualization, in certain regions of the colour space the flexographic sample performs better, particularly in the magenta, yellow, and red ranges, where its performance is comparable or even superior. Conversely, digital print continues to outperform in the cyan and green tonal areas. The gamut value of this third flexo sample is 388,433, corresponding to 46.23% of the D50 Lab gamut and 84.30% of the HP Indigo 20000 gamut. The fourth sample represents the last UV-based flexographic print in the study. It was produced in the same printing plant as the second and third samples, allowing for conclusions regarding the influence of plate-making technology on the reproducible colour gamut under identical press conditions. The sample was printed using a digitally processed plate with flat-top dots and surface microstructure. The results are shown in *Figure 6*.

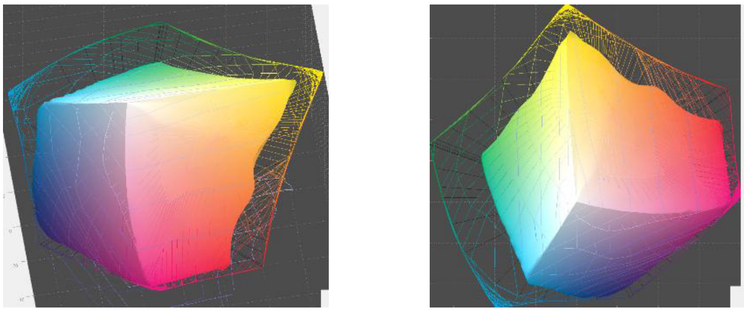

Figure 6: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 4 (Source: author)

The measured gamut volume was 340,696, indicating a considerably narrower colour gamut compared with the digital print. The closest match between the two gamuts was found in the magenta, bluish, and purplish tones, whereas the cyan, green, and yellow regions showed more substantial differences. The reproduction relative to D50 Lab was 40.55%, and relative to HP Indigo 20000, 73.94%. The fifth sample was the first solvent-based flexographic print. A relatively older-generation digital plate was used, without flat-top dot technology, resulting in rounded dot geometry. The substrate was again transparent polypropylene, consistent with previous samples. The results are presented in *Figure 7*.

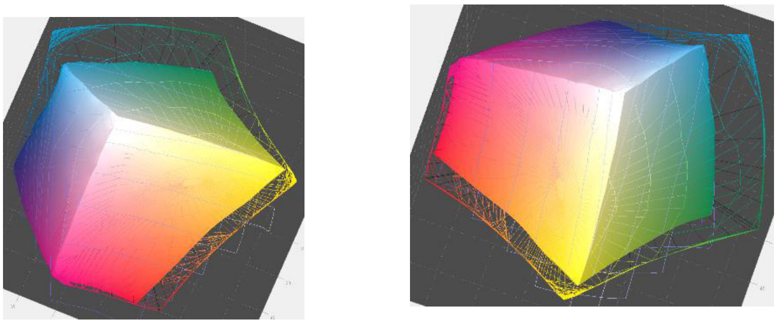

Figure 7: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 5 (Source: author)

This sample demonstrates that digital printing outperformed flexography across nearly all colour regions. The greatest deficiencies in the flexo colour gamut were observed in the blue and green areas, while even the yellow and red regions were not reproduced as effectively as in digital printing. The gamut value was 341,701, equivalent to 40.67% of the D50 Lab gamut and 74.16% of the HP Indigo 20000 gamut. The sixth sample employed Bellissima DMS screening technology on a MacDermid Lux® ITP™ 60 plate. The ink type was solvent-based, and the print was produced on transparent polypropylene. This sample was particularly interesting as it was printed on a modern, high-specification wide-web flexographic press equipped with 420 lpi anilox rollers. The results are illustrated in *Figure 8*. This sample exhibited a significantly larger colour gamut than the two previous solvent-based prints. The colour spaces are slightly shifted relative to one another, with the flexographic print performing better in the yellow–orange–red–blue regions. However, as observed in previous cases, bright green and light cyan–green tones were reproduced more effectively by the digital print.

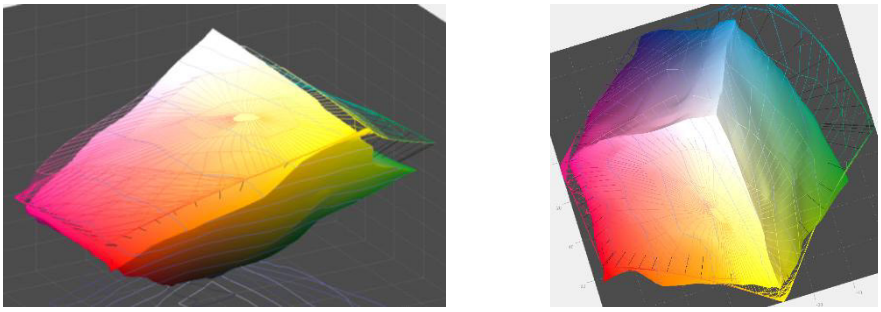

Figure 8: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 6 (Source: author)

The gamut volume for this sample was 397,610, corresponding to 47.33% of the D50 Lab gamut and 86.30% of the HP Indigo 20000 gamut. The seventh sample was produced using the Kodak Flexcel NX standard technology with solvent-based inks on transparent polypropylene. The visualisation is shown in *Figure 9*.

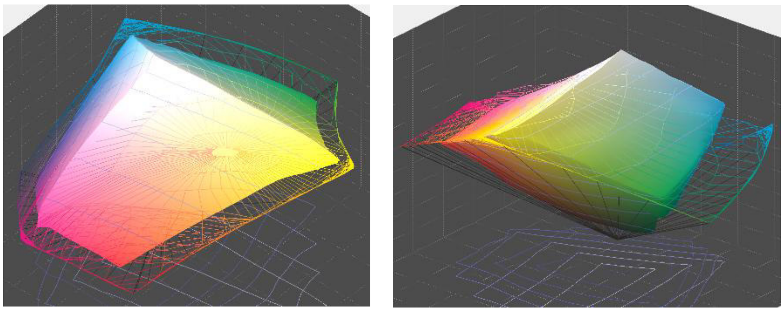

Figure 9: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 7(Source: author)

This sample represents one of the narrowest colour gamuts among all flexographic prints. Across nearly all hues, the flexo colour space is smaller than that of the digital print, with relatively uniform distribution of the uncovered regions and no pronounced outliers.

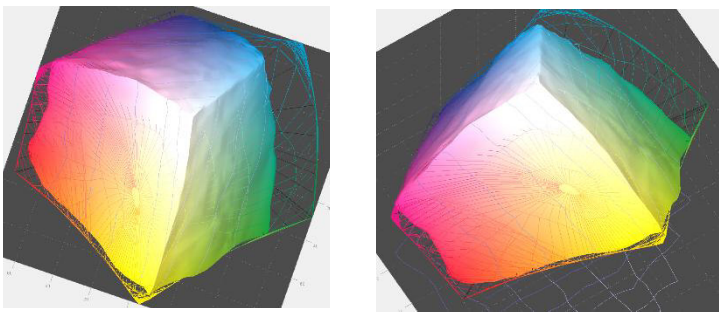

Figure 10: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 8 (Source: author)

The gamut volume was 297,472, representing 35.41% of D50 Lab and 64.56% of HP Indigo 20000. The eighth sample was produced under identical printing conditions as the seventh, with the only difference being the plate material. In this case, a Dupont ESX-R plate was used, featuring a stochastic (FM) screen developed by a Slovak plate manufacturer. This screening method eliminates screen angles and moiré effects, and forms dot structures that differ substantially from conventional AM or FM screens. The results are illustrated in *Figure 10*.

With the exception of the bright green and light blue-green regions, the flexographic sample closely approximated the digital print's colour gamut. In several cross-sections, the two gamuts ran almost parallel. The gamut value was 398,108, corresponding to 47.39% of D50 Lab and 86.40% of HP Indigo 20000. The ninth sample was also produced in the same printing plant as the seventh and eighth samples. This allows for a comparative assessment of how different plate-making technologies affect colour gamut reproduction within the same printing environment. This sample used Bellissima DMS screening on a MacDermid plate, with all other parameters held constant. The visualisation is shown in *Figure 11*.

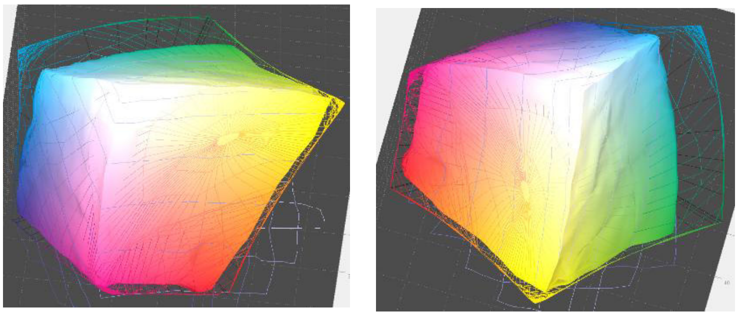

Figure 11: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 9 (Source: author)

Similarly to the eighth sample, this print exhibited a relatively wide colour gamut, performing well compared to the previous results. Although the digital print again exceeded the flexographic sample at nearly all gamut peaks, the overall performance of this plate configuration was strong. The measured gamut volume was 386,358, corresponding to 45.99% of D50 Lab and 83.85% of HP Indigo 20000. The tenth and final flexographic sample originated from a different printing plant than the previous ones. Only Kodak tests were available from this facility. The plate was produced using Kodak Flexcel NX technology with a standard Kodak NX plate.

Among all the samples, this one exhibited the closest match to the digital print's colour gamut. As in previous cases, bright green, light blue, and blue-green hues could not be fully matched by flexography; however, in all other regions, the results were notably consistent. In the light magenta region, the digital print performed slightly better, whereas in the yellow–red–green sector, the flexo print achieved stronger results. The visual comparison is shown in *Figure 12*.

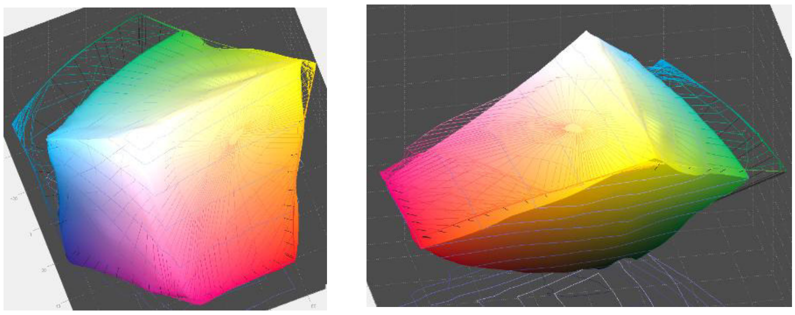

Figure 12: Comparison of the color spaces of the HP Indigo 20000 and Flexo Sample No. 10 (Source: author)

The measured gamut volume for this sample was 419,919, the highest value among all flexographic samples. This represents 49.98% of the D50 Lab gamut and 91.14% of the HP Indigo 20000 gamut.

6. EVALUATION OF THE EXPERIMENTAL RESULTS

The study included 11 samples, from which ICC profiles were measured using the appropriate technology and subsequently compared. The results obtained are summarized in the table below.

Table 2: Manufacturing parameters and test results of the color profiles involved in the study (Source: author)

Nr.	Substrate	Printing plate	Inks	Printhouse	GV	% to Lab	% to D
1.	PP TR	Digitális	digital	PH 1	460722	54,84 %	100%
2.	PP TR	Bellissima	UV	PH 2	348449	41,47 %	75,63 %
3.	PP TR	Bellissima	UV	PH 3	407321	48,48 %	88,40 %
4.	PP TR	Kodak	UV	PH 3	388433	46,23 %	84,30 %
5.	PP TR	Digital Flat	UV	PH 3	340696	40,55 %	73,94 %
6.	PP TR	Classic Digital	digital	PH 4	341701	40,67 %	74,16 %
7.	PP TR	Bellissima	digital	PH 5	397610	47,33 %	86,30 %
8.	PP TR	Kodak	digital	PH 6	297472	35,41 %	64,56 %
9.	PP TR	Digital Flat	digital	PH 6	398108	47,39 %	86,40 %
10.	PP TR	Bellissima	digital	PH 6	386358	45,99 %	83,85 %
11.	PP TR	Kodak	digital	PH 7	419919	49,98 %	91,14 %

Based on these results, the following conclusions can be drawn:

- Digital and flexographic printing technologies can cover approximately half of the Lab colo**u**r spectrum. Among them, digital printing outperformed the best-performing flexo sample by 4.86%.
- The technology and type of printing plate affect the color space reproduction in flexographic printing. Evidence of this can be seen in samples 3, 4, and 5, as well as in samples 8, 9, and 10. These samples were produced at the same printing houses, printed on the same presses, using identical anilox rollers, ink settings, substrates, operators, etc. Nevertheless, significant differences in gamut ranges are visible in both cases. At Printing House No. 2, which used UV ink, the gamut fluctuation interval was 340,696–407,321, showing a difference of 66,625. In the case of Printing House No. 6, this value was even higher: the interval was 297,472–398,108, resulting in a difference of 100,636, which should be considered significant, as compared to the higher value, the other plate's color space performance reached only 74.72%.
- The screen structure applied on the printing plate also influences the color space reproduction in flexographic printing.
- The influence of multiple factors on flexographic printing is evident. This is demonstrated by samples 2 and 3. The samples were produced by two different printing houses, but the press type and manufacturer, the printing plate, and the substrate were identical. Two different ink suppliers provided the inks to the two printing houses. This difference caused a gamut range discrepancy of 58,872. The first printing house achieved only 85.54% of the performance of the second in this area.
- For future research, it would be an interesting question to investigate methods that could expand the reproducible colo**u**r spectrum in flexographic printing.

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