How To Leverage Gamut Metrics For ECG Printing?

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gamut metrics, gamut comparison index

Abstract

Expanded Color Gamut (ECG) printing process increases the color gamut of a traditional CMYK printing process by the use of additional inks of intermediate hues, for example, orange, green and violet. The increase in the attainable color gamut, however, is not often evaluated fully. The increased color gamut may present challenges in a color reproduction workflow, such as an accurate simulation of the expanded color gamut process using an inkjet proofing device.

Gamut metrics can help in analyzing color gamuts of ECG printing processes. This study explores a number of use-cases for comparing and analyzing color gamuts in context of ECG printing process.

The results show that the gamut metrics can provide valuable insights into ECG printing process evaluation. Use of the gamut metrics should help users to select the ECG device or printing conditions or inkjet proofer that best matches the reproduction aims. It should also help users evaluate the gamut of their ECG devices against the appropriate reference color gamuts.

Introduction

The ECG printing process has been explored for a long time through several approaches (Kueppers, 1989; Ostromoukhov, 1993; Boll, 1994; Stollnitz, 1998, Morovič, 2010; Mahy, 2011), which are also summarized by Deshpande (2015b) and Seymour (2018).

Recently published ISO/TS 21328:2022 (ISO, 2022) highlights the importance of this topic. Although ECG printing process is being embraced in the printing and

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packaging industry, evaluation of the ECG printing process needs more attention, particularly in terms of color gamut analysis.

There have been several studies on color gamut comparison in general (Mahy, 1996; Reel & Penrod, 1999; Doll, 2001; CIE, 2005; Perales et al., 2009; CIE, 2021). Other studies focused on ECG printing with some elements on color gamut evaluation (Sheth, 2013; Deshpande et al., 2014; O'Hara et al., 2016; Sharma and Seymour, 2019; Joshi et al., 2021).

Gamut metrics were proposed (Deshpande & Green, 2012; Deshpande et al., 2015a; Deshpande, 2015b) for comparing and analyzing two color gamuts as below.

1. Gamut Comparison Index (GCI): quantifies the similarity between two gamuts. It can be calculated as:

$$I_{GC} = \left(\frac{V_i}{V_1}\right)\left(\frac{V_i}{V_2}\right)$$

$$I_{GC} = \frac{V_i^2}{V_1 V_2} \tag{1}$$

where
V_i is the volume of intersection of the two gamuts ($V_i = V_x \cap V_y$).
V_1 is the volume of color gamut 1.
V_2 is the volume of color gamut 2.

The value of the GCI for two color gamuts shows how closely they match. It is analogous to the color difference metric (ΔE) between two colors. It is a goodness-of-fit measure of the two color gamuts.

The range of the GCI is from 0 for no match to 1 for an exact match. If the two color gamuts are perfectly matched, then $V_1 = V_2 = V_i$ and the value of GCI is equal to unity. If two gamuts have the same volume ($V_1 = V_2$), but they don't intersect fully with each other, then the value of GCI will be less than 1. If the two gamuts do not intersect at all ($V_i = 0$), then GCI = 0.

If the color gamut V_1 completely encloses the color gamut V_2, then $V_i = V_2$. The GCI can be used when the objective is to match a source gamut to the target gamuts, for example matching the model-predicted gamut to the actual device gamut.

2. Gamut Volume ratio: compares the volumes of two gamuts without considering their intersection. It simply shows which of the two gamuts has the bigger volume. It can be calculated as:

- $[V_1 / V_2]$: ratio of the volume of color gamut 1 to that of color gamut 2
- $[V_2 / V_1]$: ratio of the volume of color gamut 2 to that of color gamut 1

3. Gamut Coverage: gives the proportion of color gamut 1 covered by color gamut 2. This can be calculated as:

- $[V_i / V_1]$: how much of color gamut 1 is covered by the color gamut 2
- $[V_i / V_2]$: how much of color gamut 2 is covered by the color gamut 1

4. Out-of-gamut Volume Proportion: gives the proportion of one gamut volume lying outside another gamut. This can be calculated as:

- $[(V_1 - V_i) / V_1]$: how much of color gamut 1 is outside the color gamut 2
- $[(V_2 - V_i) / V_2]$: how much of color gamut 2 is outside the color gamut 1

The gamut metrics can also be expressed in percentage (%) when multiplied by 100. These gamut metrics are also supplemented by the Venn Diagram which represents the relative volumes of the gamuts and the volume of their intersection (Deshpande, 2015b; Chow and Rusky, 2003). In this study, the gamut metrics are used in various scenarios pertaining to the ECG printing.

Method

There are different methods to determine the coordinates of colors on the gamut boundary, for example, by finding a convex-hull containing all colors (Barber et al., 1996), the SMGBD method (Morovič, 2008), by use of alpha-shapes method (Cholewo & Love, 1999) etc.

The convex hull is normally used to represent the color gamut. It is the smallest convex polyhedron that contains a given set of points in a three-dimensional space. However, this method has limitations, for example, uncontrolled clipping and over-estimation of the gamut volume. The convex hull method doesn't consider gamut concavities which exist frequently (Morovič, 2008).

To account for any such concavities in the gamut surface, the gamut boundary can be calculated using alpha-shapes (Cholewo & Love, 1999). For a set of measured colors, a family of alpha shapes can be derived from the Delaunay triangulation of the data set by using a virtual spherical eraser with radius α (Edelsbrunner & Mücke, 1994).

In the present study, alpha-shapes method is used since it is suitable for predicting the non-convex surfaces in gamut boundaries, such as printing devices with ECG. A flexographic printing press was calibrated and characterized for CMYKOGV inks on a white polypropylene substrate. The printing condition was stabilized before the press calibration. The CMYK process was calibrated based on G7 method (Idealliance, 2013) and the OGV calibrations were based on a Spot Color Tone Value (SCTV) method with a linear 1:1 reproduction according to ISO 20654:2017 (ISO, 2017b).

The printed test chart was measured using a spectrophotometer on a white backing material according to ISO 13655:2017 (ISO, 2017a) with M1 measurement condition. An average of multiple measurements was used as a dataset for calculating gamut volume. This gamut is called as 'ECG Flexo', which is compared against several other gamuts for each use-case as below.

Use-case 1: ECG Flexo against a reference CMYK gamut such as CRPC6 and FOGRA51

Use-case 2: ECG Flexo against a gamut covering a set of spot colors such as Pantone Solid Coated

Use-case 3: ECG Flexo against a gamut of digital proofer such as Epson Stylus Pro 9900

Use-case 4: ECG Flexo against a color exchange space such as FOGRA55 and PRMG

Use-case 5: ECG Flexo (7-color) against expanded CMYK (4-color) such as XCMYK

For all datasets, the gamut boundaries were derived using the alpha-shapes method with a radius of 40 (alpha parameter). This optimum value of 40 was found by visualizing a 3-dimensional gamut based on the criterion that the gamut should not have any voids.

Gamut volumes were calculated based on the method described in CIE 246 (CIE, 2021) and ISO/TS 18621-11:2019 (ISO, 2019). All computations were done in Matlab computing platform due to its suitability for the color science algorithms. A modular toolbox containing different Matlab functions for calculating gamut metrics was developed.

Results

Figure 1 shows two gamuts plotted from the same measurement dataset of 'ECG Flexo' with two different methods. The solid gamut based on the convex hull method looks bigger than the wireframe gamut based on alpha-shapes method with alpha parameter of 40. The regions showing these differences are highlighted with ellipses. This means the convex hull method overestimates the gamut volume.

The gamut volumes based on the convex hull method and the alpha-shapes method were 739136 and 639380 cubic CIELAB units respectively. Hence, all the gamut volumes for different use-cases were calculated using alpha-shapes method.

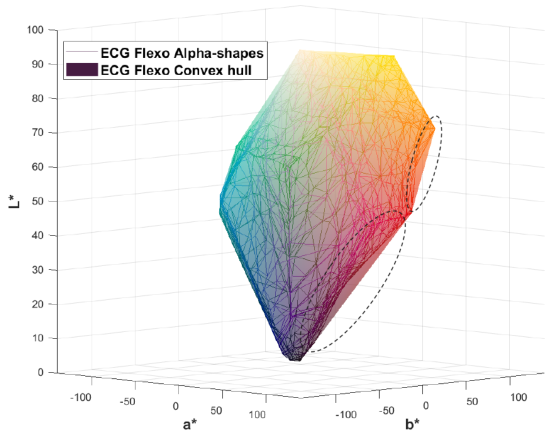


Figure 1. *Visualization of two gamuts computed from the same data set of 'ECG Flexo' using the alpha-shapes and the convex hull methods in the CIELAB color space.*

Below are the results comparing ECG Flexo against other gamuts for each of the use-cases.

Use-case 1: ECG Flexo vs. a reference CMYK gamut

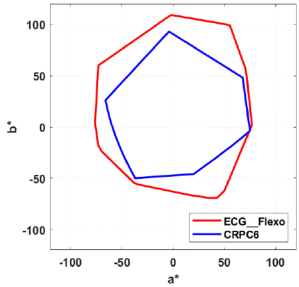
The 7-color ECG with flexographic printing was compared to the reference CMYK gamuts based on commonly used characterization data sets, such as CRPC6 (ISO, 2015) and FOGRA51 (FOGRA, 2020). These data sets provide the relationship between device values (CMYK data) and the printed color (CIELAB data) for the given reference printing condition.

Table 1 shows the gamut metrics for each pair of gamuts, ECG Flexo – CRPC6 and ECG Flexo – FOGRA51. As expected, ECG Flexo has significantly larger volume than the CMYK gamuts. This is also shown by a 'ratio of ECG Flexo to CMYK gamut' which is 1.64 and 1.60 for the respective gamut pairs.

Interestingly, there are still fractions of CMYK gamuts lying outside ECG Flexo – 2.32% of CRPC6 gamut and 3.79% of FOGRA51 gamut. Although these fractions are trivial, the CMYK gamuts are not completely encapsulated by ECG Flexo gamut. This can be visualized in Venn diagrams of Figure 2 and Figure 3. Ideally the fraction of CMYK gamut lying outside the ECG should be 0%, however in practice, the process variables, such as the substrate and inks, could affect the CMYKOGV gamut.

Gamut pairs >	ECG Flexo - CRPC6	ECG Flexo - FOGRA51
Volume of ECG Flexo gamut	639380	639380
Volume of CMYK gamut	389309	398546
Volume of intersection (ECG Flexo & CMYK gamut)	380294	383447
Gamut Comparison Index (ECG Flexo & CMYK gamut)	0.58	0.58
Ratio of ECG Flexo to CMYK gamut	**1.64**	**1.60**
Ratio of CMYK gamut to ECG Flexo	0.61	0.62
% of ECG Flexo covered by CMYK gamut	59.48%	59.97%
% of CMYK gamut covered by ECG Flexo	97.68%	96.21%
% of ECG Flexo lying outside CMYK gamut	40.52%	40.03%
% of CMYK gamut lying outside ECG Flexo	**2.32%**	**3.79%**

Table 1. *Gamut metrics for two gamut pairs: ECG Flexo – CRPC6 and ECG Flexo – FOGRA51*



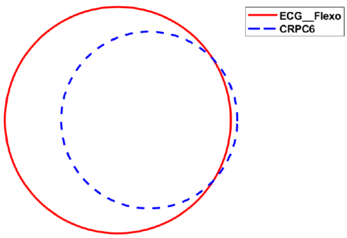
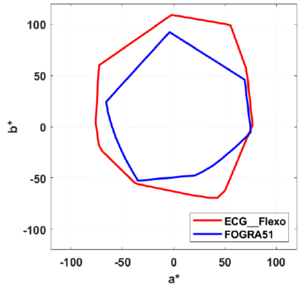


Figure 2. *Projection of two gamuts on the a* - b* plane (left) and Venn diagram representation (right) – ECG Flexo and CRPC6 gamut*



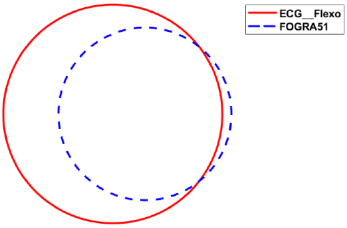


Figure 3. *Projection of two gamuts on the a* - b* plane (left) and Venn diagram representation (right) – ECG Flexo and FOGRA51 gamut*

Use-case 2: ECG Flexo vs. a gamut covering a set of spot colors

One of the key objectives for ECG is to replace the traditional spot colors and the special inks with a fixed ink-set. Although the spot colors are discreet points in the CIELAB color space, it is possible to construct a gamut boundary covering a set of spot colors to form a three-dimensional gamut. Such a gamut was formed using Pantone Solid Coated colors in Matlab, and then compared against the ECG Flexo data set.

Table 2 and Figure 4 show gamut metrics and visualization of this gamut pair respectively. While a volume ratio of ECG Flexo to Pantone Solid Coated Gamut is 0.79, the fraction of Pantone Solid Coated gamut covered by ECG Flexo is 70.7% which means 29.3% of Pantone Solid Coated gamut lies outside the ECG Flexo. Note that we are not comparing the number of spot colors against ECG Flexo; instead, we are comparing the gamut constructed from the spot color library against ECG Flexo.

Volume of ECG Flexo	639380
Volume of Pantone Solid Coated Gamut	805713
Volume of intersection	569647
GCI	0.63
Volume ratio of ECG Flexo to Pantone Solid Coated Gamut	**0.79**
Volume ratio of Pantone Solid Coated Gamut to ECG Flexo	1.26
% of ECG Flexo covered by Pantone Solid Coated Gamut	89.09%
% of Pantone Solid Coated Gamut covered by ECG Flexo	**70.70%**
% of ECG Flexo lying outside Pantone Solid Coated Gamut	10.91%
% of Pantone Solid Coated Gamut lying outside ECG Flexo	**29.30%**

Table 2. *Gamut metrics for ECG Flexo & Pantone Solid Coated Gamut*

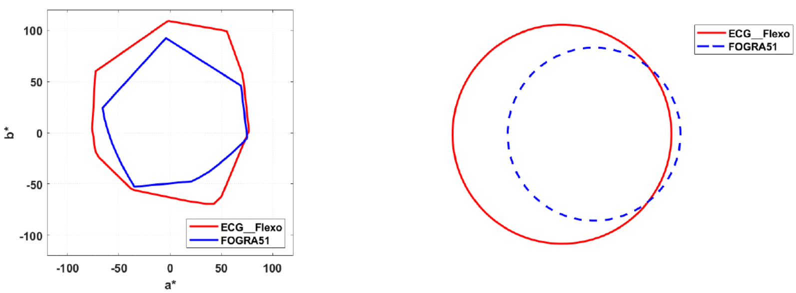


Figure 4. *Projection of two gamuts on the a* - b* plane (left) and Venn diagram representation (right) – ECG Flexo and Pantone Solid Coated gamut*

In addition, the spot colors of Pantone Solid Coated library were plotted as discreet points in the CIELAB color space against the ECG Flexo and CRPC6 gamuts

(Figure 5). Out of 1867 total spot colors, 77% of spot colors were found to be inside the ECG Flexo and 58% of spot colors were found to be inside the CRPC6 gamut.

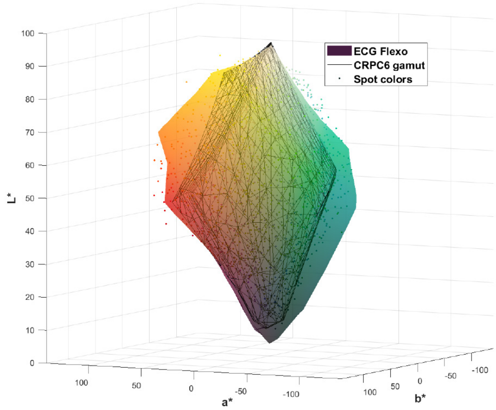


Figure 5. *Visualization of ECG Flexo and CRPC6 gamut along with the spot colors in the CIELAB color space*

Use-case 3: ECG Flexo vs. inkjet proofing gamut

Since ECG provides significantly larger gamut than the typical CMYK gamut, it is essential to evaluate ECG against the gamut of proofing device. Here, ECG data set was compared against a gamut of inkjet proofer, Epson Stylus Pro 9900 with semi-matte substrate.

Inkjet proofer gamut is larger than ECG Flexo as shown by volume ratios in Table 3. On the other hand, there is still 5.13% of ECG Flexo lying outside the gamut of Inkjet proofer (Figure 6). It is a small fraction of the gamut, but the colors from this region cannot be simulated accurately on Inkjet proofer. It is important to understand these limitations pertinent to the proofing of ECG designs.

Volume of ECG Flexo	639380
Volume of Inkjet Proofer	810973
Volume of intersection	606597
GCI	0.71
Volume ratio of ECG Flexo to Inkjet Proofer	0.79
Volume ratio of Inkjet Proofer to ECG Flexo	**1.27**
% of ECG Flexo covered by Inkjet Proofer	94.87%
% of Inkjet Proofer covered by ECG Flexo	74.80%
% of ECG Flexo lying outside Inkjet Proofer	**5.13%**
% of Inkjet Proofer lying outside ECG Flexo	25.20%

Table 3. *Gamut metrics for ECG Flexo & Inkjet proofer gamut*

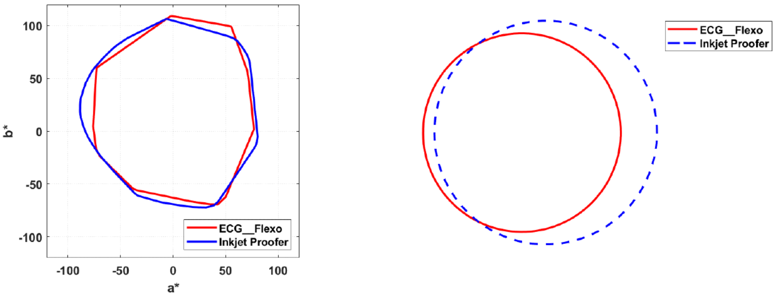


Figure 6. *Projection of two gamuts on the a* - b* plane (left) and Venn diagram representation (right) – ECG Flexo and Inkjet Proofer gamut*

Use-case 4: ECG Flexo vs. color exchange space

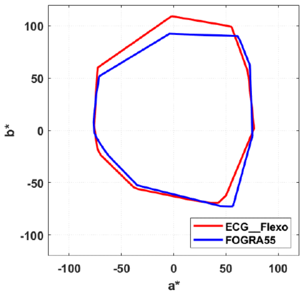
Color exchange space provides a virtual space for the exchange of data between different color encodings. FOGRA55 provides a color exchange space based on CMYKOGV. It consists of a characterization dataset and ICC-profile. It is aimed at data preparation and consistent color communication for the ECG printing workflow. Another example is a Perceptual Reference Medium Gamut (PRMG) by ICC (ISO, 2010) which provides a rendering target for perceptual rendering intent for the exchange of data between different color encodings.

Here, ECG Flexo was compared against the gamuts of FOGRA55 and PRMG (see Table 4 and Figure 7). ECG Flexo is slightly bigger than the FOGRA55 gamut, indicated by 'ratio of ECG Flexo to FOGRA55' as 1.05. However, 'Gamut Comparison Index' is 0.75 which means there are still considerable proportions of ECG Flexo lying outside the FOGRA55 gamut (15.79%) and vice versa (11.29%).

PRMG is significantly bigger than ECG Flexo i.e., ratio of PRMG to ECG Flexo 1.25. The 'Gamut Comparison Index' is 0.67 with 8.34% of ECG Flexo lying outside the PRMC gamut. This shows that both FOGRA55 and PRMG may not be adequate for some ECG printing devices.

Gamut pairs >	**ECG Flexo - CRPC6**	**ECG Flexo - FOGRA51**
Volume of ECG Flexo gamut	639380	639380
Volume of Exchange color space	606935	802106
Volume of intersection (ECG Flexo & Exchange color space)	538439	586051
Gamut Comparison Index	**0.75**	**0.67**
Ratio of ECG Flexo to Exchange color space	**1.05**	**0.80**
Ratio of Exchange color space to ECG Flexo	0.95	1.25
% of ECG Flexo covered by Exchange color space	84.21%	91.66%
% of Exchange color space covered by ECG Flexo	88.71%	73.06%
% of ECG Flexo lying outside Exchange color space	**15.79%**	**8.34%**
% of Exchange color space lying outside ECG Flexo	**11.29%**	**26.94%**

Table 4. *Gamut metrics for two gamut pairs: ECG Flexo – FOGRA55 and ECG Flexo – PRMG*



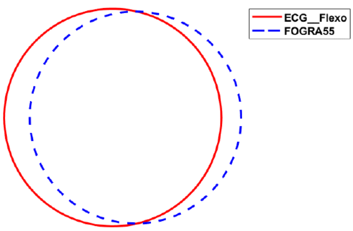


Figure 7. *Projection of two gamuts on the a* - b* plane (left) and Venn diagram representation (right) – ECG Flexo and FOGRA55 gamut*

Use-case 5: ECG Flexo (7-color) vs. expanded CMYK (4-color)

A 7-color CMYKOGV gamut is compared against XCMYK which is a 4-color expanded gamut method. The XCMYK dataset and profiles were based on 26 dedicated press-runs on offset printing presses and on digital printing devices. The ISO 12647-2:2013 (ISO, 2013) compliant CMYK inks were used with higher ink film thickness for offset printing presses. Also, a non-traditional frequency modulated (FM) screening was used. The XCMYK can be used in digital presses, proofers and traditional 4-color printing presses to produce a color space larger than that of the typical 4-color printing.

Table 5 shows gamut metrics for a pair of 7-color ECG Flexo and XCMYK gamut. As expected, the volume of XCMYK gamut is smaller than that of 7-color ECG Flexo. However, the volume ratio of 7-color ECG Flexo to XMYK is only 1.12 indicating that the 7-color ECG Flexo is only 12% bigger than the XCMYK gamut volume. ECG Flexo covers 90.29% of the XCMYK gamut resulting in 9.71% of XCMYK gamut still lying outside the 7-color ECG Flexo. On the other hand, fraction of 7-color ECG Flexo covered by XCMYK gamut is 80.49%, which means 19.51% of the 7-color ECG Flexo is outside the XCMYK gamut. This is illustrated in Figure 8.

Volume of 7-color ECG Flexo	639380
Volume of XCMYK2017IT8	569984
Volume of intersection	514634
GCI	0.73
Volume ratio of 7-color ECG Flexo to XCMYK2017IT8	**1.12**
Volume ratio of XCMYK2017IT8 to 7-color ECG Flexo	0.89
Fraction of 7-color ECG Flexo covered by XCMYK2017IT8	80.49%
Fraction of XCMYK2017IT8 covered by 7-color ECG Flexo	**90.29%**
Fraction of 7-color ECG Flexo lying outside XCMYK2017IT8	19.51%
Fraction of XCMYK2017IT8 lying outside 7-color ECG Flexo	**9.71%**
Absolute difference in volumes	69396

Table 5. *Gamut metrics for 7-color ECG Flexo & XCMYK gamut*

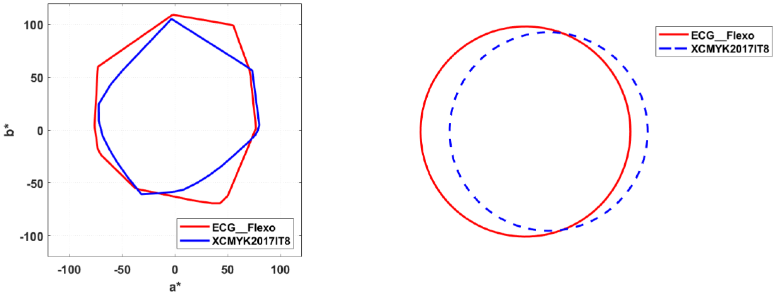


Figure 8. *Projection of two gamuts on the a* - b* plane (left) and Venn diagram representation (right) – ECG Flexo and XCMYK gamut*

The XCMYK gamut is also compared against the CRPC6 gamut which represents a typical gamut for 4-color printing. As seen from Table 6 and Figure 7, the XCMYK provides significantly larger gamut than the CRPC6 gamut without adding any extra primary inks. A volume ratio of XCMYK to CRPC6 gamut is 1.46 showing 46% increase in the gamut. This could bring the benefits of ECG to those print converters having a limited number of print-units on the press, such as 4 print units.

There is still a minor fraction (0.23%) of the CRPC6 gamut lying outside the XCMYK gamut. It is not shown in the 2-dimensional a* - b* plane diagram of Figure 9, however this is revealed in a 3-dimensional CIELAB color space (Figure 10).

Volume of CRPC6	389309
Volume of XCMYK2017IT8	569984
Volume of intersection	388425
GCI	0.68
Volume ratio of CRPC6 to XCMYK2017IT8	0.68
Volume ratio of XCMYK2017IT8 to CRPC6	**1.46**
Fraction of CRPC6 covered by XCMYK2017IT8	99.77%
Fraction of XCMYK2017IT8 covered by CRPC6	**68.15%**
Fraction of CRPC6 lying outside XCMYK2017IT8	0.23%
Fraction of XCMYK2017IT8 lying outside CRPC6	31.85%
Absolute difference in volumes	180675

Table 6. *Gamut metrics for CRPC6 & XCMYK gamut*

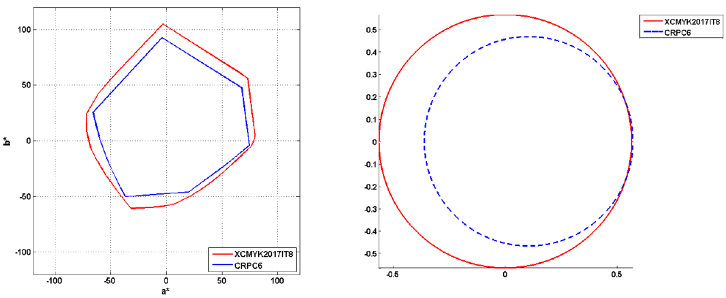


Figure 9. *Projection of two gamuts on the a* - b* plane (left) and Venn diagram representation (right) –XCMYK and CRPC6 gamuts*

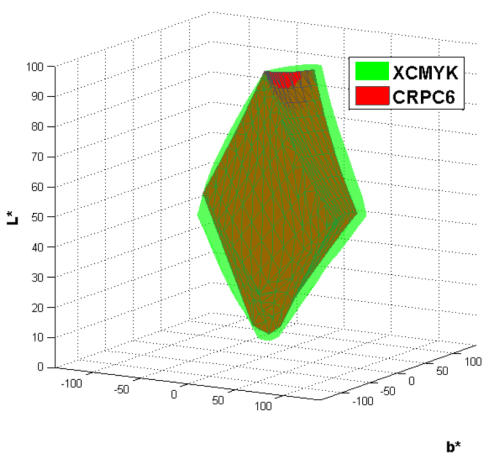


Figure 10. *Gamuts of XCMYK and CRPC6 in a 3-dimensional CIELAB color space*

Conclusion

The gamut metrics were used in various scenarios in context of the ECG printing. These gamut metrics were supplemented by a simple Venn diagram, which is a volume-proportional projection showing the relative volumes of two gamuts and the volume of their intersection.

Various use cases include comparing and analyzing ECG against other color gamuts such as, a reference CMYK gamut like CRPC6 and FOGRA51, an inkjet proofer gamut, a color exchange space like FOGRA55 and PRMG and an expanded CMYK gamut like XCMYK. In addition, ECG was compared against a gamut constructed from a set of spot colors. This study shows that users and vendors can analyze color gamuts for evaluation of ECG printing process by leveraging the gamut metrics.

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