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A Methodological Framework for the Prepress Preparation of Colour Images Based on New Approaches to Optimising the Colour Reproduction Process

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ABSTRACT

Modern colour image reproduction technologies in the printing industry require coordinated integration of colour separation, halftoning, colour synthesis, and ink consumption management while accounting for the nonlinear behaviour of printing processes. Traditional approaches do not always provide both accurate colour reproduction and efficient ink use. This study aims to establish methodological foundations for prepress preparation of colour images and to develop the conceptual model of the IT Color Print information technology for controlled colour reproduction and optimised ink consumption. The proposed methodology integrates mathematical modelling of colour synthesis, colour coordinate transformations, geometric clustering of the colour gamut, nonlinear transformation analysis, and experimental printing. A set of algorithms was developed for four-colour and multicolour prepress processing. The nonlinear transformation index of the printing process and the colorimetric characteristics of printing inks were incorporated into the colour transformation model. A relationship was established between the nonlinear transformation index and the optical densities of printed patches, indicating that minimisation of this index can be used as a criterion for identifying favourable colour reproduction conditions. Based on these relationships, a gamma-correction method for CMY and K components was developed to preserve neutral grey balance and maintain tonal and colour stability. Analysis of colour separations showed that CMY inks are used primarily to reproduce chromatic image components, whereas black ink mainly forms image structure, tonal gradation, and achromatic content. This redistribution reduced CMY ink consumption by approximately 60% while increasing the contribution of black ink. Experimental validation was performed by printing fine-art photographs on an HP Indigo 5500 press. The results confirmed agreement between theoretical predictions and experimental data and demonstrated substantial CMY ink savings without significant deterioration in colour reproduction accuracy. The IT Color Print model integrates colour separation, synthesis, halftoning, and ink-component correction into a unified framework for controlled and resource-efficient colour printing.

KEY WORDS

Colour image prepress preparation, ink consumption optimisation, colour space, colour synthesis, colour reproduction, optical density, gamma correction.

1. Introduction

The reproduction of colour images by printing technologies is a complex multistage process involving the digital representation, processing, and transformation of colour information throughout all stages of prepress preparation and print production. Accuracy and stability of colour reproduction are among the key quality indicators of printed products. Since printing processes are inherently nonlinear, while colour formation is strongly influenced by the properties of printing inks, printing substrates, and technological printing conditions, achieving predictable colour reproduction requires improved methods for processing colour information at the prepress stage.

To compensate for the influence of these factors, researchers widely employ colorimetric measurements of printed samples, as they enable an objective assessment of the final colour reproduction result and facilitate the identification of relationships between the parameters of the digital original, the characteristics of the printing process, and the colour coordinates of the resulting print (Tjandra, Heywood & Chandrawati, 2023).

Numerous colour management methods have been developed on the basis of colorimetric measurements, among which ICC profiling, colour separation techniques, and DeviceLink transformations are the most widely used (Sharma, 2018; International Color Consortium, 2024).

The relevance of this approach is supported by the current ISO 12647 series of standards, particularly ISO 12647-2, in which print quality control is based on colorimetric measurements, printing process characterisation data, and CIELAB colour coordinates (International Organization for Standardization, 2013).

These standards specify target colorimetric characteristics of prints and permissible tolerances. However, they do not define a universal methodology for achieving these characteristics under specific production conditions, nor do they provide tools for determining optimal colour printing conditions that simultaneously ensure stable colour reproduction, resource efficiency, and rational use of printing inks.

In parallel, research continues into universal colour representation systems that could serve as an intermediate framework for coordinating colour information during conversion from the three-component RGB colour space to the four-colour Cyan, Magenta, Yellow, and Black system in the colour separation process (Fraser et al., 2005). The CIELAB system has certain limitations in tasks requiring a geometrically consistent representation of the colour gamut (Kynash & Semeniv, 2025), the evaluation of colour differences, and analytical transformation of colour coordinates, because its perceptual uniformity is not consistent throughout all regions of the colour space (Li et al., 2017; Luo et al., 2023).

Another significant challenge is the reproduction of colours in a digital original that fall outside the colour gamut of the printing process and therefore cannot be reproduced accurately in print (Sikudova et al., 2016; Yuan et al., 2021). An additional factor affecting colour reproduction accuracy is the colour balance of the digital original, which is influenced by lighting conditions, digitisation parameters, and image-processing algorithms (Kovalskyi et al., 2022).

To address these issues, approaches are being investigated that account for the nonlinearity of the printing process, the colorimetric characteristics of printing inks, and the properties of printing substrates, as well as methods for replacing non-reproducible colours based on the Munsell system using the ICaS colour space (Shovheniuk et al., 2019; Kovalskyi et al., 2024).

In this context, the authors have been conducting research aimed at developing a methodology for the prepress preparation of colour images to ensure predictable colour reproduction and optimise printing ink consumption. The approach is based on colorimetric measurements of printed samples, statistical processing of experimental data, and characterisation data provided by Fogra (Fogra, n.d.).

The aim of this study is to develop methodological principles for the prepress preparation of colour images based on mathematical modelling of colour formation and reproduction processes, taking into account the nonlinearity of the printing process and the optimisation of ink consumption.

The objectives of the study are to:

- describe a mathematical model of colour synthesis on the print;
- determine the regularities governing the formation of colour components;
- investigate the nonlinearity of the printing process;
- develop principles for optimised CMYK colour separation;
- experimentally evaluate ink consumption and colour reproduction accuracy;
- develop a conceptual model of IT Color Print.

2. Materials and methods

2.1. Development of the theory of colour synthesis in printing

Colour formation on a printed sample is determined by the spatial interaction of halftone dots from individual ink layers and their overprints on the paper surface. The ambiguity inherent in converting colour from the three-dimensional RGB colour space to the four-component CMYK system necessitates the use of additional colour separation criteria. In conventional colour management systems, this ambiguity is addressed through ICC profiles generated from experimental characterisation of a specific printing process and a predefined colour separation strategy. At the same time, the inverse determination of CMYK components required to reproduce a specified colour remains a non-unique problem. Consequently, obtaining a unique analytical solution requires the introduction of additional parameters and a mathematical framework capable of simultaneously describing colour synthesis on the print and accounting for the nonlinearity of the actual printing process.

The theoretical basis of the proposed framework is formed by the ICaS colour space developed by the authors and the nonlinear transformation index γ. The properties of the ICaS colour space make it possible to integrate, within a unified mathematical description, the RGB space of the digital original, CIE colorimetric spaces used for experimental characterisation of the printing process, and the colour space of the printed output. The nonlinear transformation index γ characterises the deviation of the actual printing process from a linear model and enables the calculations to be adapted to specific printing conditions (Kovalskyi et al., 2024). Accordingly, the ICaS colour space and the nonlinear transformation index γ form a unified mathematical basis for analytical modelling and controlled colour separation.

Within this approach, four-ink colour synthesis is described by a vector equation in the ICaS colour space (1), which accounts for the relative dot areas of the CMYK components, the colour vectors of the paper and solid inks, and the vectors corresponding to their pairwise and three-ink overprints. Transformation of equation (1) makes it possible to treat one of the chromatic inks as a parameter and to describe the limiting cases of synthesis using two chromatic inks and black ink (5), or three chromatic inks and black ink (6).

where $\mathbf{F}_{ICaS}^{CMYK}$ is the colour vector in the ICaS colour space; σ_n, σ_m, σ_j, σ_k are the relative dot areas of the CMYK inks, denoted by the indices n, m, j, and K; $\hat{\mathbf{F}}_W, \hat{\mathbf{F}}_n, \hat{\mathbf{F}}_m, \hat{\mathbf{F}}_j$ are the colour vectors of the paper anwd solid chromatic inks; and $\hat{\mathbf{F}}_{j,n}, \hat{\mathbf{F}}_{j,m}, \hat{\mathbf{F}}_{n,m}, \hat{\mathbf{F}}_{j,n,m}$ are the vectors of pairwise and three-ink overprints of the chromatic inks.

In equation (1), the relative dot area of one of the chromatic inks σ_j is factored out. The amount of the third chromatic ink can be represented by the following quantity:

$$\Delta\sigma_j = (1-\sigma_j) \tag{2}$$

Equation (3) consists of two components.

At σ_j =0, equation (4) takes the following form and describes colour synthesis using two chromatic inks and black ink (Equation 5).

$$\mathbf{F}_{ICaS}^{CMYK} = (1-\sigma_K)\left(\mathbf{F}_{ICaS}^{(2)} + \Delta\sigma_j \mathbf{F}_{ICaS}^{(3)}\right) \tag{4}$$

At σ_j =1, it describes colour synthesis using three chromatic inks and black ink (Equation 6).

The validity of this mathematical representation was verified using experimental data. The CaS diagrams constructed for colours synthesised by two chromatic inks and their combinations with black ink confirmed the relationships predicted by the model (Figure 1). In particular, the introduction of black ink results in a systematic reduction of the corresponding colour surface, while the extent of this transformation is determined by the proportion of black ink and the nonlinear transformation index γ. These results confirm the appli-

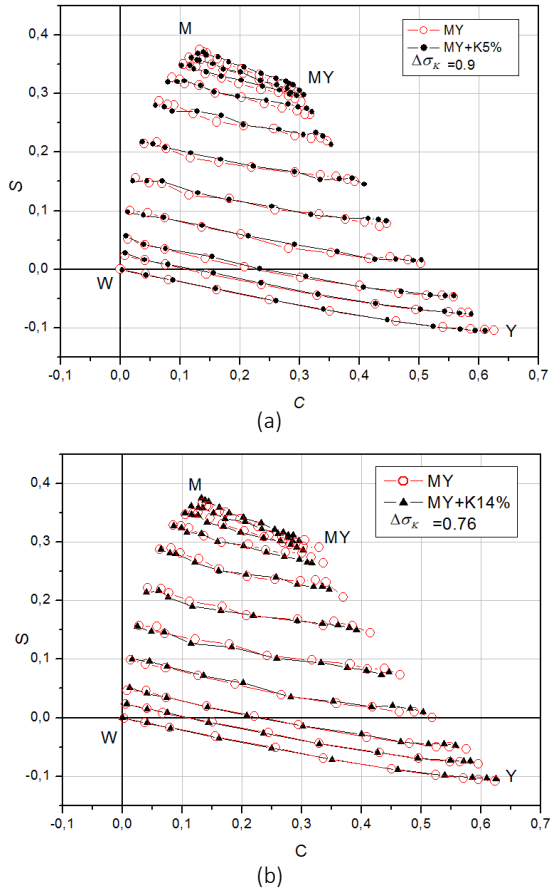
$$\begin{aligned}\mathbf{F}_{ICaS}^{CMYK} = (1-\sigma_K)\{&\hat{\mathbf{F}}_W(1-\sigma_n)(1-\sigma_m)(1-\sigma_j) + \hat{\mathbf{F}}_j\sigma_j(1-\sigma_n)(1-\sigma_m) + \\ &+ \hat{\mathbf{F}}_n\sigma_n(1-\sigma_j)(1-\sigma_m) + \hat{\mathbf{F}}_m\sigma_m(1-\sigma_j)(1-\sigma_n) + \hat{\mathbf{F}}_{j,n}\sigma_j\sigma_n(1-\sigma_m) + \\ &+ \hat{\mathbf{F}}_{j,m}\sigma_j\sigma_m(1-\sigma_n) + \hat{\mathbf{F}}_{n,m}\sigma_n\sigma_m(1-\sigma_j) + \hat{\mathbf{F}}_{j,n,m}\sigma_j\sigma_n\sigma_m\}\end{aligned} \tag{1}$$

$$\begin{aligned}\mathbf{F}_{ICaS}^{CMYK} = (1-\sigma_K)\{&\hat{\mathbf{F}}_j(1-\sigma_n)(1-\sigma_m) + \hat{\mathbf{F}}_{n,j}\sigma_n(1-\sigma_m) + \hat{\mathbf{F}}_{m,j}\sigma_m(1-\sigma_n) + \hat{\mathbf{F}}_{n,m,j}\sigma_n\sigma_m + \\ &+ \Delta\sigma_j\left[\hat{\mathbf{F}}_W(1-\sigma_n)(1-\sigma_m) + \hat{\mathbf{F}}_n\sigma_n(1-\sigma_m) + \hat{\mathbf{F}}_m\sigma_m(1-\sigma_n) + \hat{\mathbf{F}}_{n,m}\sigma_n\sigma_m - \right. \\ &\left. - \hat{\mathbf{F}}_{n,j}\sigma_n(1-\sigma_m) - \hat{\mathbf{F}}_{m,j}\sigma_m(1-\sigma_n) - \hat{\mathbf{F}}_j(1-\sigma_n)(1-\sigma_m) - \hat{\mathbf{F}}_{j,n,m}\sigma_n\sigma_m\right]\}\end{aligned} \tag{3}$$

$$\mathbf{F}_{ICaS}^{CMYK} = (1-\sigma_K)\left(\hat{\mathbf{F}}_W(1-\sigma_n)(1-\sigma_m) + \hat{\mathbf{F}}_n\sigma_n(1-\sigma_m) + \hat{\mathbf{F}}_m\sigma_m(1-\sigma_n) + \hat{\mathbf{F}}_{n,m}\sigma_n\sigma_m\right) \tag{5}$$

$$\mathbf{F}_{ICaS}^{CMYK} = (1-\sigma_K)[\hat{\mathbf{F}}_W(1-\sigma_n)(1-\sigma_m) + \hat{\mathbf{F}}_{n,j}\sigma_n(1-\sigma_m) + \hat{\mathbf{F}}_{m,j}\sigma_m(1-\sigma_n) + \hat{\mathbf{F}}_{n,m,j}\sigma_n\sigma_m] \tag{6}$$

cability of the proposed mathematical description to colour modelling under actual printing conditions.



» **Figure 1:** *CaS diagrams of colours formed by pairwise overprinting of magenta and yellow inks with the addition of 5% (a) and 14% (b) of Black ink, based on experimental data*

To solve the system of equations derived from the vector equation (7), one of the chromatic inks was treated as a parameter with a fixed relative dot area. Under this formulation, the system is reduced to three unknowns.

The solution was obtained by successive elimination of variables: one unknown was first expressed in terms of the others, and the resulting expression was then successively substituted into the subsequent equations, thereby progressively reducing the number of unknowns.

As a result, the system was reduced to a second-order equation (8) for one of the chromatic inks.

$$a + b\sigma_n + c\sigma_n^2 = 0. \tag{8}$$

Equation (8) yields the solution for one of the chromatic inks:

$$\sigma_n = \frac{1}{2a}\left(b \pm \sqrt{b^2 - 4ac}\right) \tag{9}$$

Where the coefficients of equation (8) and its solution (9) are expressed as determinants of 3 × 3 matrices (Equation 10).

After determining one of the ink components from equation (9), the values of the second chromatic ink and the black ink were obtained by back-substitution. Consequently, for each specified value of the parametric ink, an analytical solution was obtained for the remaining components, while variation of the parameter makes it possible to determine the range of admissible CMYK ratios capable of reproducing the same colour.

The development of four-ink colour synthesis theory is therefore represented by the derived colour synthesis equation (7), in which one of the chromatic inks is assigned a fixed value. This formulation enables analytical solutions to be applied to conventional image colour separation and makes it possible to determine a range of relative dot areas of the printing inks for reproducing each colour of the original image.

$$\begin{aligned}\mathbf{F}_{ICaS}^{CMK} = \sigma_K\Big\{&\hat{\mathbf{F}}_W(1-\sigma_n)(1-\sigma_m)+\hat{\mathbf{F}}_n\sigma_n(1-\sigma_m)+\hat{\mathbf{F}}_m\sigma_m(1-\sigma_n)+\hat{\mathbf{F}}_{n,m}\sigma_n\sigma_m+\\&+\Big[-\hat{\mathbf{F}}_W(1-\sigma_n)(1-\sigma_m)-\hat{\mathbf{F}}_m\sigma_m(1-\sigma_n)-\hat{\mathbf{F}}_n\sigma_n(1-\sigma_m)-\hat{\mathbf{F}}_{n,m}\sigma_n\sigma_m+\\&+\hat{\mathbf{F}}_j(1-\sigma_n)(1-\sigma_m)+\hat{\mathbf{F}}_{j,n}\sigma_n(1-\sigma_m)+\hat{\mathbf{F}}_{j,m}\sigma_m(1-\sigma_n)+\hat{\mathbf{F}}_{j,n,m}\sigma_n\sigma_m\Big]\sigma_j\Big\}\end{aligned} \tag{7}$$

$$a=\begin{bmatrix} I_{AU}^{(4)} & I_m - I_{n,m} + \Delta\sigma_j\left(I_{n,m} + I_{m,j} - I_m - I_{n,m,j}\right) & I_n - I_W + \Delta\sigma_j\left(I_W + I_{n,j} - I_n - I_j\right) \\ C_{AU}^{(4)} & C_m - C_{n,m} + \Delta\sigma_j\left(C_{n,m} + C_{m,j} - C_m - C_{n,m,j}\right) & C_n - C_W + \Delta\sigma_j\left(C_W + C_{n,j} - C_n - C_j\right) \\ S_{AU}^{(4)} & S_m - S_{n,m} + \Delta\sigma_j\left(S_{n,m} + S_{m,j} - S_m - S_{n,m,j}\right) & S_n - S_W + \Delta\sigma_j\left(S_W + S_{n,j} - S_n - S_j\right)\end{bmatrix};$$

$$b=\begin{bmatrix} I_{AU}^{(4)} & I_{n,m} + \Delta\sigma_j\left(I_{n,m,j} - I_{n,m}\right) & I_n + I_m - I_W + \Delta\sigma_j\left(I_W + I_{n,j} + I_{m,j} - I_n - I_m - I_j\right) \\ C_{AU}^{(4)} & C_{n,m} + \Delta\sigma_j\left(C_{n,m,j} - C_{n,m}\right) & C_n + C_m - C_W + \Delta\sigma_j\left(C_W + C_{n,j} + C_{m,j} - C_n - C_m - C_j\right) \\ S_{AU}^{(4)} & S_{n,m} + \Delta\sigma_j\left(S_{n,m,j} - S_{n,m}\right) & S_n + S_m - S_W + \Delta\sigma_j\left(S_W + S_{n,j} + S_{m,j} - S_n - S_m - S_j\right)\end{bmatrix}; \tag{10}$$

$$c=\begin{bmatrix} I_{AU}^{(4)} & I_n + \Delta\sigma_j\left(I_{n,j} - I_n\right) & I_{n,m} + \Delta\sigma_j\left(I_{n,m,j} - I_{n,m}\right) \\ C_{AU}^{(4)} & C_n + \Delta\sigma_j\left(C_{n,j} - C_n\right) & C_{n,m} + \Delta\sigma_j\left(C_{n,m,j} - C_{n,m}\right) \\ S_{AU}^{(4)} & S_n + \Delta\sigma_j\left(S_{n,j} - S_n\right) & S_{n,m} + \Delta\sigma_j\left(S_{n,m,j} - S_{n,m}\right)\end{bmatrix}.$$

2.2. Extension of mathematical colour separation capabilities

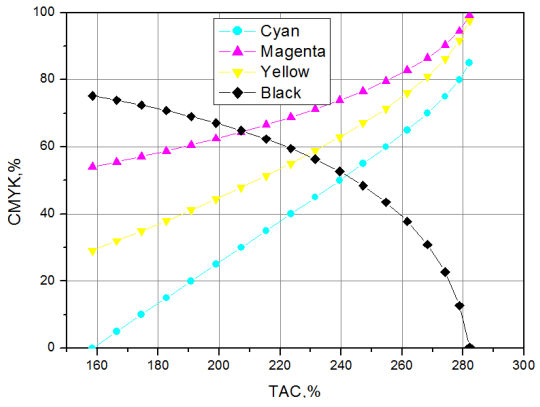
To validate the analytical relationships, modelling was performed using the colour vectors of the printing inks and paper derived from Fogra51 characterisation data for offset printing on coated paper (Table 1).

The modelling yielded a set of admissible combinations of relative dot areas capable of reproducing a specified colour. The modelling results for two colours are presented in Figure 2. For colour 1, as the Cyan component increased from 0 to 85 %, the black (K) component decreased from 75 to 0 %, while the Total Area Coverage (TAC) increased from 158 to 282 %. The limiting synthesis configurations were (M), (Y), (K) and (C), (M), (Y). For colour 2, variation of the Magenta component within the range of 57–98 % was accompanied by a decrease in black (K) from 72 to 0 % and an increase in TAC from 153 to 264 %. The corresponding limiting configurations were (C), (M), (K) and (C), (M), (Y).

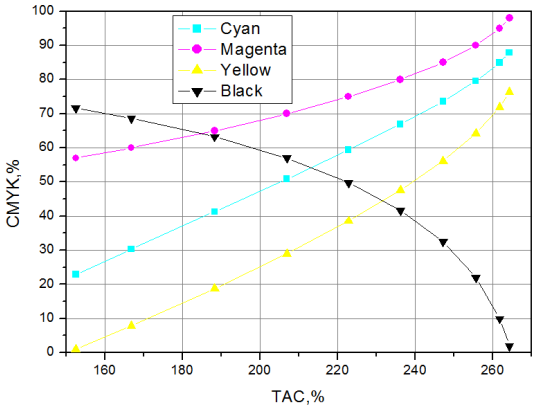
The results indicate that the minimum Total Area Coverage is achieved at the maximum contribution of black ink and the exclusion of one chromatic component. A common relationship was observed for the analysed colours: as the proportion of the parametric chromatic ink increases, the contribution of black ink decreases, while the Total Area Coverage changes accordingly. Hence, the same colour can be reproduced using different C, M, Y, and K ratios, each associated with a different level of Total Area Coverage.

2.3. Geometric clustering of the colour gamut in the icas space

Further analysis showed that the chromatic part of the colour gamut in the ICaS colour space can be represented as a set of geometrically defined regions whose boundaries are determined by the colour vectors of the chromatic printing inks (Figure 3). For CMYK, the C, M, and Y vectors form three principal clusters in the CaS plane, each corresponding to a region of colours reproducible by a specific pair of chromatic inks. The C and S coordinates determine the assignment of a colour to the corresponding cluster and, consequently, the selection of chromatic inks, whereas the I coordinate is associated with formation of the achromatic component. Once a colour has been assigned to a particular cluster, the relative dot areas of the corresponding inks can be determined from the analytical solutions of the colour synthesis equations for the printed sample.



(a)



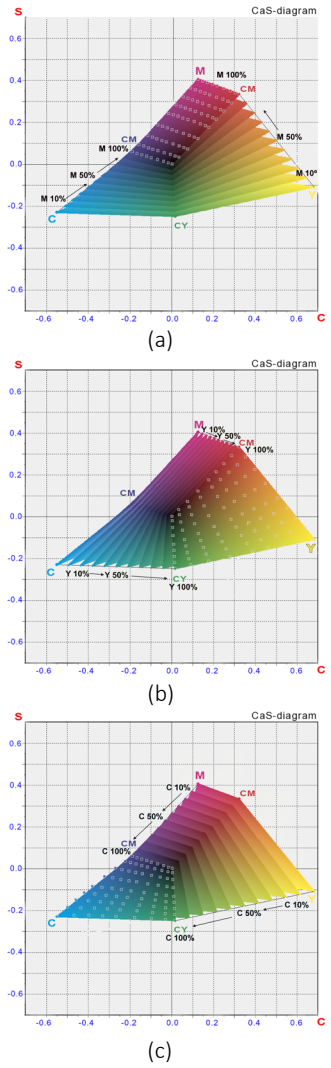
(b)

» **Figure 2:** *Modelling of colour synthesis: (a) colour 1, RGB (83, 56, 57); (b) colour 2, RGB (77, 56, 74)*

Table 1

Colour vectors of the printing inks and different paper types

	Colour coordinates in Adobe RGB (1998)			Colour coordinates in the ICaS colour space		
	r	g	b	I	C	S
C-Cyan	0.000000	0.596527	0.872391	0.8480798	–0.561970	–0.286110
M-Magenta	0.729509	0.028887	0.482240	0.7162811	0.046958	0.500307
Y-Yellow	0.947079	0.872560	0.136045	1.1291141	0.623891	–0.112620
K-Black	0.172533	0.172632	0.174278	0.2999004	–0.001360	0.000291
W-paper	0.937619	0.939018	0.986731	1.6531655	–0.038440	0.009275
CM	0.207390	0.206646	0.504935	0.5305679	–0.234820	0.063464
MY	0.736664	0.134682	0.179107	0.6064790	0.312518	0.356942
CY	0.164517	0.551749	0.305113	0.5896931	–0.029050	–0.275690



» **Figure 3:** *Modelling of colour synthesis on the print using two chromatic inks with (a) Cyan, (b) Magenta, and (c) Yellow as the parametric ink; points represent Fogra51 experimental data*

The proposed mathematical framework is not restricted to the CMYK system and can be extended to multicolour printing. Increasing the number of chromatic inks results in additional clusters in the CaS plane, while the principle of selecting inks for reproducing an individual colour remains unchanged. This establishes a mathematical basis for scalable, controlled colour separation that accounts for the characteristics of a specific printing process.

2.4. Method for determining the nonlinear transformation index of the printing process

The nonlinear transformation index γ, identified in our previous studies (Kovalskyi et al., 2024) as one of the key parameters of the proposed mathematical framework, accounts for the technological conditions of colour reproduction. Unlike parameters specified for a standardised printing process, γ is determined experimentally for a particular printing system and characterises its nonlinearity.

The method for determining the nonlinear transformation index γ was improved, and an algorithm for its calculation was developed. The input data comprise measured CIELAB colour coordinates of the gradation patches of individual printing inks and the corresponding relative dot areas. Following colour conversion to the working RGB colour space, a designated RGB component is used for each ink: R for Cyan, G for Magenta, and B for Yellow. The nonlinear relationship between the input gradation and the colour characteristic of the print was described by a power-law function:

$$F_i = C_0 + K_C(1-\sigma_i)^{\gamma}, \tag{11}$$

Where F_i is the colour characteristic of the *i*- th gradation patch, C_0 is the coordinate of the ink colour vector, K_C is the contrast coefficient, and σ_i is the relative dot area of the printing ink.

The sequence of computational procedures in the improved method was formalised as pseudocode (Algorithm 1).

Algorithm 1. Determination of the nonlinear transformation index

Input: experimental dot areas σ_i measured colour coordinates of gradation patches

1. Convert measured colour coordinates to the working RGB space.
2. Select the highlighting RGB component for the analysed ink: Cyan → R Magenta → G Yellow → B
3. Form and sort the experimental data pairs (σi, F_i).
4. Determine the colour coordinate C_0.
5. Estimate initial values γ_0 and KC using the least-squares method.
6. Set $\gamma = \gamma_0$.
7. Calculate theoretical values Fcalc using the nonlinear model.
8. Calculate the mean deviation between Fcalc and Fexp.
9. Change γ by a predefined increment Δγ.
10. Repeat steps 7–9 while the mean deviation decreases.
11. Select the γ value corresponding to the minimum deviation.

Output: optimal nonlinear transformation index γopt fitted nonlinear gradation characteristic

Initial estimates of γ and KC were determined using the least-squares method. Since this estimate is approximate, particularly when the number of exper-

imental gradation patches is limited, γ was further refined iteratively. At each iteration, the theoretical tone reproduction curve was calculated for a specified γ value together with its mean deviation from the experimental data. The γ value corresponding to the minimum deviation was considered optimal. The resulting γopt is used as a quantitative characteristic of the nonlinearity of a specific printing process.

3. Results and discussions

3.1. Influence of printing conditions on the nonlinear transformation index

Experimental studies were conducted to determine the influence of technological printing conditions on the nonlinear transformation index γ. For this purpose, gradation scales of process inks were reproduced by offset printing on coated and uncoated paper using conventional amplitude-modulated and stochastic screening. The investigated combinations of paper type and screening method corresponded to the conditions represented by Fogra characterisation data.

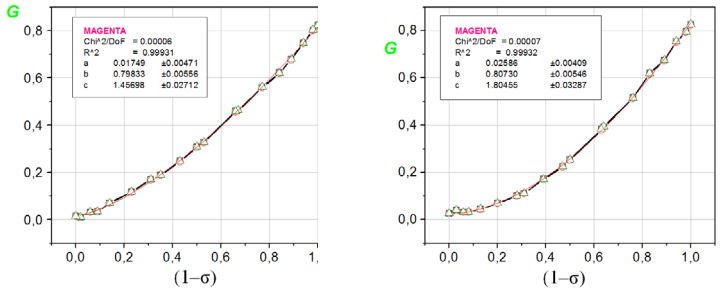
Following printing, colorimetric measurements of the gradation patches were performed. Based on the resulting experimental data (ED), the nonlinear transformation index γ was determined using the improved method for each process ink and each investigated printing condition corresponding to Fogra51, Fogra52, Fogra43, and Fogra44, respectively.

Figure 4 presents an example of γ determination for Magenta prints on coated paper using conventional and stochastic screening. The calculated nonlinear transformation index values for the other inks and technological conditions are presented in Table 2. For comparative analysis, the table also includes γ values determined by the same method from standardised Fogra characterisation data.

The results confirmed that the nonlinear transformation index is characteristic of specific reproduction conditions and depends on the technological parameters of the printing process. Analysis of the tone reproduction characteristics demonstrated the influence of both the printing substrate and the screening method. Higher γ values were obtained for uncoated paper than for coated paper, which is consistent with more pronounced dot gain and the specific interaction between the ink and the paper surface. Stochastic screening was also characterised by higher γ values than conventional amplitude-modulated screening.

The nonlinear transformation index was additionally investigated for digital printing technologies. The analysis was based on colorimetric data from prints produced under production conditions using Konica Minolta bizhub PRESS, Xerox 700 DCP, and HP Indigo 5000 sheet-fed digital presses, as well as Canon Pixma and Epson Stylus Pro inkjet printers.

The resulting values confirmed that the nonlinearity of digital reproduction depends substantially on the image-forming principle and the characteristics of the specific printing system. The mean γ values for the CMY components were 1.51 for Konica Minolta,



» **Figure 4:** *Nonlinear characteristics of Magenta prints: (a) AM screening and (b) FM screening, coated paper*

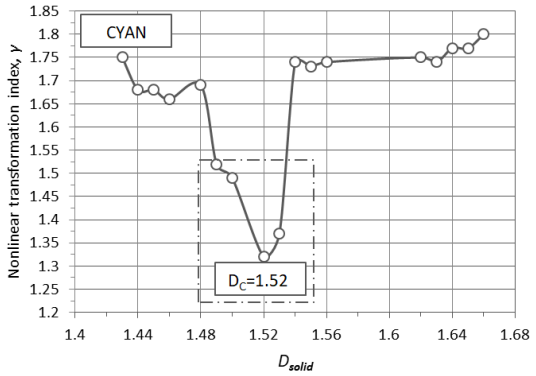
Table 2

Nonlinear Transformation Index for Offset Printing under Different Paper and Screening Conditions

	Fogra 51	ED*	Fogra 52	ED*	Fogra 43	ED*	Fogra 44	ED*
C-Cyan	1.59	1.66	1.98	1.71	2.29	1.82	2.34	1.87
M-Magenta	1.61	1.46	1.99	1.54	2.41	1.80	2.44	1.97
Y-Yellow	1.59	1.54	1.97	1.65	2.25	1.82	2.28	1.91
K-Black	1.57	1.72	2.05	1.80	2.32	1.70	2.32	1.81

1.28 for Xerox 700 DCP, 1.51 for HP Indigo 5000, 1.23 for Canon Pixma MG5240, and 1.29 for Epson Stylus Pro. The investigated digital systems therefore exhibit different degrees of nonlinearity, confirming the need to determine γ experimentally for the specific printing method and operating conditions.

The effect of ink film thickness on the nonlinear transformation index γ was also investigated. Prints were produced on a sheet-fed offset press using Vega Gloss 115 g/m² glossy paper and Huber Group Perfection offset inks. The ink film thickness was varied during printing, while the optical density of the 100 % solid patches was monitored using a densitometer. The colorimetric characteristics of the gradation scales were measured spectrophotometrically in CIELAB coordinates.



» **Figure 5:** *Dependence of the nonlinear transformation index on the optical density of Cyan solid patches*

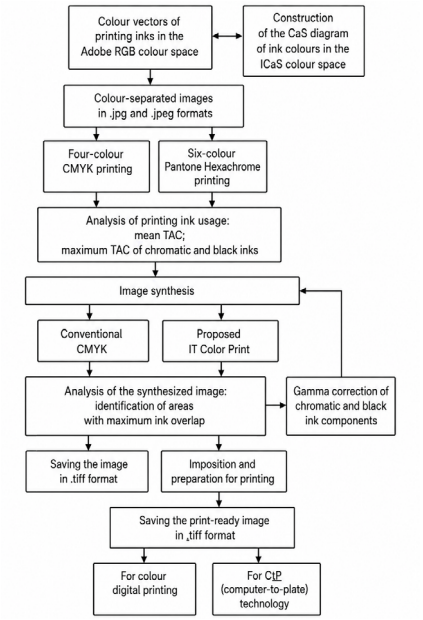
To establish the relationship between the nonlinear transformation index γ and ink film thickness, γ was plotted against the optical density of Cyan, Magenta, and Yellow solid patches. Figure 5 presents the corresponding relationship for Cyan ink. Local minima of the nonlinear transformation index were identified at optical densities of D=1.52 for Cyan, D=1.59 for Magenta, and D=1.46 for Yellow. These results indicate that the minimum γ value can be used as a criterion for selecting a rational ink film thickness and optimising colour reproduction conditions.

Standardised characteristics can therefore serve as a reference basis, although they do not fully represent the nonlinearity of a specific production process. To improve colour reproduction accuracy, prepress preparation should account for the nonlinear transformation index determined experimentally under the actual printing conditions. Such an approach accounts for deviations of the real process from standardised conditions and improves the predictability of tonal and colour reproduction.

3.2. Software implementation of the proposed prepress framework

For the practical implementation of the proposed mathematical framework, the IT Color Print software was developed for prepress preparation of colour images. Its functional structure integrates colour gamut construction for specified printing conditions, analytical colour separation, modelling of image synthesis using printing inks, Total Area Coverage (TAC) analysis, correction of ink components, and generation of colour-separated images for subsequent printing. The software supports both four-colour CMYK and extended multicolour configurations.

The model inputs comprise the colorimetric characteristics of the paper, printing inks, and their overprints, together with the nonlinear transformation index γ determined for the specific printing conditions. The software therefore establishes a direct relationship between the mathematical model of colour synthesis and the actual characteristics of the printing system. The functional scheme of the proposed approach to colour image prepress processing is shown in Figure 6.

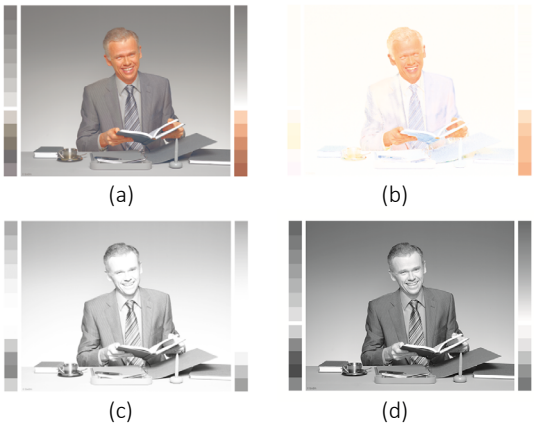


» **Figure 6:** *Functional scheme of colour image prepress processing*

For comparative evaluation of the colour separation results, roman16 bvdm reference test images (Bundesverband Druck und Medien, n.d.) were used. These images were specifically developed for analysing colour reproduction and detail rendering in prepress and printing workflows. The set includes images with different colour, tonal, and subject characteristics and is intended, among other purposes, for evaluating RGB→CMYK transformations and comparing colour separation strategies. The RGB originals from the roman16 set were processed using the conventional

approach with the PSO Coated v3 ICC profile and the proposed IT Color Print method, after which the resulting colour separations were comparatively analysed.

The modelling revealed fundamentally different patterns in the formation of the chromatic and achromatic image components. The C, M, and Y components predominantly form the chromatic content of the image, whereas K plays a greater role in reproducing tonal structure, detail, and achromatic regions. Such redistribution of the inks creates the potential to reduce the use of CMY chromatic inks while preserving the specified colour characteristics of the image.



(a) (b) (c) (d)

» **Figure 7:** *Comparison of colour separation results obtained using an icc profile and the proposed method: (a) cmy image synthesis using the icc profile; (b) cmy image synthesis using it color print; (c) black (k) channel obtained using the icc profile; (d) black (k) channel obtained using it color print*

Figure 7 presents the results of simulated synthesis of the test image using only the chromatic C, M, and Y components: conventional colour separation using the ICC profile (Figure 7a) and the proposed method based on analytical solutions of the colour synthesis equations in the ICaS colour space (Figure 7b). The comparison demonstrates a fundamental difference in the formation of the achromatic component. With conventional colour separation, overprinting of C, M, and Y contributes to the reproduction of grey and low-chroma regions, whereas in the proposed method the chromatic inks predominantly form the chromatic component and the achromatic information is transferred to the K channel. The corresponding black ink channels for the two colour separation methods are shown in Figure 7c and 7d.

In terms of CMY and K redistribution, the resulting separation may visually resemble colour separation with a high degree of grey-component replacement by black ink. The fundamental distinction of the proposed approach is that the colour transformation is not based on precomputed tabular relationships and their interpolation; instead, it is determined analytically from the colour synthesis equations in the ICaS colour space while accounting for the characteristics of the specific printing process.

3.3. TAC analysis and gamma correction of ink components

For technological control of colour-separated images, the software incorporates Total Area Coverage (TAC) analysis. Rather than determining only the global maximum TAC value, the proposed approach identifies pixels and image regions in which the total ink coverage exceeds a specified threshold. Potentially critical regions can therefore be detected during prepress preparation.



(a) (b)

» **Figure 8:** *Identification of local critical regions with maximum ink overlap (b) in the test image (a)*

A separate module implements gradation gamma correction of the colour-separated components. Correction can be applied individually to C, M, Y, and K while accounting for the nonlinear transformation index of the specific printing process. Modification of one or more ink channels is accompanied by recalculation of the remaining components according to the colour synthesis conditions.



» **Figure 9:** *Result of gamma correction of a two-ink colour-separated image*

A specific feature of the developed method is the preservation of the neutral balance of the image during correction of the ink components. Their tone reproduction characteristics and ink consumption can consequently

be modified without disturbing the component ratios required to reproduce achromatic tones. Gamma correction is therefore used not only to compensate for process nonlinearity but also as an element of controlled ink redistribution during prepress preparation.

3.4. Experimental validation and ink consumption reduction

The effectiveness of the proposed approach was evaluated using a set of reference test images. For each original, a control colour separation was generated using an ICC profile and an experimental colour separation using the IT Color Print method. The comparison was based on the maximum CMYK Total Area Coverage (TAC) and the mean use of the chromatic C, M, and Y components over the image area.

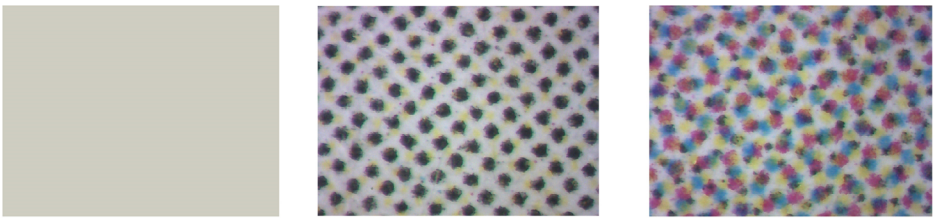
The comparison results are presented in Figure 10. With conventional ICC-based colour separation, the maximum TAC for most test images was approximately 300 %, whereas for the same originals processed using IT Color Print, the maximum TAC did not exceed 250 %. This indicates a reduction in local ink loading in the most highly saturated regions of the images.

More pronounced differences were observed in the analysis of mean chromatic ink usage. The reduction in C, M, and Y depended on the tonal and colour composition of the individual image. For some test originals, the differences were relatively small, whereas the greatest reduction in chromatic components was observed for images dominated by midtones and dark tones, as well as dark olive and brown hues. On average, across the investigated image set, the combined use of C, M, and Y decreased by approximately 60 % compared with ICC-based colour separation, accompanied by an increased contribution of black ink K. These results confirm that the effectiveness of the proposed redistribution of ink components depends on the colour and tonal structure of the image.

For experimental validation, the images were printed on an HP Indigo 5500 digital press. The resulting prints were evaluated spectrophotometrically by comparing the colorimetric characteristics of the control and experimental samples, and the microscopic structure of the halftone dots was also examined. Grey gradation control patches were particularly informative: with IT Color Print, the grey tone was formed predominantly by black and yellow halftone dots, whereas conventional colour separation employed halftone dots of all CMYK components. Micrographs of the prints are presented in Figure 11. The experimental results confirmed the feasibility of implementing the proposed colour separation technology on digital printing equipment, the agreement between the theoretical modelling and the actual structure of the print, and the possibility of



» **Figure 10:** *Comparison of maximum CMYK total area coverage and average CMY ink coverage for ICC-based and IT Color Print colour separation*



(a) (b) (c)

» **Figure 11:** *Grey colour: (a) digital original; (b) colour separation using IT Color Print; (c) colour separation using the conventional approach*

substantially reducing chromatic ink usage without significant deterioration in colour reproduction accuracy.

The theoretical and experimental results were consolidated into the conceptual model of IT Color Print, which integrates printing process characterisation, analytical colour separation, colour synthesis, screening, TAC control, and correction of ink components within a unified system for prepress preparation of colour images.

A key feature of the model is the direct incorporation of parameters of the specific printing process into the mathematical description of colour separation. The colorimetric characteristics of the inks and paper determine the geometry of the available colour gamut, the nonlinear transformation index γ characterises tonal reproduction, and the analytical solutions of the colour synthesis equations determine the admissible ratios of the ink components. Together, these elements form an integrated sequence — characterisation → colour separation → correction → synthesis → printing — in which prepress preparation is adapted to the actual conditions of colour reproduction.

4. Conclusions

The proposed approach to colour image prepress preparation is based on solutions to the colour synthesis equations derived in the ICaS colour space. For practical implementation, a limiting solution is used in which one of the three chromatic components, C, M, or Y, is equal to zero. The component to be excluded is determined by the position of the colour in the chromatic CaS diagram: assignment of the corresponding point to a geometric cluster defines the pair of chromatic inks used for reproduction. Analytical determination of the ink components requires the colour vectors of the process inks, their pairwise overprints, and the paper, together with the nonlinear transformation index γ. The combined use of these parameters enables the proposed mathematical framework to be adapted to a specific printing system.

The proposed approach was implemented in the IT Color Print system, which integrates colour separation based on the developed mathematical model, TAC control, colour synthesis modelling, and correction of ink components. Experimental studies confirmed the dependence of the nonlinear transformation index γ on the printing technology and operating conditions, as well as its applicability as a parameter for prepress preparation. For the investigated images, the proposed colour separation method reduced the total use of CMY by approximately 60% and decreased the maximum TAC from 300 to 210%. Spectrophotometric and microscopic analyses confirmed the practical feasibility of the proposed method, the agreement between the actual distribution of ink components and the theoretical model, and the preservation of acceptable colour reproduction accuracy.

Further research should focus on extending the experimental validation of the method to different printing technologies, substrates, and reproduction conditions; refining the criteria for selecting the optimal ratio of ink components; and investigating the applicability of the proposed mathematical framework to multicolour printing systems.

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