https://doi.org/10.24867/GRID-2026-p18

AI in Electrophotographic Printing: Quality Evaluation and Decision Making

ABSTRACT

Print quality evaluation in electrophotographic printing continues to rely predominantly on operator expertise, visual inspection, and conventional quality control procedures, which may limit the consistency and objectivity of decisions made in digital print production. This study investigates whether an AI-assisted recommendation framework, developed from spectrophotometric measurements and experimental colour-difference data, can support the selection of paper substrates and screening conditions for specified CMYK inputs. The purpose is to examine the feasibility of transforming measured print-quality data into practical decision support for the operator. The study introduces Artificial Intelligence-assisted Print Quality Intelligence (AI-PQI), a data-driven recommendation framework that uses spectrophotometric colour measurements and local CMYK-based estimation of CIEDE2000 colour differences. The experimental dataset comprised 400 CMYK patches printed on four paper substrates using six screening conditions on a Xerox electrophotographic printing system. This produced 24 paper–screening combinations and 9,600 measured colour patches. Target CIELAB values, measured CIELAB values and the corresponding ΔE_{00} values were retained as generated within the original experimental and measurement workflow. The results show that the screening condition with the lowest measured colour difference can vary among individual CMYK patches and paper substrates. The proposed framework uses these experimental relationships to estimate the expected ΔE_{00} for the investigated paper–screening combinations and to identify a potentially suitable production condition. Because the reference CIELAB values were defined within the original substrate-specific workflow, the present recommendations should be interpreted as preliminary decision support within the investigated experimental system rather than as a fully standardised comparison against a single substrate-independent colour target. Establishing such a common target and validating predictions for previously unmeasured inputs remain objectives for future research.

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KEY WORDS
Artificial intelligence, electrophotographic printing, print quality evaluation, decision support, digital printing

1. Introduction

Colour reproduction is a critical aspect of print quality in digital and electrophotographic printing, where the reproduced result is influenced by the interaction between digital colour data, the printing process, substrate and colour-management conditions. Objective instrumental measurement therefore provides an important basis for evaluating the quality and consistency of printed output. ISO 13655:2017 specifies procedures for spectral measurement and colorimetric computation for graphic arts images, including those produced by digital printing processes (International Organization for Standardization, 2017). ISO/TS 15311-1:2020 additionally defines print-quality metrics, measurement methods and reporting requirements for printed products, with particular relevance to digital printing systems (International Organization for Standardization, 2020).

Colour difference provides a quantitative basis for comparing a reproduced colour with its reference. The CIEDE2000 colour-difference formula was developed as an improved CIELAB-based colour-difference equation, incorporating weighting and interaction terms to improve the agreement between calculated colour differences and visual colour discrimination (Luo, Cui & Rigg, 2001). Its implementation and mathematical characteristics were subsequently examined in detail, including recommendations for reliable computational implementation (Sharma, Wu & Dalal, 2005). CIEDE2000 (ΔE_{00}) therefore provides a suitable quantitative measure for comparing colour reproduction under different printing conditions.

The resulting colour reproduction is affected not only by the digital colour specification but also by the properties of the printing substrate and the printing conditions. Research on digital printing has demonstrated that paper surface characteristics can influence printing quality and measured print properties (Ataeefard, 2014). In addition, variations in print quality have been associated with paper and printing-process parameters, demonstrating the importance of considering their combined influence on the final printed result (Lundström et al., 2013). These findings indicate that print-quality evaluation should consider both the substrate and the conditions under which a colour is reproduced.

The increasing availability of objective print-quality data also creates opportunities for data-driven assessment and decision support. Machine-learning methods have been investigated for automated print-quality assessment using objectively measured quality attributes and image analysis, demonstrating the potential for replacing or supporting parts of conventional manual evaluation (Lundström & Verikas, 2013). More recently, neural-network-based approaches have been applied to multidimensional digital-print image-quality evaluation, further demonstrating the application of machine learning to quantitative print-quality analysis (Zhong et al., 2024).

However, using experimentally measured colour-difference data to assist the selection of a paper substrate and screening condition for a specific CMYK input represents a more specialised decision-support problem. This study therefore proposes an Artificial Intelligence-assisted Print Quality Intelligence (AI-PQI) approach for electrophotographic printing. The objective is to investigate whether colour-difference relationships contained in an experimental dataset can be used to estimate the behaviour of the tested paper–screening combinations and provide the operator with a preliminary recommendation for a given CMYK input.

The study does not attempt to replace instrumental verification or operator judgement, but to examine how profiling, colour measurement and data analysis can be integrated into a practical decision-support workflow.

The study evaluates four paper substrates and six screening conditions on a Xerox Colour C60/C70 electrophotographic production system. Colour measurements were obtained using an X-Rite i1Pro 2 spectrophotometer, and the resulting experimental dataset was used to examine screening- and substrate-dependent variations and to develop the AI-PQI recommendation procedure.

The central research question was whether experimentally obtained print-quality data could provide a useful basis for estimating colour-difference behaviour and supporting the operator's selection of a paper–screening combination for a specified CMYK input.

2. Methods and materials

The experimental methodology was designed to investigate variations in colour reproduction among paper substrates and screening conditions and to provide a controlled dataset for developing the AI-PQI approach. The study combined controlled printing, instrumental colour measurement and data-driven analysis of the resulting colour-difference values. Four paper substrates and six screening conditions were evaluated using the same 400-patch CMYK chart, resulting in 24 experimental paper–screening combinations and 9,600 measured colour patches. Target CIELAB, measured CIELAB and ΔE_{00} values were retained in the form generated during the original experimental workflow.

No retrospective ICC-based transformation or recalculation of the reported colour values was performed. The measurement approach was based on established principles of instrumental colour measurement and print-quality evaluation in graphic technology (International Organization for Standardization, 2017; International Organization for Standardization, 2020). The use of substrates with different surface characteristics was also intended to account for the known influence of paper properties on digital printing quality (Ataeefard, 2014).

2.1. Materials and experimental setup

The experimental study was conducted using a Xerox Colour C60/C70 electrophotographic production printing system operated through a Fiery colour-management workflow. Four paper substrates with different grammages and surface characteristics were used. Their basic characteristics are presented in Table 1.

The same FOGRA39L_coated.icc colour profile was used throughout the printing experiment, while the paper substrate and screening condition were varied as the principal experimental factors. The profile was part of the applied colour-management workflow; it was not subsequently used to regenerate or replace the Target CIELAB values contained in the original measurement dataset.

Table 1
Paper substrates used in the experimental study

No.	Paper substrate	Commercial name	Grammage (g/m²)	Surface / finish	Paper category
1	Offset paper	Amber Graphic Offset	80	Uncoated, smooth	Uncoated paper
2	Matt-coated paper	Garda Matt Art	135	Matt-coated, smooth	Coated paper
3	Offset paper	Amber Graphic Offset	170	Uncoated, smooth	Uncoated paper
4	Specialty paper	Sirio Pearl – Oyster Shell	300	Pearlescent surface	Specialty paper

2.2. Experimental design and colour measurement

The printed patches were measured using an X-Rite i1Pro 2 spectrophotometer. CIELAB values were determined under D50 illumination using the CIE 1964 10° standard observer, in accordance with the settings applied in the original i1Profiler measurement workflow. For each patch, the dataset contained the input CMYK values, Target CIELAB values, Measured CIELAB values and the corresponding CIEDE2000 colour difference, ΔE_{00}. These values were retained without subsequent conversion or recalculation. The same CMYK patch definitions enabled comparisons between screening conditions within each substrate. However, because the Target CIELAB values were established within the original substrate-specific workflow, direct comparisons of ΔE_{00} between different substrates do not represent deviations from a single substrate-independent colour target.

The screening conditions selected in the experimental configuration were 150 dot, 200 dot, 300 dot and 600 dot (clustered-dot screens), 200 line (rotated-line screen), and stochastic screening. These settings describe the halftoning applied during printing; they are distinct from the system's 2400 × 2400 dpi print resolution. The same FOGRA39L_coated.icc profile and colour chart were used throughout the experiment, while the paper substrate and screening condition were varied.

The printed patches were measured using an X-Rite i1Pro 2 spectrophotometer. CIELAB values were determined under D50 illumination using the 10° standard observer. For each patch, the dataset contained its input CMYK values, reference CIELAB values, measured CIELAB values and the corresponding CIEDE2000 colour difference (ΔE_{00}). The same CMYK inputs enabled comparisons between screening conditions within each substrate. The reference CIELAB values differed between substrates; consequently, cross-substrate comparisons depend on the reference specified for each paper.

2.3. AI-PQI model and recommendation procedure

The AI-PQI model was developed to estimate the expected colour difference for a given CMYK input under each of the investigated paper–screening combinations.

It uses a weighted 12-nearest-neighbour regression procedure based on the experimentally obtained ΔE_{00} dataset. Before calculating distances, the C, M, Y and K values were normalised to the 0–1 range to provide a common numerical scale for all four channels. The procedure models local relationships within the available experimental data and does not independently reconstruct spectral or CIELAB values.

For each paper–screening combination, the 12 experimental patches with the smallest distance from the input CMYK value were identified. Their measured ΔE00 values were combined using distance-based weighting to obtain the predicted colour difference:

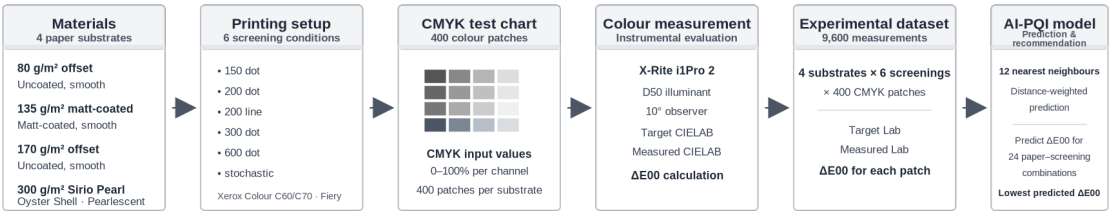
$$\hat{\Delta E}_{00} = \frac{\sum_{i=1}^{12} w_i \Delta E_{00,i}}{\sum_{i=1}^{12} w_i} \quad (1)$$

where $\hat{\Delta E}_{00}$ represents the predicted colour difference, $\Delta E_{00,i}$ is the measured colour difference of the *i*-th nearest experimental patch, and w_i is the corresponding distance-based weight.

The prediction was performed separately for all 24 combinations of the four paper substrates and six screening conditions. The prediction procedure was applied separately to all 24 combinations of four paper substrates and six screening conditions. The combination with the lowest estimated ΔE_{00} was presented as the AI-PQI recommendation. In the present study, this output represents a relative ranking within the original experimental dataset.

Because substrate-specific reference values were used, the recommendation should not yet be interpreted as proof that the selected substrate provides the closest reproduction of one common, substrate-independent target colour.

This approach enables the recommendation procedure to account for local relationships between CMYK composition and experimentally obtained colour difference rather than relying only on the overall mean performance of a screening condition. It therefore represents an initial data-driven decision-support method whose predictive performance for previously unmeasured colours requires separate validation. The overall experimental and AI-PQI workflow is illustrated in Figure 1.



» **Figure 1:** *Workflow of the experimental procedure and AI-PQI recommendation*

3. Results

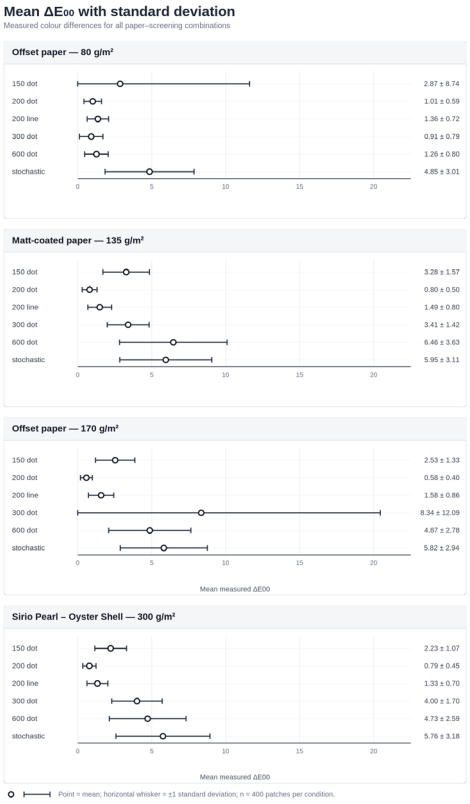
The experimental results were analysed to describe colour-difference behaviour among the investigated paper–screening combinations and to demonstrate how the resulting dataset can be implemented in the AI-PQI decision-support procedure. The results are presented at the overall experimental and individual-patch levels, followed by examples of AI-PQI prediction and recommendation outputs. Descriptive statistics and graphical representations illustrate differences in mean colour difference and variability among the investigated conditions. Predictive accuracy for independent or previously unmeasured inputs was not evaluated in the present study.

3.1. Experimental colour-difference results

The measured colour-difference values for the four paper substrates and six screening conditions are summarized in Table 2 as mean values with their corresponding standard deviations.

The 200 dot screening condition yielded the lowest mean ΔE_{00} on three substrates: 0.80 on the 135 g matt-coated paper, 0.58 on the 170 g offset paper and 0.79 on the 300 g specialty paper. On the 80 g offset paper, 300 dot yielded the lowest mean ΔE_{00} (0.91), followed by 200 dot (1.01). Mean ΔE_{00} values obtained with other screening conditions varied considerably between substrates. These descriptive values refer to the Target and Measured CIELAB data generated within the original measurement workflow. Accordingly, the results describe the colour-difference behaviour recorded for each experimental condition and should not be interpreted as a standardised cross-substrate comparison against one common Target CIELAB dataset.

Differences in variability were also observed between the investigated conditions. The highest standard deviations were recorded for 150 dot on the 80 g offset paper (SD = 8.74) and 300 dot on the 170 g offset paper (SD = 12.09), whereas the 200 dot condition showed comparatively low standard deviations across all four substrates, ranging from 0.40 to 0.59. The mean values and corresponding standard deviations are visualized in Figure 2.



» **Figure 2:** *Comparison of colour-difference behaviour across the investigated paper–screening combinations*

Table 2

Mean measured ΔE00 and standard deviation for the investigated paper–screening combinations

Paper substrate	150 dot	200 dot	200 line	300 dot	600 dot	Stochastic
Offset 80 g	2.87 ± 8.74	1.01 ± 0.59	1.36 ± 0.72	0.91 ± 0.79	1.26 ± 0.80	4.85 ± 3.01
Matt 135 g	3.28 ± 1.57	0.80 ± 0.50	1.49 ± 0.80	3.41 ± 1.42	6.46 ± 3.63	5.95 ± 3.11
Offset 170 g	2.53 ± 1.33	0.58 ± 0.40	1.58 ± 0.86	8.34 ± 12.09	4.87 ± 2.78	5.82 ± 2.94
Specialty 300 g	2.23 ± 1.07	0.79 ± 0.45	1.33 ± 0.70	4.00 ± 1.70	4.73 ± 2.59	5.76 ± 3.18

Table 3

Patch-level comparison of 200 dot with the lowest measured ΔE_{00} on each substrate. The final column is the mean of the lowest measured ΔE_{00} among six screening conditions for each patch; it is not a prediction by the AI-PQI application

Paper substrate	Patches with the lowest ΔE_{00} at 200 dot	Patches with a lower ΔE_{00} at another screen	Mean ΔE_{00} at 200 dot	Mean of the lowest measured ΔE_{00} per patch
Offset 80 g	73 / 400	327 / 400	1.01	0.48
Matt-coated 135 g	310 / 400	90 / 400	0.80	0.71
Offset 170 g	333 / 400	67 / 400	0.58	0.53
Specialty 300 g	266 / 400	134 / 400	0.79	0.65

The 200 dot setting produced the lowest mean ΔE_{00} on three substrates, whereas 300 dot produced the lowest mean on the 80 g offset paper. Nevertheless, the screening condition with the lowest measured ΔE_{00} varied among individual CMYK patches.

The 200 dot setting gave the lowest measured value for 73 of 400 patches on the 80 g offset paper, 310 patches on the 135 g matt-coated paper, 333 patches on the 170 g offset paper and 266 patches on the 300 g specialty paper. Selecting a screen solely from its overall mean therefore does not always identify the condition with the smallest recorded colour difference for a specific input colour.

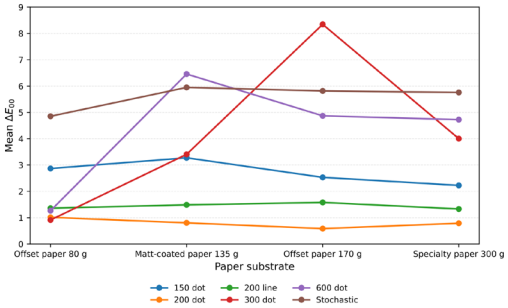
These patch-level results provide the experimental basis for colour-specific screening recommendations within each substrate and demonstrate the potential value of a more comprehensive operator-support system.

3.2. Descriptive relationship between paper substrate and screening performance

The effect of the paper substrate on the colour-difference response of the investigated screening conditions is presented in Figure 3. The results show that the mean ΔE_{00} values of the screening conditions varied differently across the four substrates.

The 200 dot condition maintained relatively low mean ΔE_{00} values across all substrates, ranging from 0.58 to 1.01. In contrast, the response of 300 dot varied substantially, from 0.91 on the 80 g offset paper to 8.34 on the 170 g offset paper.

The 600 dot condition also showed noticeable variation, with mean ΔE_{00} values ranging from 1.26 to 6.46. The 200 line condition exhibited comparatively small changes between substrates, with values ranging from 1.33 to 1.58. Stochastic screening remained within a relatively narrow but higher range, from 4.85 to 5.95.



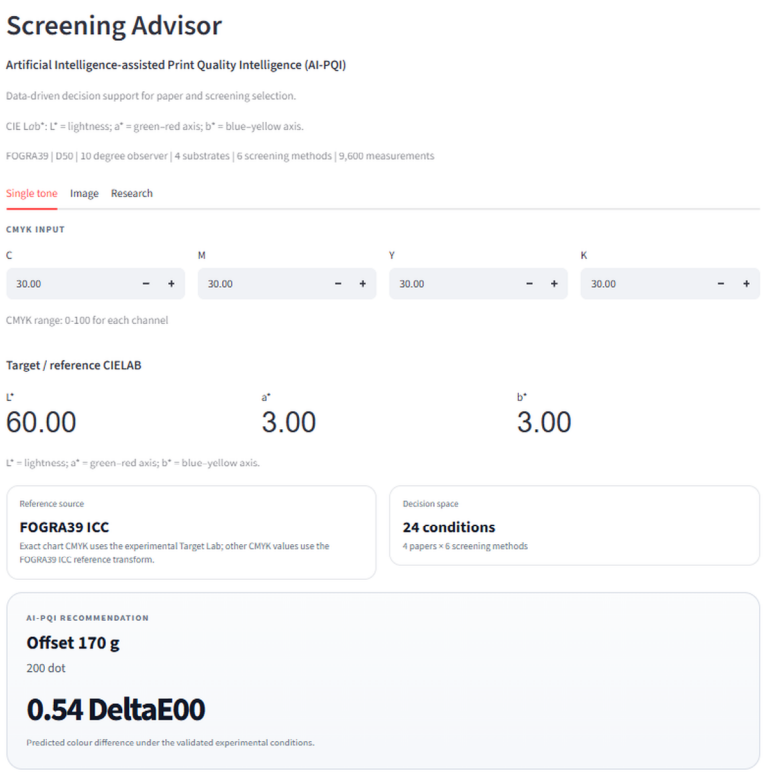
» **Figure 3:** *Descriptive variation in mean ΔE_{00} across paper substrates and screening conditions*

3.3. AI-PQI application and prediction output

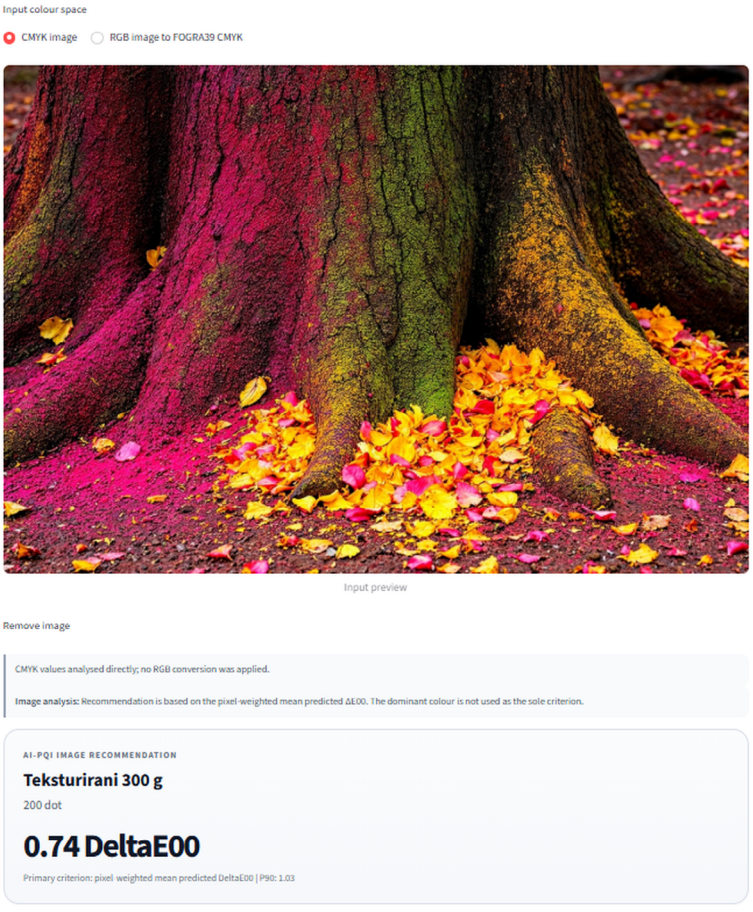
The experimentally obtained colour-difference dataset was implemented in the AI-PQI application to demonstrate prediction for a specified CMYK input across the investigated paper–screening combinations. The application estimates the expected ΔE_{00} for each combination and ranks the available alternatives according to the predicted values, as illustrated in Figure 4. This output demonstrates the operation of the recommendation procedure but does not constitute independent validation of its predictive accuracy.

In addition to single-colour CMYK analysis, the application includes an image-analysis mode in which the input image is evaluated according to its colour content. The image-level estimate is derived from the pixel-weighted contribution of the analysed colours.

This enables the recommendation procedure to consider the overall colour composition of an image rather than only its dominant colour. Figure 5 presents an example of the application output. The current implementation should be regarded as a functional demonstration; its recommendations require validation using independent print samples and complete images. The developed application therefore provides two complementary input modes: prediction for an individual CMYK colour and prediction based on the colour content of a complete image.



» **Figure 4:** *AI-PQI application output for CMYK-based colour-difference prediction and screening recommendation*



» **Figure 5:** *AI-PQI image-analysis mode for substrate and screening recommendation*

4. Discussion

The experimental results show that colour-difference behaviour in electrophotographic printing depends on the combination of paper substrate and screening condition. The 200 dot condition produced consistently low mean ΔE_{00} values on three of the four substrates, whereas the lowest mean value on the 80 g offset paper was obtained with 300 dot screening. We therefore consider screening and substrate to be interdependent production parameters rather than independent choices. This interpretation is consistent with previous research showing that paper surface characteristics affect measured properties and overall print quality in digital printing (Ataeefard, 2014). The pronounced changes observed with 300 dot and 600 dot screening further demonstrate that substrate-dependent variations can remain substantial even when the printing system and colour-management workflow are unchanged.

The dataset also revealed individual colour patches that deviated considerably from the general behaviour of a screening condition. The most pronounced cases occurred with 150 dot screening on the 80 g offset paper and 300 dot screening on the 170 g offset paper, where isolated high ΔE_{00} values increased the overall variability. Because the colour chart, profile and measurement procedure remained consistent, we interpret these deviations as evidence that some paper–screening combinations reproduce different regions of the CMYK space with unequal accuracy. Although the present experiment does not isolate the physical causes of these deviations, it shows why evaluation based on a large set of colour patches is more informative than testing only a few selected colours.

The AI-PQI approach uses this experimentally measured relationship between CMYK composition and ΔE_{00} for each paper–screening combination. Instead of selecting one screening condition for every colour based on its overall average, the model uses neighbouring CMYK samples to estimate the expected colour difference for a specified input. Differences in data uniformity among substrates directly affect these estimates and are therefore relevant to the recommendation procedure. In our view, this colour-specific use of measured data is the main practical contribution of the proposed approach. It is also consistent with earlier research demonstrating the potential of machine-learning methods for print-quality assessment based on objectively measured attributes (Lundström & Verikas, 2013; Lundström et al., 2013).

The difference between the best overall screening condition and the condition producing the lowest measured ΔE_{00} for an individual patch confirms the value of colour-specific decision support. The present application uses these relationships to identify the most promising of the tested conditions for a specified CMYK input and to support the operator's decision before print verification. The current results describe the choices represented in the measured dataset, while evaluation using previously unmeasured CMYK inputs remains an important next stage in the development of the model.

A methodological limitation of the present experiment concerns the definition of the Target CIELAB values. Although the same CMYK patch definitions were used, the reference values were established within the original substrate-specific measurement workflow.

Consequently, the reported ΔE_{00} values provide a valid basis for examining screening behaviour within the corresponding experimental conditions, but direct rankings across papers do not yet represent comparisons against a single paper-independent target. We therefore interpret the current AI-PQI output as preliminary production support based on the original experimental reference structure.

In future research, we intend to establish one traceable Target CIELAB dataset for all paper and screening conditions. The workflow could begin with the original CMYK patch definitions stored in a CGATS text file and transform them into CIELAB coordinates using a documented independent ICC reference profile, such as FOGRA39 or another profile appropriate to the intended reference condition. The resulting Target values could then be incorporated into a compatible CGATS or MXF workflow in i1Profiler. Documenting the ICC profile, rendering intent, black-point compensation and other transformation parameters would allow every printed patch to be evaluated against the same Target CIELAB value.

The colorimetric conditions should also be harmonised before measurements begin. The present study retains the D50 illumination and CIE 1964 10° observer settings used in the original workflow. In the proposed future workflow, both Target and Measured CIELAB values would be generated using D50 illumination and the CIE 1931 2° standard observer. These conditions would be selected directly in i1Profiler before measuring the printed charts. When Target and Measured values are generated under the same D50/2° conditions from the outset, subsequent recalculation of Measured CIELAB values from M1 spectral data is unnecessary.

A common Target dataset and harmonised measurement conditions would enable all paper–screening combinations to be compared on the same colorimetric basis. The resulting system could provide the operator with a ranked list of paper, screening and profile configurations, together with their expected ΔE_{00} values and the need for additional print verification. Validation using CMYK colours excluded from model development, repeated print runs and complete test images would then allow us to evaluate the reliability of these recommendations.

We consider the present study an initial but relevant step towards AI-assisted selection of electrophotographic printing conditions. It demonstrates how profiling, instrumental measurement and local data analysis can be integrated to generate colour-specific recommendations from experimental results.

The objective has been partially achieved: the current model provides structured decision support, while a common Target CIELAB dataset, harmonised D50/2° conditions and independent validation are required to develop it into a standardised instruction system for print operators.

5. Conclusions

The study investigated colour-difference behaviour across four paper substrates and six screening conditions in Xerox Colour C60/C70 electrophotographic printing and examined whether the resulting experimental data could support an AI-assisted recommendation workflow. The original Target, Measured and ΔE_{00} values were retained without retrospective transformation. The findings support the following conclusions:

- The recorded colour-difference response varied among the investigated paper substrates and screening conditions. The 200 dot condition produced the lowest mean ΔE_{00} on the 135 g matt-coated, 170 g offset and 300 g specialty papers, whereas 300 dot produced the lowest mean on the 80 g offset paper. The condition with the lowest measured ΔE_{00} nevertheless varied among individual CMYK patches.
- The experimental data indicate that screening performance should be considered together with substrate characteristics. Particularly pronounced variations were observed for the 300 dot and 600 dot conditions. These results describe the investigated experimental workflow and should not be generalised to other printing systems without additional validation.
- The dataset of 9,600 measured patches provided a basis for developing a local CMYK-based estimation procedure for the investigated paper–screening combinations. The weighted nearest-neighbour approach enables colour-specific estimates rather than recommendations based only on overall screening averages.
- The AI-PQI application demonstrates the feasibility of integrating profiling, instrumental colour measurement and data analysis into an operator-oriented decision-support workflow. Its outputs should currently be interpreted as preliminary recommendations within the investigated dataset, not as independently validated predictions or definitive paper-independent optimisation.
- Future development should establish a common Target CIELAB dataset from the CMYK patch set using a documented independent ICC reference profile. Target and Measured values should be generated directly in i1Profiler under harmonised D50/2° conditions. The resulting method should then be validated using previously unmeasured colours, repeated print runs and additional substrates, screening conditions and colour-management profiles.

The study partially achieved its objective by demonstrating how experimental profiling, colour measurement and AI-assisted data analysis can be combined to support the selection of printing conditions. A fully standardised operator-guidance system will require a common target definition, harmonised colorimetric conditions and independent validation of the resulting recommendations.

6. Acknowledgments

The authors gratefully acknowledge the financial support provided by the Ministry of Scientific and Technological Development, Higher Education and Information Society of the Republic of Srpska under project No. 19.032/961-60/24, titled “Critical Assessment of Color Quality Control in the Printing Industry in Accordance with the Recommendations of ISO 12647, ISO 15311, and ISO 13655 Standards.” and by the Provincial Secretariat for Higher Education and Scientific Research of the Autonomous Province of Vojvodina, Republic of Serbia, through the project "Digital and Ecological Transformation of the Graphic Industry" (No. 004351431 2025 09418 003 000 000 001 04 002).

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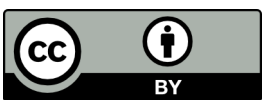
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