Original scientific paper

Evaluating the reliability of spectrophotometer for print quality control

ABSTRACT

This study investigates the measurement system variability of a spectrophotometer, used for color control in the printing industry. A Type 1 Gage Study and Gage R&R was conducted for the Nix Spectro 2 spectrophotometer to evaluate the precision and accuracy in measuring color values of Cyan, Magenta, Yellow, and Black (CMYK) on 10 printed samples. The study assesses both repeatability and reproducibility to determine the overall measurement system capability. The results revealed high repeatability and low bias with Cg and Cgk metrics greater than 1.33, %Contribution below 1% and %Study Variation under 10%, thus confirming the reliability and suitability of Spectro 2 for color measurements. The findings shall aid the printers, quality control team, and designers in the optimization of color management workflows, ensuring consistent print quality.

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KEY WORDS
type 1 gage study, gage R&R, spectrophotometer, repeatability, reproducibility, print consistency, color management, quality control, process capability

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Introduction

Brands need to connect, communicate, and build trust with their consumers to maintain brand loyalty. The brand identity depends on the consistency of product and package printing as it conveys ideas and connects with potential consumers. Color is an integral part of brand identity and has an impact on consumers' emotional state. Hence, color control is paramount in the printing industry, where consistency and accuracy are critical for meeting client expectations, minimizing production waste, and easier brand recognition and loyalty.

These colors are printed on various substrates, like absorbent and non-absorbent, with different types of inks and printing processes. Maintaining color consistency is a challenge due to several process variables in the color management workflow across design, prepress, ink room and printing machine. Spectrophotometers play a vital role in providing quantitative measurements of color values and enable printers to monitor and adjust ink densities, tone value increase or dot gain, and other key quality metrics.

However, the reliability of these measurements is fundamental. Inconsistent measurements shall misguide the printers leading to incorrect adjustments of process parameters, higher color deviations, increased waste, and dissatisfied customers.

The ability of the color measurement system to consistently measure accurate colors directly impacts the validity of data-driven decisions, for example, pass-fail decisions by printing press operators or quality control teams. The variations in the color measurement systems arise from different sources like the instrument, the operator, and the printed sample (part). Evaluating the measurement system is essential to minimize these variations. A Type 1 Gage Study serves as a crucial analytical method for evaluating the color measurement systems. It is the first step in a comprehensive measurement system analysis (MSA) and lays the foundation for more detailed studies that consider other sources of measurement variation. It focuses solely on the gage (measurement device), assessing the repeatability and bias of a single measuring instrument to ensure the reliability of the data for the process (Muelaner, n.d.).

Repeatability refers to the extent of variation in measurements when a single part is measured repeatedly by the same operator, using the same instrument, and under consistent environmental conditions. Bias on the other hand compares the accuracy of the measuring instrument to a known standard (Minitab, n.d.). A Type 1 Gage study assesses a measurement device's capability for consistent readings under the same conditions. This makes it an excellent initial assessment to ensure the stability and precision of the gage itself before moving on to more complex analyses involving multiple operators or parts. It helps to determine if the measurement device, such as the Spectrophotometer, is capable of discriminating differences in color being measured. Type 1 Gage Study involves data collection, statistical analysis with metrics such as Cg (repeatability) and Cgk (bias) to quantify the gage's capability, and run chart to visually assess the measurement variation and identify any patterns or trends (SPC for Excel, 2024).

Gage R&R (Repeatability and Reproducibility) quantifies the variability originating from the measuring instrument (repeatability) and the operators (reproducibility) (Minitab, 2017). Reproducibility describes the extent of variation in measurements when multiple parts are measured by different operators and instruments on the same sample (American Society for Quality, n.d.; Soares et al., 2022; Burdick, Borror & Montgomery, 2003). Gage R&R is expressed in percentage and quantifies the proportion of total observed process variability attributable to the measurement system. If the Gage R&R% is below 10%, the measurement system is adequate and reliable while between 10% to 30% may be acceptable depending upon the specific application. The measuring system is unacceptable if it exceeds 30% and requires improvement (Hessing, n.d.; Mikulová & Plura, 2018; Automotive Industry Action Group, 2010; SAE Industry Technologies Consortia, 2022). Gage R&R study is performed by the Analysis of Variance (ANOVA) method as well as the Average and Range method. ANOVA method is preferred over the Range method as the latter does not support the computation of confidence interval. Incorporating the confidence intervals for the measurement standard deviation and the discrimination ratio (β) into the decision-making process offers a more robust and informative approach. Moreover, a limitation of the Average and Range method is its inability to account for interaction effects between operators, parts, and the measurement gage (Senvar & Firat, 2010; Čepová et al., 2018; Healy & Wallace, 2011).

Effective color communication requires correct color scale, CIE illuminant, CIE standard observer, instrument geometry, sample preparation, and sample presentation (MyColorDoc.com, 2018). ISO 13655:2017 defines color measurement conditions including M0, M1, M2 and M3, along with D50 illuminant, 45°/0° or 0°/45° instrument geometry for printing and packaging industry (International Organization for Standardization, 2017). ISO 15790:2004 describes how to use certified reference material and report the combined uncertainty of color measurement systems in printing industry (International Organization for Standardization, 2004). Studies on uncertainty of color measurements have been reported by Burns & Berns (1997) and Gardner (2000).

Tarasov & Milder (2020) evaluated the accuracy of the ColorMunki and i1 Pro spectrophotometers by color difference and reflectance comparisons. An acceptable accuracy with the magnitude of color differences below 0.45 $\Delta E76$ was observed for both devices. Sharma, Leung & Adams (2017) evaluated the inter-instrument agreement of ten commercial spectrophotometers used in the printing industry across various substrates. Wyble & Rich (2007) compared twelve spectrophotometers evaluating traditional color difference metrics with the multidimensional methods outlined in ASTM E2214 for short-term, medium-term, and long-term repeatability. A comparative study by Sanderson (2015) on Konica Minolta and X-Rite handheld reflectance spectrophotometers revealed that the consistency of the measurements across various colors, textures, and materials was dependent on the measurement procedure and the instruments' geometric design. Novotny (2011) assessed the measurement accuracy of Gretag-Macbeth Spectrolino, Techkon SpectroDens and X-Rite 530 spectrophotometers on rough and smooth substrates. Spectrolino using diffuse illumination showed better accuracy on rough and texture substrates while Techkon SpectroDens and X-Rite 530 using directional illumination exhibited better accuracy on smooth coated substrates. An inter-instrument agreement study by Nussbaum, Hardeberg & Albregtsen (2011) with six color-measuring instruments on three different substrates evaluated by polynomial regression showed consistent performance of the model across all three substrates. However, the inter-instrument agreement can be further improved by 50% with the characterization model. Centore (2016) assessed the repeatability of six spectrophotometers on 290 samples by the Coefficient of Variation (CoV) method and identified surface geometry of the instrument as the major source of variation.

This study evaluates the measurement variability of the Nix Spectro 2 instrument using a Type 1 Gage Study and Gage R&R for CMYK printed samples, examining both repeatability and reproducibility.

Materials

Substrate

In this study, the samples printed on both absorbent and non-absorbent substrates with Gravure, Flexography, and Digital printing processes were used (Table 1).

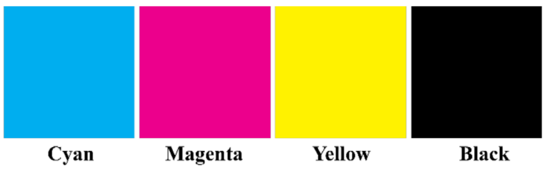
Table 1

Substrates and Printing Processes

S. No	Substrate	Printing Process
1	12 µ PET	Gravure
2	85 GSM High Gloss	Flexography
3	80 microns Vinyl	Digital (Wide Format Ink Jet)
4	Vinyl Lamination	Digital (Wide Format Ink Jet)
5	Vinyl	Digital (Wide Format Ink Jet)
6	Texture16	Digital (Electrophotography)
7	350 GSM Ivory	Digital (Electrophotography)
8	300 GSM Art paper	Digital (Electrophotography)
9	270 GSM Ensemble	Digital (Electrophotography)
10	170 GSM Art paper	Digital (Electrophotography)

Layout Design

Cyan, Magenta, Yellow, and Black (CMYK) solid patches of size 4 mm x 4 mm were generated for the measurement analysis (Figure 1). These are widely used colors in the printing industry.



» **Figure 1:** *CMYK Solid Patches*

Experimental Process

Type 1 Gage Study

Type 1 Gage Study was performed first to check the precision, capability, and accuracy of spectrophotometer. The analysis was limited to Nix Spectro 2 instrument. It did not include comparisons with other instruments such as X-Rite, Techkon, or Konica Minolta which will be covered in the next phase of this research. For the present study, the same part of CMYK solid patches were measured 50 times on each substrate by the same operator using the Nix Spectro 2 instrument, having 45°/0° geometry and a 2 mm aperture (Nix Sensor, n.d.). M1 measurement mode with the D50 illuminant and 2-degree observer angle as per ISO 13655:2017 was used for all the measurements.

Before the experimentation, the Nix Spectro 2 was calibrated using the manufacturer-supplied white tile. The instrument measured the known reflectance of the tile to set the reference white, and successful calibration was confirmed in the Nix Print Pro software.

The objective of this exercise was to assess the consistency of the Spectro2 instrument when measuring CMYK patches multiple times by the same operator. The variations in the readings of an identical CMYK patch evaluated the repeatability of the instrument while the Study Variation to the Tolerance and the true value of the instrument were assessed by Bias.

The mean L*a*b* values of 50 measurements for each patch (CMYK and the substrate) were considered as the target. Color difference CIEDE2000 (ΔE00) between the target and the individual measurements was calculated. Further, the reference (true value) for the Type 1 Gage Study was established and the tolerance limits were set at 3.5 for CMY, and 5.0 for K.

From Figure 2, the Run Chart for CMYK shows that all the ΔE2000 measurements are within the tolerance limits without any presence of outliers. The observations indicate the absence of unusual variations and outliers. The random distribution of data around the reference line shows no specific trends in the ΔE2000 values. A standard deviation less than 0.1 for CMYK indicated good repeatability.

As shown in Equation (1), the Gage Capability Index (Cg) for Repeatability compares the gage's spread (6 x standard deviation) to % Tolerance. The Cgk metric shown in Equation (2), considers both the repeatability (spread) and the bias (accuracy) of the Spectro 2 instrument.

$$Cg = \frac{\left(\frac{K}{100}\right) x\ Tolerance}{L\ x\ s} \tag{1}$$

$$Cgk = \frac{\left(\frac{K}{200}\right) x\ Tolerance - \left|\bar{X}g - Xm\right|}{L\ x\ s} \tag{2}$$

K = Tolerance % (20 is default)
s = Standard Deviation of Measurements
L = No. of standard deviations that represent the entire process spread (6 is the default)
$\bar{x}_g$ = Mean of Measurements
x_m = Reference Value

From Figure 3 and 4, it is evident that the Cg value was higher than 1.33 for CMYK on all the substrates, indicating that Spectro2 is precise enough as measurements are very close together compared to the acceptable variation. The Cgk (Repeatability and Bias) values are also above the benchmark of 1.33 and confirm that lower bias is not negatively impacting the overall capability of Spectro 2. The higher average Cg and Cgk metrics were observed for 85 GSM High Gloss (4.39 and 4.37), 300 GSM Art paper (3.39 and 3.37), and 170 GSM Art paper (3.18 and 3.15) indicating excellent measurement system capability. Black exhibited lower Cg/Cgk values than other colors for the majority of the substrates printed by digital process.

This may be due to micro-variations in the same patch due to banding, graininess, pigment loading, etc.

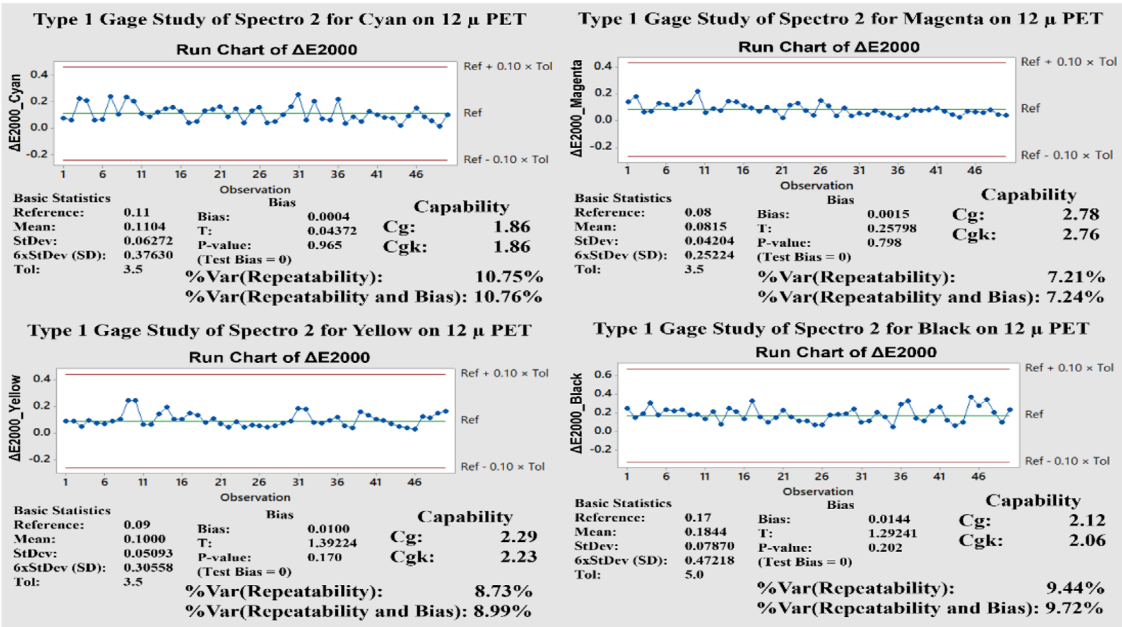
The %Var (Repeatability) values below 10% are considered excellent while between 10% to 20% are acceptable depending on the application. For the values above 20%, the measuring instrument needs to be evaluated.

Figure 5 shows (Repeatability) denoted by %VarR for CMYK on all the substrates. Figure 6 provides %Var (Repeatability and Bias) represented as %VarR and Bias. All the values are below 15% indicating minor total variability and bias and the instrument fitness for use of color measurements. Excellent repeatability was observed for 85 GSM High Gloss, 300 GSM Art paper, 170 GSM Art paper, Vinyl, and 12 µ PET substrates. The remaining substrates showed acceptable repeatability. The higher micro-print inconsistencies in Black led to higher values of %Var (Repeatability) and %Var (Repeatability and Bias) as compared to Cyan, Magenta, and Yellow.

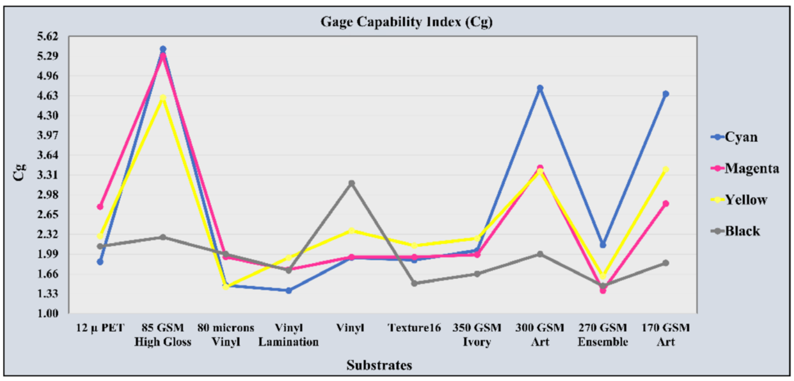
This precision and repeatability for Black measurements is still acceptable.

Bias is the difference between the average of observed measurements and the reference or true value. The systematic error refers to the consistent shift in measurements either above or below than the true value. The P-value for bias (Figure 7) determines the statistical significance of systematic error in the Spectro 2 instrument. The significance level (α) was kept at 0.05 and the null hypothesis of bias = 0 was tested.

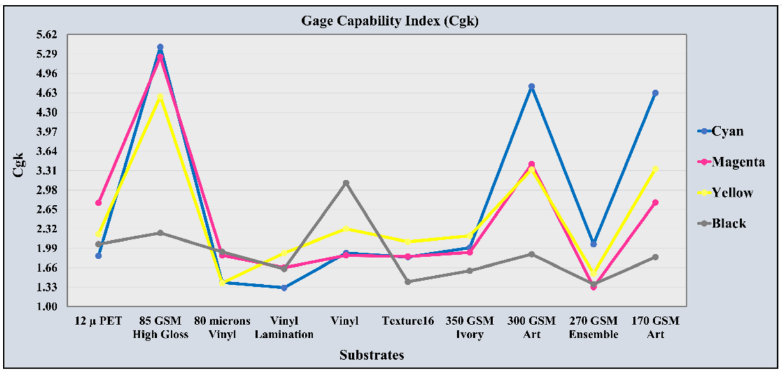
From Figure 6 and 7, it is evident that there is no statistical significance of bias for colors on any of the substrates as the p-value>0.05. Although the CMYK measurements on all the substrates exhibited good accuracy, the Black measurements on Texture 16, Vinyl Lamination, and 270 GSM Ensemble were close to the significance level of 0.05. It was due to the larger variation in the data set from the true value.



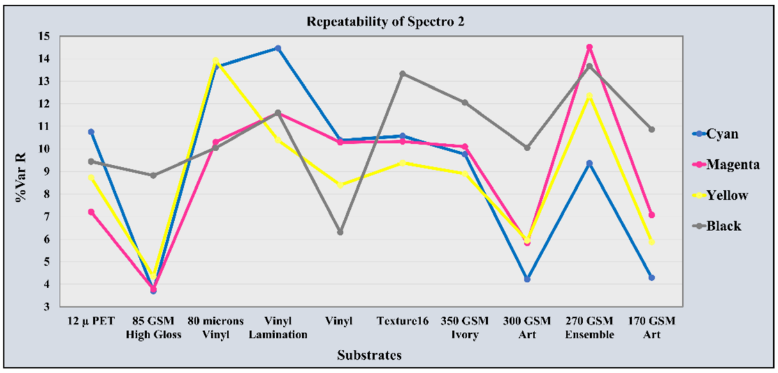
» **Figure 2:** *Type 1 Gage Study of Spectro 2 for CMYK on 12µ PET*



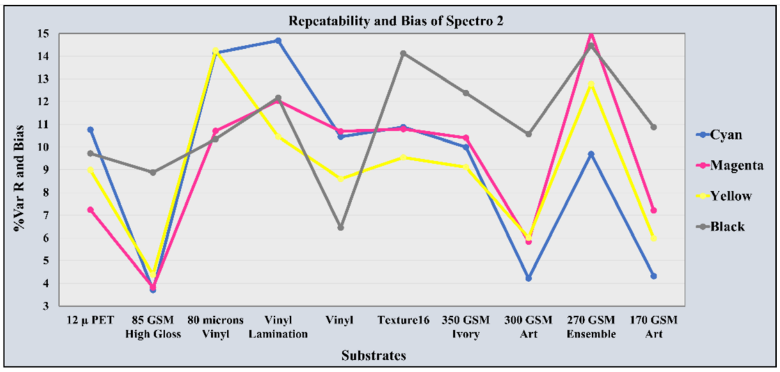
» **Figure 3:** *Gage Capability Index (Cg) of CMYK for Substrates*



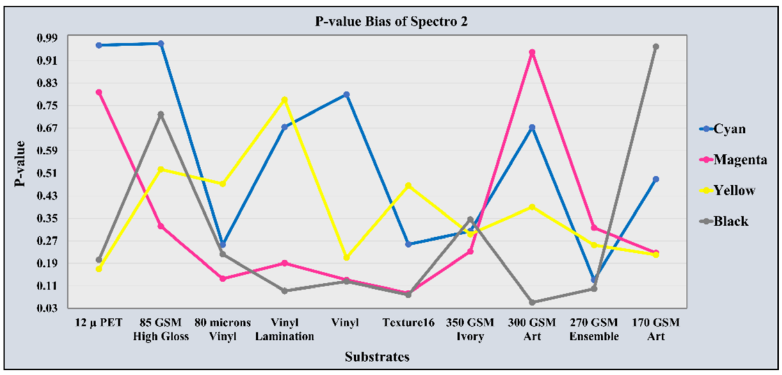
» **Figure 4:** *Gage Capability Index (Cgk) of CMYK for Substrates*



» **Figure 5:** *Repeatability of Spectro 2 for Varying Substrates*



» **Figure 6:** *Repeatability and Bias of Spectro 2 for Varying Substrates*



» **Figure 7:** *Bias P-value of Spectro 2 for Varying Substrates*

The accuracy of Spectro 2 was significantly influenced by the substrate surface characteristics. The smoother substrate 12 µ PET, 85 GSM High Gloss, and Art papers (300 GSM, 170 GSM) consistently resulted in higher p-values, indicating more robust accuracy. Conversely, the substrates with comparatively lower smoothness such as the Vinyls, Texture 16, and 270 GSM Ensemble resulted in lower p-values and accuracy.

Gage R&R

The Crossed Gage R&R Study was conducted on 10 different parts of CMYK patches with 3 operators and 3 replicates, thus a total of 90 measurement data per color. The L*a*b* values specified for the premium coated paper on white backing in ISO 12647-2:2013 (International Organization for Standardization, 2013) were considered as a reference for CMYK. The ΔE2000 was calculated between the reference and the individual measurement. The Nix Spectro 2 instrument was used with the same settings as the Type 1 Gage Study. The objective of this exercise was to evaluate the variation due to the instrument, operator, or process. The ANOVA method was used for the Gage R&R Study.

The Two-Way ANOVA (Tables 2 to 5) for CMYK shows that the p-values for parts and the part-operator interaction are less than the significance level $\alpha=0.05$, indicating a statistically significant effect for these factors.

In contrast, the p-value >0.05 for the operator in Cyan, Magenta, Yellow, and Black indicates no statistically significant difference among the average measurements provided by the operators, hence the null hypothesis is rejected.

Table 6 shows %Contribution of variance components for CMYK solid patch measurements by Spectro 2 instrument. The %Contribution of Total Gage R&R is less than 1% of the Total Variation for Cyan (0.29%), Magenta (0.90%), Yellow (0.60%), and Black (0.92%). This reveals that Spectro 2 spectrophotometer is highly capable of distinguishing part differences.

Lower Repeatability variance for CMYK (0.16% to 0.48%) indicates that there were no significant measurement variations, confirming the consistency of Spectro 2.

Lower Reproducibility variance (0.13% to 0.57%) indicates minimal effect of operator on measurement variation with individual operator effect impacting not more than 0.04%. The contribution from Operator * Parts interaction was 0.12–0.53% due to differences in the surface properties of the substrates which is still in the acceptable limits. The lower %Contribution of operators and its interaction with parts confirms that operators are well trained for measurements and do not introduce meaningful measurement bias.

Part-to-Part variation (>99%) was major contributor to overall variation for all the colors. This higher contribution confirms that the variation exists due to substrates and printing processes, and not measurement error. A clear distinction in Parts indicates the reliability and accuracy of Spectro 2 for color measurements of CMYK.

Table 2

Two-Way ANOVA with Interaction of Spectro 2 for Cyan

Source	DF	SS	MS	F	P
Parts	9	680.861	756.512	1765.1	0.000
Operator	2	0.164	0.0819	1.91	0.177
Parts * Operator	18	0.771	0.0429	3.14	0.000
Repeatability	60	0.818	0.0136		
Total	89	682.615			
α to remove interaction term = 0.05					

Table 3

Two-Way ANOVA with Interaction of Spectro 2 for Magenta

Source	DF	SS	MS	F	P
Parts	9	419.568	46.6187	932.779	0.000
Operator	2	0.069	0.0347	0.693	0.513
Parts * Operator	18	0.9	0.05	3.147	0.000
Repeatability	60	0.953	0.0159		
Total	89	421.49			
α to remove interaction term = 0.05					

Table 4

Two-Way ANOVA with Interaction of Spectro 2 for Yellow

Source	DF	SS	MS	F	P
Parts	9	272.028	30.2253	734.615	0.000
Operator	2	0.144	0.072	1.75	0.202
Parts * Operator	18	0.741	0.0411	4.933	0.000
Repeatability	60	0.5	0.0083		
Total	89	273.413			
α to remove interaction term = 0.05					

Table 5

Two-Way ANOVA with Interaction of Spectro 2 for Black

Source	DF	SS	MS	F	P
Parts	9	363.065	40.3406	458.099	0.000
Operator	2	0.275	0.1376	1.562	0.237
Parts * Operator	18	1.585	0.0881	5.536	0.000
Repeatability	60	0.954	0.0159		
Total	89	365.88			
α to remove interaction term = 0.05					

Table 6

Variance Component of Spectro 2 for CMYK

Source	%Contribution (of VarComp)			
	Cyan	**Magenta**	**Yellow**	**Black**
Total Gage R&R	0.29	0.90	0.60	0.92
Repeatability	0.16	0.48	0.25	0.35
Reproduc-ibility	0.13	0.41	0.35	0.57
Operator	0.02	0.01	0.03	0.04
Operator* Parts	0.12	0.41	0.32	0.53
Part-To-Part	99.71	99.10	99.40	99.08
Total Variation	100.00	100.00	100.00	100.00

Table 7

Gage Evaluation of Spectro 2 for CMYK

Source	(%Study Variation)			
	Cyan	**Magenta**	**Yellow**	**Black**
Total Gage R&R	5.41	9.47	7.76	9.60
Repeatability	4.02	6.96	4.97	5.94
Reproduc-ibility	3.62	6.42	5.95	7.55
Operator	1.24	0.84	1.75	1.91
Operator* Parts	3.40	6.37	5.69	7.30
Part-To-Part	99.85	99.55	99.70	99.54
Total Variation	100.00	100.00	100.00	100.00
No. of Distinct Categories	26	14	18	14

Table 7 shows the %Study Variation that compares the measurement system variation to the total variation. As per the Automotive Industry Action Group (AIAG), the measurement system is acceptable if the %Study Variation (%SV) of Total Gage R&R is below 10%. The %SV of Total Gage R&R for Spectro 2 was well below the acceptance criteria for Cyan (5.41%), Magenta (9.47%), Yellow (7.76%), and Black (9.60%). This indicates that Spectro 2 is adequate and reliable for accurately measuring the CMYK colors.

The lower repeatability variation for CMYK color measurements (4.02 to 6.96%) shows that Spectro 2 contribution was less in overall measurement variation. The lower reproducibility variation (3.62% to 7.55%) shows minimal influence of operators on color measurement variation with individual operator effect ranging from 0.84% to 1.91%.

The interaction between parts and operators ranging from 3.40% to 7.30% can be attributed to the surface characteristics of varying substrates printed by different printing processes. Overall, the individual effect of operator and its interaction with parts shows minimal impact of operators on color measurement variation.

As per the AIAG guidelines, the measurement system should have at least 5 number of distinct categories to be acceptable. Spectro 2 has exceeded this minimum requirement with Cyan (26), Magenta (14), Yellow (18), and Black 14) indicating the detection of small differences in parts. This shall help in pass/fail criteria for process control and quality monitoring in print production.

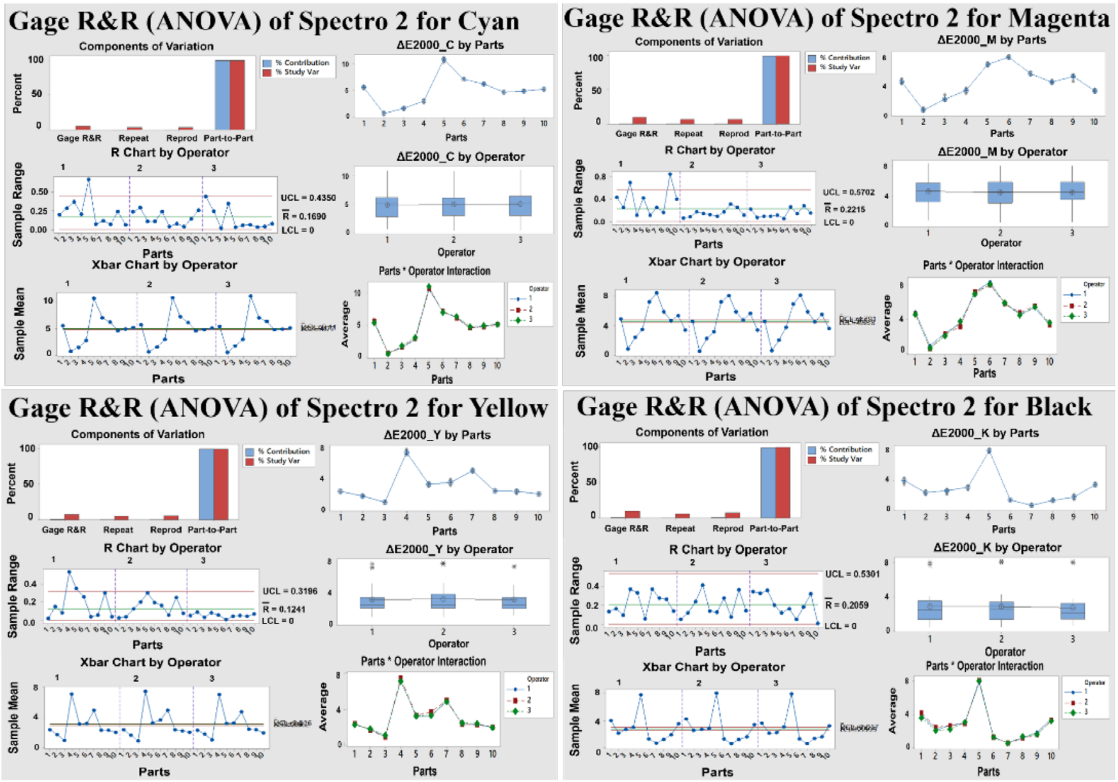
The Components of Variation and ΔE2000 by Parts in Cyan, Magenta, Yellow, and Black (Figure 8) show that much of the variation is due to the parts. The R chart shows a minor inconsistency in measurements by Operator 1 for Cyan, Magenta, and Yellow, although the magnitude is negligible and do not affect the quality output.

Majority of the data points are within the upper and lower control limits indicating that measurement variation within the operators is stable. The differences in measurements between the operators are small as compared to parts, as seen by ΔE2000 by the operator for all the 3 colors. The box plot of ΔE2000 by operators for CMYK shows that there is a marginal difference in measurement variation and no significant bias in the readings by the 3 operators. All the data points are falling outside the control limits as seen in the X-bar chart shows the variation mainly due to parts.

This means that Spectro 2 is efficient enough to detect the differences in the mean ΔE2000 values of all the colors which is necessary for print quality control.
The interaction between parts and operators shows overlapping of lines for all the parts measured by 3 operators. This suggests similar methods employed by the operators for the measurement of data. The graph exhibits good repeatability and reproducibility and is effective in distinguishing parts with consistent performance by Spectro 2, hence is fit for the intended use.

Result and Discussion

The performance of Spectro 2 spectrophotometer was assessed using both Type 1 Gage and Gage R&R studies. Type 1 Gage Study was conducted to evaluate the inherent bias and precision of the Spectro 2 with the same operator measuring 50 times for each CMYK solid patch. The Cg and Cgk values were found to be above 1.33 signifying low bias and high precision. The %Var (Repeatability) and %Var (Repeatability and Bias) of the system were within acceptable limits, indicating Spectro 2 as an acceptable measurement system.



» **Figure 8:** *Gage R&R of Spectro 2 for CMYK*

Furthermore, to evaluate the variation due to operators and parts, Gage R&R Study was conducted. The %Contribution of Total Gage R&R, and %Study Variation of Total Gage R&R, for CMYK were well below the acceptance limits while the number of distinct categories above the threshold limit. The scope of this work includes intra-instrument reliability of Nix Spectro 2 measurement system. The consistent performance of Nix Spectro 2 can be attributed to its fixed measurement geometry and measurement conditions, standardized white tile calibration, spectral measurement approach, and controlled measurement methodology. The findings of this study proved the suitability of Spectro 2 for color measurements of CMYK in print production, quality control, and decision-making.

Conclusion

Color perception is subjective, hence measuring and maintaining print quality during color reproduction is required. Several Spectrophotometers are used in the printing industry for color measurement. In this study, reliability and precision of Nix Spectro 2 was evaluated. Both the Type 1 Gage Study and the Gage Repeatability and Reproducibility (R&R) confirmed that Spectro 2 is capable of measuring CMYK colors with high precision and reliability. The findings of this study shall provide confidence to the stakeholders in the printing supply chain to use Spectro 2 for color measurement, quality control and process optimization. It offers the brand owners, print convertors, ink manufacturers, and suppliers a practical approach for selecting a spectrophotometer suitable for their operational use. The future scope involves evaluation and comparison of different spectrophotometers used in printing industry.

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