The Character and Magnitude of Color Variations on Press - with A Strategy for Reducing Them

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Abstract: Two different types of color variations on lithographic presses are identified, and means for quantifying them are described. The magnitudes of such variations, in terms of density and delta E, are determined as a function of tonal area and the number of overprinted colors for three typical presses: a 28 inch sheetfed press and a 40 inch sheetfed press without closed loop color control, and a 38 inch web press with closed loop color control. A strategy for reducing color variations on a given press is outlined, based on this work.

Introduction

Printing is like most manufacturing operations in that it is subject to variations in the properties of its end product, a multi-colored print. Perhaps the most important of these property variations are the deviations that occur in the color of different prints from the same job. The purpose of this paper is to provide a better understanding of the nature of the color variations that occur on press, with the hope that such an understanding will lead to further improvements in color control. More specifically, the objective is to provide further insight into the character of color variations and to show how their magnitude is related to this character. Toward this end, the paper has been divided into four sections that sequentially provide background information, describe the plan followed in collecting and analyzing experimental data, and set forth the results obtained along with the corresponding conclusions reached. The last section contains a recommended strategy for reducing color variations on a given press.

Background Information

The pioneering work of Walter Shewart and his follower, W. Edwards Deming, is looked upon as the foundation of modern process control (Wheeler and Chambers, 1986). For this reason, it will be very pertinent to review their thesis. Briefly, Shewart concluded that all manufacturing processes produce products

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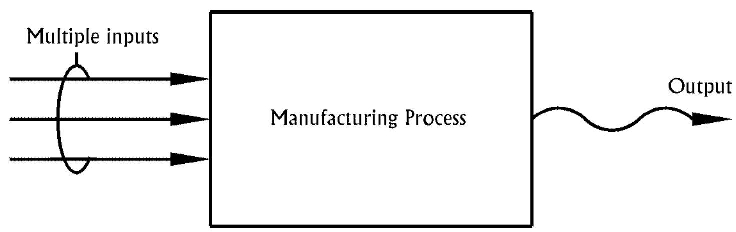
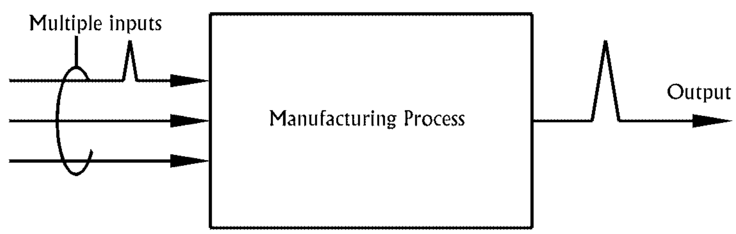
having properties that deviate in value from one unit of production to the next. He also found that the deviations, or variations, were of two types, distinguished by the types of causes that produced them and defined these as assignable versus chance causes. Deming redefined them as common versus special causes. Because the writer has found that neither pair of names for the causes is easy to remember, the choice here is to refer to the variations using the names inherent versus extraneous. Regardless of the terminology used, the important point to remember is that the first (inherent) type of variation is beyond control by the operator because it stems from the design and condition of the process, i.e., is caused within the process. In contrast, the second (extraneous) type of variation is due to events outside the process such as operator error, or variations in one or more of the inputs to the process. This basic difference is illustrated in Figure 1.



(a) Variation within the process produces an inherent type variation in output.



(b) Variation in a process input produces an extraneous type variation in output.

Figure 1 Simplified diagrams of a manufacturing process that illustrate the difference between inherent type variations in the process output versus extraneous type variations. Wavy line and spikes indicate presence of variations in properties of the indicated variable.

Beyond the basic difference, there are several other very important distinctions between these two types of variations that can be deduced as follows: The inherent types occur at a relatively high repetition rate, are predictable, and have a normal distribution. In contrast, extraneous variations occur less frequently, are unpredictable, and generally exhibit a corrupted normal distribution. Additionally, the magnitude of the inherent variations constitutes the lower limit that the process operator can hope to realize while the magnitudes of any extraneous variations are superimposed on this lower limit to produce the gross magnitude of all variations that occur in practice. All of these differences are summarized in Table I.

Table I Summary of the two types of process variations.

Attribute	Type of variation	
	Inherent	Extraneous
Name of cause: Shewart	Chance cause	Assignable cause
Name of cause: Deming	Common cause	Special cause
Source of cause	Within process	Outside event
Occurrence	Predictable	Erratic
Frequency of occurrence	Relatively high	Relatively low
Frequency distribution	Normal (Gaussian)	Corrupted normal
Effect on gross magnitude	Constitutes lower limit	Adds to lower limit

By now, if he did not already know it, the reader will have realized that the best performance that a process can achieve in its as-designed condition is to operate with zero externally caused variations. In theory this state, referred to as the best potential process performance, or process potential, can be achieved by anticipating and negating all extraneous types of variations. However, it is no easy matter to fully achieve this ideal in practice on a press.

If the process model just described is accepted, a number of observations can be made, as follows, when it is applied to printing:

1. It should prove insightful in controlling color variations on press to distinguish between those variations that are inherent in the process and those that are of the extraneous type.

2. It should also prove insightful to determine the relative magnitude of the two types of color variations and to determine if they are a function of either dot area or ink trapping.

3. It should be possible to identify inherent color variations as those that occur as frequently as from print to print and, as will be demonstrated, have an uncorrupted normal frequency distribution.

4. It should also be possible to identify extraneous type color variations as those that occur over longer periods and, by their nature, act to corrupt the otherwise normal frequency distribution.

Plan of Investigation

Armed with the process model described in Table I and the above observations, it was decided to embark on an investigation consisting of three major steps, as follows:

Step 1. Confirm that two different types of color variations can be distinguished.

Step 2. Measure the magnitude of density variations as a function of both the type of variation and screen area. Also, measure the contribution of trapping to these variations.

Step 3. Obtain measures of the above density variations in terms of ΔE.

To carry out this investigation it was decided to analyze prints from three long press runs from three different presses as follows:

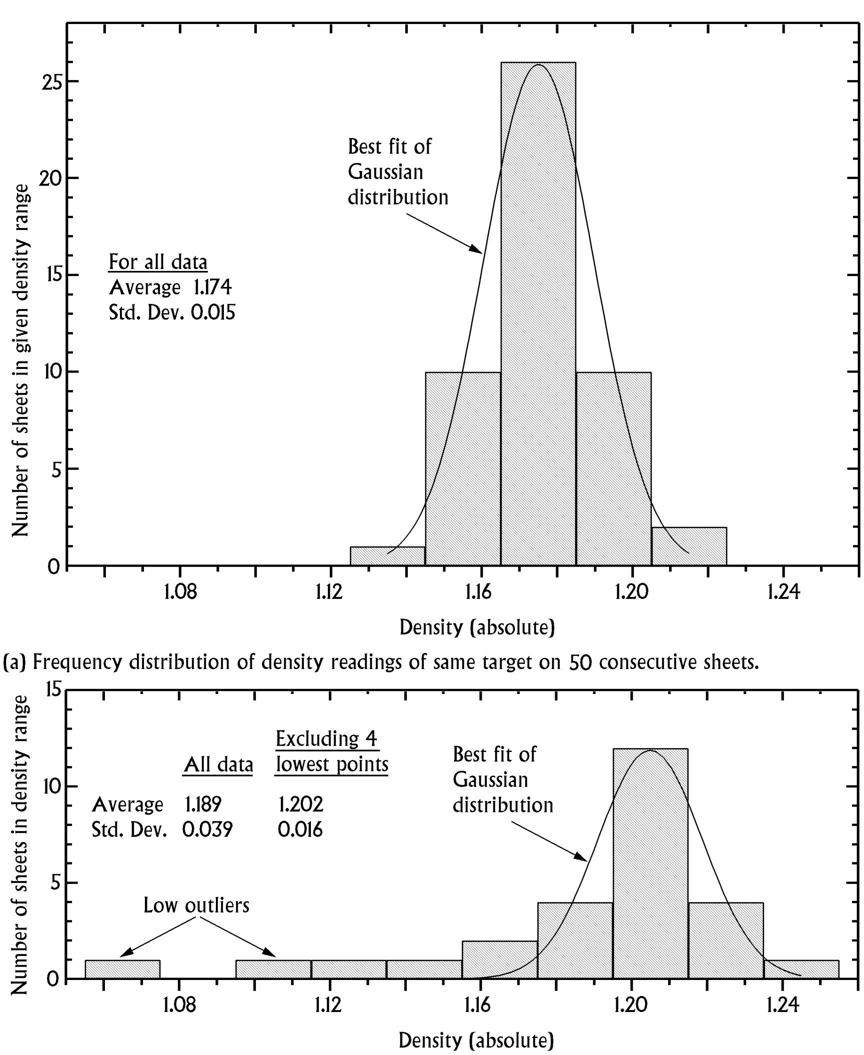
Press 1. A 38 inch wide 4/c web heatset press.

Press 2. A 40 inch wide 6/c sheetfed press.

Press 3. A 28 inch wide 6/c sheetfed press.

Press 1 was equipped with a closed loop color control system. Presses 1 and 3 were of recent vintage while Press 2 was 8 years old. Lengths of the runs subsequently selected were 59,000 impressions on Press 1, 35,000 on Press 2, and 41,000 on Press 3, all of which were on coated paper.

The initial approach used in Step 1 was to analyze the frequency distributions of the densities of different color targets of sheets that had been pulled at approximately every 2000 and 1000 impressions from Presses 1 and 3. The frequency distributions of the densities were analyzed in this step because density variations are a mirror of them and it was found more convenient to do so. The purpose of the analysis was to determine if it would be possible to distinguish between those densities in a given target that fell within a normal distribution and those that did not. When this approach proved unsuccessful it was decided to make pulls of 40–50 consecutive sheets on subsequent runs during a period when the press had settled down and no changes had been made in the controls. This was done on the assumption that there was a high probability that the frequency distributions of the densities of these sheets would



(a) Frequency distribution of density readings of same target on 50 consecutive sheets.

(b) Frequency distribution of density readings of same target on 27 sheets pulled at approximately equal intervals during run of 59,000 sheets.

Figure 2 Frequency distributions of density readings of 90 percent magenta tint in a tone scale on groups of sheets from Press 1.

be strictly normal and thus exhibit only inherent variations. On Press 2, 50 sheets of the two types of pulls were made during the same run.

This subsequent analysis revealed that for two of the three presses it was only necessary to make a single pull to obtain a set of consecutive sheets having frequency distributions that were strictly normal. (In the case of the Press 3, a second pull was required.) Such a frequency distribution is illustrated in Figure 2(a) for a typical set of density readings. In contrast, as shown in Figure 2(b), the corresponding density readings for the set of non-consecutive sheets exhibited a corrupted normal distribution in that four readings were below the best fit of a Gaussian function.

As a consequence, the calculated standard deviation from the average of all data for the sample set of non-consecutive sheets was 0.039 versus 0.015 for the consecutive sheets. Curves similar to those in Figure 2 were constructed for all of the measurements described in the next paragraph. More will be said about Figure 2 in the section on results.

In Step 2, the average and standard deviation of the various density measurements made in Step 1 were calculated. The measurements were made to three places and were of as many as nine different colored targets (Press 2), with care being taken to minimize errors due to positioning of the instrument. Depending on target availability, the densities of each color were measured over a range of dot areas from 20 to 100 percent. The three-sigma limits for each set of densities were calculated where the three-sigma limit was defined as three times the calculated standard deviation from the center of production (the average) of each set of density readings. This limit was selected based on the proven Rule of Thumb that 99–100 percent of a given population of data will be located within a distance of three standard deviations of the average, for a wide variety of frequency distributions (Wheeler and Chambers, 1986). The three-sigma limits were then plotted versus screen area to illustrate the effect of the type of variation, dot area, color, and trapping on the magnitude of the variations.

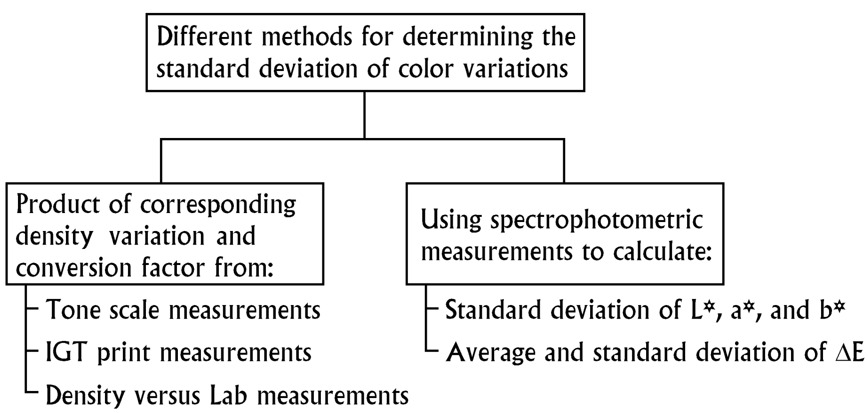


Figure 3 Classification of the five methods used to determine the magnitude of color variations in terms of ΔE, relative to the center of production.

In Step 3, five different methods, identified in Figure 3, were used to determine the magnitude of color variations, in terms of ΔE, in the selected test areas. In two of the methods spectrophotometric measurements of were used as the starting point in calculating ΔE. In the remaining methods three sigma limits in terms of ΔE were determined by deriving conversion factors for converting the density readings of the single color targets to equivalent ΔE values. Here, three different procedures for calculating the conversion factor were evaluated. The effect of dot area and paper grade on the magnitude of conversion factors was also assessed as part of this evaluation.

Findings and Conclusions

Frequency Distributions

A total of 84 sets of density readings were made on the nonconsecutive sheets; 35 from Press 1, 22 from Press 2, and 27 from Press 3. To ascertain their frequency distributions, the best fit of a Gaussian function was obtained for each set of data. The only common feature found among the 84 best fits was that every distribution could be defined as being a corrupted normal distribution. Table II contains a tally of the type of corruptions identified in each data set, and their number as a fraction of the total number of data sets from the given press. In preparing the tallies given in Table II, one of four different types of frequency distribution corruption was assigned to each frequency distribution. The first two of these, low and high outliers, refer to frequencies at densities above or below the best fit curve, as shown in Figure 2(b). Double peak refers to a data set that exhibited two peaks within the best fit curve. The corruption, "Increase in Width," refers to a distribution that was normal but wider than the distribution of the corresponding data set from the consecutive sheets.

Table II Tally of corruptions of normal frequency distributions of density measurements of nonconsecutive sheets run on Presses 1–3. Only the dominant type of corruption was assigned to each data set.

Press number	Total number of data sets	Type of corruption and fraction thereof			
		Outliers		Double peak	Increase in width
		Low	High		
1	35	31.4%	14.3%	11.4%	42.9%
2	22	–	95.5%	4.5%	–
3	27	7.4%	44.4%	29.6%	18.5%

A review of the tally in Table II shows that each press exhibited a different pattern of corruption. For example, double peaks, indicating a shift in the average, showed up on almost 30 percent of the sheets from Press 3, but only on 4.5 percent of those from Press 2. Also, while the percentage of outliers on Presses 1 and 3 were about the same, low outliers predominated on Press 1, while high outliers predominated on Press 3.

A total of 52 sets of density readings were made on the consecutive sheets; 15 from Press 1, 22 from Press 2 and 15 from Press 3. All of these data sets exhibited a common trait: an uncorrupted normal frequency distribution. A typical such distribution is shown in Figure 2(a).

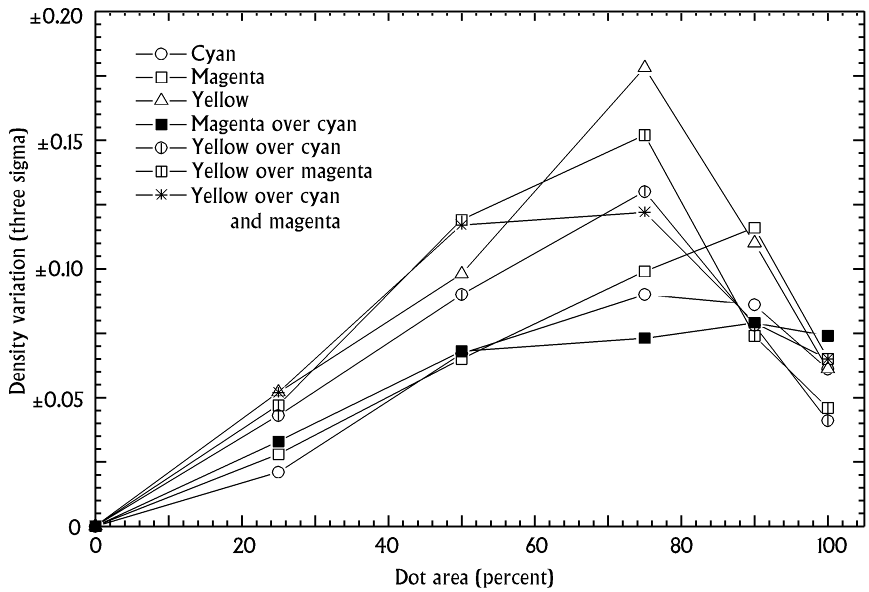
Some, *but by no means all,* of the pairs of frequency distributions exhibited a very pertinent common property. This was that the standard deviation of the data within the best-fit curve was the same, as exemplified by the data in Figure 2, for a pair from Press 1. A similar result for *some* of the pairs from Presses 2 and 3 confirm that some of the normally distributed readings exhibited by the nonconsecutive sheets, vis-à-vis the corresponding readings of the consecutive sheets, were of the same kind, i.e., inherent type.

Based on these results and the fact that the density variations are a mirror of density readings, there are a number of very significant conclusions that can be drawn, as follows:

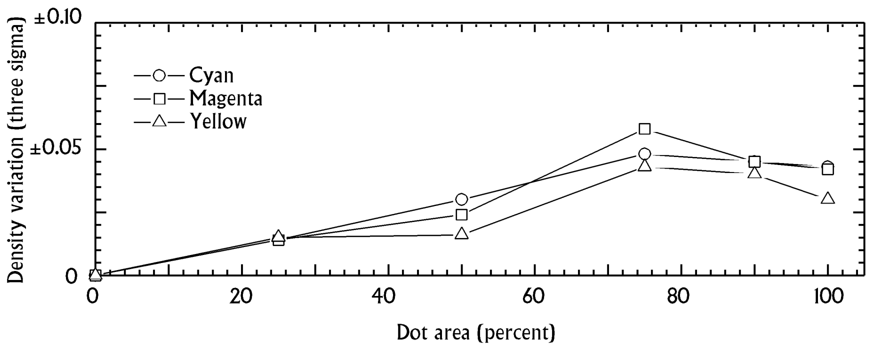
1. The magnitude of color variations produced by inherent causes can be determined by measuring the color variations of a group of consecutive signatures. This is based on the finding that there is a very high probability that such groups will not include any extraneous type variations. Of course, when making this determination, the normality of the frequency distribution should always be checked to confirm the absence of extraneous type variations.

2. The incremental effect of extraneous type color variations can be gauged by comparing the standard deviations of two groups of like signatures, one pulled consecutively and one pulled at equal intervals throughout a given run. This is because the tally in Table II shows that the corruptions attending extraneous type variations always act to widen the overall frequency distribution, and hence increase the standard deviation, compared to a group exhibiting only inherent deviations. In other words, the three sigma limits of a data set exhibiting both types of variations will always be equal to or exceed those of a corresponding set exhibiting only inherent type variations.

3. When assessing the two types of color variations by analyzing consecutive and nonconsecutive collections of prints, it is not necessary that both collections be pulled from the same run, provided no changes have been made in the process or operating procedures. Nevertheless, whenever possible, it will be



(a) Density variations produced by both types of causes, i.e., on nonconsecutive sheets.



(b) Density variations produced by inherent type causes, i.e., on consecutive sheets.

Figure 4 Measured density variations on sheets from Press 1.

prudent to use pulls from the same run. The number of sheets collected in each pull should be at least 25, and preferably 50.

4. The frequency distributions of variations produced by both types are unlike those of inherent type color variations in that they are unpredictable. Thus, there is no such thing as a typical or average frequency distribution of variations produced by both types of causes, nor is there a typical magnitude of such variations. However, the distributions of a group of presses may exhibit some

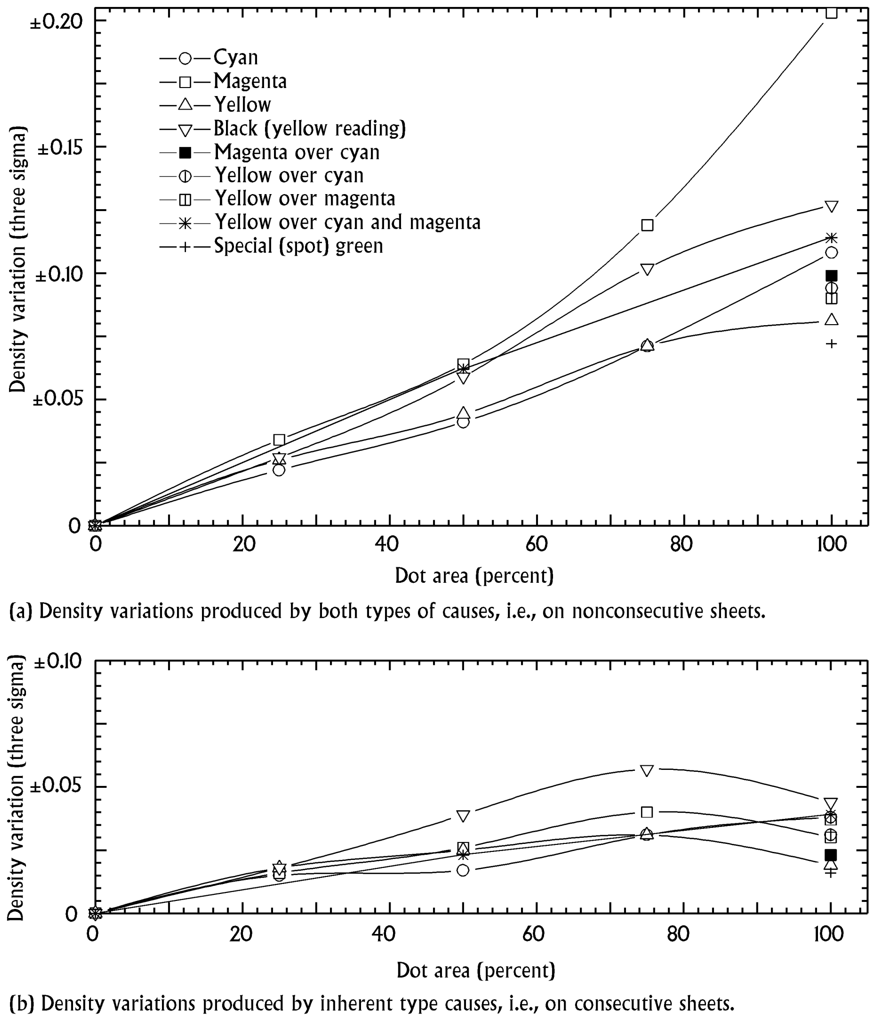


Figure 5 Measured density variations on sheets from Press 2.

common traits if the same operational procedures are followed throughout the group.

5. The use of a closed loop color control system will not be effective in reducing the magnitude of inherent type color variations because they are so fast acting. However, such a system can be effective in reducing extraneous type color variations, provided that the speeds of the specific external causes are no faster than the response time of the closed loop color control system, *and that the cause can be compensated for by a change in ink key settings.*

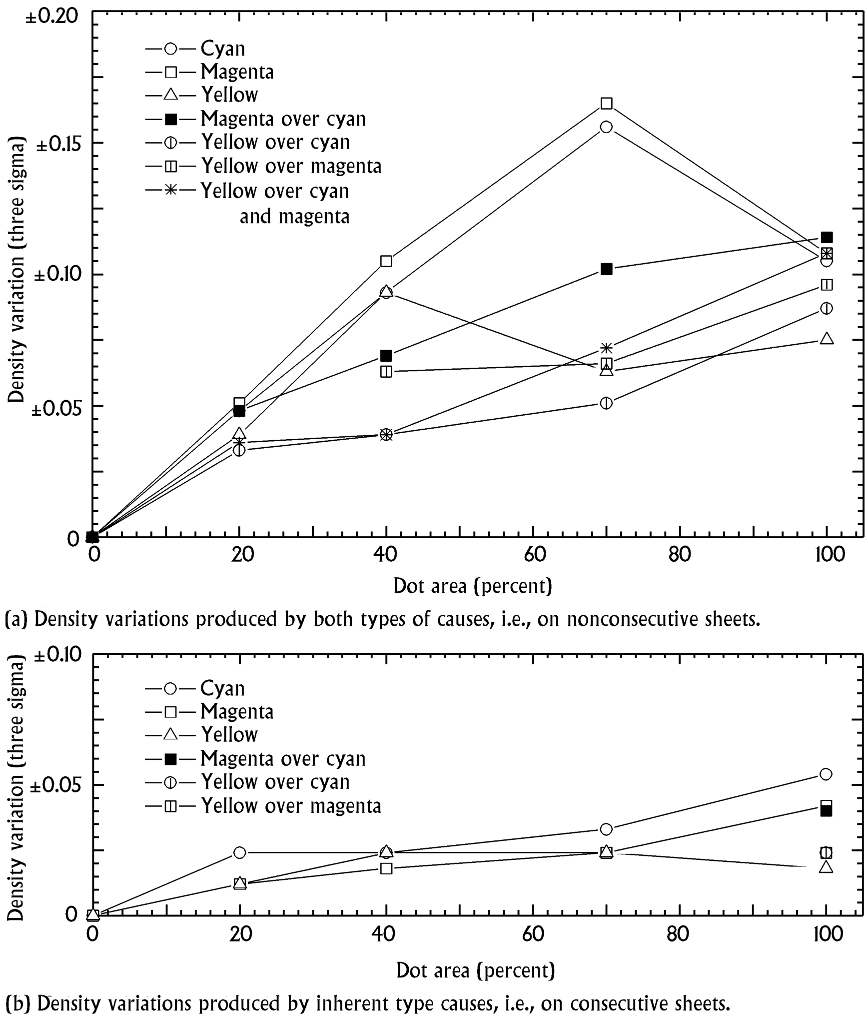


Figure 6 Measured density variations on sheets from Press 3.

<u>Density Variations</u>

The variations in the densities of both the nonconsecutive and consecutive sheets from the three presses are plotted versus dot area in Figures 4, 5, and 6. For each press, the density variations exhibited by the consecutive sheets are lower than the variations exhibited by the corresponding nonconsecutive sheets. In addition, some of the density variations of the nonconsecutive sheets rise to a peak in the mid to shadow tones. In contrast, this trend is absent in the plots of the consecutive sheets. Perhaps the most striking difference is the consistency of the plots of the consecutive sheets from all three presses, compared to those of the nonconsecutive sheets.

Another important finding is that the trapping of overprinted inks did not appear to have an effect on the magnitude of its density variation. This is most evident in the plots of variations produced by both causes, i.e., Figures 4(a), 5(a) and 6(a).

There are three important conclusions to be drawn from these findings, as follows, bearing in mind that these conclusions are limited to the presses used in this study:

1. The data in Figures 4–6 confirm the previous conclusion that the magnitude of the inherent type variations is always lower than that of the corresponding variations caused by both inherent and extraneous types.

2. Figures 4(b), 5(b) and 6(b) show a remarkable consistency in the magnitude of the inherent type variations from press to press.

3. The difference in magnitude of density variations produced by both types of causes versus those produced by inherent causes is greatest in the mid to shadow tone areas in two of the three presses used in the tests. This seems to indicate that the extraneous type variations in these two presses resulted more from variations in dot area rather than density.

4. If trapping had any effect on the magnitude of density variations, it was one of mitigation rather than aggravation.

5. By way of comparison, the density variations of the cyan, magenta, and yellow midtone targets measured in this study due to both types of causes (as plotted in Figures 4(a), 5(a), and 6(a) are one third to one half less than the comparable variations for the offset web presses measured in a study of color variations in web offset and gravure printing (Schläpfer and Widmer, 1995). It is to be noted, however, that the densities in this study were measured using Status T filters whereas those of Schläpfer and Widmer were most likely measured using narrow band filters.

Color Variations

More and more, the color fidelity of printed material is being measured in terms of the CIELAB color units where color variations or differences are expressed in terms of ΔE. As already noted in Figure 3, there are five different methods available for calculating ΔE. Three are based on density measurements and two are based on spectrophotometric measurements. In the former, which are limited to single color targets, density variations are multiplied by a conversion factor to

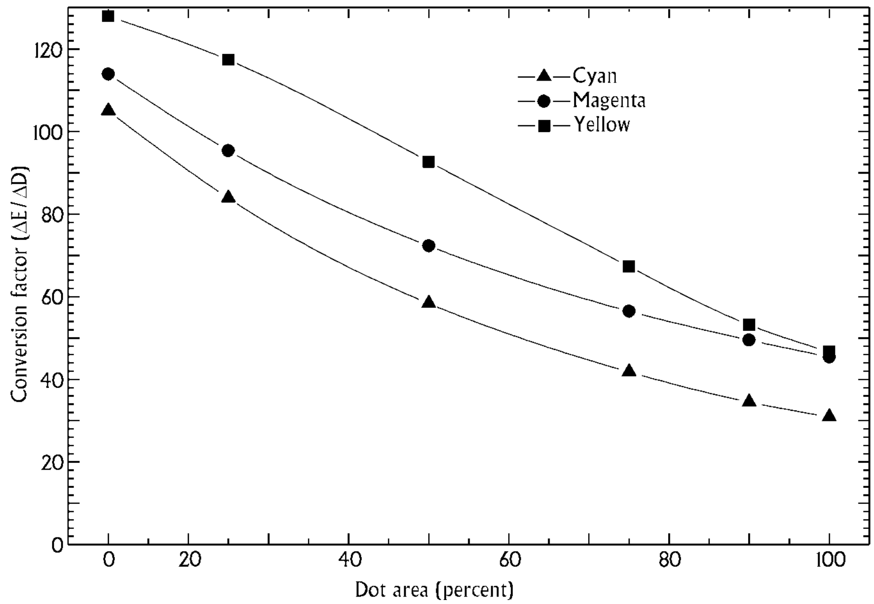


Figure 7 Factors for converting density variations, ΔD, to color variations, ΔE, for inks and paper used on Press 1.

obtain color differences in terms of ΔE. The results reported here for this approach utilized the conversion factors plotted in Figure 7 as a function of dot area. These were obtained from tone scale measurements in accordance with the following steps where D equals density and A equals dot area:

Step 1. Using the targets in a single color tone scale, measure and plot both primary density and Lab values versus dot area.

Step 2. Obtain best fits of third order linear equations to the plotted data.

Step 3 At selected dot areas, use the best fit equations to calculate the slopes of all four best fit curves, i.e., ΔD/ΔA, ΔL*/ΔA, Δa*/ΔA and Δb*/ΔA. Use the latter three slopes to calculate ΔE/ ΔA.

Step 4. Divide ΔE/ΔA by ΔD/ΔA to obtain conversion factor ΔE/ΔD.

The two other approaches identified in Figure 3 for calculating conversion factors were also tested. In the first, dry test prints, made using an IGT Print Tester, were used in place of a tone scale and Steps 1 – 4 above were repeated with ink film thickness taking the place of dot area. In the second approach, a set of ΔD and ΔE values was obtained for each set of color targets on the nonconsecutive sheets. These were then plotted against each other. The slopes of the best linear fits, ΔE/ΔD, then provided the third assessment of conversion factors.

Of the three approaches for calculating conversion factors, the agreement between the first and last was quite good, while that of the second was less so.

In the last two methods for determining color differences, the spectrophotometric measurements are converted to CIELAB values and one of the two following procedures is employed to calculate ΔE values:

1. The standard deviations of the L*, a*, and b* measurements of a data set are calculated with reference to the center of production. The three sigma limits of ΔE are then calculated using three times the standard deviations of L*, a*, and b* to calculate ΔE.

2. The color difference between a given test image and the center of production are calculated in terms of ΔE and the average and standard deviation of all the ΔEs in the data set are calculated next. The three sigma limits are then taken as the sum of the average ΔE and three times the standard deviation.

Schläpfer and Widmer state that the second procedure for calculating ΔE has no statistical significance, presumably because it was argued the frequency distribution is not normal (Dolezalek, 1994). However, good agreement was

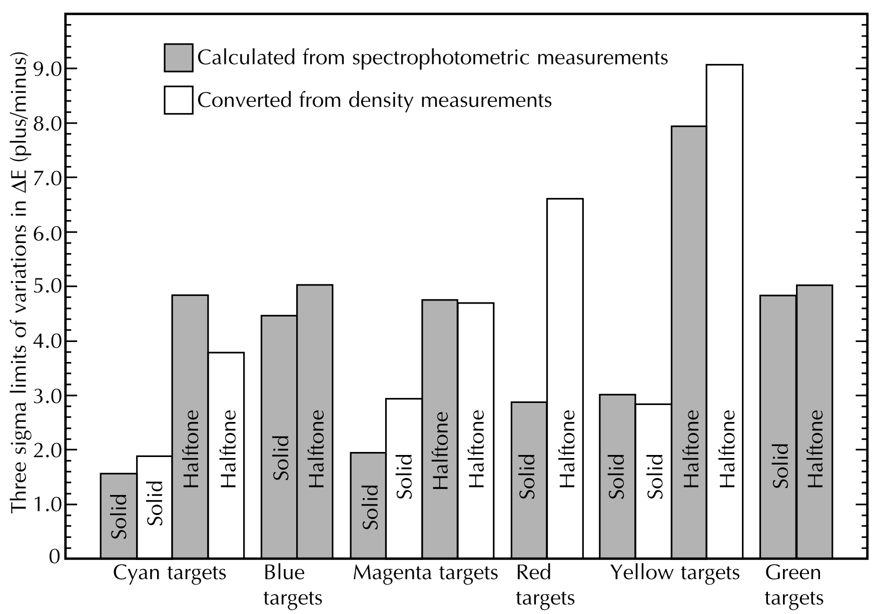


Figure 8 Color variations due to both types of variations, as on nonconsecutive sheets on Press 1. Factors used to convert density variations were obtained from measurements of tone scale on first sheet.

found between the two methods when calculating three sigma limits in this study. This good agreement is consistent with the previously cited Rule of Thumb. Nevertheless, only the results obtained with the first method of calculation are given here.

Figure 8 provides a comparison of the values of the color variations exhibited by the nonconsecutive sheets obtained from Press 1, using the two different methods for determining ΔE, one based on density measurements versus one based on spectrophotometric measurements, in which calculations were made of the standard deviations of L*,a*, and b*. As shown by this bar chart, the agreement between these two methods for determining color differences is quite good. This presentation of ΔE data also brings out a disadvantage of the procedure based on density measurements, namely that it cannot be used on the secondary or overprinted colors blue, red, and green

The relationships between color variation and dot area are shown in Figure 9 for the three primary color targets on the Press 1 nonconsecutive sheets. For comparison, the corresponding density variations have been superimposed. For all three colors, the ΔE curves are proportionately higher in the highlights, and lower in the shadows. This is explained by the shape of the conversion factor plots in Figure 8 that show that the conversion factor, $\Delta E/\Delta D$, decreases monotonically as dot area increases. Stated another way, the color fidelity of highlights are much more sensitive to density changes than are shadows.

Given these findings, the important conclusions regarding color variations are considered to be the following:

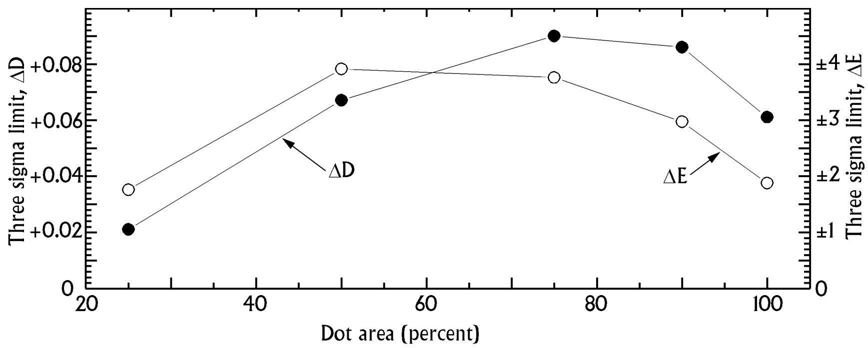
1. The methods for determining color variations used here result in comparable values. However, the one based on density measurements is limited to primary color targets (cyan, magenta, and yellow).

2. The concept of using a factor to convert density variations (ΔD) to color variations (ΔE) is insightful in that the conversion factors demonstrate that the color variations of the highlight areas of a print are more sensitive to a given density variation than are the corresponding shadow areas.

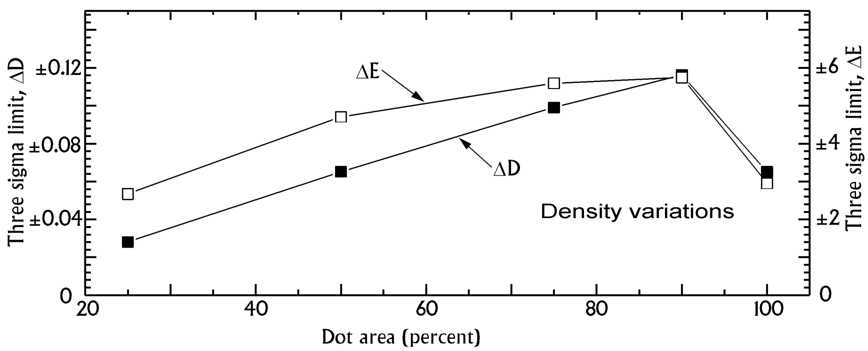
3. The color variability exhibited by a set of prints cannot be assessed or controlled solely by measurements of the solid colors.

Recommended Strategy for Minimizing Color Variations

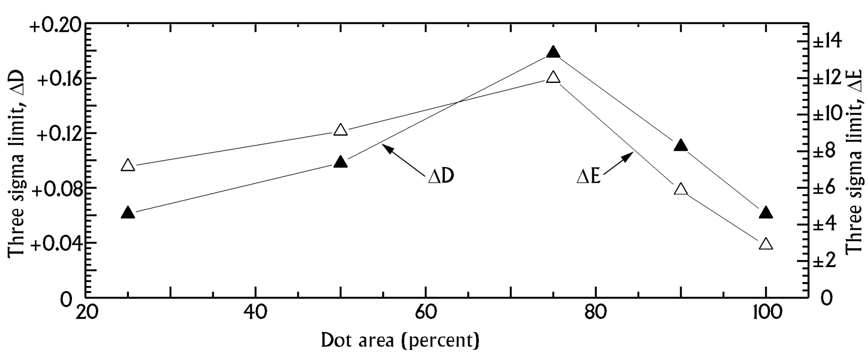
The findings of this study suggest that it may be possible to reduce the color variations that occur in printing under the operating conditions existing on a given press run. Further consideration leads to a strategy for accomplishing this, which is based on the twin findings that there are two types of color variations and that the magnitudes of one are superimposed on those of the other.



(a) Cyan targets.



(b) Magenta targets.



(c) Yellow targets.

Figure 9 Density and color variations in test targets on nonconsecutive sheets from Press 1, i.e., on sheets exhibiting both types of variations. Density data were measured while ΔE data were calculated using conversion factors.

Thus, the broad strategy is to focus first on reducing extraneous type variations. The addressing of inherent type variations is then left to the time when extraneous type variations have been reduced to the point where they add little to the gross magnitude of the color variations that are occurring.

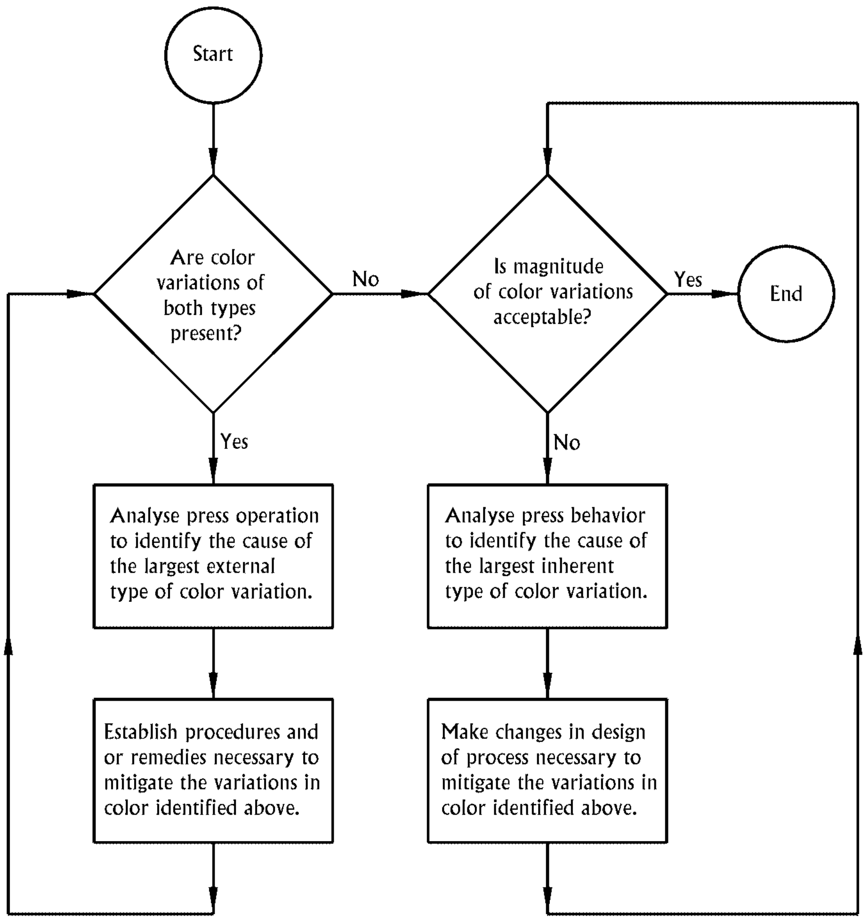


Figure 10 Flow diagram of the strategy that is recommended for minimizing color variations.

A more detailed presentation of this strategy is given in Figure 10, in flow diagram form. This strategy has not yet been applied in practice, so its details will probably have to be worked out through trial and error. Nevertheless, some suggestions can be made regarding them, as given in the following paragraphs.

The first step in the proposed strategy is to determine if both types of color variations are present in the given press installation. This can be done using the methods described in the first part of this paper. The answer to this question should be considered 'yes' if the variations due to both types of causes are (say) twenty percent larger than the variations due to inherent causes.

In such an event the program of investigation should then travel along the left hand loop in Figure 10. This will amount to doing an analysis of press operation. Three types of data should prove particularly helpful in this regard: frequency distributions, running plots of densities, and time records of important press operating events such as shutdowns, blanket washes, and paper changes.

Once the answer to the first question in Figure 10 has been switched to a 'no', the investigation then proceeds to the right hand loop, which amounts to an analysis of the printing process and, as such, will take on more of the character of a research program. More specifically, it is anticipated that such an investigation would involve studying the effect that the properties of such things as paper, ink, blankets, and plates have on the magnitude of inherent type variations. If this proves correct, then this latter type of investigation need only involve short press runs.

The final observation to be made in this paper is that it may prove more expeditious to first attack inherent type color variations, that is, proceed directly to the right hand loop in Figure 9. The rationale for this suggestion is that if inherent type color variations were to become vanishingly small, extraneous type variations might stand out even more and thus be much easier to identify and correct.

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