

Analysis of Color Targets for Output Characterization

*Marc Mahy
Agfa-Gevaert N.V.
Mortsel, Belgium*

Abstract

In most cases, standard color targets are taken to characterize output devices. However, there is no reason why these color targets contain the best set of color patches to build an accurate printer model. For an offset printing press, for example, there is a significant difference between the dot gain of normal offset printing and newspaper printing. Hence, the optimal color target for both systems is likely to be different. Moreover, there is no reason to use color targets that are rather regularly sampled in colorant space such as the IT8.7/3 target.¹

To overcome previous problems, a technique has been developed with which an optimal color target can be reconstructed to model an output device with a minimum number of color patches. In this way some insight is obtained into how many and which color patches are needed to model printers accurately. Based on this technique, an automatic color target generation system can be build for a dedicated output system or printer technology.

Introduction

In digital color management systems, printers are modeled by printing a number of *color patches* and measuring them.² The color patches are defined in the device color space of the printer and constitute the *color target*. Based on these data sets, i.e. the *colorant values* of the color patches on the one hand and the measured *color values* on the other hand, a *printer model* is constructed that predicts color in function of colorant values. Hence, the printer model is a function from *colorant space* to *color space*. The domain is called the *colorant domain*, the corresponding range the *gamut*.³

For a CMYK printer, the CMYK values are the colorant values. The colorant space is a 4-dimensional space obtained by representing the CMYK values along four perpendicular axes. It is assumed that colorant values range from 0 to 100. If there are no ink limitations, the colorant domain is the *colorant cube*. The color space in general is a 3-dimensional device independent color space such as XYZ or CIELAB.⁴

The accuracy of the printer model largely depends on the choice of the color patches. There are several color

targets standardized to model printers. The most common color target for CMYK devices is the IT8.7/3 target. Here the colorant space is sampled rather regularly. For $K = 0$ and $K = 20$, the CMY values are sampled for the colorant values 0, 10, 20, 40, 70 and 100. For $K = 40$ and $K = 60$, only the values 0, 20, 40, 70 and 100 are taken into account for CMY. In case of $K = 80$, this set is reduced to 0, 40, 70 and 100. And finally, for $K = 100$, only combinations of 0 and 100 are included. Apart from these colors also step wedges for CMYK and a number of custom colors are included.

There are two main characteristics in the design of this color target. First of all, less colors are provided if K increases, or in other words if the colors become darker. From an intuitive point of view, this is logical as less colorant combinations are needed in the darker part of the gamut to model the printer accurately. On the other hand, there are more sampling points at lower values to compensate dot gain.

However, there is no guarantee that a color target based on these intuitive characteristics is optimal for a given printer. Are there enough color patches, what about the big gap between 70 and 100, and what for printing systems with different dot gain values?

The reduction of a set of sampling points is a problem that occurred in several other areas. In image compression for example, a technique called RBN (Recursive Binary Nesting) divides an image block in four equal blocks till the image in that block can be described by the four corner points of that block.⁵ Also reducing the number of points on curves to describe the curve with lesser points has been studied several times. In color, however, this problem is not 1-dimensional but 3- or 4-dimensional. The design of color targets for a given printer has been studied in general by Chang and al.⁶ However, although their aim is the same, our technique to reduce the number of patches is significant different.

Printer Models

In literature, there are several models to characterize output devices.⁷⁻⁹ By preference, a model is chosen that mimics the color mixing behavior of a given printer technology. The advantage of choosing such a model is that less color patches are needed to characterize the

printer properly. Typical examples of color mixing types for which a minimum number of color patches are needed are additive and subtractive color mixing.

In practice, however, there are no printers that can be modeled easily. In literature, both global and localized models are presented.¹⁰ In general, *global models* are higher order polynomials whereas *localized models* make use of a simplified model in a limited region of the colorant space. In reality, other types of models can be used but most of them can be approximated accurately by polynomials, e.g. by making use of Taylor expansions. Both types of printer models require an extensive set of color patches. For global models, the coefficients of the polynomials are fitted with least square error techniques such that the difference between the prediction of the model and the measurements are restricted to a minimum. For some localized models, on the other hand, the exact measurements can be predicted.

Complete and Incomplete Localized Models

In this publication, localized models are used to model output devices. Localized models can be seen as a set of models that each define the printer behavior in a given region of the colorant space. The different regions are called *cells* and the corresponding model the *elementary model* of the cell. In general, cells may overlap, however in this publication only localized models will be used with a finite number of *non-overlapping cells*. It is also assumed that the union of all the cells constitutes the colorant domain of the localized cell.¹⁰

In the present implementation, the boundaries of the cells are defined by a lower and upper colorant value per colorant axis. In the case of a finite number of non-overlapping cells, all these colorant values give rise to a finite number of points per colorant axis. These points are the *sampling points* of the corresponding axis, ordered from the lowest to the highest value. In general, the i^{th} colorant axis has n_i sampling points s_{ji} such that

$$s_{0i} = 0 < s_{1i} < s_{2i} < \dots < s_{n_i-1} < s_{n_i} = 100 \quad (1)$$

The lower and upper colorant values will also be referred to as the *lower and upper boundaries* of the cell.

The elementary model will be a Neugebauer process as this model can be seen as the basic color mixing behavior of printing processes.¹¹⁻¹² The elementary models themselves are defined by the color values at the *corner points* of the cell. A printer model constructed in this way is called a *localized Neugebauer model*.^{10,13}

If for all cells, the lower and upper boundaries per axis are succeeding sampling points, a *complete localized model* is obtained. If the elementary models are Neugebauer processes, a *complete localized Neugebauer model* is constructed. In this case, all the color values for the regular grid in colorant space, defined by the sampling points per colorant axis, are needed. A color target containing all these color patches is a *complete color target*.

If at least one measurement value of the regular grid in colorant space is missing, an *incomplete localized model* is obtained. The corresponding color target is an *incomplete color target*.

To represent printer models easily, consider a printer model that transforms colorant values C_1, C_2 from a 2-dimensional colorant space to a 2-dimensional color space X_1, X_2 . In all figures of this publication, the horizontal axis corresponds to the C_1 -value, whereas the vertical axis is the C_2 -coordinate. It is assumed that there are 6 sampling points per colorant axis. The sampling points of the C_1 axis is given by 0, 10, 20, 40, 70 and 100, these of C_2 by 0, 20, 40, 60, 80 and 100. To build a complete localized printer model, all the 36 combinations of C_1 and C_2 have to be printed.

In fig. 1 the sampling points are represented in the C_1, C_2 colorant domain. These sampling points constitute a regular grid indicated by the dashed lines, the *grid lines*. Color patches contained by a color target are indicated with a black bullet. In the example at the top in fig. 1 a complete color target is shown, whereas at the bottom an incomplete color target is represented.

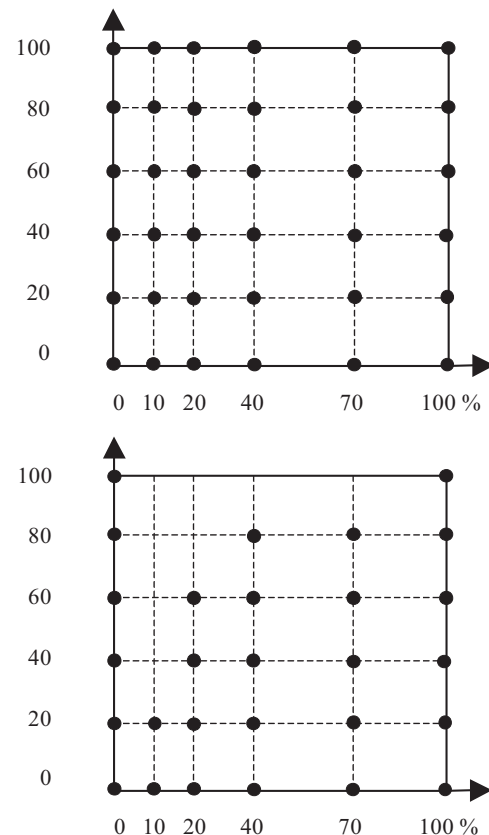


Figure 1. Sampling points in colorant domain and corresponding color patches (black bullet) to build the localized model. In the top figure, a complete localized model is represented, for the bottom figure some colorant combinations are missing and hence only an incomplete model can be obtained.

Construction of Complete and Incomplete Localized Neugebauer Models

Complete Localized Neugebauer Process

For a complete color target, the cells are determined by the regular grid, defined by the sampling points of the colorant axes. Here, the regular grid indeed determines the unique division of the colorant cube in a number of cells. If n_i represents the number of sampling points for colorant i , the number of cells is given by

$$\prod_{i=1}^D (n_i - 1) \quad (2)$$

with D the dimension of the colorant space and n_i the number of sampling points of colorant axis i .

Incomplete Localized Neugebauer Process

In case of an incomplete color target, however, there is not always a unique division of the colorant cube in a number of cells. Let us take the incomplete color target as represented in the top image of fig.2.

Maximum number of cells

To determine the maximum number of cells, a new set of sampling points are determined. In this set, only those sampling points are taken for which there is at least one color patch with this value. These sampling points will be referred to as the *new sampling points*. Instead of having 6 sampling points per axis, there are only 5 left (see fig. 2). For C_1 there are no color patches with $C_1 = 40$, for C_2 on the other hand there are no combinations with $C_2 = 60$. Hence, the maximum number of cells is $4 \times 4 = 16$. These cells are indicated in the bottom image of fig. 2.

There is, however, still a problem to be solved. To determine the elementary models, all the color values at the corner points of the corresponding cells have to be known, and, as can be seen in fig. 2, this is not the case.

A simple strategy to determine the unknown corner points is the following one.

- Order the different colorant axes, e.g. first C_2 then C_1 . In the same way as iterating over a number of colorant values, C_2 is considered as the slowest changing colorant, whereas C_1 is the fastest changing colorant.
- Initialize the lower boundary for C_2 to 0.
- In a third step, the upper boundary for C_2 is looked for. This is the next new sampling point for C_2 related to the lower boundary value for C_2 . In our example this value is 20. Consider now the ink process in the interval 0-20 for C_2 and 0-100 for C_1 . Such an ink process with a limited range for one colorant, e.g. C_2 , and the full range for the other colorants is referred to as a *subprocess*, in our case a *subprocess of C_2* .
- In a fourth step, the color values of the corner points of the subprocess are looked for. In our example, the corner points of the subprocess are the colorant combinations (0,0), (100,0), (0,20) and (100,20). If there are no corresponding color values for some of

these colorant combinations, they have to be determined. Take the combination (0,20) as an example. For this point there are no color values provided and hence they have to be deduced from the other color patches. Therefore we look along the C_2 -axis for the largest lower and smallest upper colorant combination for which color values are provided (i.e. C_2 will vary but C_1 is fixed). In our example these are (0,0) and (0,100). The color values for the colorant combination (20,0) are obtained by interpolating between the largest lower and smallest upper colorant combinations. As the interpolation occurs along a line parallel to one of the colorant axes, the Neugebauer equation is reduced to linear interpolation. In a similar way the color values for the colorant combination (100,20) are calculated.

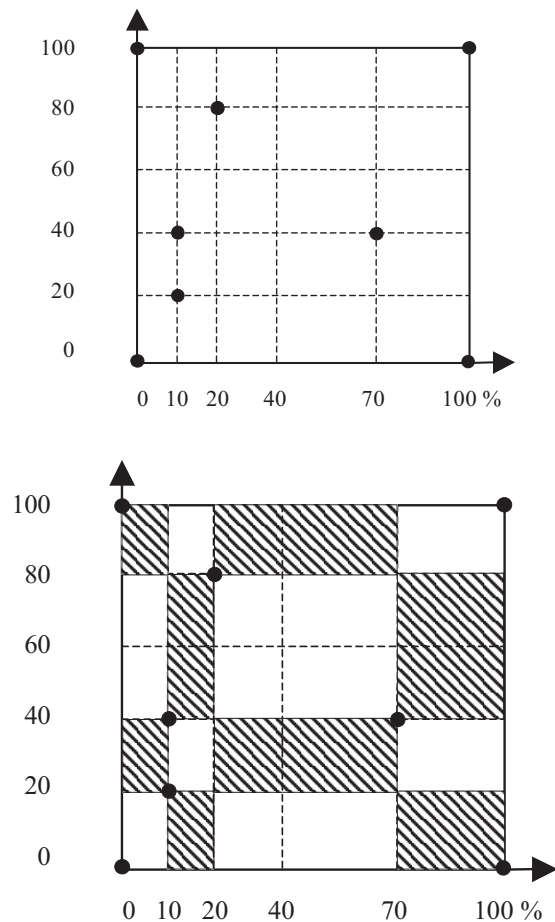


Figure 2. Sampling points and a set of color patches in the colorant space on which only an incomplete localized model can be constructed. A division of the colorant space resulting in a maximum number of cells is given in the bottom image.

- In a fifth step, the lower boundary for C_1 is set to 0.
- In a sixth step, a new cell is determined. The upper boundary for C_1 is the succeeding new sampling point for C_1 . Hence the new cell in our example is the cell with range 0-10 for C_1 and 0-20 for C_2 . Also in this case, no color values are provided for some corner points. As before, these values are obtained by linear interpolation but in this case the interpolation occurs along the C_1 -axis. For the corner point (10,0) the largest lower and smallest upper colorant combinations are looked for along the C_1 direction. These are (0,0) and (100,0). The color values for (10,0) are obtained by linear interpolation between these largest lower and smallest upper colorant combinations.
- Assign the upper boundary for C_1 as the new lower boundary for C_1 and restart the sixth step till the lower value of $C_1 = 100$.
- Assign the upper boundary for C_2 as the new lower boundary of C_2 and restart the whole procedure from the third step till the lower boundary for $C_2 = 100$.

In this way all the corner points are determined and all the cells are found.

Reduction of the number of cells

In the previous method a maximum number of cells is obtained. However, there is some redundancy. The second, third and fourth cell (range C_1 : 10-100, range C_2 : 0-20) are all described by the same elementary model. This leads to too many cells and elementary models, and hence the localized printer model is too large. This can be detected by the previous procedure. Instead of taking the next sampling point for C_1 , the next sampling point is taken for which a color patch is available within the specified range of C_2 . This division of the C_1C_2 -colorant cube is represented in the upper part of figure 3 and is referred to as the *horizontal division* of the colorant cube. However, instead of taking C_1 as the fastest changing value, we could take C_2 as the fastest changing value. Again a division is obtained as shown in the bottom part of figure 3. This division is referred to as the *vertical division* of the colorant cube.

An important characteristic of this technique to divide the colorant cube in cells is that all the color patches are at corner points of cells. This is simply due to the way cells are constructed. If color patches should lie at corner points of cells, then with each color patch a number of line segments can be assigned that are boundaries between cells for any division for which the color patches have to lie on corner points. These lines start from the color patches and go along the grid lines through the color patch till a next new grid line is met, perpendicular to this line. In fig. 4 all these line segments are represented with thick black lines and immediately four cells appear. These cells are shaded in fig. 4. Hence for this color target these four cells will always be present if the color patches have to lie at corner points of cells (see also the division of the colorant cube in fig. 2 and fig. 3). The thick black line segments represent

invariant boundaries, the four resulting cells are *invariant cells*.

All the other parts of the colorant cube can be divided in different ways. Two examples are already shown with the horizontal and vertical division, but there are many more. If the number of cells is counted, we see that with different techniques, a different number of cells are obtained. In the case of the horizontal division there are 11 cells, for the vertical division 12 cells are obtained.

The number of cells obtained with the horizontal division technique can be determined as follows. Take a subprocess and count the number of color patches belonging to this subprocess which do not lie at the boundary of the colorant cube, assume S_1 . Then, calculate the number of pairs of color patches with the same C_1 -value, assume S_2 . The number of cells for this subprocess is given by $S_1 - S_2 + 1$. The sum of the cells for all the subprocesses is the total number of cells obtained with the horizontal division technique.

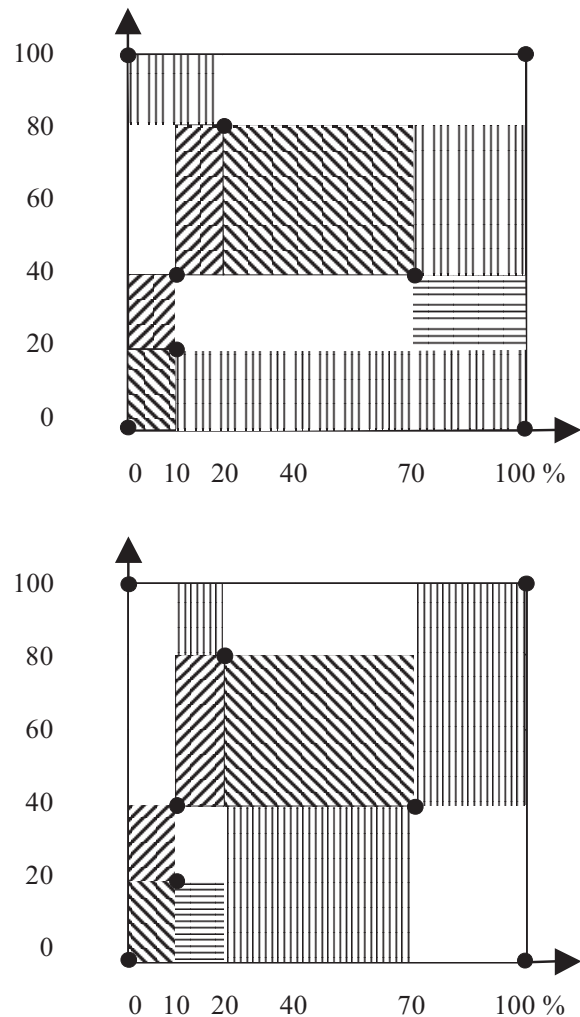


Figure 3. Construction of cells in the colorant cube via the horizontal (top image) and vertical (bottom image) division technique to reduce the maximum number of cells.

In a similar way the number of cells can be determined for the vertical division technique.

Now, the different number of cells with the vertical and horizontal division technique can be explained. For the vertical technique, there is no cell with a value S_2 different from zero. For the horizontal technique, however, there are two color patches with the same C_1 value in the second subprocess of C_2 (range C_2 : 20-40). Hence in the horizontal division technique one cell less is obtained.

In general, neither the horizontal, nor the vertical division technique leads to a division of the colorant cube with a minimum number of cells. In our example, the horizontal division corresponds to the minimum number of cells, however, there are several ways of dividing the colorant cube resulting in this minimum number of cells. In our example there are 8 different divisions resulting in 11 cells. In fig. 5 one of these possibilities is represented.

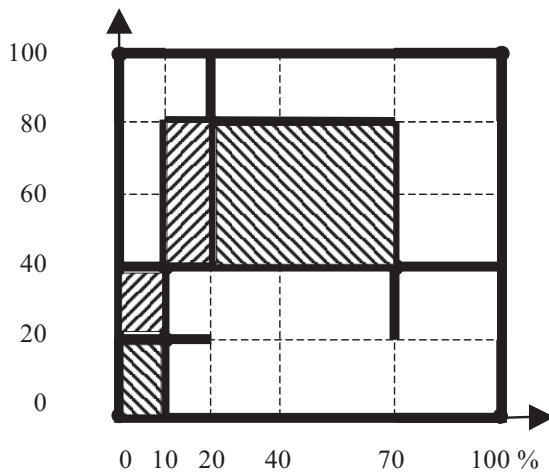


Figure 4. The thick black line segments indicate the basic framework of the division of the colorant cube in cells if the color patches should lie at the corner points of cells. Also the resulting four invariant cells are shown, i.e. cells that are always present for such a division of the colorant cube.

Minimum Number of Cells

If the color patches don't have to lie at the corner points of cells, the number of cells can be reduced significantly. In our example, the number of cells can be reduced from 11 to 3. This division is represented in fig. 6.

By making use of simple characteristics of the Neugebauer equations, a given set of color patches can be rearranged to obtain the *canonical representation*. In this canonical representation all color patches lie at corner points of the cells. Hence in the previous techniques, immediately the canonical representation was obtained as the division was constructed in this way.

IT873 Target

The IT8.7/3 target is a CMYK target of which most color patches can be described by the sampling points (0,

10, 20, 40, 70, 100) for cyan, magenta and yellow and with the sampling points (0, 20, 40, 60, 80, 100) for black. This sampling is represented in the bottom image of fig. 1 for the cyan-black colorant cube. The invariant boundaries are represented in the top image of fig. 7 and, as can be seen, a number of invariant cells are obtained. From this image, the horizontal and vertical division can be easily constructed. The maximum number of cells is 25 for the cyan-black process. For the horizontal division still 21 cells are needed, for the vertical division 24 cells are found. If these results are extended for the CMYK process, there are at most 625 cells. For the vertical division (K fastest variable) this number is reduced to 446 cells, for the horizontal division (K slowest variable) still 405 cells are required. It can be verified that the minimum number of cells is obtained by the horizontal division technique, both for the cyan-black process and the CMYK process.

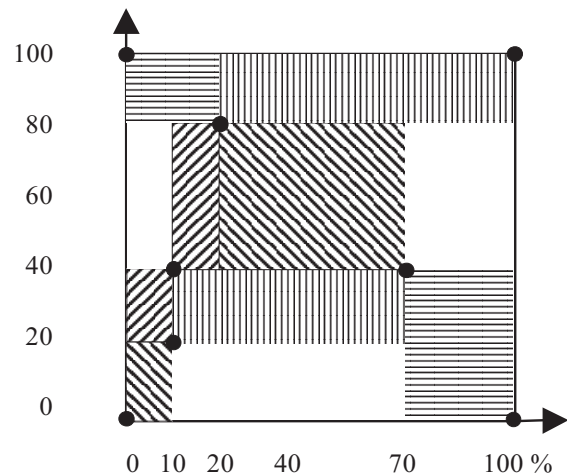


Figure 5. Alternative division of the colorant cube, with the requirement that color patches should lie at corner points of cells, resulting in the same number of cells as the horizontal division technique.

Localized Neugebauer Model with Color Tolerance

Based on the previous techniques to divide the colorant cube in cells, a localized model can be constructed for a complete or incomplete grid of color patches. The size of the model or equivalently the number of cells of the localized model largely depends on the color target. Hence there may be still too many color patches taken into account for the printer model.

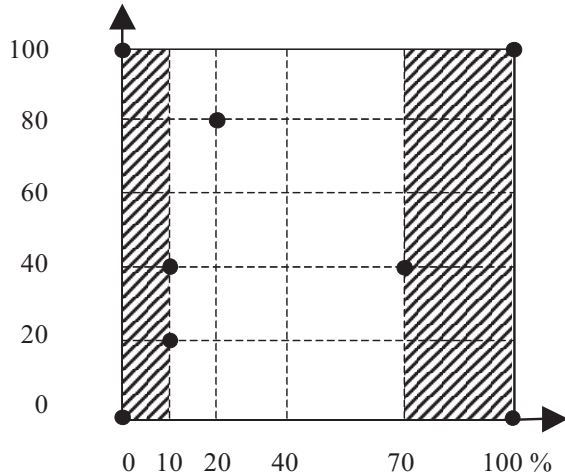


Figure 6. Division of the colorant cube in a minimum number of cells.

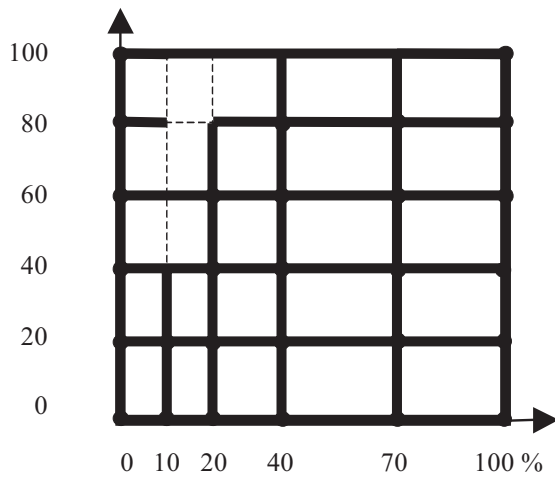


Figure 7. Invariant boundaries of a 2-dimensional sampling similar to the IT8.7/3 target.

Table 1. For two printing technologies the number of patches and the number of cells are represented if the localized model is constructed in combination with an error criterion. Here the error criterion corresponds to the CIELAB difference between the measured color values and the predicted values by the localized model.

error	Swop		Newspaper	
	nbr patches	nbr cells	nbr patches	nbr cells
0.0	754	405	754	405
1.0	309	252	570	353
2.0	94	60	225	177
3.0	44	21	100	72
4.0	28	7	73	36
5.0	24	4	58	24
10.0	19	3	24	4

To eliminate a number of color patches, a criterion is needed that indicates the importance of each color patch to model the printer adequately. One way of doing so consists of making use of the localized model by evaluating how good a color patch can be predicted by its neighboring color patches. However, also in this case several approaches are possible.

One approach is based on the horizontal or vertical division technique. Therefore, common boundaries of cells are checked to see if they can be predicted by the boundaries just before and after the common boundary. This evaluation is applied for all the color patches at the corner points of the common boundary. If at least one corner point cannot be predicted properly, the boundary is retained. As error criterion, the color difference between the predicted values and the measured values can be used. To take into account measurement errors and instabilities of the printer, the color tolerance may depend on the colorant combinations. The more ink is laid down, the darker the colors and hence the printer will be less stable and most color instruments will provide less accurate color values.

Depending on the color tolerance, the number of cells can be reduced significantly. The number of color patches and the number of cells are given in table 1 for swop and newspaper printing. The error criterion corresponds to the CIELAB color difference measure between the predicted color values and the real measurements. If no error is tolerated, there are 754 color patches and 405 cells. For large errors, there is only one cell and 16 corner points. For error values in between, the different printing technologies behave differently.

Table 2. The most typical sampling points are represented for swop and newspaper printing in case the localized model is constructed with a color tolerance of 2 CIELAB values.

Subprocess	Printing technology	
	Swop	Newspaper
0 - 20	0-20-40-70-100	0-10-20-40-70-100
20 - 40	0-40-70-100	0-10-20-40-70-100
40 - 60	0-40-70-100	0-40-70-100
60 - 80	0-70-100	0-40-70-100
80 -100	0-100	0-70-100

The sampling points that influence the model are represented in table 2 for a maximum color difference of 2 CIELAB units. In the first column, the subprocess is represented. For the horizontal division technique that is used in this case, the subprocess is determined by the range of the K-value; i.e. two succeeding sampling points corresponding to the K-component. In table 2, the *typical sampling points* for CMY-coordinates are given for the corresponding subprocesses of K. The typical sampling values can be seen as the sampling values that characterize the printing process the best.

Optimal Color Targets

As the color patches of the color targets and the corresponding color values are used to model printing devices, the accuracy of the printer model largely depends on the color target. Therefore it is desirable to build a color target of which the colorant values of the color patches closely corresponds to the typical sampling points for a given printer. On the other hand, the number of color patches in the color target should not be too large, and by preference it is as small as possible. A color target that is designed in this way is called the *optimal color target* for the given printing process.

To determine the typical sampling points for a given printer, a large set of color patches are printed and measured. By preference the color patches lie on a regular grid in colorant space. Based on the colorant combinations of these color patches and the corresponding measured color values, a regular localized model can be built.

In a next step, color patches are looked for that can be predicted quite well by neighboring patches. This prediction is guided by the complete localized model. If the error between the measured values and the predicted values are smaller than a given color tolerance, these color patches can be seen as redundant and hence a reduced set of color patches is obtained. This set is referred to as the *basic set* of color patches for a given printer. Based on the basic set, typical sampling points can be determined for the different colorants and the optimal color target can be constructed. Hence, the color patches belonging to this color target are mainly determined by the basic set.

Because the dot gain of print processes not only depends on the printing system itself but is also determined by other factors such as the paper, the optimal color target should be independent of variations in dot gain. This can be done by a proper design of the calibration procedure. If for example the colorants are calibrated in such a way that the colorant scale is linearly related to a scale in a color space, by preference the CIELAB space, the sampling points in the colorant space may be uniformly distributed along the colorant axes. Hence, in a first approximation, the optimal color target will have a uniform distribution of its sampling points. The color patches of the color target can be determined with the same procedure as explained before.

Conclusion

In contrast to the complete localized Neugebauer process, there is no unique way to construct the incomplete localized Neugebauer process based on an incomplete color target. In this publication, different techniques are presented to divide the colorant cube in cells in case of an incomplete target.

Different approaches were given under the condition that the color patches should lie at the corner points of the cells. First of all, a logical upper limit on the number of cells was given. To reduce this number, the horizontal and

vertical division technique were introduced. However, in general none of them give a division resulting in the minimum number of cells. By making use of combinatorics, the minimum number of cells can be found that in fact is a combination of the horizontal and vertical division technique.

If, however, the color patches do not have to lie at the corner points of cells, the number of cells can be reduced significantly. This was shown by relocating the color patches in such a way that a canonical division is obtained.

To reduce the number of cells even more, a color tolerance was used to change the color values of the color patches between certain limits. This color tolerance originates from imprecise measurements and printer instabilities. If a color patch could be predicted by neighboring color patches, the color patch can be seen as redundant. The CIELAB error between the predicted values and the measured values was used as error criterion. Based on this error criterion, the number of basic color patches and the typical sampling points were shown for a few printing processes.

As the typical sampling points can be seen as the most characteristic sampling points of a printing process, the sampling of an optimal color target should correspond to the typical sampling points. Further on, there should be as less color patches in the optimal color target as possible. And finally, the optimal color target should be insensitive to changes in the printing process such as dot gain.

Based on the localized Neugebauer process, it is possible to generate the optimal color target for a given printing technique. By printing a large set of color patches, the typical sampling points can be found and the basic set of color patches can be determined. A proper calibration technique on the other hand has to take care of changes in the print process such as changes in dot gain.

References

1. ANSI IT8 7.3-1993, American National Standard, Graphic Technology, Input Data for Characterization of 4-color Process Printing, NPES, 1993.
2. E. J. Giorganni and T. E. Madden, Digital Color Management, Addison-Wesley, Reading, Massachusetts, 1998.
3. M. Mahy, Calculation of color gamuts based on the Neugebauer model, Col. Res. Appl. Vol 22, Nr. 6, 1997.
4. G. Wyszecki, W. S. Stiles, Color Science: Concepts and Methods, Quantitative Data and Formulae, 2nd edition, John Wiley & Sons, 1982.
5. K. Vanhoof, S. Desmet, J. Rommelaere, A. Oosterlinck, Comparison of two interpolative coding methods: DIDT and RBN, Proceedings SPIE, applications of digital image processing X, vol. 829, pp. 109-114, August 19-21, 1987, San Diego, California, USA.
6. James Z. Chang, Charles A. Bouman, and Jan P. Allebach, Recent Results in Color Calibration Using Sequential Linear Interpolation, IS&T's 47th Annual Conference/ICPS, pp. 500-505, 1994.

7. Yule J. A. C., (1967), Principles of Color Reproduction, John Wiley & sons, Inc., New York.
8. R. W. G. Hunt, The reproduction of colour, 5th edition, Fountain Press, England, 1995.
9. H. R. Kang, Color Technology for Electronic Imaging Devices, SPIE Optical Engineering Press, 1997.
10. M. Mahy, Output characterization Based on the Localized Neugebauer Model, ICPS 98, pp. 30-34, Sept. 7-11, 1998.
11. H. E. J. Neugebauer, Die theoretischen Grundlagen des Mehrfarbenbuchdrucks, Zeitschrift für wissenschaftliche Photographie, Photophysik und Photochemie, Band 36, Heft 4, pp. 73-89, 1937.
12. E. Demichel. Procède, 26, 17-21, 26-27, 1924.
13. R. Rolleston and R. Balasubramanian, Accuracy of various Types of Neugebauer Model, presented at the 1993 IS&T and SID's Color Imaging Conference on Transformation & Transportability of Color.