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Color and Weave Relationship in Woven Fabrics

Kavita Mathur¹ and Abdel-Fattah M. Seyam²

¹*Precision Fabrics Group Inc., Greensboro NC*

²*College of Textiles, North Carolina State University, Raleigh NC
USA*

1. Introduction

In woven designs from colored threads, a colored pattern is a consequence of two possible arrangements where warp is over the weft or vice versa. Thus the primary elements of woven fabric design are combination of weaves and blending of colors using such weaves. Weave is the scheme or plan of interlacing the warp and weft yarns that produce the integrated fabric. Weave relates specially to the build or structure of the fabric. Color is differently related to effects of weave and form. The methods of utilization of color in woven textiles depend upon the composition of the weave design to be woven and the structure parameters of the cloth.

Color and ornamentation in woven fabrics is imparted through the pre-determined placement and interlacing of particular sequences of yarns. A solid color is produced by employing the same color in warp and weft. On the other hand, different colors may be combined to produce either a mixed or intermingled color effect in which the composite hue appears as a solid color. Figured ornamentation is created through the selection of different groups of colored yarns, placed in the warp and/or in the weft; while in certain patterns, textural effects may be created entirely through the use of different values and closely associated hues of certain colors. The figure is formed for the purpose of displaying different pattern formations, adding dimension or color reinforcement and for enhancing a particular motif.

Modern CAD systems provide a variety of design tools that are supported by standardized color databases that allow simulation of weave structures on the computer monitor that could be printed on paper. However, deviations of the color values of these simulations still occur. Also, the color on fully flat fabric simulations on paper or computer screen is two-dimensional that differs from the real three-dimensional nature of fabrics and yarns.

In textile wet processing, the uses of colorimetry systems and associated software have proven their worth over the years, in objective estimation of color, and have minimized misunderstandings between textile manufacturers and their customers. However, color communication within textile design is largely a subjective process. Recent experimental studies (Osaki 2002; Dimitrovski & Gabrijelcic 2001, 2002, 2004) have revealed that the use of colorimetry has helped to achieve better reproducibility and accuracy in the shade matching of textiles products. Colorimetry is, however, less used when fabrics are made from colored

yarns than when yarns and fabrics are dyed to a solid color, or are printed. Recent research work (Mathur et. al. 2005, 2008, 2009 and 2011) provided a model that involves colorimetry for color prediction and is discussed briefly in section 4.

Several measuring and imaging systems are now available commercially that can record colorimetric data and convert these data into visual images. Hence, the designer can generate a numerical color specification that can be visualized accurately on a suitably calibrated monitor. Recent advances in color curve generation and image processing provide opportunities for additional improvements in the areas of collaborative color development, color marketing, and color prediction in multi-step processes. Contemporary techniques of computer-aided fabric design offer new possibilities for using colorimetry in weaving practice.

Along with the fundamental description of weave and color relationship, and recent advances in woven fabric design, this chapter also includes the research models developed to quantify the color proportion and color values, in effort to eliminate the expensive and time consuming process of prototyping and color matching in woven fabric design.

2. Woven fabric design and structure

This section introduces the reader to the basic knowledge of woven fabrics design and structure and the concept on how colored patterns are created using colored yarns. It sets the stage for the next sections that deal with objective evaluation of color in woven structures.

Woven fabrics are formed by interlacing two orthogonal sets of yarns; warp yarns that are vertically arranged and weft yarns that are horizontally placed. While all weave structures are created from a binary system (that is a warp yarn is over or under a weft yarn at the crossover areas), infinite number of weaves can be formed. The distribution of interlacement is known as weave design or pattern. There are three types of weaves that are known as basic weaves, which include plain weave (the simplest and smallest repeat size possible; 2 warp yarns x 2 weft yarns) and its derivatives, twill weaves and their derivatives, and satin/sateen weaves and their derivatives. These basic weaves are characterized by their simplicity, small size, ease of formation, and recognition. However, they form the base for creating any complex/intricate structures (such as multi-layer fabrics and pile weave structures) and weaves with extremely large patterns that are known as Jacquard designs. Figures 1-3 show examples of basic weaves. More on the rules to construct basic weaves and their derivatives can be found in Seyam 2001.

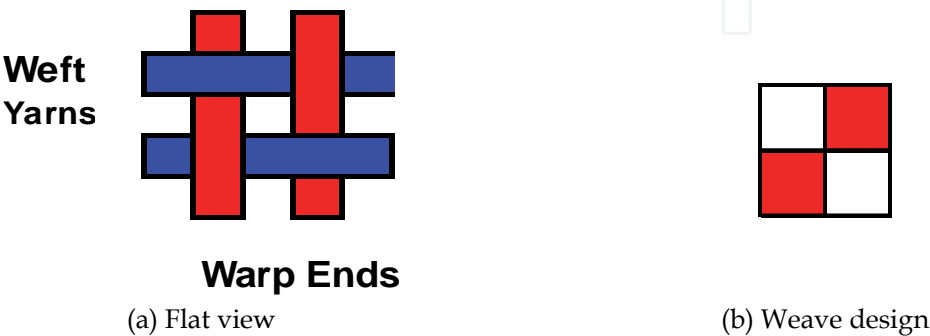


Fig. 1. Plain weave

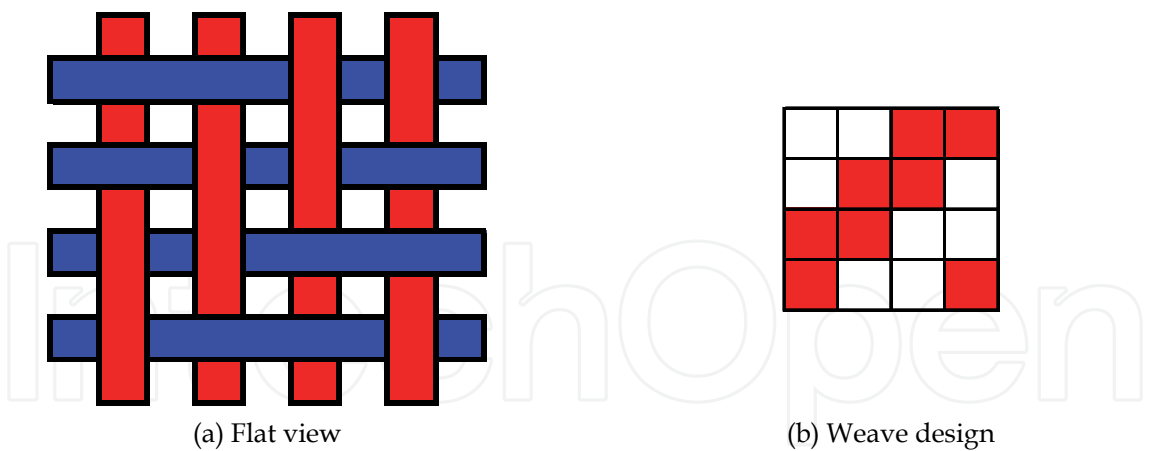


Fig. 2. Example of twill weave (2x2 Right Hand Twill weave)

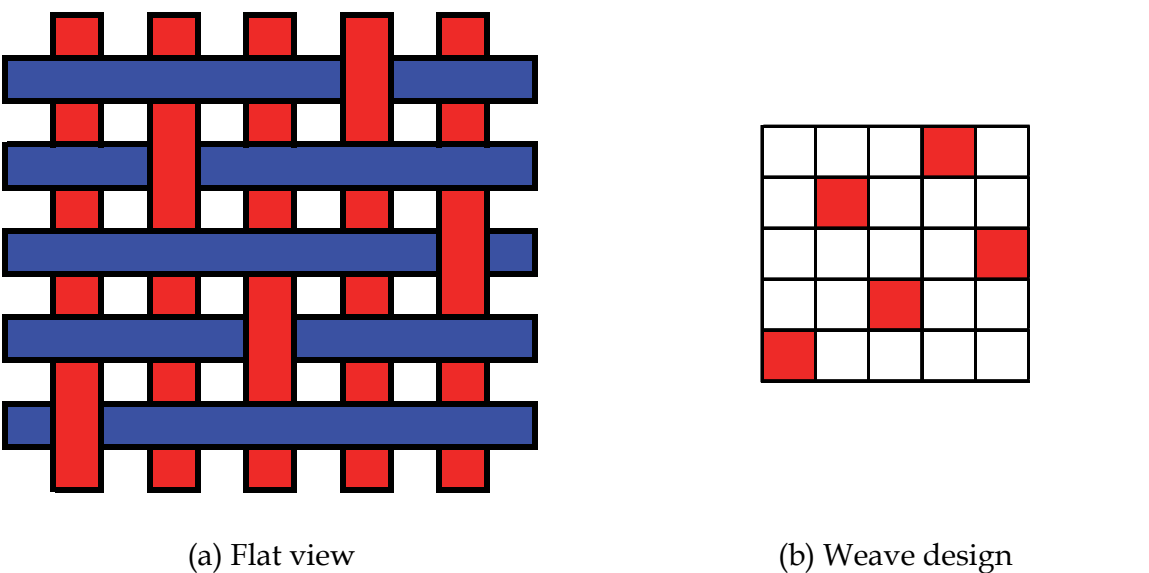


Fig. 3. Example of sateen weave (5-Harness Sateen Weave)

Figures 1-3 depict two methods of presenting weaves namely flat view and weave design. While the flat view presentation provides better understanding in regards to the warp and filling yarn interlacing, it takes time to draw especially for large size repeats. The weave design presentation was created to communicate in a much simpler and easy to draw weave illustration using weave design paper (squared paper). In the weave design presentation the spaces between yarns are eliminated and only the squares where warp yarns are over the weft yarns are shown, which is reasonable since in most of woven fabrics the yarns cover most of the fabric surface. Any color or marks (such X, /, or \, etc.) can be used to indicate where a warp yarn is over a weft yarn. The squares that are left blank indicate otherwise.

2.1 Color/weave relationship

Figure 4 shows another illustration of the weaves of Figure 1-3. In Figure 4 all the squares of the weave design presentations are painted using the color of warp and weft yarns (red and blue). This is known as color effect presentation. It should be pointed out that a square in the

design paper represents extremely small size area in the woven cloth. The colors of Figure 4 will be perceived by human eye as a mixture of two colors with different ratios.

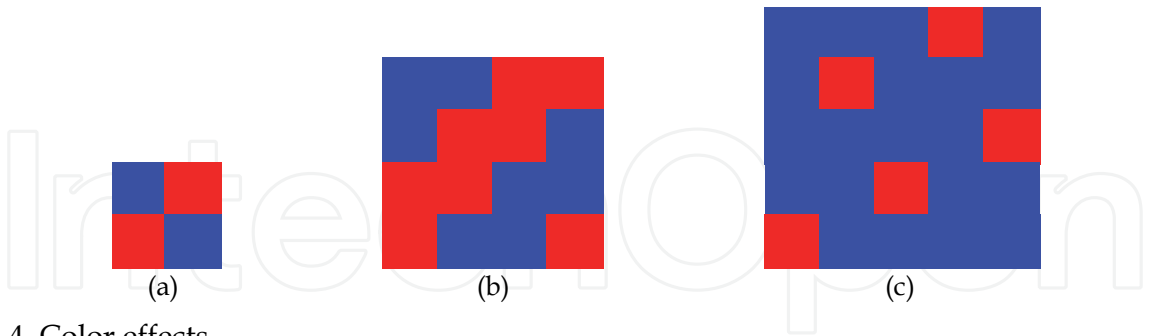


Fig. 4. Color effects



Fig. 5. Color simulation of the plain weave of Figure 1

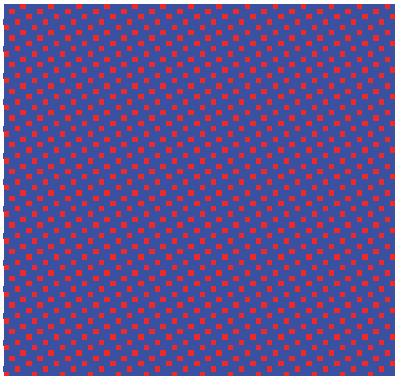


Fig. 6. Color simulation of the sateen weave of Figure 3

Thus, the use of colored warp and weft yarns combined with the weave structures permit the development of striking patterns. For a given pattern with multi-color, a color can be strategically placed in the pattern by merely using the binary system of warp and weft interlacing. The desired color of a yarn appears when the yarn is over the crossing yarns for a desired length and small or large area if several yarns are used. Moreover, numerous mixtures of colors to produce other colors can be obtained from few colors of the warp and weft yarns through proper weave interlacing. Figures 5 and 6 are two examples of such mixtures. They were produced using many repeats in warp and weft directions, thread count close to real cloth, and assuming there are no spaces between the yarns, which is reasonable assumption

for most woven fabrics. Figure 5 is the color simulation produced from red warp yarns and blue weft yarns and plain weave of Figure 4(a). While the color simulation of Figure 5 is produced from red warp yarns and blue weft yarns woven in sateen of Figure 4(c). These two examples indicate that numerous purple colors can be produced from only two colors (red and blue). Using this concept striking patterns can be created using few colors in warp and weft directions such as the Jacquard design of Figure 7.



Pattern is courtesy of Manual Woodworkers and Weavers, Hendersonville, N.C., USA

Fig. 7. Color simulation of Jacquard fabric

2.2 CAD and woven fabric design

Designing fabrics is a creative/technical process that is dependent upon the ability of the textile designer to combine aesthetic sensibility with a strong knowledge of the technology of materials and fabric production machinery. Most Dobby and Jacquard fabrics producers' facilities are now equipped with Computer Aided Textile Design systems. In the pre-computer era, the designing process was done in the following manner: (a) a piece of artwork was created on paper, (b) the artwork was then rendered as a scaled grid (known as squared paper or design paper), whose columns and rows represented warp and weft yarns, respectively, (c) weaves were then assigned to specific areas to represent the original pattern, and (d) a technician then punched cards, direct from this technical design layout, in which each card represent one pick of the actual fabric.

Computers have been utilized in woven textile design for almost 25 years, and this has revolutionized the entire design process. They have revolutionized the entire thought-process from the initial artwork to final production. CAD systems in woven designing operate in a series of basic steps. The first step is that of digitizing the artwork. This feature allows the designer to see the artwork on a computer monitor by scanning the original piece or creating a design using the CAD system drawing tools directly. This is generally done in 8-bit format (256 colors) and allows the designer to modify patterns and reduce the number of colors to a manageable number as he/she wishes. The second step is fabric designing, in which the artwork image data is transformed (i.e. the grid system, above) into weaving

information for fabric production. Weave allocation is the third step, in which information from the artwork image can be converted into a woven fabric. The designer created the appropriate weave structure or chooses one (from a weave library) to match the desired color, shape or texture in the artwork. This part of the program also helps the designer to see a simulation of the final fabric on the display monitor. By looking at the preview, the designer can easily modify the design, and can change the weaves to recolor the design as required. All these developments have greatly increased the ease of woven fabric designing. It is now possible to perform the entire process on a personal computer, and then transfer the ready-to-weave file (electronic punch-card file) via the internet, direct to the dobby or Jacquard controller at the loom, or to some interim storage area.

Textile CAD/CAM systems are mainly modular in structure and, in addition to covering yarn and fabric design may also include very realistic 3D simulation packages. A complete automated process with immediate response to the customer's demand seems to be a reality in the near future with these systems (Dolezal & Mateja 1995; Bojic 1999; Dimitrovski & Bojic 1999). Moreover, developments of powerful modem systems and electronic controls have brought the weaving machine into the design studio. This evolution has, in turn, given an entirely new meaning to the term *Quick Response*.

The impetus for use of CAD in the textile industry was to improve efficiency in the production process. Initial textile designing software packages were mainly derived from graphic design software, without putting much emphasis upon the underlying fabric structures. CAD systems have evolved, however, by considering the designing process and technical limitations. These systems are now extensions of creative expression which comply with technical requirements (Doctor 1997). Numerous descriptions of this process exist within the computer environment (Lourie 1969, 1973; Lourie & Bonin 1968; Lourie & Lornzo 1966) addressing, algorithmically, the problems that arise when one attempts to harmonize visual pattern with the notational point paper diagrams of those used for warp and weft interlacing.

Innovation in the field of textile design CAD systems for woven fabrics has provided the opportunity to design intricate fabrics with the use of a variety of tools. There is also the possibility of seeing the resultant fabric on a computer monitor that gives the visualization of real fabric prior to weaving. There is constant improvement and development in the CAD system to develop several design features (CAD tools) to keep pace with new market demands. At ITMA 2003, 40 companies exhibited CAD systems. Most of the weaving machinery companies showed CAD systems as an accessory. Many CAD companies (UVOD, Fractal Graphics, Yxendis, ScotWeave, EAT, NedGraphics, Pointcarré, Mucad, Informatical Textil, Booria CAD/CAM systems, Arahne etc.) showed constant improvement in the quality of CAD systems such as, easy-to-use software modules, flexibility of changing constructional parameters, speed of defining technical data and enhanced visualization of fabric structures (Gabrijelcic 2004, Seyam 2004).

3. Color visualization in woven fabrics

In pre-colored yarn or fabric, when light falls on the colorants (dyes or pigments), the white light is broken into its component wavelengths. Depending upon the particular molecular structure of a colorant and surface, light may be reflected back to the viewer, absorbed into the molecular surface, scattered by the molecular surface, transmitted through the surface or be subjected to some combination of reflection, absorption and transmission. One of the three processes always dominates; however, this in turn produces color effects (Lambert,

Staepelaere & Fry 1986; Menz 1998). The color effect of perceived color is a consequence of three types of color mixing principles:

- a. **Additive Color mixing** is a basic phenomenon for color perception, which involves addition of wavelengths of light to create higher-value colors. The broadest bands of color seen in the visible spectrum are those belonging to red-orange, green and blue-violet, known as *Primaries*. When all these colors are projected and overlapped, their specific wavelength mix together and produce white light (Figure 8). Magenta, cyan and yellow are known as *Secondary* colors where only two colors overlaps and their respective wavelengths add together.

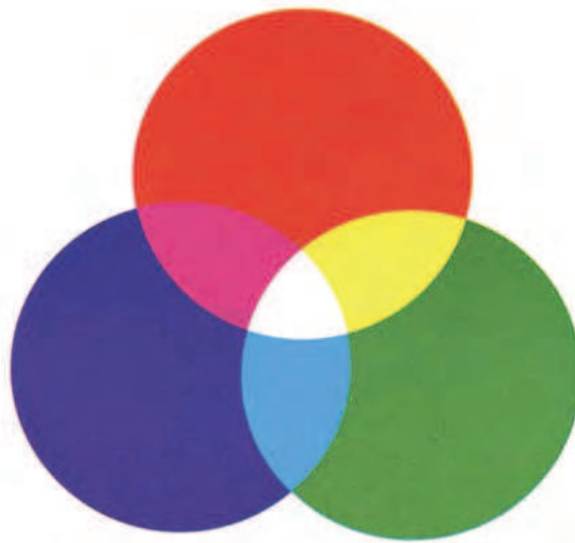


Fig. 8. Additive color mixing (McDonald 1997)

- b. **Subtractive Color Mixing** is created by the addition of pigment materials such as dyes, inks, and paints that remove reflecting wavelengths from light from each other, allowing us to see new color. When the pigment primaries that are cyan, magenta and yellow are mixed together, they culminate in black (Figure 9).



Fig. 9. Subtractive Color Mixing (McDonald 1997)

- c. **Optical Color Mixing** is also known as *Partitive* Color Mixing because optical mixtures combine additive and subtractive color mixing phenomenon. This is an effective method of creating mixtures that appear to vibrate and mix at particular distances when small areas of color are juxtaposed as shown in Figure 10.

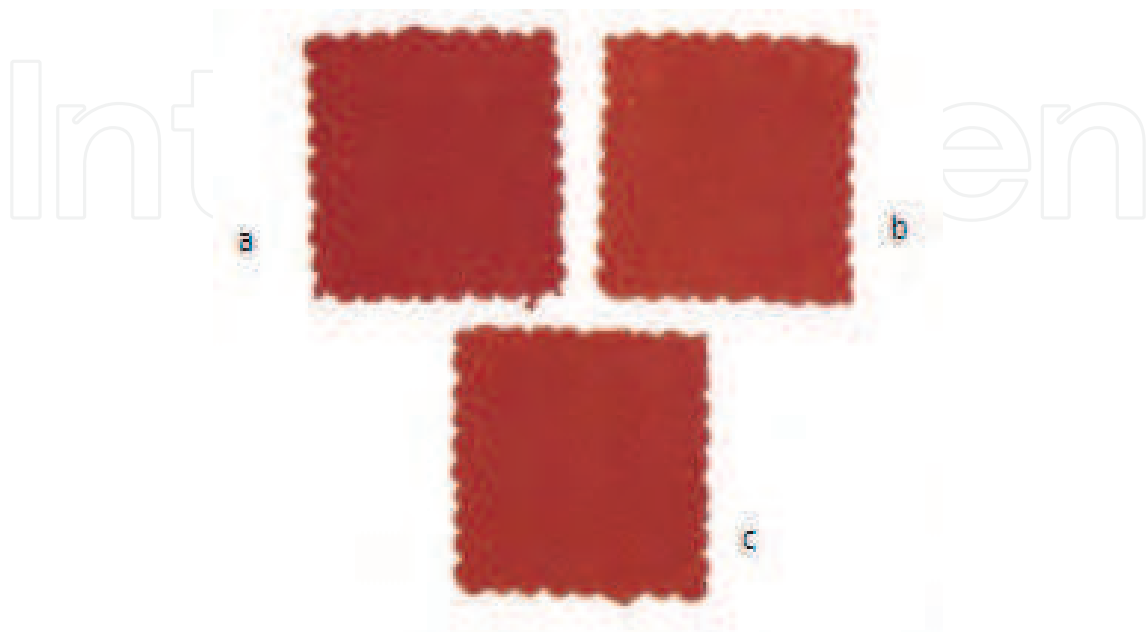


Fig. 10. The Optical mixture (c) is a result of weaving the yarn used in sample (a) with yarn used in sample (b) (Lambert, Staepelaere & Fry 1986)

Partitive color achieved in woven fabrics does not follow the same rules as the other cases (such as in additive and subtractive color mixing), presumably because the individual yarns are not completely opaque and moreover the fabrics are made from blends of several colored yarns with different weave effects.

Furthermore, the relation between the color values of different colors and their size must be carefully considered. When two colors are in juxtaposition with each other, each takes on the complement of its neighbor. This is known as law of 'Simultaneous Contrast'. In woven fabrics, the appearance of the color is a consequence of light reflected back from different areas of color surface of the yarns involved in the fabric structure. Looking at the color wheel (Figure 11), if color values of warp and weft are taken into account, behavior of the color contrast and harmony can be well understood.

Complementary colors lie on the opposite sides of the color circle, and their sum of reflected light gives an unsaturated color, which can be observed as a grayish hue on the fabric. On the other hand, the close positioning of two harmonic colors gives similar color value.

In woven designs, in case where fabric is made of multi-colored yarns, the final visualized color is a contribution of each color component present on the surface of the structure. Individual color components are blended and seen as one solid color. This blending of color is governed by the above mentioned color mixing principles. Blending of fibers has been very well studied in the past (Pierce 1997, Burlone 1990, Friele 1965, Miller 1979, Guthrie 1962, Burlone 1983, Walowit 1987, 1988, Burlone 1984, Reed et. al. 2004, Amisharhi & Pailthorpe 1994), but very few literatures have discussed the blending of yarns in fabric structure (Mathur 2007).

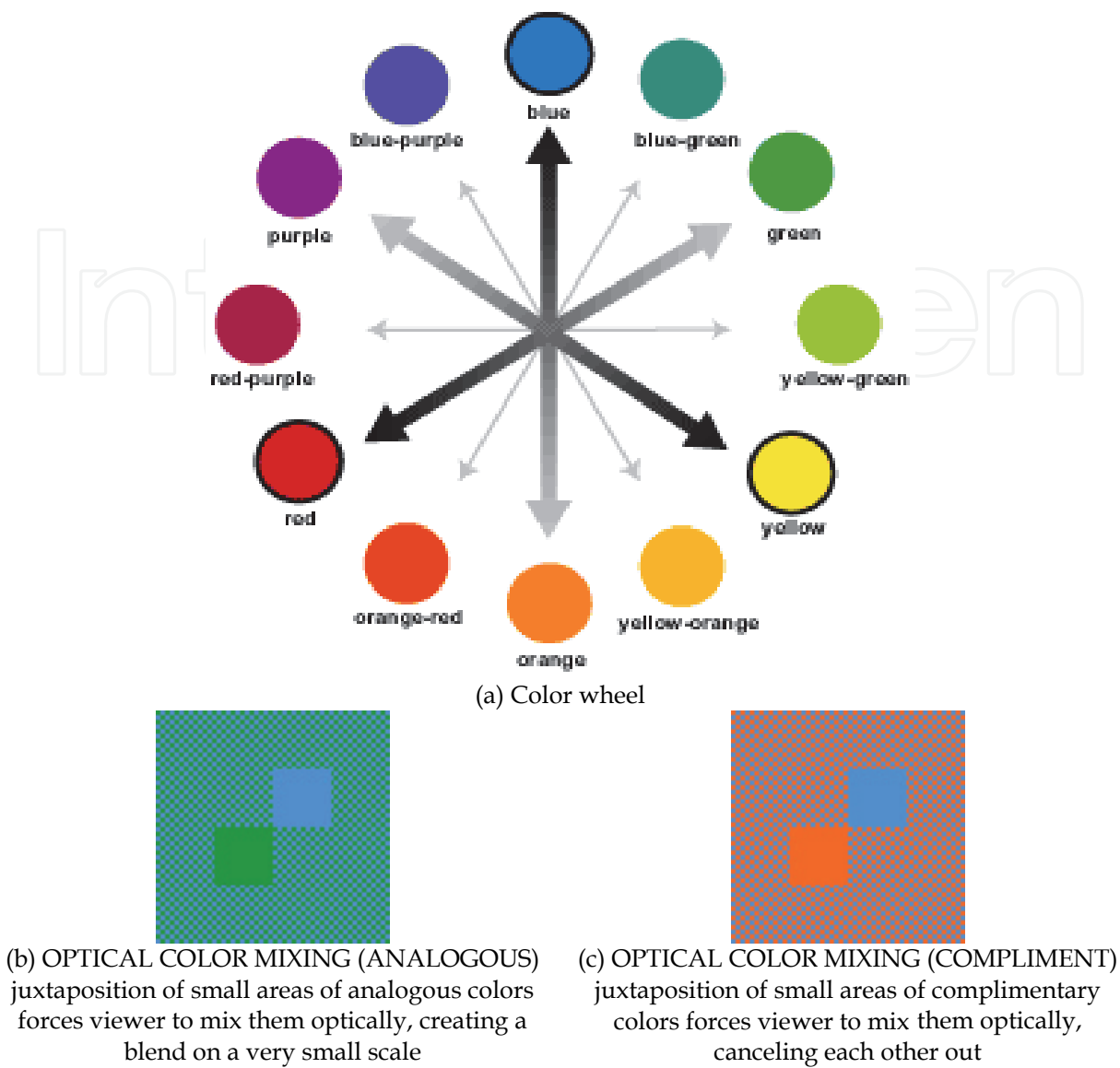


Fig. 11. Optical Color Mixing (Richard & Struve 2005)

3.1 Color visualization in CAD systems

In computer-aided design, there is a popular acronym called “wysiwyg”, which means “what you see is what you get”. Unfortunately, the wysiwyg concept often fails when dealing with the issue of color and reproducing color for different output devices. For example, it is difficult to match three different fabrics, all of which have different fiber content, because each fiber requires a different dye formulation. The same concept holds true in the world of computer generated color. Each color device used in CAD and production, including monitors, desktop printers, and commercial four-color process printers, have unique definitions and limitations for color by virtue of their own unique technology (Ross 2004).

Hoskins et al. (1983, 1985) developed an algorithm to analyze the color of woven structures. Since size of the design and restricted color sets were the limitation for the industry requirements, this algorithm was developed to provide the possibility of capturing any kind

of image by the system. The system could then provide important elements of color in the image without compromising the storage requirements or degrading the system's response time. Rich (1986) discussed the basic colorimetry of CRT (Cathode Ray Tube) displays, both instrumental and visual, as applied to textile design systems. His paper emphasized CRT-based graphical displays to generate colored images. He also suggested some technical aspects for accurate and repeatable representation of the weave and color of the textile on display. Similarly, Takatera and Shinohara (1988) developed a search algorithm to determine the color-ordering of the yarns and weave, to obtain a given pattern of color-and-weave effect. Dawson (2002) examined color-and-weave effects with small repeat sizes. He studied the effects of yarn color sequences over several weave repeats. Grundler and Rolich (2003) proposed an evolution algorithm to combine the weave and color, in order to have a predetermined idea of the appearance of the fabric to be produced. Based on the algorithm, software was then developed to access different fabric patterns and allowed the creation of new patterns, based on the user's choice.

Colors displayed via computer monitors cannot be specified independently. Therefore, color is considered as one of the major aspects of a user-centered design process. Most current CAD systems use uncalibrated color and, in consequence, designers are unable to define or communicate accurately the color of the image-design effect that they produce on the computer screen. A system with calibrated colors gives precise definitions for all colors seen. The numerical specifications for colors used in current CAD systems are expressed in terms of red, green, and blue (RGB) or hue, value, and saturation (HVS) combinations. Importantly, the CIE system of color specification (via tristimulus values, XYZ) is independent of any specific reproduction system and is widely used to specify color in textile manufacturing (Polton & Porat 1992).

The color issue represents not only one of the most frustrating aspects of CAD, but the area with the most rapidly advancing technology. A color management system, or CMS can be used to create color for specific output devices. Theoretically, this allows for more consistent and accurate color results between different output devices. A CMS works in the background and translates colors based upon pre-defined color profiles for specific output devices, allowing for more consistent color viewing and output. CMS's provide new possibilities for accurate color communication, but they cannot be considered an ultimate solution (Ross 2004).

Since the introduction of spectral-based imaging systems some years ago, algorithmic data communication of color standard and production 'submits', between retailers and suppliers, has proven to be one of the primary economic applications of the technology. Recent advances in color curve generation and image processing provide opportunities for additional improvements in areas of collaborative color development, color marketing, and color prediction in multi-step. At the same time, there are other aspects of imaging technology that have strong economical implications in other areas besides color communication. The other applications are derived from what is considered the very heart of such a system – the spectral base for color. Contrary to most CAD type systems, the input and output channels are spectral reflectance values either measured or generated and are largely device and illuminant independent. The spectral data are by far the most basic characterization of an object's color. From these spectral values, we derive all the other higher level output forms such as colorimetric values (X , Y , Z , L^* , a^* , b^* , C^* , H^*), output to the monitor in calibrated color (R , G , B), and to the calibrated printer in C , M , Y , K . By

combining the spectral base, colorimetric functions, and an image processor, the color imaging system is a powerful tool for color management (Randall 2004).

4. Advances in color and weave design

Recently, a number of technological advancements have been introduced by weaving machine producers, such as: high speed weaving, higher levels of automation, new shedding concepts, automatic (on the fly) pattern change, and filling color selection. Along with the advances in weaving, significant development has also occurred in the field of CAD systems, which enables automation in the design process. Despite this automation, the process of assigning weaves/colors is still done by the designers or CAD operator, which therefore requires physical sampling prior to production. This section includes the recent research work done to automate the process of assigning weaves/colors in order to reduce or even eliminate the need for physical sampling and to assist woven fabric designers in the creation of pictorial fabrics that are a very close match to the original “artwork” or target.

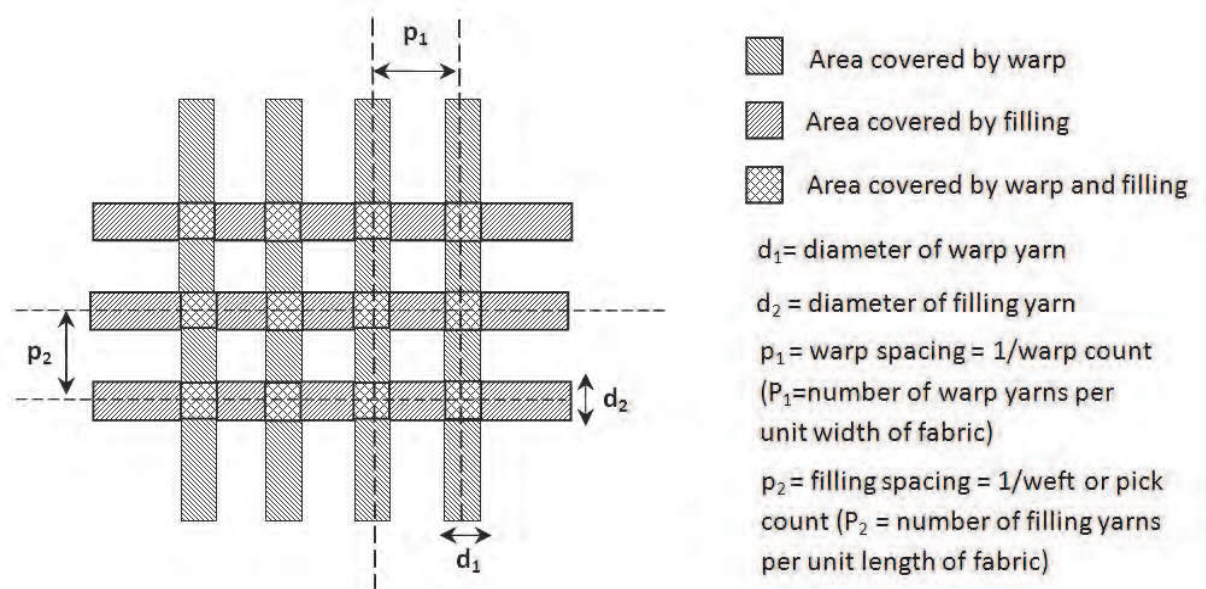


Fig. 12. Cover factor calculation for a Plain weave fabric

In woven fabrics, which are highly textured, various patterns become visible through their different structures. The color of such patterns also depends upon the color of the yarns involved, their combinations and different structures on the pattern surface. The final visible color on the fabric surface is mainly due to the contribution of fabric covering properties, namely optical cover and geometric cover (Lord 1973; Adanur 2001, Peirce 1937). The optical cover properties are defined as the reflection and scattering of the incident light by the fabric surface and are a function of the fiber material and fabric surface. Geometric cover (characterized by fabric cover factor) is defined as the area of fabric actually covered by fibers and yarns. Fabric cover factor is the ratio of surface area actually covered by yarns, to the total fabric surface area (shown in Figure 12).

The following Equations are used to calculate total fabric surface area covered by warp and weft yarns;

$$\text{Warp cover factor } C_1 = P_1 \times d_1 \quad (1)$$

$$\text{Filling cover factor } C_2 = P_2 \times d_2 \quad (2)$$

$$\text{Total cover factor } C_f = (C_1 + C_2 - C_1.C_2) \times 100 \quad (3)$$

Using the fundamental theory as discussed above, Dimitrovski & Gabrijelcic (2002) developed a method for predicting color values on woven fabric surfaces by calculating the color values from the known color values of the used yarns and the constructional parameters based on the cover factor Equations. The author estimated the deviation of the calculated fabric color values and measured fabric simulation color values from the measured color values of a real fabric with identical parameters. Theoretical calculations of color values of a fabric made from single colored warp and filling yarns were reported, based on constructional parameters of each yarn in the fabric. By using fabric geometry, fractions of individual color components in a color repeat was calculated and CIELAB color space was then used to calculate color difference tolerance. This method was experimented for the fabrics composed from single colored warp and filling yarns, where the weave design is divided into two units (when warp is interlaced with weft and vice versa. However, a weave design with varying warp/filling colors and diameters will have more than two units, which was not explained in this study. Also, no specific explanation (assumptions) regarding yarn diameter and yarn spacing was provided. For their calculation purpose, yarn diameter was measured (using microscope), which actually requires weaving a fabric and hence, defeat the purpose of predicting color proportions.

Dimitrovski & Gabrijelcic (2002) also discussed that the accuracy of prediction greatly depends upon the type of yarn. Multifilament yarn with relatively small number of twists tends to relatively big deformations of the diameter in the interlacing points, where deformations depend upon the type and the parameters of the yarns with which they interlace on the fabric surface. Deformation in the yarn diameter at interlacing points also depends upon the constructional and technological parameters the warp and the weft tension and reed plan are most important. Due to considerable deformability of such yarns their spectrophotometrically measured color values vary as well, so that it is difficult to accurately predict the color values of the woven surfaces. The effect of the technological parameters on the color values discussed in the paper was not, however, experimentally verified.

Mathur et. al. 2007, developed a model using the same cover factor principle discussed above that enables calculation of color proportions on the fabric surface in terms of weave pattern and color sequence of warp and weft yarns. The following assumptions were made for the calculations: yarn diameters were uniform cylinders, warp spacing at the weave intersection and under the float are of same value, pick spacing at the weave intersection and under the float were of same value, the projection (two-dimensional) of the fabric on a plane parallel to fabric plane is considered, and yarns are uniformly colored. Geometric calculations obtained from the model were employed in the number of Kubelka-Munk based models to predict the final colorimetric value of the woven design. The colorimetric values obtained were compared with spectrophotometric values for the color difference. Further, the color values obtained from the Kubelka-Munk based color models were simulated on the color calibrated monitor and compared with real woven samples for visual comparison. The detailed test method and results of this model is published elsewhere (Mathur et. al. 2005, 2008, and 2009).

Apart from the work that directly addresses the issue of representing color in interwoven yarns, there is another class of work, based on the influence of various fabric parameters that also addresses the problem of color reproduction in woven fabrics. Yarn count and density have a direct influence on the visible fractions of each individual color component within a color repeat, and consequently on resultant color values of that fabric surface (Gabrijelcic & Dimitrovski 2004). However, during the different stages of producing fabric (spinning, weaving, knitting, etc.), color change evolves due to different surface textures (Menz 1998). Dupont et al (2001) proposed a model of color evolution during the spinning stage, when the roving is transformed into yarn. After spinning, if the yarn is not dyed, the color depends uniquely on the initial color of the roving. Study done by Dimitrovski et al, concluded that the colored yarns used in weaving, if dyed by different methods, also affect the fabric color woven from the same yarns (Dimitrovski & Gabrijelcic 2001).

The optical color values in a fabric depend on the shape of the structural units, such as length of the fiber, yarn floats, diameter of the fiber and the yarn, cross-sectional shape of the fiber, and the longitudinal shape of the fiber and the yarn. Each of these structural units provides surface that reflect and absorb light, and the configuration of these surfaces dictates both the total light reflectance possible from the finished fabric and the direction in which the light is reflected. The amount and direction of reflectance is in turn responsible for the perceived value of the fabric color. A high level of total light reflectance results in a high value (or light color), while a low level of total light reflectance results in a low value (or dark color). If light from a surface is organized and reflected in a single direction, as happens with light from a single large flat shape, the surface appears either very light (if it is reflecting toward the viewer) or dark (if it is reflecting away from the viewer). If light is scattered from a surface in many directions, as happens with light from a curved surface, a uniform value will be seen from all points of view (Lambert, Staepelaere & Fry 1986; Berns 2000; McDonald 1997).

4.1 Color prediction model

Recent research (Mathur et. al. 2005, 2008, and 2009) provided a method to calculate the contribution of each color in an area of a pattern through numerical examples. The method utilized in this research is tedious, especially in the case of large patterns with numerous warp and filling yarns, colors, and weaves. Additionally, the method cannot be programmed to enable the automatic calculations of color contribution from basic design parameters. In this section, a generalized model is discussed briefly that enables the user of a computer simulation to input basic design parameters. The basic parameters used in the generalized model are warp and filling yarns linear densities, warp and pick densities, weave, color arrangements of warp and filling yarns, and color of the background. With proper computer programming of the model, a suitable color mixing equation (Mathur 2007), and databases of yarns colors, yarns, and weave, the process of color/weave selection could be automated without operator/designer intervention and without the need to weave color gamut (Seyam and Mathur 2008).

Figure 13 demonstrate an example to provide a clear understanding of the parameters involved the modeling and the contribution of each color component. Figure 13 is a flat view of 2x2 L.H. Twill with various warp and filling colored yarns (warp color arrangement: 1 purple, 1 light blue, 1 red and filling color arrangement: 1 dark blue, 1 green, 1 black). Using the generalized model, area of each color in the pattern can be calculated using Equations 4-6.

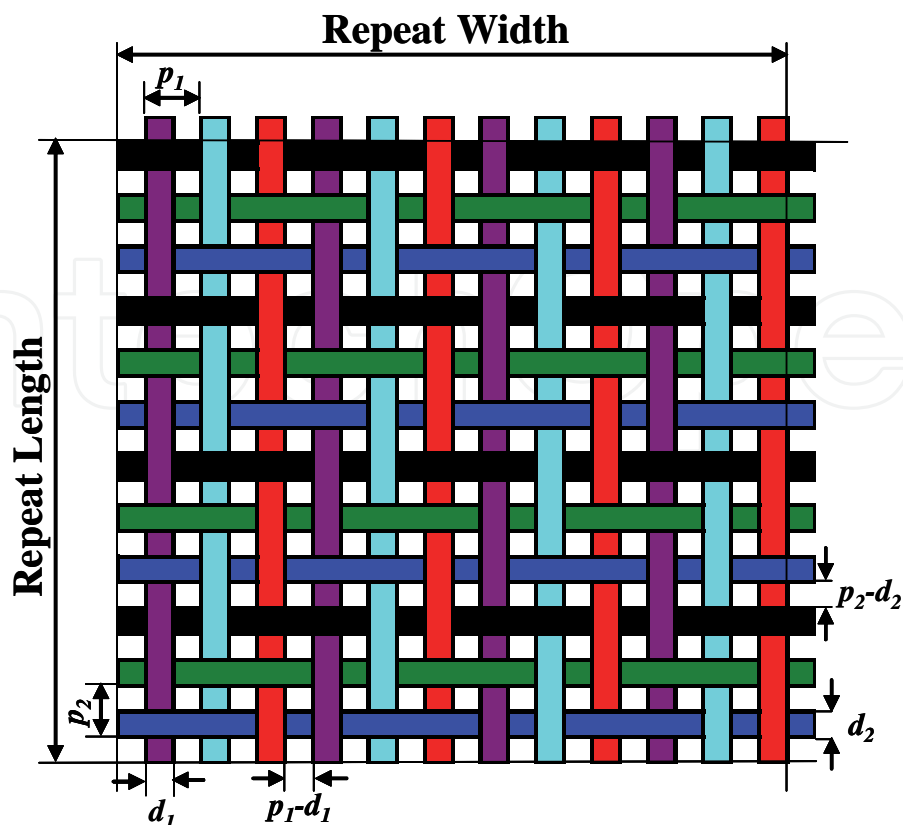


Fig. 13. An example of a weave with colored warp and filling yarns (Seyam and Mathur 2008)

General fraction cover of warp yarns of the i^{th} warp color is;

$$c_{1i} = \frac{m_{1i}l_2d_1(p_2 - d_2) + m_{1i}(l_2 / n_2)n_{col}d_1d_2}{p_1l_1p_2l_2} \tag{4}$$

General fraction cover of weft yarns of the j^{th} weft color is;

$$c_{2j} = \frac{m_{2j}l_1d_2(p_1 - d_1) + m_{2j}(l_1 / n_1)n_{col}d_1d_2}{p_1l_1p_2l_2} \tag{5}$$

The fraction of the area covered by the background color (white in Figure 2) is,

$$c_b = \frac{(p_1 - d_1)(p_2 - d_2)l_1l_2}{p_1l_1p_2l_2} = \frac{(p_1 - d_1)(p_2 - d_2)}{p_1p_2} = 1 - c_f \tag{6}$$

- Where,
- m_{1i} = number of warp yarns of warp color i
 - m_{2j} = number of filling yarns of filling color j
 - l_1 = number of ends/weave and color combined repeat = LCM (n_1, m_1); where LCM is Least Common Multiple
 - l_2 = number of picks/weave and color combined repeat = LCM (n_2, m_2); where LCM is Least Common Multiple;
 - n_1 = number of ends/weave repeat

n_2 = number of picks/weave repeat

m_1 = number of warp yarns

m_2 = number of weft yarns

d_1 = warp yarn diameter, cm = $\frac{1}{280.2} \sqrt{\frac{N_1}{\phi_1 \rho_{f1}}}$; N_1 = Warp yarn linear density (g/km or tex);

ρ_{f1} = warp fiber density in g/cm³; ρ_{y1} = warp yarn density in g/cm³; ϕ_1 = warp yarn packing fraction/ factor = ρ_{y1}/ρ_{f1} ;

d_2 = filling yarn diameter, cm = $\frac{1}{280.2} \sqrt{\frac{N_2}{\phi_2 \rho_{f2}}}$; N_2 = Filling yarn linear density (g/km or tex);

ρ_{f2} = filling fiber density in g/cm³; ρ_{y2} = filling yarn density in g/cm³; ϕ_2 = filling yarn packing fraction/ factor = ρ_{y2}/ρ_{f2}

P_1 = warp density, ends/cm

P_2 = Pick density, picks/cm

p_1 = warp spacing = $1/P_1$

p_2 = pick spacing = $1/P_2$

$d_1 d_2$ = cross over area where a warp (or filling) yarn is over a filling (or warp) yarn

n_{co1} = number of cross over areas where warp is over filling/weave repeat

n_{co2} = number of cross over areas where filling is over warp/weave repeat

The detailed discussion of the generalized model along with derivation and examples are discussed elsewhere (Seyam and Mathur 2008). A numerical example is provided in Appendix 1 to demonstrate the use of Equations 4-6 and to investigate the effect of weave and color pattern of warp and filling yarns on the contribution of each color used to construct the weave design.

The color proportion data obtained from this model can be employed in color models to obtain colorimetric calculation to predict the final color values of woven structures. Kubelka-Munk theory (K/S model) is commonly used to model the color of various forms of textile materials, with applications including computer color matching formulation, paints, printing and plastics coloration. To determine the most appropriate color model to use with different structures, a number of Kubelka-Munk theory based approaches were employed (Mathur 2007). In terms of textile structures, these previous works dealt with dye formulation for color matching of woven and knitted structures made from uncolored yarns. Other workers dealt with homogeneous mix of colored fibers to obtain a set color target for fabrics made from such fibers including nonwovens. In the following equations, the color contributions of dyes were replaced with the color contribution of each colored yarn a woven pattern as predicted from the model (Equations 4-6), and therefore the derived equations can be used to calculate the colorimetric values as:

$$\left(\frac{K}{S}\right)_{mix} = \sum_{i=1}^v \left(\frac{K}{S}\right)_{s_i} + \sum_{j=1}^{\lambda} \left(\frac{K}{S}\right)_{s_j} + \sum_{i=1}^v c_{1i} \left(\frac{K}{S}\right)_{1i} + \sum_{j=1}^{\lambda} c_{2j} \left(\frac{K}{S}\right)_{2j} + c_b \left(\frac{K}{S}\right)_b \quad (7)$$

$$\log \left(\frac{K}{S}\right)_{mix} = \sum_{i=1}^v c_{1i} \log \left(\frac{K}{S}\right)_{1i} + \sum_{j=1}^{\lambda} c_{2j} \log \left(\frac{K}{S}\right)_{2j} + c_b \log \left(\frac{K}{S}\right)_b \quad (8)$$

Where,

K = Light Absorption coefficient

S = Light Scattering coefficient
 $(K / S)_{mix} = \left(\frac{K}{S} \right)$ of the woven area
 $(K / S)_{si} = \left(\frac{K}{S} \right)$ of the undyed yarn substrate in warp
 $(K / S)_{sj} = \left(\frac{K}{S} \right)$ of the undyed yarn substrate in filling
 $(K / S)_{li} = \left(\frac{K}{S} \right)$ of the of i^{th} colorant in the mixture
 $(K / S)_{2j} = \left(\frac{K}{S} \right)$ of the of j^{th} colorant in the mixture
 $(K / S)_b = \left(\frac{K}{S} \right)$ of the background
 c_{1i} = fraction cover of warp with warp color i (proportion of i^{th} colorant in the mixture)
 c_{2j} = fraction cover of filling with color j (proportion of j^{th} colorant in the mixture)

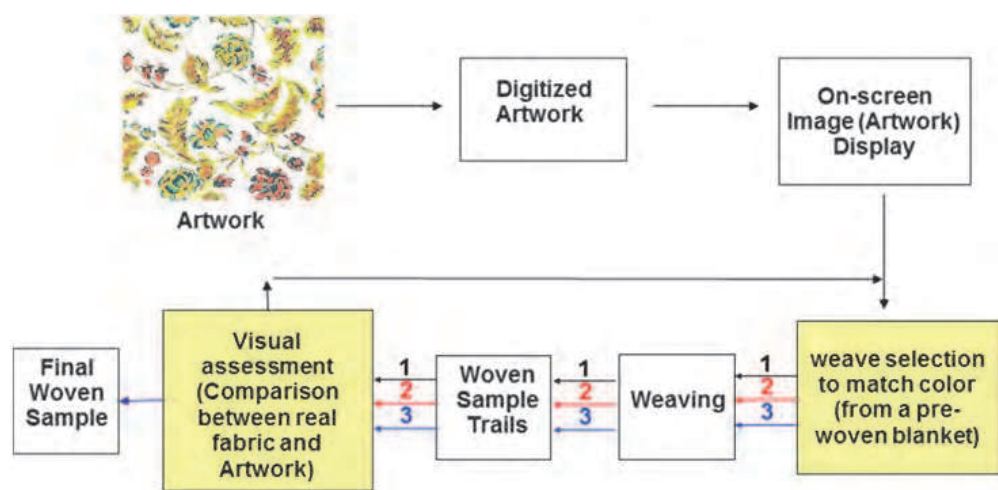


Fig. 14. a) Current/Traditional Design Process - Weave selection and sample matching still require the intervention of designer, who works from color gamut (blanket)

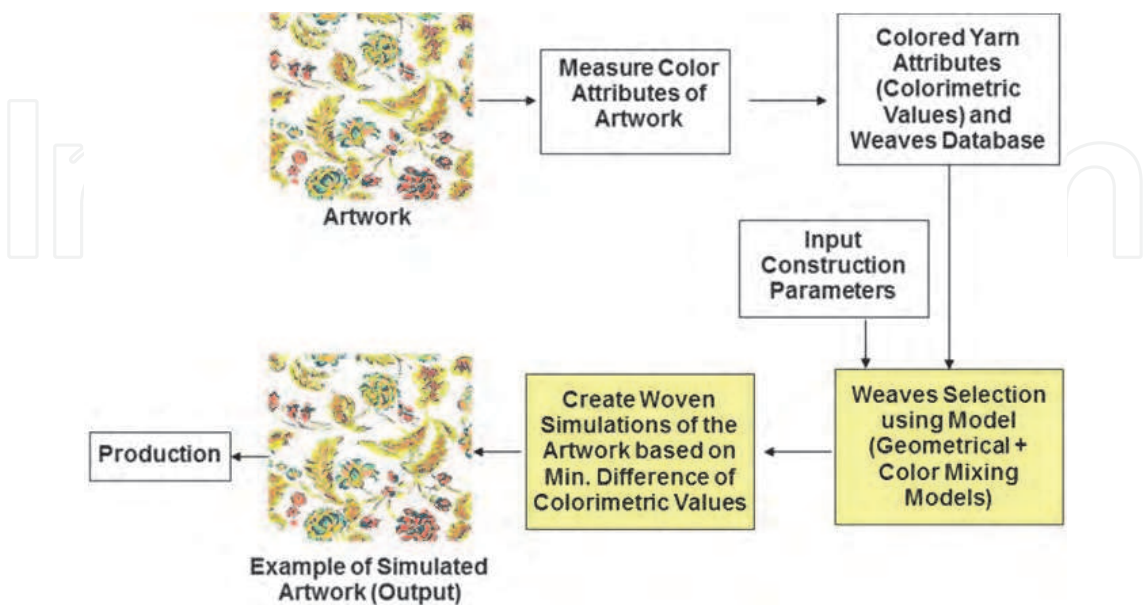


Fig. 14. b) Implementation of the Model in the scheme of the design process

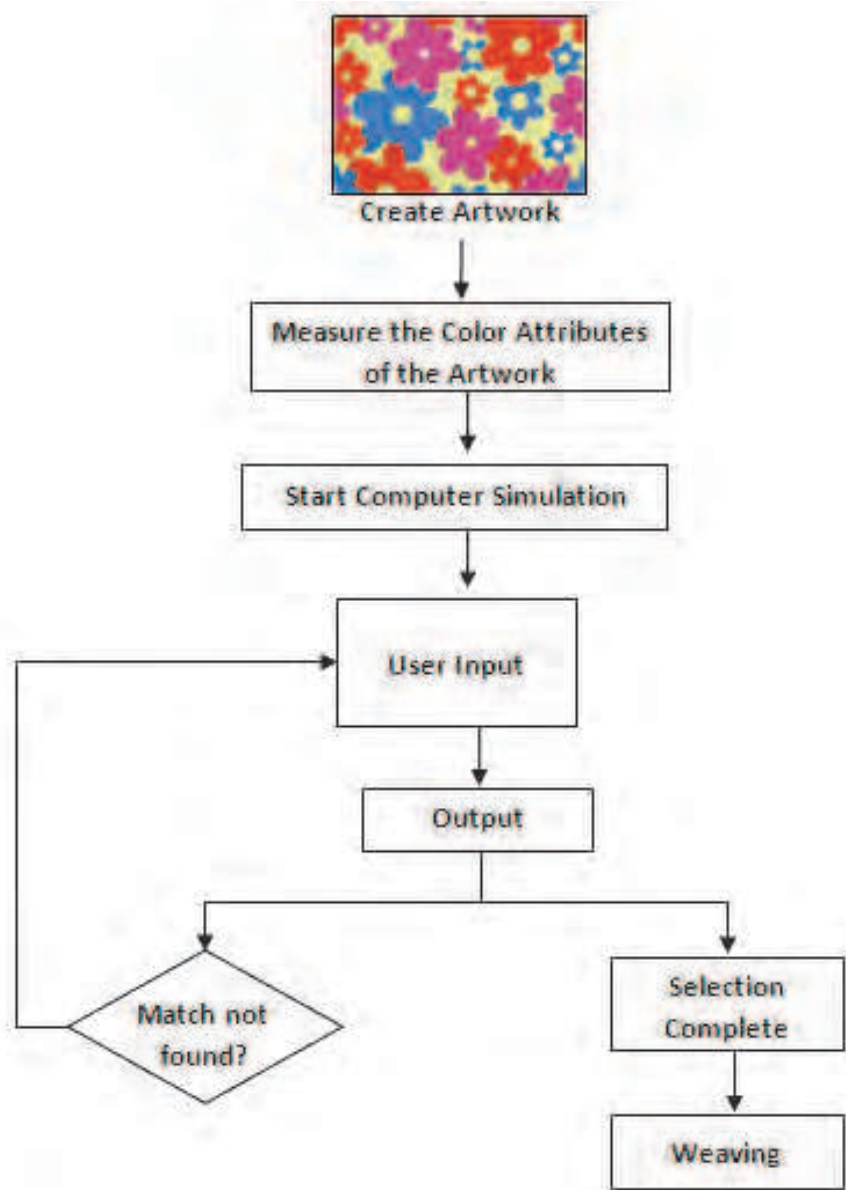


Fig. 15. Implementation of the Model in the scheme of design of patterned woven fabric (Seyam and Mathur 2008)

The color values obtained from these color equations (Equations 7 and 8) were analyzed statistically to validate the predicted color using the CIELAB $\Delta E_{CMC}(2:1)$ color difference equation (McDonald 1997). Also, extensive visual assessment experiments were designed and conducted for assessing the visual difference between the predicted and the actual color appearance of the woven structure. The results obtained from statistical analysis and visual assessment are reported elsewhere (Mathur et. al. 2008) The equations show how the geometric model and color model are combined to obtain the final color prediction in an objective way so the woven fabric color for each part of the design can be calculated using computer programming to automate the process of weave selection, which is currently (traditionally) decided subjectively by the designer which leads to more trials, high cost and long lead time to achieve the final target fabric (Figure 14a and b). Figure 14 a shows that three trials were conducted to reach to the target artwork while Figure 14 b indicates the

benefit of employing geometric and color models to automate the process of weave (color) selection.

The schematic flow of the design process using the model is illustrated in Figure 15. The process starts from creating artwork and measuring color attributes (defined in CIELAB color space (McDonald 1997)) for each color in the artwork. The computer simulation of the model allows the user to enter the design parameters. Next, the developed geometrical model calculates the contribution of each color and in combination with the color mixing equation, the final color of an area in the pattern can be obtained. The calculated color attributes are compared to the measured from the artwork. The difference of color attributes between the measured and calculated is checked. If the difference is within the tolerance, the program reports output that include the color attributes for calculated and actual, color arrangement, specific weaves within the classified weaves.

In case if the color differences are out of tolerance, the program reports to the user and suggests possible changes to the input parameters. This iteration continues until a reasonable match for each color in the artwork is achieved.

Below is an example to demonstrate the use of Equations 4-6 and to investigate the effect of weave and color pattern of warp and filling yarns on the contribution of each color used to construct the weave as shown in Figure 13. In this example, there are seven colors and the contribution of each color can be calculated from Equations 4-6. From the design parameters of Table 1, the parameters required for the color contribution can be calculated as shown below.

Construction Parameters									
Fabric ID	Warp Yarn		Filling Yarn		Warp Density (end/cm)	Pick Density (picks/cm)	Weave	n_{co1}	n_{co2}
	tex	Material	tex	Material					
A	30	Cotton, Ring Spun	30	Cotton, Ring Spun	41	24	1x3 Twill	1	3
B							2x2 Twill	2	2
C							3x1 Twill	3	1
Color Arrangement									
Warp				Filling				Background	
Color		Number		Color		Number		Color	
Purple		1		Dark Blue		1		White	
Light Blue		1		Green		1			
Red		1		Black		1			

Table 1. Construction and color parameters of fabrics with different weaves

d_1 = warp yarn diameter, cm = 0.020469 cm; d_2 = filling yarn diameter, cm = 0.020469 cm; p_1 = warp spacing = $1/P_1 = 1/41$ cm; p_2 = pick spacing = $1/P_2 = 1/24$ cm; c_1 = warp fraction cover = $d_1/p_1 = 0.020469 \times 41 = 0.839$; c_2 = filling fraction cover = $d_2/p_2 = 0.020469 \times 24 = 0.491$; c_f = fabric fraction cover = $c_1 + c_2 - c_1 c_2 = 0.839 + 0.491 - (0.839)(0.491) = 0.918$; ν = number of warp colors = 3; λ = number of filling colors = 3; l_1 = number of ends/weave and color; combined repeat = $\text{LCM}(n_1, m_1) = \text{LCM}(4, 3) = 12$; l_2 = number of picks/weave and color combined repeat = $\text{LCM}(n_2, m_2) = \text{LCM}(4, 3) = 12$; The values of n_{co1} and n_{co2} (defined below) are weave dependent as shown in Table 1.

n_{co1} = number of cross over areas where warp is over filling/weave repeat
 n_{co2} = number of cross over areas where filling is over warp/weave repeat
The example under consideration has equal number of warp (or filling) yarns per color, thus,
 m_{1i} = number of warp yarns of the i^{th} warp color = 4; m_{2j} = number of filling yarns of the j^{th} filling color = 4
Now all the parameters needed for the calculations of each color contribution are known. Since there are three warp colors, three filling colors, and a background color, seven color contributions are required. These are:
 c_{11} = fraction cover of warp with warp color 1 (Purple); c_{12} = fraction cover of warp with warp color 2 (Light Blue); c_{13} = fraction cover of warp with warp color 3 (Red); c_{21} = fraction cover of filling with filling color 1 (Dark Blue); c_{22} = fraction cover of warp with filling color 2 (Green); c_{23} = fraction cover of warp with filling color 3 (Black); c_b = fraction cover of background (White). The seven parameters are calculated from Equations 4-6. Their values for the three fabrics of Table 1 are shown in Table 2. The total color contribution for each fabric (must be 1.0) is also shown to validate the correctness of the calculations.

Color	Weave		
	1x3 Twill	2x2 Twill	3x1 Twill
Purple	0.177	0.211	0.245
Light Blue	0.177	0.211	0.245
Red	0.177	0.211	0.245
Dark Blue	0.129	0.095	0.061
Green	0.129	0.095	0.061
Black	0.129	0.095	0.061
White	0.082	0.082	0.082
Total	1.000	1.000	1.000

Table 2. Color contribution of different weaves

The results of Table 2 indicate that the weave has a significant effect on the contribution of colors. For example, the purple color appeared on an area on the fabric surface of 17.7% for 3x1 twill weave. The same color covered 24.5% of the fabric surface by changing the weave to 2x2 twill. These two weaves are of the same size and interlacing (same tightness), but differ only in the number of crossover areas where warp yarn is over filling yarns. The effect of spacing can also be seen from the results of Table 2. For each weave of Table 2, a warp color dominated more area than a filling color. This is attributed to the fact that warp density (ends/cm) is higher than the pick density (picks/cm).

5. Conclusion

Color blending in woven fabrics is defined as the process of mixing color by combining different colored yarn components to produce a homogenous color appearance. Different colored yarns are mixed in certain proportion to obtain a required color. The final color is a function of the constructional parameters that manifest changes in the area of each yarn on the surface. The colorimetric data of the weave structures can be calculated by using the combined effect of the two aspects of fabric covering power, the optical (reflectance) and the

geometric. The geometric model is discussed in this chapter combined with suitable color mixing model can be used to calculate colorimetric attributes on the surface of the woven fabric. These calculations can be easily programmed and the process of assigning weaves/colors can now be automated and therefore the subjective intervention of the designer is no longer needed. This will help in eliminating the need for physical sampling prior to production and the subjective opinions as the color/weave selection will be done automatically by computer based on the colorimetric values that are very close match to the original artwork.

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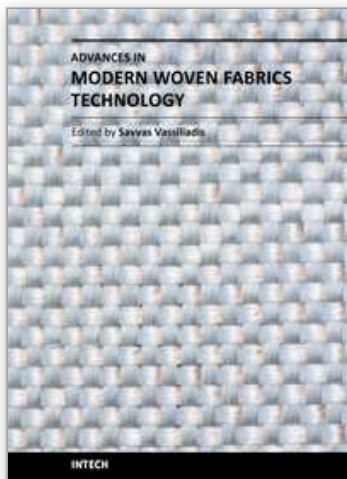
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The importance of woven fabrics increases constantly. Starting from traditional uses mainly in clothing applications, woven fabrics today are key materials for structural, electronic, telecommunications, medical, aerospace and other technical application fields. The new application fields of the woven fabrics is directly reflected in the contents of the book. A selected collection of papers in the technological state-of-the-art builds the book “Advances in Modern Woven Fabrics Technology”. It is written by internationally recognized specialists and pioneers of the particular fields. The chapters embrace technological areas with major importance, while maintaining a high scientific level. This interdisciplinary book will be useful for the textile family member as well as for the experts of the related engineering fields. The open access character of the book will allow a worldwide and direct access to its contents, supporting the members of the academic and industrial community.

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