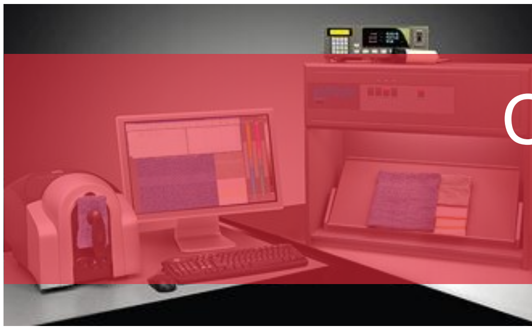

Color Differences & Tolerances

Commercial Color Acceptability

Manufacturers of colored products are expected to supply them at a level of color quality sufficient to satisfy their customers. Since customer requirements are often not easy to satisfy, management of the color acceptability process can prove to be difficult.

Customers employ various methods to assess color when determining the commercial acceptability of products. Most color evaluations are made visually, comparing a sample of production to a pre-approved standard. Although a controlled visual evaluation can consistently identify matching colors, difficulties may arise when color tolerances need to be considered.

Color measuring instruments and industry accepted color difference systems are widely utilized in industrial color acceptability applications. Colorimetry is used to supplement the visual evaluation process, as it provides a way to consistently quantify color differences, and thus facilitate the management of product color tolerances.

Color Tolerancing Systems are used in the management of production and customer acceptability activities. The tolerancing systems discussed in this Datafacts are:

CIE L*a*b*, CIE L*C*h*, CMC, CIE94

These systems are based on the CIELAB 1976 L*a*b* colorimetric system, which is described in more detail in the two DataFacts entitled "Colorimetric Fundamentals".

CIELAB in Acceptability Applications

Since its publication in 1976, CIELAB (**CIE L*a*b* and CIE L*C*h*)** has been extensively employed in the management of color acceptability. However, the desired perceptual uniformity of CIELAB color space has not been realized. Studies have shown that as the chroma of a color increases CIELAB increasingly overstates the magnitudes of perceived chroma and hue differences. CIELAB color space is also non-uniform regarding hue angle, although the specific nature of the non-uniformity is not yet definitively determined.

The primary limitation on the use of CIELAB in acceptability applications results from the non-uniformity of the color space. Different numerical tolerances must be applied to different standard colors depending upon their location in the color space. Pass/fail matching.

DataFacts tolerances must be established for each of the three coordinate differences (lightness, chroma, hue), and this process usually requires the making of numerous samples.

A secondary limitation on the use of CIELAB in industrial acceptability applications is that it provides no way to systematically weight the relative effect of lightness, chroma, and hue differences. The weights are applied through the individual tolerances, which must be determined separately for each product color.

CIELAB can be effectively employed in industrial color acceptability applications. However, the necessary establishment of (potentially different) tolerance sets for each color is an important limitation.

CIE L*a*b* Color Difference

The **CIE L*a*b*** system describes and orders colors based on the opponent theory of color vision. The opponent theory is that colors cannot be perceived as both red and green at the same time, or yellow and blue at the same time. However, a color can be perceived as a combination of: red and yellow, red and blue, green and yellow, or green and blue. In the CIE L*a*b* color space the color coordinates in this rectangular coordinate system are:

L* - the lightness coordinate.
a* - the red/green coordinate, with +a* indicating red, and -a* indicating green.
b* - the yellow/blue coordinate, with +b* indicating yellow, and -b* indicating blue.

CIELAB color difference, between any two colors in CIE 1976 color space, is the distance between the color locations. This distance is typically expressed as D E*, where:

$$\Delta E^* = \left[\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}\right]^{1/2}$$

Δ L* being the lightness difference.
Δ a* being the red/green difference.
Δ b* being the yellow/blue difference.

CIE L*a*b* Color Tolerances

CIE 1976 color space is approximately uniform for the perception of small color differences. That is, for specimens compared to a standard, color differences (distances) in any direction are of about the same importance (weight). Thus; **CIE L*a*b*** color difference (**ΔE***) is an equally weighted combination of the coordinate (**L*, a*, b*)** differences.

Industrial color acceptability decisions are often not based solely on the equally weighted CIE color difference (**ΔE***) function. By establishing tolerances that may differ for different colors, and also may differ for each coordinate, an effective color acceptability management system is possible using **CIE L*a*b***.

A drawback to using CIE L*a*b* in tolerancing systems is that the rectangular acceptability volumes do not conform well with visual experience. A visual acceptability volume (in CIE 1976 space) typically takes the form of an ellipsoid, whose minor axis aligns in the direction of changing hue. Since both the shape and alignment of the L*a*b* volume do not agree well with visual experience, colors near the edges of the volume may be calculated as acceptable although visually judged unacceptable.

CIE L*C*h* Color Difference

Colors can also be described and located in **CIE 1976** color space using the method of specifying their **L*, C*,** and **h*** coordinates. In this method, **L*** coordinates are the same as in L*a*b*, while the **C*** and **h*** coordinates are computed from the a* and b* coordinates. The same color is still in the same location in the color space, but **CIE L*a*b*** and **CIE L*C*b*** are two different ways to describe its position.

CIE L*C*h* color space is three dimensional, with colors located using cylindrical coordinates as follows:

L* - the lightness coordinate (the same as in L*a*b*).
C* - the chroma coordinate, the distance from the lightness axis.
h* - the hue angle, expressed in degrees, with 00 being a location on the + a* axis, continuing to 90^o for the + b* axis, 180^o for - a*, 270^o for - b*, and back to 360^o = 0^o.

Many CIE system users prefer the L*C*h* method of specifying a color, since the concept of hue and chroma agrees well with visual experience.

For industrial color tolerancing applications, CMC offers these primary advantages over the CIE L*a*b* and CIE L*C*h* systems:

- A single (**ΔE_{CMC}**) tolerance may be employed, rather than multiple tolerances (**ΔL*, ΔC*, ΔH***).

ΔC* being the chroma difference.
Δh* being the hue angle difference.
ΔH* being the metric hue difference.

The metric hue difference (**Δ**H*) is the color difference that remains when the lightness and chroma differences are zero. **Δ**H* is used in the total color difference computation, where all terms are distances (not angles), as follows:

$$\Delta E^* = \left[\Delta L^{*2} + \Delta C^{*2} + \Delta H^{*2}\right]^{1/2}$$

CIE 1976 **Δ**E* and D **Δ**L* differences are the same for any pair of colors whether using CIE L*a*b* or CIE L*C*h*.

CIE L*C*h* Color Tolerances

The **CIE L*C*h*** system locates a color in the three dimensional **CIE 1976** color space, based on the **L*, C*,** and **h*** coordinates. Color acceptability management using this system is similar to using **CIE L*a*b***, except that chroma (**C***) and hue angle (**h***) are used instead of the **a*** and **b*** coordinates.

The CIE L*C*h* acceptability volume conforms better to the visual evaluation ellipsoid than is the case with CIE L*a*b*. Alignment of the acceptability volumes are typically the same although the shapes differ significantly. Colors near the edges of the L*C*h* solid will often be calculated as acceptable although visually judged unacceptable.

CMC Color Difference and Tolerances

The **CMC** color difference formula is based on the colorimetric principles of the **CIE 1976** system. It is typically employed as a color tolerancing system in industrial applications. **CMC** color difference (D ECMC), a modification (transformation) of **CIE L*C*h*** color difference, has proven to be a useful measure of the commercial acceptability of colored products.

CMC color difference is often employed in pass/fail color production applications, where a single numerical tolerance can be established and utilized to make acceptability decisions. An important advantage of **CMC** is that once a tolerance has been successfully implemented for a product, the same tolerance may prove applicable for other colors produced under similar commercial conditions.

- The same (**ΔE_{CMC}**) tolerance may often be utilized for a group of similar products, no matter their color.
- Computed color differences (**ΔE_{CMC}**) generally correlate better with visual assessment, in both acceptability and perceptibility applications.

The CMC formula is based on CIE lightness (**Δ**L*), chroma (**Δ**C*), and hue (**Δ**H*) differences.

$$\Delta E_{CMC} = \left[\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*}{cS_C}\right)^2 + \left(\frac{\Delta H^*}{S_H}\right)^2\right]^{1/2}$$

S_L, S_C, and S_H are **CMC** weighting functions that adjust the CIE differences (**Δ**L*, **Δ**C*, **Δ**H*) depending upon the location of the standard in **CIE 1976** color space.

A user of the **CMC** formula usually sets values for the l and c parameters according to practice in his industry. l and c are numeric parametric factors that permit the independent weighting of lightness (**ΔL***) and chroma (**ΔC***) differences, relative to the hue (**ΔH***) difference. Current practice is that c is set to 1 for all industries, and l is set to 2 for textiles, and to about 1.4 for paint and plastics applications.

CIE94 Color Difference and Tolerances

In 1995, the CIE published a recommended practice for industrial color difference evaluation (CIE 116-1995). It included a complete color difference model for industrial evaluation designated **CIE 1994** (abbreviated to **CIE94**), with symbol **ΔE***$_{94}$.

The **CIE94** formula is similar to the CMC formula, and is based on CIE lightness (D **L***), chroma (D **C***), and hue (D **H***) differences.

D E* 94 =

$$\left[\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*}{k_H S_H}\right)^2\right]^{1/2}$$

SL SC SH are **CIE94** weighting functions that adjust the CIE differences (**ΔL*, ΔC*, ΔH***) depending upon the location of the standard in **CIE 1976** color space.
$S_L = 1$; $S_C = 1 + 0.045\,C^*$; $S_H = 1 + 0.015\,C^*$.

k_L, k_C, k_H are numeric parametric factors that permit the independent weighting of lightness (**Δ**L*), chroma (**Δ**C*), and hue (**Δ**H*) differences. Values selected for the parametric factors are shown in the naming convention CIE94 (k_L, k_C, k_H). CIE94 parametric factors (k_L, k_C, k_H) have initially been set equal to unity for the defined viewing reference conditions for perceived color difference. The reference conditions are: CIE D65, CIE 100 Observer, 1000 lx illuminance, gray background, minimal specimen separation, and homogeneous specimen structure, 0 to 5 **Δ**E*, and normal color vision. For textile industry acceptability applications, k_L is typically set to 2.