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Colour Management of the Brand Colour

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<p>The purpose of the thesis was to create worldwide brand colour management guide for the company's packaging printing. The packages are printed all over the world and the uniform colour management guidelines are needed. That is the only way to ensure that quality of a package will remain exactly same regardless of where it is printed.</p> <p>The colour specification was determined for Brand Colour. Guideline includes the reference and tolerance values of colour. Measurement was performed on reference samples and tolerance samples. Both LAB and density values were measured and both uncoated and coated surfaces were determined. One sheet includes several billets. Therefore, for ΔE^* tolerance to one die-cut was also determined. The paper surface has an influence for print result. Therefore, also the paper surface was specified.</p> <p>To ensure similar measurements, the measurement settings were also needed to be specified. The following settings has to be done before the spectrophotometric measurements: D50 illuminant, 2° observer, calibration to absolute white, UVCut filter and black backing. While density is measured, the settings are following: 0/45 or 45/0 observer and calibration to paper white. GretagMacbeth SpectroEye is recommended as the measurement instrument.</p> <p>The final result was a uniform guideline for printing houses that will be distributed to all over the world. The test printing will continue globally to enhance the on-going colour quality. The reference samples and tolerance value will be sent to printing houses. The printers compare print with reference sample and measure if it is in limit of tolerance.</p>	
Keywords	colour management, printing process control, CIE colour system, colour difference, paper qualities

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<p>Insinööri­työn tarkoituksena oli luoda yri­tyksen tuote­pakkauksille maailmanlaajuinen väri­hallintaohjeistus. Väri­määri­tykset tehtiin yri­tyksen brändivärille. Väri on tunnistettava, joten on tärkeää, että se pysyy muuttumattomana paino­prosessissa. Pakkauksia painetaan ympäri maailmaa, joten yhtenäistä ohjeistusta tarvitaan. Tällä varmistetaan, että pakkaukset ovat samanlaisia riippumatta siitä, missä ne on painettu. Jotta voitiin varmistua, että määri­tykset oli tehty oikein, tehtiin mittauksia kahdessa eri paikassa. Lopputulos muodostui yhdistelemällä näistä kahdesta parhaat tulokset.</p> <p>Työssä laadittu väri­hallintaohjeistus sisältää referenssi- ja toleranssiarvot brändivärille. Mittaukset tehtiin sekä referenssi­värille että vielä hyväksytyissä rajoissa oleville väreille. Näin saatiin raja-arvot, joiden sisällä väri saa muuttua. Molemmat Lab-väriarvot ja densiteetti­arvot määritettiin sekä päällystetylle että päällystämättömälle paperille. Koska yhdellä painoarkilla on useita pakkauksia, on myös määritettävä toleranssiarvot yhdelle pakkaukselle. Myös painoalustalla on suuri vaikutus lopputulokseen, joten raja-arvot määritettiin myös sille.</p> <p>Koska monet muuttujat vaikuttavat mittauksiin, on mittaukset suoritettava aina kuten määritetty. Spektrometrisiä ja densiteettisiä mittauksia varten määritettiin omat asetukset, jotka tulee asettaa mittalaitteeseen ennen mittauksia. Spektrometrisiä mittauksia tehtäessä, tulee mittalaitteeseen asettaa valoksi D50 ja havaintokulmaksi 2° ja suotimena tulee käyttää UVCut:a. Mittalaite tulee kalibroida absoluuttiseen valkoiseen, ja mittaukset on tehtävä mustaa taustaa vasten. Densiteettisiä mittauksia tehtäessä tulee mittalaitteeseen asettaa havaintokulmaksi 45/0 tai 45/0. Mittalaitteen kalibrointi tulee tehdä paperivalkoiseen. Jotta voidaan varmistaa mittauksien samankaltaisuus, on suositeltavaa, että mittauksissa käytetään GretagMacbeth SpectroEye -mittalaitetta.</p> <p>Lopputuloksena saatiin yhtenäinen ohjeistus, joka jaetaan painotaloille ympäri maailmaa. Brändivärin testipainatuksia jatketaan. Tällä pyritään siihen, että väri­hallinta olisi tehokasta ja jatkuvaa. Painotaloille lähetetään valmiiksi painetut referenssi­värimallit, tavoite­densiteetti ja toleranssiarvot sekä Lab-väriarvoille että densiteetti­arvoille. Painajat vertaavat painettua painotuotetta referenssi­värimalliin ja mittaavat, että se on toleranssi­rajoissa.</p>	
Hakusanat	väri­hallinta, paino­prosessin hallinta, CIE-värijärjestelmä, väritoleranssit, paperilaadut

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1 Introduction

The purpose of the thesis was to create a worldwide brand colour management guide for a company's packaging printing. The packages are printed all over the world and uniform colour management guidelines are needed. This is the only way to ensure that quality of a package will remain exactly the same regardless of where it is printed. The impression of the company becomes concrete through packages. The company brand takes form when end customer receives the package. The high quality package also gives a trustworthy impression of product to the customer.

The first step was to focus on the Brand Colour, which is the colour most commonly used by the company. Even a slight colour tone difference between packages may be noticed. Specially, when packages are covered with that colour. So, to ensure that the colour remains unchanged during printing process is the most important thing. This can be achieved by specifying the colour and its tolerances and measurement methods. The print surface has an influence for print result and colour formation. Also, the guideline for paper surface needs to be specified. This also ensures that colour in package surface is exactly uniform.

Measurements were done by two measures in two different places to make sure that everything was done as expected. After that the reference and tolerance values were defined for colour management guide. More test printing was done to ensure the guidelines of Brand Colour work as they should and everything is taken into account.

The brand colour management guide will be distributed to all over the world especially for printing houses. The test printing will continue globally to enhance the on-going colour quality.

The theory part of colour perception and colour models may use as educational material in the company. Also, a brief summary of color theory is presented in this thesis.

2 Colour Theory

Before it is possible to understand colour management in printing process, we need to define basic knowledge of colour perception and colour models [1,17]. First we have to understand that colour is a phenomenon. It is a sensation based on the eye's ability to see light of different wavelengths of the colours [2,5].

Colour is a result from interaction in which there are always three elements: *light*, *object* and *observer*. Colour is said to be an event that occurs among those elements, and all the elements must be present. Light is the first important element in colour event, simply because without it there is not much to see. Light is a visible part of the electromagnetic spectrum to which human eyes are sensitive. [2,4–5;3,4]

The final perception phenomenon of the colour happens in the human eye and brain. Eye receives the light source that is modified by object. The eye converts the light into nerve impulses. These nerve impulses are carried to the brain, which interprets the colour observation. If even one factor changes, colour transaction will change and colour is seen as a different colour. [2,4–5]

Light

Light is usually described as band of *wavelengths*. Spectrum of colour can be seen for example when visible light goes through prism and when light is broken apart into colour. The light reflected from coloured object is changed when certain wavelengths are absorbed by the object and different wavelengths are refracted various ways and eye distinguishes them as colours. The wavelengths of light are measured in terms of nanometres (nm). A nanometres is one-millionth of a millimetre. [3,4]

The whole spectrum of all colours is present in the light. The part of the electromagnetic spectrum visible to the human eye ranges from about 380 to about 780 nanometres. Eyes have light sensors that are sensitive to those wavelengths. The sensory experience

of colour is unique, so the human colour perception is subjective. The exact range of visible light varies from person to person. [2,7–8]

The composition of wavelengths depends on which colour our brain is receiving. As figure 1 shows, the part that is visible to human eye is a tiny slice of the enormous electromagnetic spectrum. In that part human eye has varying responses to different wavelengths that produce different impression of colour from the violets at the *high-energy end* (about 380 nm) through the indigos, blues, greens, yellows to the oranges and reds at the *low-energy end* (about 700 nm). Therefore, each wavelength has its own specific colour. [2,8]

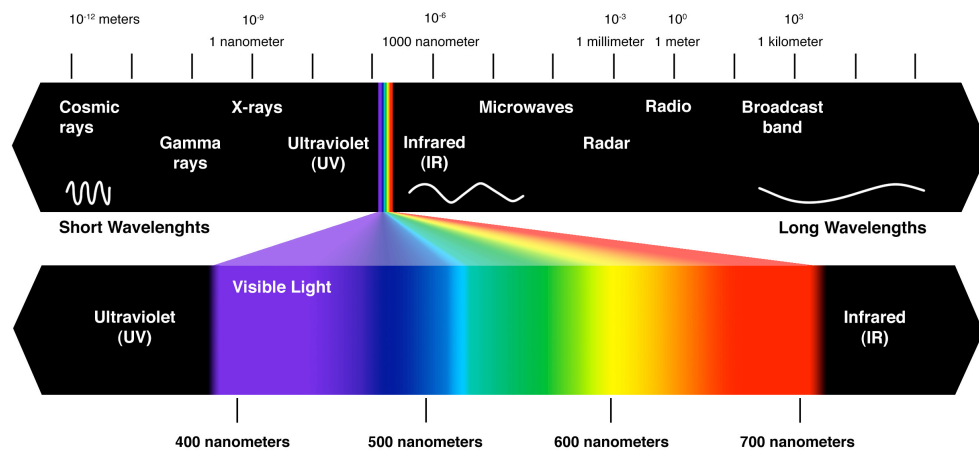


Figure 1. The electromagnetic spectrum [4].

The parts of spectrum that are just outside from the visible range are ultraviolet (UV) and infrared (IR). The electromagnetic spectrum contains also gamma rays, x-rays, microwaves, radar and radio waves. Even though those wavelengths are not visible to human eye, are they still useful. For example, when using radios and television, the section from short-wavelength X-rays to the Broadcast wavelengths are needed. [3,4]

As figure 2 shows, each colour has its own *spectral curve*. Its means that colours are determined by specific blend of wavelengths, also called as spectral energy. All of these spectral energies can be represented by a diagram, which shows the light reflected by the object. [2,9;3,4]

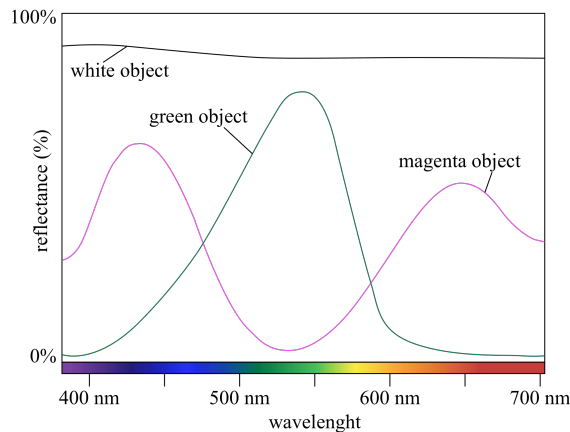


Figure 2. Three different objects spectral curves [2,9].

The figure above presents colours of white, green and magenta that reach to observer eye. As can be seen, the white light contains all the visible wavelengths and the amount is equal. White light is seen when all the waves are together. Light from green object contains mostly medium-wavelengths, a few short-wavelengths at the high-energy end and a few long-wavelengths at low-energy end. Magenta is quite the opposite: it contains the short and long wavelengths and a few in the middle of the visible spectrum. When no wavelengths are observed, brain perceives colour of black. [2,9;3,4]

Object

The light waves strike to the object surface, which absorbs some of the spectrum's energy, while other parts of the spectrum interact with surface and re-emerges to observers' eyes, and eventually affects the colour sensation. Surface may contain various pigments, dyes, and inks that modified light and form unique composition of wavelengths. Therefore, the reflected light is not always the same as incoming light. [2,13;3,6]

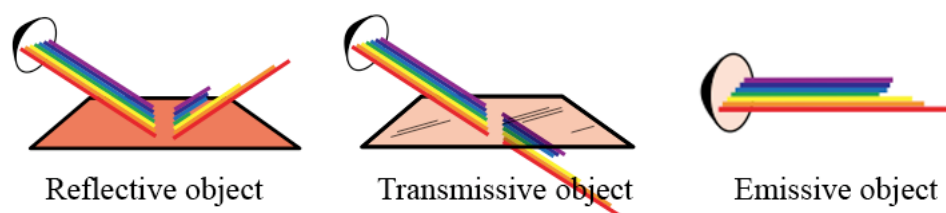


Figure 3. The reflective, transmissive and emissive object [3,6].

As figure 3 shows, light can be modified by *reflective*, *transmissive* or *emissive* object. The reflective object such as paper, reflects the modified light. The transmissive object such as film, lets the light pass through. The emissive object such as artificial lighting or a computer monitor are light sources themselves and have their own wavelength composition. Therefore, each object affects light in its own unique way. [3,6]

Observer

Human eyes have colour sensors, *receptors*, which are sensitive to the visible spectrum's wavelengths. There are two types of receptors: *rods* and *cones*. The rods are light sensitive in low-light conditions and are largely blinded by daylight conditions. Those cells are colour blind. The cones are responsible for perception of colour. There are three different types of cone. Each cone is sensitive to a particular area of the spectrum. The cones are called according to which part they are primarily responding: long wavelengths are responding to red cones, middle wavelengths to green cones and short wavelengths to blue cones. [2,16–18]

In human colour vision, the distribution of the various wavelengths areas is combined, which eventually leads to the impression of colour [1,19]. For example, when we see a red object, we are observing light that contains mostly wavelengths that are approximately situated at 700 nm, where the represent colour red is situated [3,5]. The colour formation in brain is represented below.



Figure 4. The rose is actually colourless without observer. The object reflects the wavelength composition necessary for observer to see red rose. [3,8]

As figure 4 shows, the rose is colourless before the observer visual system has noticed it. The eye's light sensors send unique patterns of electrical signals to the brain from observed light that reflects from an object. The signals are furthermore processed into sensation of sight. Finally, observer's *colour memory* associates the name to the colour. In case of red rose, the brain has got the red's composition of wavelengths and the observer sensed the sensation of colour and remembers the pattern as red. Therefore, the final definition of colour happens in mind. [3,8]



Figure 5. Brain breaks the visible spectrum down its most dominant regions of blue, green and red [3,8].

The human visual system receives every second a new wavelength to process and it is impossible for our brain to examine discrete wavelength information of every colour that is seen. Instead, the brain is using the “mass-processing” method to process wavelengths to colours. As seen in figure 5, the visible spectrum is divided to its most dominant regions of red, green, and blue. After that visual system concentrates quicker on these colours and calculates the colour information. [3,8]

2.1 Colour Reproduction Principles

There are two principles how colours are formed: the *additive* and *subtractive formation*. Both of them are based on mixing primary colours. The primary colour is usually defined as the colour that is not obtained by mixing other colours. The definition of the primary colour also includes that, by mixing it primary colours together, other colours are produced. [5,72.] The principals of additive and subtractive colour mixture are outlined in figure 6 on next page.

Even though additive colour mixture appears quite different from subtractive method, there is still a relationship between them, which can be defined [6,19]. To form a certain colour, both methods are working by manipulating the wavelengths that enter our eyes and simulate three cone receptors [2,20].

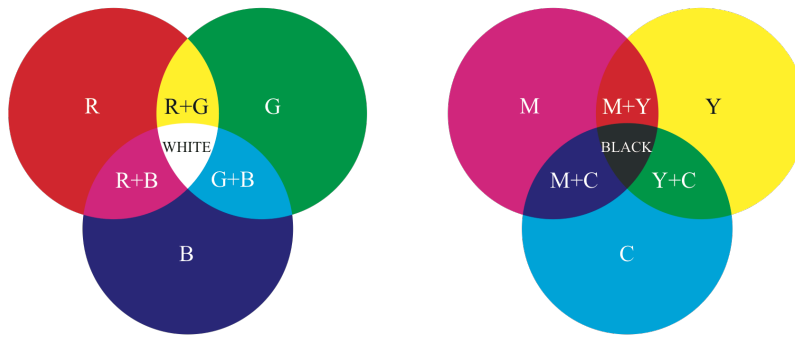


Figure 6. Additive and subtractive primary colours [3,20].

One way to distinguishing colours is to describe its three attributes: *hue*, *saturation* and *lightness*. Hue is the property of a colour that gives it its basic name, such as blue or yellow. Saturation describes the purity of colour as well as its vividness. The lightness is the brightness of an object and it ranges from “dark” to “light”. [3,34–35]

When speaking about colours, we can run into attributes *achromatic* and *chromatic*. If the object reflects equally the white light of all wavelengths, object appears white, gray or black, depending on the intensity of reflection. White surface reflects all incoming radiation, the gray part of it and the totally black surface does not reflect anything. Such colours are called as achromatic. Thus, those colours do not have a tone. If some wavelengths reflect to each other more strongly from the object some colour is sensed. Then it is a chromatic colour. In turn, chromatic colour such as yellow, red and blue have a tone. The chromatic colour’s attributes, hue and saturation, are then commonly associated with colours. [3,34]

RGB – The Additive Colour Model

In the additive formation, colour forms by mixing of different light sources by *additively* with each other. If the colours of the light sources contain a mix of pure red, green, and blue light equally in the right proportions, the colour produced is white (figure 6). This is because the three colours add wavelengths, until it gets white, in which case all wavelengths are in even proportions as shown in figure 2 on page 8 [2,20]. In turn, the absence of these colours results colour black, in other words when no light is present. [3,9]

This technique is also called as RGB. The designation comes from the additive primary colours: red (R), green (G) and blue (B). With various combinations of *additive primaries* all the colours can be produced. As figure 6 on previous page shows, in the areas where two additive primary colours overlap, the secondary colour appears. [7,23]

The combination of red and blue light produce the sensation of magenta, red and green produce yellow and blue and green produce cyan. When the proportions of colour change, all the other hues and levels of saturation are achieved [6,20].

The human colour vision is based on the production of three-color additive colour formation. Also, colour television and computer screen are based on this principle, where every element on the screen is made up of fluorescent dots of red, green and blue. Like the human eye, these devices must also process a large amount of colour information at once – on screen. These devices imitate the eye's response to the additive primaries to create a colourful illusion. [1,22;3,9]

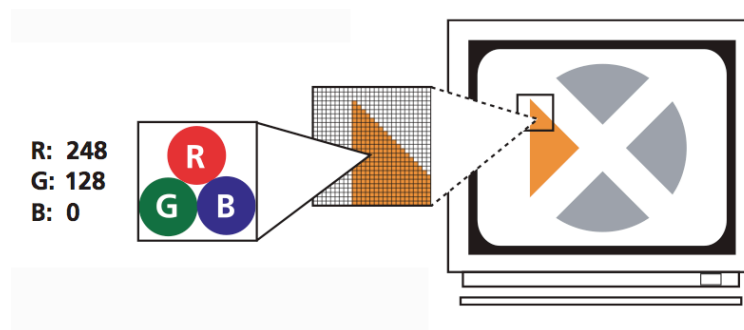


Figure 7. Monitor screen generate images using microscopic pixels, which contains RGB phosphors. [3,9]

Figure 7 shows that a monitor blends varying intensities of red, green, and blue light at each of its tiny *pixels*. These pixels are so small and tightly packed that the eye's RGB response is fooled into the perception of many different colours when really there are only three. [3,9]

CMYK – The Subtractive Colour Model

The subtractive formation works the opposite way to additive formation. Sensation of colour is produced *subtractively* when coloured wavelengths absorb white light [8,390]. Therefore, if none of the *subtractive primaries* are present, the colour produced is white, because nothing has been subtracted from the white light. As figure 6 on page 11 shows, in the areas where all the colours are present at their maximum amounts, the colour produced is black because all of the light has been subtracted from the white light [7,24].

The primary colours of subtractive system are cyan, magenta and yellow, which are simply those that absorb red, green and blue on reflective substrate. Each of the three primary colours absorbs certain wavelength to itself. The colour that is seen, is the light that is reflected or transmitted. If a visible spectrum is arranged in a form of circle, it is possible to see, which one of the primary colours is absorbed, because each colour absorbs its complementary counterpart from the oncoming white light. As figure 8 shows, the cyan's complement is red, magenta's green and yellow's blue. [3,10;6,22–23]

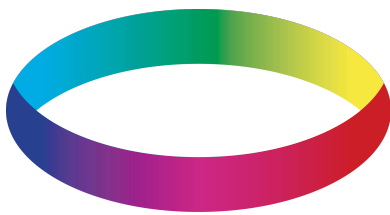


Figure 8. The visible spectrum is arranged in form of circle [6,23].

Because the eye has receptors responsive to red, green and blue light, those lights have to be subtracted when forming colours on paper and other substrates. In case of printing, an unprinted white paper is the target from which white source of light is subtracted with ink to produce colour. The cyan (C), magenta (M) and yellow (Y) inks are used to control the amount of red, green, and blue light that is reflected from white paper. Thus the ink absorbs a part of the light and reflects remaining wavelengths, which form the desired colour composition. [3,10;6,20].

Transparency of inks makes it possible to overlap colours. The transparency has an influence to formed colour [6,21]. Figure 9 shows the colour combinations and colours that are corresponding. The ink cyan for example, absorbs red to itself and reflects green and blue light back. Thus the cyan ink subtracts long wavelengths (red) from white light and sensation of cyan produces to eye. By overprinting two subtractive primary colours red, green and blue are formed. For example with a combination of cyan and magenta the result is blue because the cyan absorbs the red and magenta absorbs the green. Only the blue is left and the observer senses that. [2,20;6,20]













































	Ink Colour	Absorbs	Reflects	Appears
Single Ink		▷ 	▷  	▷ 
		▷ 	▷  	▷ 
		▷ 	▷  	▷ 
Over-prints	 	▷  	▷ 	▷ 
	 	▷  	▷ 	▷ 
	 	▷  	▷ 	▷ 
	  	▷   	▷ (no light)	▷ 
	(no pigment)	▷ (no light)	▷   	▷ 

Figure 9. Inks and their corresponding colours [3,10].

Theoretically, sensation of colour black should appear when cyan, magenta and yellow are overprinted. But in practice, it is not possible to accomplish black with CMY-colours, because the colours are not totally pure. Also, inks do not mix with each other, but end up to substrate on each other. This makes the uppermost ink the dominant one. [5,85]

As shown in figure 6 on page 11, the centre of circles of the subtractive primary colours results in something nearer to black, typically a muddy gray. For this reason, to achieve high black, the black ink is added as a *fourth colorant* in colour printing. Also, it is more practical when it comes to black and white printing, like in textbooks. Then it can be done with the one ink, not with the three inks. In colour printing black is needed for details and to improve the overall tonal colour gamut of process printing. [3,10]

The printing technique presented is called CMYK. The designation comes from three subtractive primary colours: cyan (C), magenta (M), yellow (Y) and from fourth colour: black (K). The colour black is called as key and the letter K comes from that. Otherwise the black would be mixed up with RGB's blue (B). [5,85]

In printing process, it is also possible to print one or two more colours besides CMYK – the process colours. This common principle is used, when one wants to improve colour range and accuracy. For example, *spot-colours* are used beside the process colours. They can also replace one of the four-process colours. Spot colour can be any colour or special colour, like metallic toned colour, that cannot be processed with CMYK-colours. *Pantone Matching System* (PMS) has become a standardized system for spot colours in offset printing industry. [5,85]

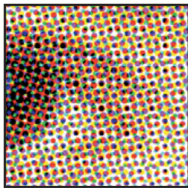


Figure 10. Halftone dots form the patterns on paper [3,10].

CMYK-colours are formed on paper with *halftone dots* (figure 10). Halftone is a process, where the different tones of the images are converted into different size halftone dots, so that the image can be printed in the printing process. When varying the size, balance and angle of the dots you can create a sensation of different colours and tones. The larger the dot, the darker is shade. The smaller the dot, the brighter the tone is. [3,10.]

HSL – The Three Attributes of Colour

Three attributes that describe the colour are *hue*, *saturation* and *lightness*. Figure 11 shows the wavelength's affect on those attributes. The dominant wavelength determines the colour's hue. The hue is the property of colour that distinguishes it from other colours. Thus hue is the property that gives a colour its principal name, such as red, orange or yellow. [2,34]

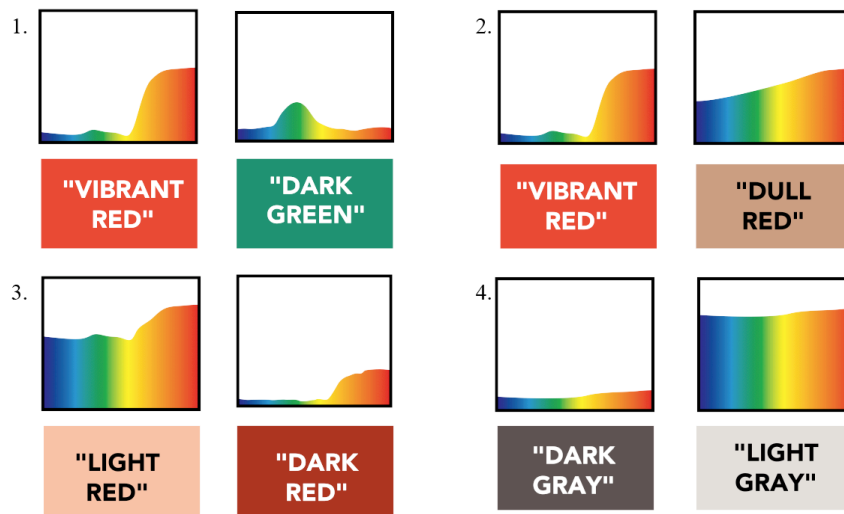


Figure 11. Four sections represent spectral curves of hue (1.), saturation (2.) and lightness (3–4) [3,11].

Saturation refers *visual purity* of the colour. The curve's purity determines the saturation. As shown in figure 11 (part 2) when the curve consists of a narrow peak more saturated colour appears. A wide spread in the curve produces unsaturated colour. The colour saturation may range from vivid to dull. The curve also determines how far it is from neutral gray. As shown in figure 11 (part 4), when the curve is uniform, low saturation colour appears. That colour is seen as gray. [2,35;3,11]

The third attribute is *luminous intensity* of a colour and it is a degree of lightness. As shown in figure 11 (in part 3), the curve is the same, but the amplitude of the wavelength determines lightness. When comparing the value of lightness, the two reds can be classified as light or dark. [3,11;9,8]

Lightness attribute is sometimes called as brightness. But the definition of lightness is that it is related to brightness. Lightness is the object's brightness that is relative to an absolute white reference. As mentioned above, lightness ranges from dark to light with definitions of black and white, while brightness ranges from dim to bright with no real limits. In other words, lightness can be measured, while brightness is a subjective sensation. [2,34]

2.2 Colour Spaces

The colour can be presented *three-dimensionally*. Figure 12 shows how hue, saturation and lightness are related to each other in three-dimensional space. Colour space model consists of stacked levels that illustrate these characteristics. Circular movement around each level varies the hue. The colours are changing when hue's degree changes. It ranges from red through yellow, to green and blue, and back to red. [3,12]

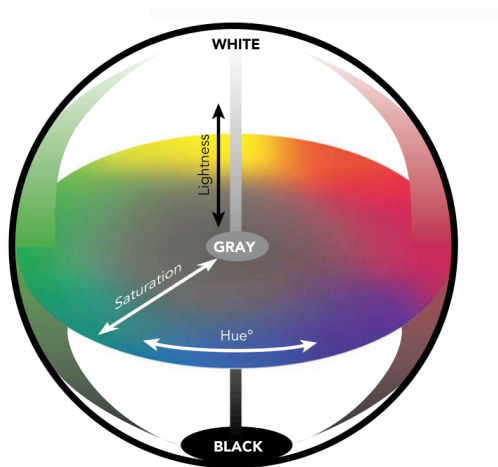


Figure 12. The colour space [3,12].

Upwards movement from bottom level to upper increases the lightness. The darkest colours are situated at the bottom and the lightest colours at the top. Radial movement from centre of each level to outwards increase saturation. Unsaturated colours such as gray, black and white are situated in the middle of the colour space. High-saturated colours are situated in the edge of the colour space. [3,12]

There are also colour spaces that are represented different from the above distribution. Such colour spaces are described with the terms of HSV (hue, saturation, value), HSL (hue, saturation, lightness) and HVC (hue, value, chroma). Those are commonly used terms in the printing industry and image processing. [5,159.] All those three spaces are an adaptation of the RGB colour model [2,543].

2.3 Metamerism

Metamerism is the phenomenon where two different coloured samples produces the same colour sensation to normal human viewer under one light source but look different under another light source. This occurs due to the ability of human eyes to see two colours as being the same even when the spectral curves of the two colours are slightly different. These two matching colours are called *metamers*. Also, the spectrum of light illuminant has an impact on how the colour forms. Thus these colours are *metameric* under certain lighting or to a certain type of observer. [2,25;6,29.] A single sample can never be a metamerism – it is always the relationship between two colour samples [2,26].

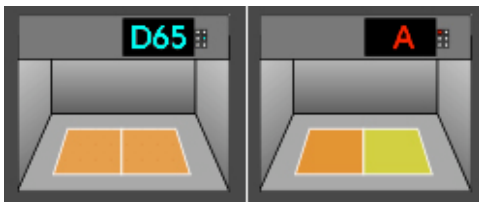


Figure 13. Two metameric samples in the light booth [10].

This leads to the situation where samples look alike under one light source but appear different when viewed with a dissimilar light source. As figure 13 shows, two metameric samples show exactly the same in illuminant D65 (daylight), but in illuminant A (incandescent lamp) the difference is noticeable. The optical illusion forms when spectral curves are quite similar but not the same. This also tells that the colorants of the samples are not the same. [10]

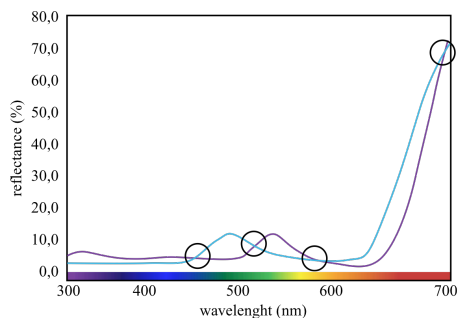


Figure 14. The spectral curves of two metameric samples [10].

When looking at the spectral curves of two metameric samples in figure 14 it can be seen that there are several crossing points of the curves. This makes the risk higher for a metamerism effect to appear. [10]

3 CIE Colour System

The International Commission on Illumination is responsible for the international colour measurement standards. The word CIE is a shortening for its French title *Commission Internationale de l'Eclairage*. CIE has high reputation among the professionals since its inception in 1913. It is also recognized by ISO as an international standardization body. The organization has set the recommendations for lights, light sources, colours and colour spaces. [11]

In 1931, the CIE established a CIE XYZ model of colour, which identifies colour coordinates in three-dimensional curved space. This makes it possible to represent colours in numerical terms. Model is *device-independent*, which means that the range of colours that can be found in these colour spaces is not limited to the rendering capabilities of a particular device. This gives possibility to compare the varying colour spaces of different viewers and devices against repeatable standards. The CIE XYZ model represents impression of colour that people with normal colour vision would experience under precisely defined viewing conditions. [2,69–70;3,14]

The coordinates X, Y and Z were assigned to the three light primaries of red, green, and blue. From these coordinates the CIE constructed the xyY Chromaticity Diagram. [3,14–15.] The notation xyY specifies colours by identifying value (Y) and the colour in the chromaticity diagram (x,y) [9,11]. Between them x and y define any colour's saturation and hue. Movements represent saturation from the central white area out toward 100% saturation. Hue is represented by at all points around diagram [9,11].

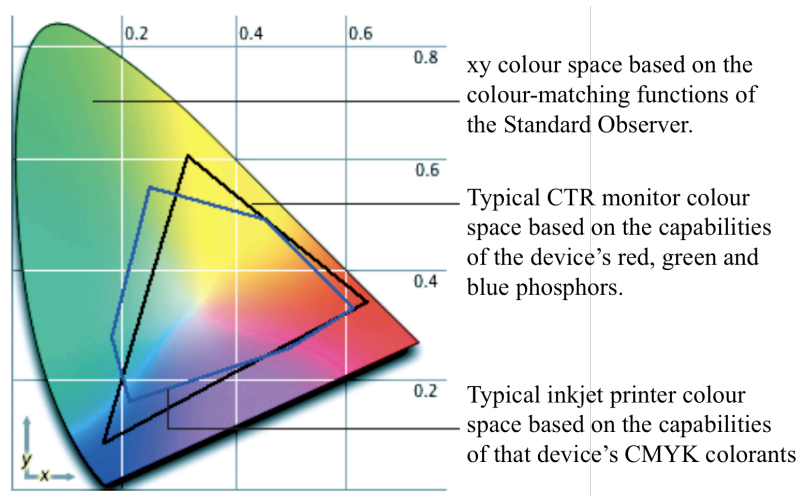


Figure 15. CIE 1931 (x, y) Chromaticity Diagram [3,15].

The xy colour space is representing all the colours of the visible spectrum. As figure 15 shows there are limitations of colour spaces in CRT-monitor (RGB) and inkjet printer (CMYK). Those are showing only small section from whole diagram. Therefore, RGB and CMYK gamuts in individual device are not possible to illustrate all the colours. [3,15]

3.1 CIELAB and CIELCh

The CIE developed the variants of CIE XYZ colour space and produced CIELAB, CIELUV and CIE LCh colour spaces. Those are also utilizing three coordinates to locate colour from the colour space as well as CIE XYZ colour space. As well the CIELAB, CIELUV and CIE LCh are represented mathematically. Of these three models, CIELAB and CIE LCh are the most widely used. [2,69]

CIELAB

CIELAB is international colour standard. The CIE recommended the CIELAB colour scale for use since 1976. It is based on a three-dimensional coordinate system where values of L^* , a^* , and b^* are plotted to one another in the colour space. L^* component represents lightness, a^* component the red/green axis, and b^* component the yellow/blue axis. [12,1.] The a^* and b^* axis get the colours according to theory that a

colour cannot be both blue and yellow at the same time, nor green and red at the same time [3,16].

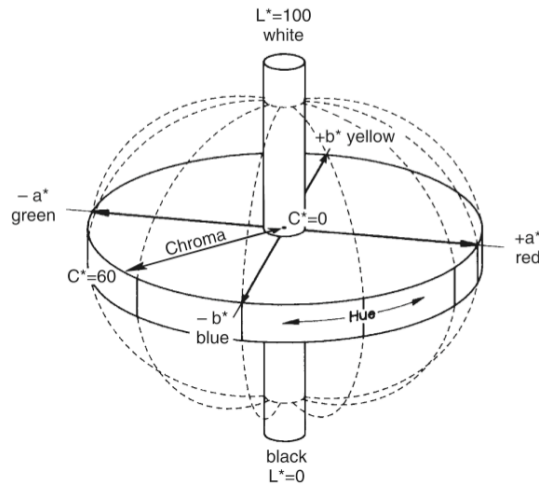


Figure 16. L^* value is situated on the centre axis and a^* and b^* axes appear on the horizontal plane [9,13].

As illustrated in figure 16, the value of a^* represents how red or green colour is: the positive value gives redder colour and negative value the greener colour. In axis of b^* the positive value gives yellower colour and negative value the bluer colour. The black colour is situated at the bottom of the vertical L^* axis and the white at top of the axis. The value of L^* runs from zero to 100 from black to white. [2,70;12,1]

CIELCh

LCh colour space is a variant from the LAB colour space. The coordinates are the same than in LAB-space but the shape is different: it is in shape of a cylinder instead of the ball. The model is similar to human colour vision. LCh uses polar coordinates and its attributes are lightness (L), chroma (C) and hue (h). [5,169]

LCh colour space is also known as $L^*C^*h^\circ$, which is representing the axes on colour space. L^* axis is vertical and it runs from white (100) to black (0). C^* axis is horizontal and it represent the distance from the central axis. H° axis is the circular movement around the cylinder. The hue varies with reds around 0 degrees, yellows around 90 degrees, greens around 180 degrees and blues around 270 degrees. [2,536;5,169]

3.2 CIE Standard Observer and Illuminants

CIE worked to derive the concept of a *standard observer* (figure 17), which is based on how the average human eye emphasizes the incoming signals from different wavelengths [9,10]. There are two types of observers: CIE 2° (1931) and 10° (1964). The first one is most commonly used. [2,41]

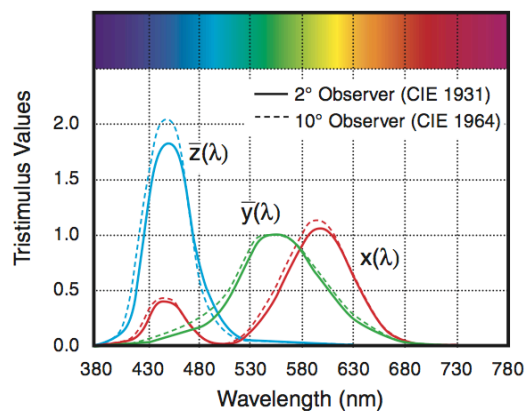


Figure 17. CIE 2° and 10° standard observers [9,10].

The colour changes with every different viewing situation. Therefore, lighting conditions also influence the appearance of colours. CIE has established *standard illuminants* for light sources. Those are spectral definitions of set of light sources under where most colour matching is done [2,41]. Illuminant is a set of numbers that represent the spectral quality of a white light source found in home, office and exterior conditions [13,2].

The CIE's Standard introduced in 1931 illuminants from A to F that provide a universal system of pre-defined spectral data for several commonly used illuminant types. Illuminant A represents the average incandescent light (2856° Kelvin), illuminant B represents the direct sunlight (4874° K) and illuminant C represents average day light (6774° K). From those only A is still commonly used. Later CIE introduced series of D illuminants, hypothetical E illuminant and series of F illuminants. [3,8;13,2]

In 1965 CIE introduced, new recommendations of standard light that simulate the ultraviolet regions of daylight. This is relevant, when observing surfaces that contain

fluorescent toner. The D illuminants represent various modes of daylight conditions. The two most important standard illuminants in graphic world are D50 and D65, which are commonly used in viewing booths.

These days the D50 plays bigger role in the graphic industry because the existing ISO standard for graphic arts printing 3664:200 recommends to use the CIE D50 standard light. The D50 represents the colour temperature of 5000 K. It represents warm daylight or sunrise or sunset [13,2]. So the tone is much warmer than in D65, but it is perceived as neutral interiors. [3,8;5,264]

The D65 correlates the colour temperature of 6504K, which is the daylight standard temperature. Visually it corresponds to natural light, 6500 K lamp. The D65 used to be the most important standard in colour observation since 1965. When the CIE published standard, which state that in general use the colour measurements should be done in either the A or D65 standard light. D65 light source was then recommended for the most demanding colour observation situations. This was used in printing industry, until the rapid increase of the ink-jet printing brought the metamerism problems to colour observation, and forced to change the light source. Therefore, the D65 is commonly used these days. [5,264]

Illuminant E is the equal-energy illuminant, while illuminant F represents fluorescent lamps of various compositions [3,8]. The F2, F7 and F11 are mainly used. The F2 represents a cool white fluorescent (4100 K), F7 represents a broadband fluorescent lamp, which is approximates CIE illuminant D65, and F11 represents a narrow tri-band fluorescent of 4000 K [13,2].

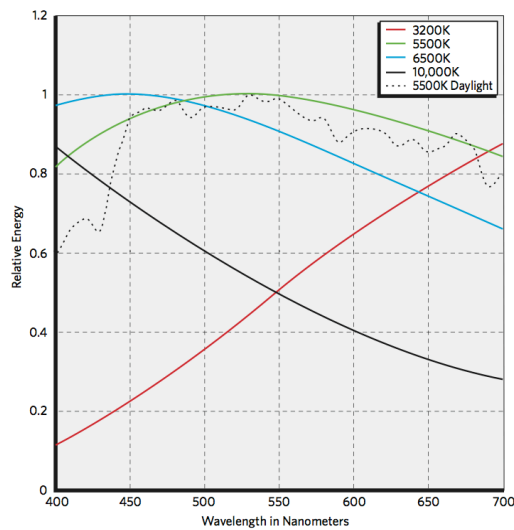


Figure 18. Relative spectral energy curves for different colour temperatures [7,20].

The above figure 18 shows the visible wavelengths of the relative energy emitted at each wavelength of various colour temperatures and in 5500K daylight. At red curve (3200K) there is a relatively large amount of the long wavelengths and small amount of short wavelengths. This is quite close to the CIE illuminant A (2856K), which represented the incandescent light. At the colour temperatures 5500K (green), 6500K (blue), and 10000K (black) the curve is opposite: the relative amount of the long wavelength energy decreases and the relative amount of the short wavelength energy increases. [7,19]

As represented above, the 6500K is corresponding to CIE D65 light. However, the shape of curve would be as irregular as the daylight curve. The daylight curve (dotted black) is not as smooth as 5500K curve because daylight is a combination of the energy emitted by the sun. The daylight light curve is comparatively close to the CIE illuminant D50. [7,19]

3.3 Delta-value – Colour Difference

Delta-value (Δ) represents the difference or distance between two colour samples. Two colours are plotted as points in uniform space when the distance is computed between them. It can be calculated in CIELAB or in CIELCH colour spaces. [2,43]

The distance correlates well to the difference a human observer will see. For example, this can be used to calculating how far off and in which direction the sample is away from the original. [2,43.] The absolute values of the standard will be subtracted from the standard values of the trial, to get the delta values [14].

ΔE^* value shows how far away is the sample in *total* from the standard [14]. In theory, the smallest value of colour difference that human can observe is 1.0. But exact number does not tell how well the difference is noticed. For example, when comparing samples between two oranges or two blues the noticeable difference varies. In blue the small difference can be seen easily, while in orange ΔE^* value can be greater than 2 units and samples still looks visually equal. [14]

Typical customer tolerance of ΔE_{LAB} varies in between 2 and 6 in the graphic arts industry. That defines the tolerance box limits within to remain (see Figure 20 on page 27). In this case when the samples that lay more than 6 units outside of the tolerance limit from the standard are unacceptable. If the limit is less than 2, it is said that it is unachievable in normal process variation. To most viewers the colour difference is not visible when the ΔE_{LAB} is below 4. [3,39]

ΔE^* value does not give the information in which direction the deviation is [14]. For this reason the delta value may also be calculated by using only one attribute from CIELAB and CIELCH colour spaces. Then the delta values are represented as ΔL^* , Δa^* , Δb^* , ΔC^* and ΔH^* . [12,1;16,1]

For example, in two greys within the delta value $\Delta a^* = 0.5$ or $\Delta b^* = 0.5$ can be given two really colours, especially when other gray has a greenish touch and the other looks more reddish [14].

While comparison is done between the standard and sample ΔL^* , Δa^* , Δb , ΔC^* and ΔH^* colour differences follow a particular pattern, as follows [14]:

- ΔL^* represent the difference in lightness/darkness value: positive is lighter and negative is darker than standard.
- Δa^* the difference on red/green axis: positive redder and negative greener.
- Δb^* the difference on yellow/blue axis: positive yellower and negative bluer.
- ΔC^* the difference in chroma: positive more saturated and negative duller.
- ΔH^* the difference in hue, which depends on the quadrant: 1st: positive yellower and negative redder; 2nd: positive greener and negative yellower; 3rd: positive bluer and negative greener; 4th: positive redder and negative bluer

Colour Tolerancing

Comparison between colour specifications and sample can be done by using tolerances that are based on numeric colour measurement data. There are some *colour tolerancing* methods, which can be used to calculate the colour difference between the several colour samples and colour reference. [3,38]

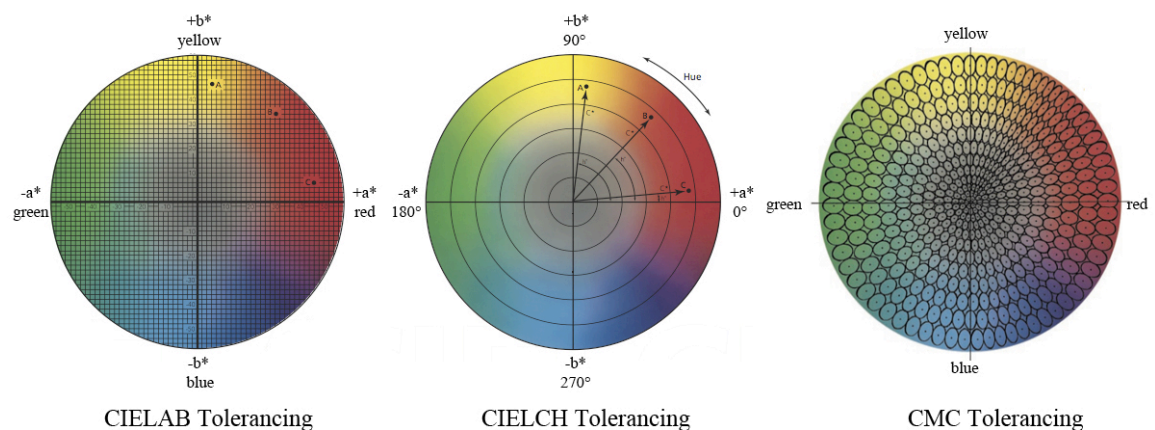


Figure 19. The CIELAB, CIELCH and CMC tolerancing coordinates [15].

CIELAB and CIELCH can be used to create tolerance for an acceptable colour match consists of a three-dimensional boundary with varying limits for lightness, hue and chroma, and must agree with visual assessment [9,15]. As shown in figure 19, CIELAB tolerancing uses rectangular coordinates and CIELCH polar coordinates and additional

tolerancing formulas, CMC and CIE94 produce ellipsoidal tolerances [9,15]. More details of tolerancing methods are presented further on. ΔE^* value equations are represented in Appendix 1: The delta value equations.

Table 1. Visual assessment vs. instrumental [9,18]

Tolerance Method	% agreement with visual
CIELAB	75%
CIELCH	85%
CMC or CIE94	95%

Though no colour tolerancing system is perfect, the table 1 shows the how well each tolerance method is concordant with visual perusal. Visual acceptability is best represented by shape of ellipsoid. Therefore, the best equations tolerance methods are CMC and CIE94 [9,18]. More about subjective assessment is discussed in Chapter 5.4.

CIELAB Tolerancing

ΔE (CIE 1976) is the standard CIE colour difference method, which calculated from LAB colour space. This may also be denoting as ΔE_{CIE76} . [17.] CIELAB tolerancing method uses rectangular coordinates as shown in figure 19 (on previous page). Limits of ΔL^* , Δa^* , and Δb^* create rectangular tolerance box around the standard as shown in figure 20 [9,15].

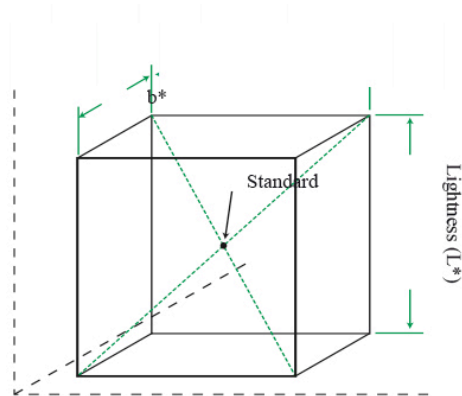


Figure 20. CIELAB tolerance [15].

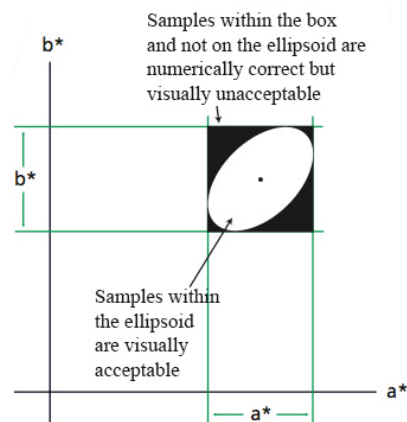


Figure 21. Numerically correct vs. visually acceptable [15].

As mentioned above, the visual acceptability is more in the shape of ellipsoid. Therefore, some problems occur when above represented tolerance box is compared with the visually accepted ellipsoid. As shown in figure 21, when a sample falls inside the square but outside the ellipse, it can give a good value even though it is visually unacceptable. On the other hand if sample fall inside the bigger ellipse that square would accept, but is still be visually acceptable, that batch would be failed by CIELAB tolerancing. Therefore, the selected tolerances may cause problems when the numerical value does not agree with visual evaluation. Over all, CIELAB tolerancing corresponds to a visual assessment as well as 75 percentages (table 1 on page 26). [9,15;18,3]

CIELCH Tolerancing

ΔE (CIE 1994) calculated from LCh colour space. This is a more recent modification. This may also be denoting as ΔE_{CIE94} . CIELCH tolerancing method uses polar coordinates as shown in figure 19 (on page 26). Limits of ΔL^* , ΔC^* , and Δh° create wedge-shaped tolerance box around the standard. The polar coordinate system makes the tolerance box rotated in orientation to the hue angle as shown in figure 22. [9,16;17]

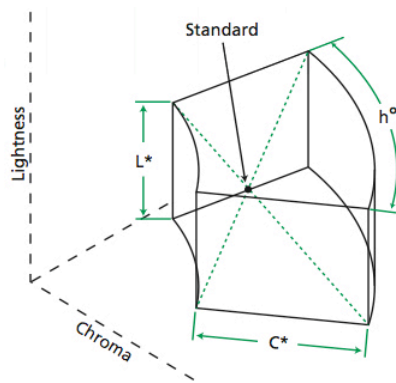


Figure 22. CIELCH tolerance wedge [15].

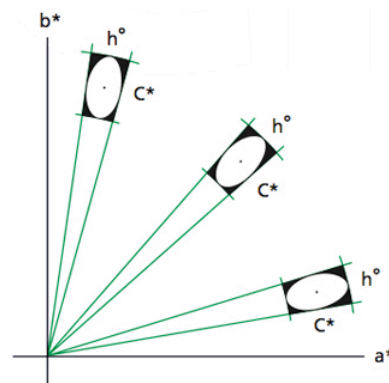


Figure 23. CIELCH tolerance vs. visually acceptable tolerance [15].

CIELCH tolerancing corresponds to a visual assessment as well as 85 percentages (table 1 on page 27). Therefore, it conforms better to the visual evaluation ellipsoid than CIELAB tolerancing. Method also reduces the amount of disagreement between the

visual assessment and the instrumental values (figure 23). But the same problems may occur between unacceptable and acceptable samples than in CIELAB tolerancing as shown in figure 21 (on page 27). [9,16]

CMC Tolerancing

CMC tolerancing is a modification of CIELCH tolerancing developed by Colour Measurement Committee of the Society of Dyers and Colourists in Great Britain. It is based on $L^*a^*b^*$ colour space. CMC tolerancing equation is based on ellipsoidal space (figure 24) with semi-axis corresponding to the attributes of hue, chroma and lightness. The values of hue (SH), chroma (SC) and lightness (SL) define the size and shape of the ellipsoids. The equations are represented in Appendix 1: The delta value equations. [9,16;19]

As shown in figure 19 (on page 26), the ellipsoids vary in size and shape depending on the position of the colour in colour space: the tolerance ellipsoids are larger in the green region and tightly packed in the orange region. The size and shape of the ellipsoid also represent the chroma and/or lightness of colour. For example the ellipsoids in high-chroma regions are larger, than those in low-chroma regions. [3,39;9,16;15]

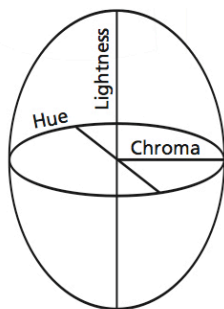


Figure 24. CMC tolerance ellipsoid [15].

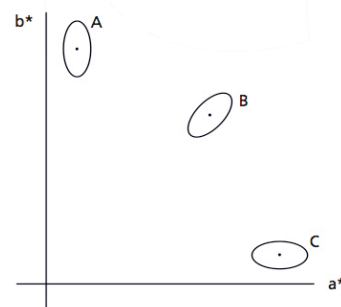


Figure 25. ΔE_{CMC} tolerance vs. visually acceptable [15].

As shown in table 1 (on page 27), CMC tolerancing method provides 95-percentage agreement between visual assessment and measured colour difference (figure 25). This method is used within measuring the commercial acceptability of coloured products, when the surface is textured or irregular. It is a typical tolerancing system in industrial applications, especially in the textiles industry. [9,16;3,39;17]

ΔE (CMC) is a model using two parameters l (*lightness*) and c (*chroma*), typically expressed as $CMC(l:c)$. Ratio of $l:c$ influence the shape of the ellipsoid. The CMC equation allows product-specific ratio adjusting, which leads to better match acceptability [18,6]. CMC (1:1) implementation uses a *lightness weight* of 1.0 and a *chroma weight* of 1.0. As the eye is more sensitive to chroma than lightness, the CMC (2:1) allowing for 2 times the difference in lightness than chroma. This is the typical ratio in for most applications especially for textiles. [17;19]

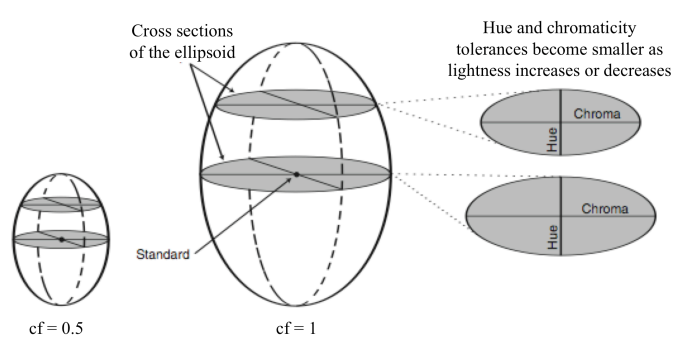


Figure 26. Value of commercial factor has an influence on tolerance [9,17].

In commercial situations, the amount of colour tolerance may be applied by a single *commercial factor* (cf), which determines all dimensions of the ellipsoid. Therefore, the ellipsoid can be made as large or small as necessary to match visual assessment [9,16]. Figure 26 illustrates how the cf -ratio effects to size of ellipsoid. The cf value represents the tolerance. For example when cf is set to be 1.0, then the less than 1.0 would pass, but more than 1.0 would fail the ΔE_{CMC} tolerance. Thus the acceptable limit is when the $\Delta E_{CMC} < cf$. By varying the cf , the ellipsoid can be made smaller or larger. [9,16;19]

CIE94 Tolerancing

As mentioned above, CIE94 tolerancing method also produces an ellipsoid. It is based on $L^*a^*b^*$ colour space. Like CMC, CIE94 method tolerancing equation is based on ellipsoidal space with semi-axis corresponding to the attributes of hue, chroma and lightness. Also, the commercial factor can be determined. CIE94 method is more likely to be used in the paint and coatings industry. CMC method is commonly used when the surface is smooth and regular. [3,39;9,18]

4 Colour Management

Colour management process is a way to ensure that original idea and colour specification will remain intact through out this complicated process. Because of wide range of formation of RGB colour spaces, the conversion into printing form is not always straightforward. Computer software that interprets the colour transition between software and hardware are needed. [5,85]

As figure 27 shows there are many different individuals who pass the responsibility for keeping the client colour specifications intact. The client determines the colour that is wanted to attain and graphic designer provides the colour specifications and creates the printing files. A pre-press worker prepares the designer's file to qualified file for printer, after that the file is possible to print. The material supplier provides inks and papers that correspond with colour specifications. A printing worker prints the final print. Each step adds some more information to specifications. Control at each production step ensures controlled and best result. [3,1–2]

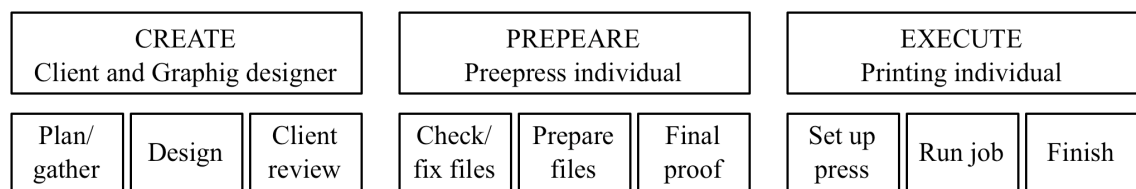


Figure 27. There are many different workers who are responsible for keeping the colour specifications constant [3,2–3].

Different viewing situation presents one colour its own way. For example, when taking the picture, original scene contains a wide range of natural, vivid colours but when a photographer captures picture, there are only some colours left from the scene and some tones are lost. When the picture is removed from camera to computer, some colours are furthermore lost or changed when image is seen on monitor. Also, different monitor show colours slightly differently. The way colours are seen also depends on the computer program in which the picture id processed. [3,2]

When a photograph is intended to print, colours have to change from RGB data to CMYK data. Different printing devices represent colour a bit differently. When examining the final print, light conditions affect the colour appearance in different ways. Also, individual's vision skill and colour memory interact to final result. As you can see, there are lots of factors that need to take into account during control of colour management. [3,3]

To achieve colour accuracy is not easiest thing, but without colour management it is impossible to achieve. When client approves the colour proof, printer has to attend to exact same colour. This leads to situation where final prints match to proof print. Using visual perception and measurements can this be attained. Human vision is a complex phenomenon, therefore, the way colours are seen have an impact to result. Metamerism and light source have an impact on result. Colour measurements help to control the colour during printing process. [6,137]

Standards

The standards play a large role in production industry. They ensure seamless integration and help different firms work together. The standards have become some kind of quality definition to graphic industry. There is a list of international standards for printing industry and also for colour management. [1,78]

In standards there are definitions and requirements how to make artwork for printing, control the printing process and what material to use. The guidelines are meant to help printing houses to keep their eligible quality always the same. Standards give the lowest permissible target values of quality and what is the gamut. Standardisation makes it possible that with the same printing methods will be produced exactly same results. Therefore, the same advertisement should look exactly the same in different publications like magazines, when it is printed with same method. [20,150–151]

One organisation, which has developed and published standards, is *International Organization for Standardization (ISO)*. They have different kinds of standards for different fields of graphic industry. Standards also serve users, because manufactures cannot change international standards afterwards when those are defined. Manufactures also have to work according to those standards. This excludes its competition. [1,78;21]

ISO 12647 standard-family forms the one of the most important standard for processing the printing quality. It contains process control for the production of half-tone colour separations, proof and production prints. In part one (12647-1) there are all the parameters and measurement methods presented. Part 2–7 (12647-2–12647-7) contains all the different printing methods and their differences in process. For example part 2 defines offset lithographic processes. [21]

In ISO 12647 there are also defined standard values such as CIELAB coordinates, gloss and ISO brightness for 5 papers: gloss-coated (wood-free), matt-coated (wood-free), gloss-coated (web), uncoated (white) and uncoated (slightly yellowish). [22,4–5]

If printing houses are doing everything as defined in ISO 12647, then the printing result is regular. All the print data and proofs need to be done as specified. After all there is no need for creating every printing machines own specified profile when using standardized printing. Other relevant colour management and print production standard are ISO 12642 for Test Charts to Create Profiles, ISO 12640 for Characterization Data, ISO 15076 / ICC for Colour Profiles and ISO 15930 PDF/X. [1,78–79.]

There are also some other standards. For example, in America they are using GRACoL (General Requirements for Applications in Commercial offset Lithography) and SWOP (Standard for Web Offset Printing) standards, which are partly compatible with ISO 12647. [1,79;1,102]

5 Printing Process Control

The control of the printing process is necessary if you want to produce high-quality prints consistently. The print quality can be evaluated visually or it can be measured with different measuring instruments. The visual evaluation is usually based on the comparison between the print and proof print. The visual evaluation should be always performed in the standard lighting because lightning has a big effect on the colour observation. Measurements are the main key in controlling the printing process. It is said that if you can measure colour, you can control it [3,1].

During the printing it is important to control the variable all the time while printing machine is running. Print quality has been defined as the degree to which all the many variables involved in printing combine to achieve the desired result [8,257]. Awareness of influence factors, such as press settings and materials, will influence to final result. Printer should always manage to control all the factors. The following variable factors must be controlled at least: ink-layer and solid density, dot gain, gray balance and trapping. [6,120]

The *gray balance* has influence to pleasant result of final print. Therefore, it is visually an important factor in printing process. The deficiency in gray balance may be noticed easier than colour errors because the eye is good at discerning whether gray is neutral or not. While 70 % cyan, 50% magenta and 50% yellow (CMY) inks are combined result is neutral gray colour. This is simple way to evaluate the colour reproduction. [6,132–133]

5.1 Quality Management

The purpose of use defines the overall quality of the printed product. The instance of uses effects to quality requirements. Therefore, the quality level must be defined before print production. A good example of this is to comparing print quality of daily newspapers, which are thrown away after reading, and art publication, which are saved for years. In case of packages, the outer cover is selling the product and the demand for colour reproduction is high. [20,147]

Usually the cost of product also determines the visual quality. The balance between economic and visual choices determines the final wanted overall quality of printed product. For example, when choosing paper for printed product, it is very important that not only cost is taken into consideration but also that decisions are right for the print product. And that it supports also the message. For example, when choosing too light carton to package the result can be devastating. The package may damage in transit and delivery process and savings from the materials costs makes more costs. Consumers do not buy product if the package is damaged. [23,336]

The print quality can be measured with different measuring instruments or it can be estimated visually. Only by measuring, it is possible to set the target values for standardizes printing process. Different units of measurements are necessary during print process. By visually it is possible to say if the result looks like it should by comparing the approved proof print and the final result. [20,148]

In ISO 12647-1 -standard it is said that “because the proof print is the principal means of communication between pre-press, print-buyer and printer, it is important that in production printing attempt to match the visual characteristics of the approved proof print” [24,vi]. Using measuring instruments and evaluating the print subjectively this can be achieved.

5.2 Measuring the Colour

Even though colour is event with three participants (the light source, the object and the observer), the colour sensation happens in the mind of observer. It is possible to infer with instruments how stimulus will produce a sensation of colour, after the light has entered to observer’s eye. There are different kinds of instruments to measure the stimulus, how observer will eventual see colours. [2,37–38]

Colour measurement instruments gather and filter the wavelengths of light and in the end receive the colour that is reflected from an object. So the instruments receive the colour the same way the observer’s eyes receive the colour. The only remarkable

difference is that instruments perceive the reflected wavelengths as numeric values. [3,22]

Instruments help to assign a specific value to the colour. Only after that, it is possible to analyse terms of numeric tolerances and control limits [3,23]. Without numerical measurement, describing and verifying colour can be ambiguous and unreliable because otherwise it base on the subjective assessments [3,40].

The most commonly used instruments for measuring colour are *densitometers* and *spectrophotometers*. Instruments are interpreting data differently: densitometers measures value of density and spectrophotometers measures the spectral properties of a surface. [2,38;3,23.] These values are recorded as points across the visible spectrum and are called spectral data, which is represented as a spectral curve [9,10].

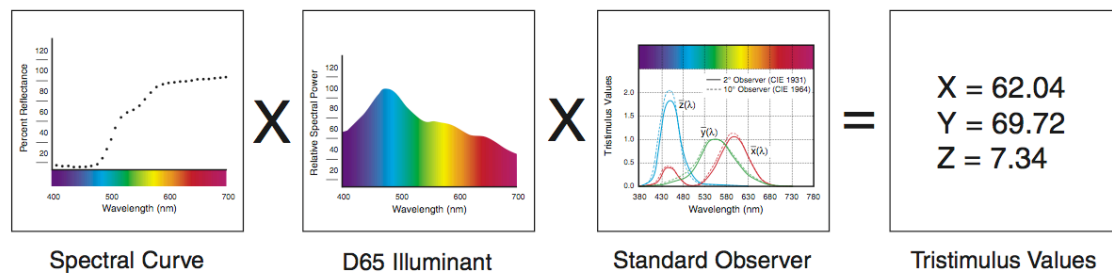


Figure 28. Trimulus values of a sample [9,10].

After as the colour's reflectance curve has been perceived, the numerical value of colour can be placed onto a colour space, as shown in figure 28. The sample is viewed under daylight (D65). Result is multiplied by the CIE standard observer. The data is then converted into the tristimulus values of XYZ, which are identifying the colour numerically. [9,10]

Densitometer

The densitometer is an instrument for computing density from material measurements, such as ink, paper and film. The quantity of density is the ability of a material to absorb light. On the other hand the instrument compute the density by directing light onto

surface and measuring the amount of light reflected through filters. The higher the value of density, the more light material absorbs and less light material reflects.

Densitometers are widely used in printing industry for measuring and controlling most of the stages of reproduction. [2,38.] It is primarily used in printing, pre-press and photographic applications to determine the strength of a measured colour [3,23].

When defining density, light must be incidented upon a sample. After this, the amount of reflected light can be measured. [6,119.] Density is not measured directly.

Densitometer measures the ratio between the intensity of light shine on, or through the surface, and the light that reaches the detector on the instrument [2,39].

There are two kinds of densitometers: reflection and transmission densitometers.

Reflection densitometer computes density by measuring light reflected from a surface.

When measuring reflective materials such as ink or paper, the ratio is called as the reflectance (R). Transmission densitometer measures the light that survives transmission through a material. When measuring transmitted materials, such as film, the ratio is called the transmittance (T). The factor R and T can be defined as below

$$Density = \log \frac{1}{R} \text{ or } \frac{1}{T} \quad (1)$$

Today all the densitometers do this calculation automatically and value of density can be read off directly. [6,119]

In densitometers there are filters, which matches to the specific wavelengths reflected by cyan, magenta, yellow and black inks. Densitometers measure the dominated wavelengths. Therefore, right filter has to be chosen according to measured colour. For example, to measure the density of magenta ink, the reflection densitometer has to measure how much green is absorbed. To do this, the densitometer must know the function of blue wavelength's curve for that it can be particularly sensitive to these wavelengths and give an accurate reading of how much green is absorbed. Filters, on the other hand, isolate one colour. [2,39]

Table 2. The densitometer's reflectance values equivalent to density [2,40].

Reflectance (R)	Density (D)
1.0	0.00
0.5	0.3
0.1	1.0
0.01	2.0
0.001	3.0
0.0001	4.0
0.00001	5.0

The reflectance values in table 2 have been changed to the density values by using a logarithmic function, as seen in equation 1. As seen, when the reflectance value is 1.0 is the density 0. This means that surface reflects 100% of all light that strikes, so there is no density value for that. And when reflectance is 0.5 means that surface reflects 50% of all light that strikes and then density is 0.3. And so on.

Spectrophotometer

Spectrophotometers have become “most important colour-measuring instrument in colour management” [1,52]. Spectrophotometer measures spectral data that reflects from object and gathers the complete composition of light – the colour information. Therefore, the information can be translated into colorimetric or densitometric data. It provides both LAB and LCh colour measurements. This makes the spectrophotometer a flexible instrument. The main applications are checking individual proofs and colour control of print processes. [1,52;3,25]

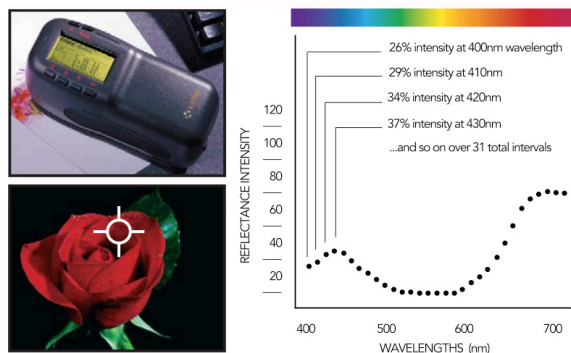


Figure 29. Spectrophotometer measures the intensity percentage of the spectrum that leaves from object [2,25].

The object always reflects the different amounts of the spectrum at each wavelength. Spectral data gathers those amounts as percentage of each wavelength as shown in figure 29. The spectral curve forms from at several intervals along the visible spectrum. The result is complex data set of reflectance values. [3,21–25]

The light source and measurement angle can be chosen from standards. The principles of angles and illuminants have been discussed in chapter 3 (The CIE colour system) and 3.2 (CIE Standard illuminants).

5.3 Subjective Assessment

Human eye has the ability to distinguish colour differences based on their own colour observation skills. Poor colour memory, eye fatigue, colour blindness and viewing conditions have also the large influence to colour formation and sensation. Different individuals notice the observation of colour differences differently. The average observer first notices the hue differences. It is followed by perception in saturation differences. Finally the differences in lightness will be noticed. [9,15]

All this may lead to situations where colour differences are observed in different way. One person may accept a colour sample while an other one rejects it simply because they perceive colour differently. One factor that influence for visual perception is the experience of the observer, how to see colours and where to draw attention. [18,1;23,336]

Because of this varying boundary limits of lightness, chroma and hue bound the acceptable colour match. Especially in printing industry only the visual assessment may lead to confusions customers, supplier, vendors, production and management. Therefore, the instruments are needed to ascertain the colour matches. The colour acceptability limits can also to determine avoiding the confusion situations. That helps to control the colour in the process and ensures colour consistency within production run. [18,1–2]

CIE has developed tolerancing methods that best correlate to the eye's sensitivity. Comparison of visual assessment and instrumental was discussed more in Chapter 3.3.

6 Paper

Paper is mainly formed of bounded fibres that are randomly distributed to plate.

The fibres are the main raw material for papermaking but may also contain pigments, fillers, inks, etc. Fillers are often white pigments that improve paper properties such as brightness and smoothness. [25]

Paper is made of chemical, mechanical or chemi-mechanical (CTMP) pulp. In chemical pulp the wood fibres have been separated by chemical means and in mechanical by mechanical means. In chemi-mechanical those techniques are combined. [25]

After paper has been manufactured, some finishing may be done depending on the end product and customer's requirements. By calendaring, the paper gets its finish glaze. The paper passes between two or more rolls that are usually situated after paper machine. Calendaring improves paper surface and printing properties and adjust paper uniformity thickness. The surface of paper can be coated either one or both sides. The coating improves printability, such as optical properties, brightness and gloss. Coating material may also contain pigments, binding agents and special additives. High-grade papers are coated even three times. Coating interacts to grammage because the amount of coating increases the weight. To prevent leaking, the liquid packaging boards may be coated with plastic and aluminium extrusion. [25]

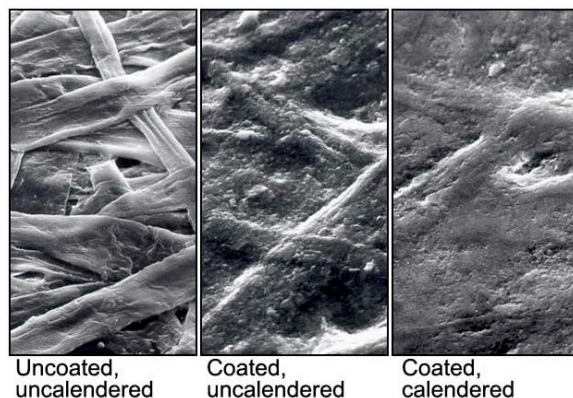


Figure 30. Influence of coating and calendaring to smoothness of paper [25].

As figure 30 shows, the paper surface becomes smoother after coating and calendering. Applying a mineral coating before calendering can attain the smoothest finish to a paper. The quality of finishing depends on an amount of coating material and its quality and the degree of calendering. [8,228]

6.1 Paper Classes

Papers are divided into three classes on the grounds of their weight: papers, paperboards and boards. Classification is not always clear but generally speaking it is done as follows. [25]

Paper is a thin and light one-layer fibre product with two identical sides. It is the lightest; usually its basic weight is under 150 g/m^2 . It is mostly used in general printing. Paperboards are usually manufactured with multi-layer technique. Surface of paperboard contains two or more layers, which makes it heavier and thicker than paper. Basic weight varies from 125 up to 600 g/m^2 . Paperboard is usually used in packaging. The top and bottom of paper may be different. If purpose is only to print to the top of the paper, then the bottom paper is not as good as the top one. Paperboards can be divided into cartonboards, container boards and graphical boards. [25]

Boards are structured from consists of several papers and paperboards that are glued to together. It is heavy and its basis weight is over 400 g/m^2 . It is used to products that need reliable stability for advertising sights. Some thick special paperboards are also called as boards even though those are not manufactured by gluing. [25]

Corrugated board usually consists of three essential elements. It is manufactured by gluing one layers of corrugation into a layer of top and bottom liner. The corrugation in the middle makes the board airy. The height of used corrugation determines the final thickness of the finished corrugated board. The lines give the holding strength for the boards. The printing can be done to the liners. [25]

6.2 Paper Properties and Measurements

Printing materials also influence the quality and durability of end product. It is important that the paper properties are well defined and controlled, like the control of printing process. The properties influence relationships between inks and printing process, like how ink is deposited onto the substrate and how well substrate manages on different running speeds. [8,257]

The printability and runnability are relevant paper properties. The printability of the paper defines its ability to consistently reproduce images and text to standard quality. The printability is main factor when it comes to impression of quality. Characters like ink absorption, surface smoothness and optical variables have an influence to printability, for example to print sharpness, density and colour range. [8,257]

The runnability defines the easiness which printing or finishing process may be operated. The properties that influence to these factors are for example flatness, dimensional stability and surface strength. The main problem concerning the runnability is, when running speed must be slowed down during production. [8,257]

The network of fibres and pores of paper and also papers absorption, permeability, formation and thickness influence the printing result. The fibres that have been used and the treatment during pulp preparation interact with papers' strength factors, which are moreover effecting to runnability. There are not two same sheets that have exactly same structure. By doing measurements it is possible to get useful indicators, which help to understand and predict how paper will behave during printing process. [8,258]

Paper properties that affect printability and runnability are divided to three categories: surface and directional properties, optical properties and strength properties. The first two methods are explained further below, because they are relevant to colour management guide. [8,258]

All the properties have standard test methods to test them. Different testing methods have been developed, which means different test techniques do not necessary measure

the same property. Also, all test methods do not consider the actual printing conditions because it is impossible to relate all individual press condition and performance together. [8,258]

Both International and British standards are well documented and controlled [8,258]. ISO organization has standards for test methods and quality specifications for paper and board. These are part of TC 6 work programme. For example ISO 5631 -standard specifies determination of colour by diffuse reflectance. Part 1 includes indoor daylight conditions (C/2 degrees), part 2 outdoor daylight conditions (D65/10 degrees) and part 3 indoor illumination conditions (D50/2 degrees). [26]

6.3 Surface and Directional Properties

Surface and directional properties have an influence on for example on substance, thickness, bulk and smoothness. These properties depend on used fibres and how paper is manufactured. Forming, coating and finishing processes also influence on those. [8,258]

Substance

Substance indicates the grammage or basis weight of a paper. It can be also described as mass per unit area of paper, which is specified in grams per square metre (g/m^2) [8,258]. This can be measured by using ISO 536:1995 -standard, which specifies a method of determining the grammage [26]. This is common used test method. Stora Enso and M-real are using this technique according them technical information about papers.

Caliper

Caliper indicates the thickness of the paper. It is the perpendicular distance between two surfaces of single sheet of paper. Measurements are made with micrometer. Also, called as thickness. [8,259]

Bulk

Bulk indicates the thickness of the paper in relation to its grammage. Thick paper that is less compact (light) is considered high bulk paper. Thinner and compact is low bulk paper. [8,259]

Table 3. Influence of basis weight and bulk to book thicknesses [25].

Basis weight g/m ²	Bulk cm ³ /g	Sheet of paper	Book thickness cm
60	2	128	1.536
80	1,6	128	1.536
100	1,2	128	1.536

The values in table 3 illustrate the interaction between the basis weight and bulk. The same amount of sheet with different paper grammage and different paper bulk has got exactly same book thickness. Usually papers for book production are wanted to be bulky so that fewer pages give the appearance of greater thickness [8,259].

Smoothness

Smoothness indicates the quality of paper's surface, how flat and smooth it is. The character of the surface is a great importance because smoothness gives better printability and greater degree of dot sharpness can be achieved. It also influences, how well surface receptive ink because print plate can only contact surface equally when surface is smooth. [8,260]

Concerning the smoothness, the main influences to surface are compression and material transition, which affects, for example, to degree of fibres and to extent of calendering and coating. When the surface is processed with calendering and coating, it will be smoother. [25]

Opposite of smoothness is roughness, which is also commonly used term to determine smoothness. This is why there is a wide range of measuring instruments available and

these are grouped into smoothness and roughness testers. Also, lots of different methods have been developed to measure both smoothness and roughness. [8,260–261]

Overall the main purpose of different measurement methods is to give the unevenness of paper surface a single, characteristic number. Most measuring instruments compare the contact that occurs between the paper surface and an even reference surface. The most popular measurement is done with airflow because those instruments are easy to use. [8,261.] Airflow instruments are based on how quickly or how much air permeates the gap between the paper and a polished surface or sharp blade [25].

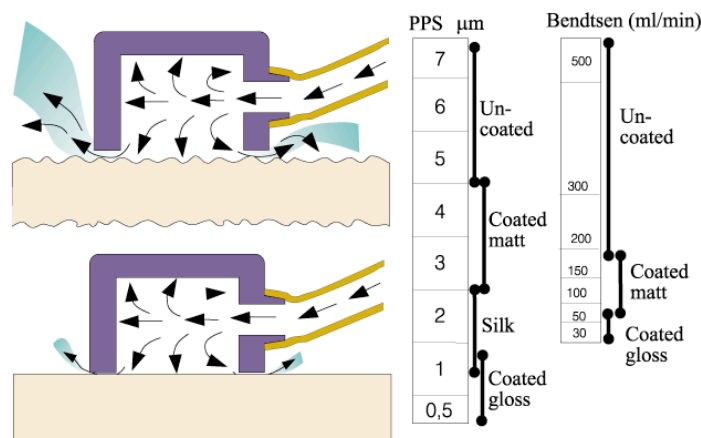


Figure 31. The Bendtsen and Parker Print-Surf testers are using airflow method to measure the roughness of surface. On side there is also the average score scale from different papers. [25]

As figure 31 shows, the annular ring is pressed against the paper and the amount of air escaping between the ring and paper surface is measured. The Bendtsen and Parker Print-Surf (PPS) testers are based on this method. In the Bendtsen test the roughness is expressed as rate of airflow, in millimetres per minute (ml/min). When surface is rough, the loss of air is grater than in smoother thereby Bendtsen tester produces a higher reading. The lower number, the smoother is the surface. The Parker Print-Surface tester calibrates the airflow rate to PPS roughness, which is expressed in micrometers (μm). [8,264;25]

Other testers are Pira Printing Smoothness tester (PPST), Bekk air leak tester and Sheffield tester. [8,262–253;25]. Testing methods are standardized. For example, ISO 8791 -standard determines the roughness/smoothness air leak methods. Part 1 determines general method, part 2 the Bendtsen method, part 3 Sheffield method and part 4 the Print-surf method [26].

6.4 Optical Properties

Optical properties influence to the visual quality of the print product. These factors are brightness, whiteness, colour, opacity and gloss. Those are used to describe the optical impression received from the paper. The opacity and brightness are represented below. [25]

Opacity

Opacity determines how transparent the paper is. This influence in situation where paper is printed on both sides or printed sheets lie on top of other. The ink should not be seen through. As figure 32 shows the left side paper is opaque and on right side the paper the butterfly can be seen through the other side. [8,283; 25]



Figure 32. The opacity determines how transparent paper is [25].

Brightness

Brightness describes how much of visible light is returning from the paper to eye. If the intensity is high the apparent of visual brightness is also high. High density can be achieved within good brightness. There are two standardized methods to determine the

value of brightness: TAPPI and ISO brightness. Both are measured at wavelength of 457 nanometres on where the brightness changes most. That is the in the blue region where also the lignin absorption happens. Lignin is the glue that holds fibres together. It gives to the paper the yellowish colour. The more paper is bleached and more lignins are removed the brightness increases. The chemical treatment of pulp removes the lignins. So the yellowing effect has been disappear from the paper. [8,280–282;25]

ISO has published two standards for brightness measurements. One of the standards is ISO 2470 – Paper, board and pulps – Measurement of diffuse blue reflectance factor. That includes part 1 for indoor daylight conditions (ISO brightness) and part 2 for outdoor daylight conditions (D65 brightness). [26.] The first one is more recommended to be used in measurements [27].

7 Background of the Project

The company is recognisable by its Brand Colour. This makes it important to specify the colour management guidelines. This is the only way to achieve packages, whose quality level is exactly the same, and also colour of surface is the same. The colour must remain unchanged during whole process from designing to execution.

Packages are printed all over the world, which make the colour management even more challenging. At the moment there are several printing houses where the print production is done. All regions use different print materials, printing standard and inks. Regardless of printing place, the quality must be equally. The colours should be within the tolerances that human eye cannot distinguish between the print results in packages on shelves of retail dealers. The colour of packages must be identical. [28]

First step was to define theoretical standard for Brand Colour. This attained by measuring the wanted colour sample and its tolerances from samples that are still acceptable, but where there are no remarkable noticeable difference between samples. The surface has also impact on the final result of colour formation and how wet ink will place itself until it is dry. So it is also important to determine the limits for print surface

for example the surface's smoothness and brightness. Together, with colour and paper definition, the result is predictable. [27;28]

The colour tolerances can be achieved through standards, measurements, and by controlling the printing process. The aim is to standardize the print result globally. These both ensure the high quality and it is possible to avoid the counterfeiting.

The absolute co-ordinates of colours are difficult to determine. But those are needed so that tolerances can be specified. At the moment, solid colour covers the company's packages. For technical reasons solid colour in print cannot be entirely even within one package die. That is why tolerances are really important. The printers compare print with reference sample and measure if it is in limit of tolerance. The reference samples should reprint every once in a while because colour changes with time. Also, the storage conditions greatly affect the colour changeling. Taking good care of the reference sample ensures that printed colours in packages are exactly the same ones. [27]

While measuring the colours, it is extremely important that measurement setting has been set down as defined. The result of values can vary if measurements are not done correctly. The measurer must acquaint oneself to measure methods and to instruments. Different measurement instrument also give different results. All of the above-mentioned matters will bring uncertainty to the measurements. Therefore, everything must be done as specified. [27]

There are several individuals, who had made the final decision of proof print. This makes the process even complicated. The Brand Colour is very sensitive for changes. And because there are several acceptors, everyone chooses the colour that pleases oneself. Therefore, the decision of proof print has been based on matter of opinion. When the choice has been made between two similar colours the winner is always the one, which is pleasing to the eye, not the one that is closest the reference. [28]

At the moment, the company has decided that only few individuals are responsible for the colour approvals in relation to this project. This ensures that colour in packages is always the identical as decided. [28]

To understand the colour management, basic knowledge of colour perception and colour models are necessary. Therefore, the theory part may use as educational material in the company. One part in thesis was to make small summary from colour theory in order that when necessary to present the subject easily and quickly. More information on the subject can be read from this thesis.

Progress

A decision to start this study was made in the end of October in 2009. The guidelines for the project were discussed in the meeting with instructor from the company and supervisor Merja Nieppola from Helsinki Metropolia University of Applied Science. The project went forward by getting acquainted to subject and the processes at the company. The projects timeline is described in figure 33.

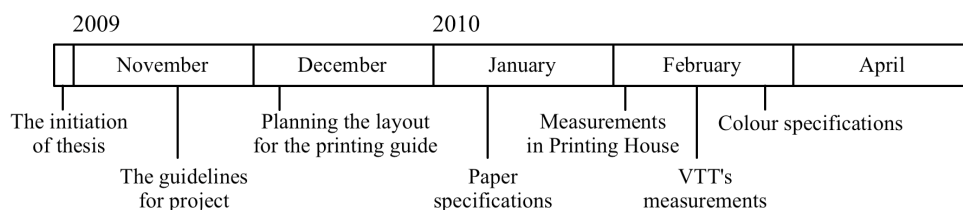


Figure 33. The timeline of the project.

It took quite a while until the decision of the right tone of Brand Colour was made. Some test prints from Brand Colour were printed, and on grounds of those the decision of the reference colour and tolerances were made. The jury of experts, the graphical, packaging and brand designs and engineers, agreed what is the reference colour and what are the limits that fit in to specifications. Before colour measurements, the definition for paper specification was started. After examining the available information of all used papers, it was possible to draw a summary. The result was a uniform paper guideline that was based on given paper information.

It was not possible until February to carry out the measurements. First we did measurements at printing house. Because colour measurement is a challenging task to do, it was decided that measurements are also done by *VTT Expert Services Ltd* (VTT). This was the right decision to do, because there were some differences in colour numerical values between VTT's and 1st measurements. This was due, because all our measurement settings of instrument were not correct. Therefore, the instrument settings and colour values got more defined guidelines.

8 Paper Specifications

The information of used paper was gathered all around the world. The company is using corrugated board and cartonboard in packages. Both uncoated and coated are in use. The paper manufactures were asked to send the paper specifications and general information of the papers. It was decided that the brightness and smoothness are the two criteria that have the most influence of print result and colour formation. So, information of those were written down and compared together.

There are several measurement methods and manufactures use only some of them. While specifying tolerance a decision about which methods could be accepted for this project had to be made. We chose the percentage method to inform the value of brightness (chapter 6.4). This is also called as ISO brightness, which is then measured by using the ISO 2470 standard.

First the idea was to make specifications for four surfaces. But in the end, specifications were done only to coated and uncoated surfaces: in the end it does not matter whether the used board is cartonboard or corrugated board. Also, the paper grammage can be chosen according to the use. The both cartons are thick, so the surface's thickness does not have influence to the print result that much. Especially corrugated board consist of topliner, fluting and innerliner. The topliner and innerliner are printed and glued to fluting. The printers must carry on the process to determine what CIE LAB-values the Brand Colour can get when ink is wet, because the colour specifications are done to dry ink. [28]

9 Colour Specifications

The company uses the spot ink as Brand Colour. But it seemed quite dominant with Brand Colour while packages are only covered with that colour. Previously determined colour was not then quite what is wanted at the moment. So specifications needed to be done once again. [28]

Measurements in Printing House

The first time when measurements were planned to be carried out in printing house, the spectrophotometer did not work. This time the test prints were evaluated and looked through together. The company's Packaging Design Specialist, showed the reference and tolerance colours and those, which are out of tolerances. Test prints were printed according to the old samples of Brand Colour that was sent to print houses. Some of them were exactly as company had defined before. The main problem, with those that were not acceptable, was that the Brand Colour had changed a little bit for some other colour.

Week later we managed to do the measurements in printing house. The used measurement instrument was GretagMacbeth SpectroEye and the measurement settings were set to instrument in accordance with ISO 12647:1. When measuring the spectrophotometric values, the setting must be set as follows: D50 illuminant, 2° observer and black backing. The calibration was done to absolute white. The densitometric values were also done in accordance with the same standard, which determines that geometry is 0/45 or 45/0. The calibration was done to paper white.

The reference Brand Colour sample was measured from both uncoated and coated surfaces and LAB-values were determined. When the reference sample was measured, measurements were targeted at five different points and instrument calculated the average from those points. One way to control colours while printing is to control one value of ΔL^* , Δa^* and Δb^* not only the ΔE^* . Therefore, next the ΔL^* , Δa^* , Δb^* and ΔE^* between reference and tolerance samples were measured. The instrument itself made the calculation difference between two Brand Colours.

One sheet includes several billets. Therefore, for ΔE^* tolerance to one die-cut is also needed to be determined. This was measured around of reference target from reference sample.

Measurements were done from several targets and the highest ΔE^* value from reference sample. ΔE^* 's value then determines the tolerance within one package die and the values that cross that ΔE^* value can be noticed. Especially it may be noticed when the die-cut is folded in a box and the upper and lower edges are combined.

The density reference value from reference sample was also measured. That is the density that printers must pursue during the printing. The density tolerance was measured around the reference samples. It must remain within the range of results.

Measurements in VTT

Expert from VTT carried out the same measurements as presented above. The measurement instrument was also the same: GretagMacbeth SpectroEye. He used measurement parameters from ISO 13655 standard. That determines as follows: D50 illuminant, 2° observer, calibration to absolute white, both with UVCut-filter or no filter, black backing and ten measurements per sample. [27]

There was not significant impact to result while the UVCut is used and when it is not. The values change a little, so it is important to determine the instruction whether to use filters or not. Exper of VTT calculated himself the colour tolerances. The ΔE^* value was calculated by using the ΔE_{CIE76} equation.

VTT's expert also calculated reference coordinates of LCh colour space. The ΔE^* value was calculated by using the ΔE_{CIE94} . After also the ΔE_{CMC} tolerance was calculated, he noticed that the tolerance (ΔE) value ΔE_{CIE94} and ΔE_{CMC} correlated with each other. So it is reasonable to consider only the ΔE_{CIE76} value. [27]

10 Analysis of the Colour Measurements

The overall conclusion was that it is easiest to compare the LAB values during printing. With spectrophotometer those values can get quite easily and it calculates the tolerances also automatically after the reference target values has been set to it. VTT's expert also specified that the tolerance (ΔE) can be best calculated using the ΔE_{CIE76} equation. [27]

The measurements that were done in 1st and VTT are quite similar. The main difference is the amount of measurements per sample. We took only five sample points and VTT ten. Although the use of filter did not make much difference, VTT's measurements (with UVCut-filter and no filter) are still closer to each other than the measurements where the filter was not used between own and VTT's measurements. The chosen measurement points certainly influences to this. In 1st measurement the measured points were taken in a quite narrow area of reference sample, just around the wanted colour.

This highlights how extremely important it is that the settings to measurement instrument are made correctly, and always in the same way. This is the only way to ensure that the results are closer to each other or completely similar. In this case the LAB-values are from VTT's measurements. This is because VTT's measurer is an expert in this field and took into account all variable attributes that needed to. Also, the setting for measurement instrument is collected from VTT's measurements. Both topline and innerliner of board get the same reference values.

Since the tolerance (ΔE) is only a numerical value rather than a particular value of the co-ordinate, the selected values are taken from measurements that were done in printing house, although the LAB values are taken at VTT's measurements. This is because the VTT's measurements were not taken into account the different qualities of paper. Therefore, the tolerance values were calculated together and uncoated and coated surfaces were not separated.

The limit for ΔE (1976) is pretty tight. This will ensure that a desired colour is reached. The colour differences balance between the noticeable and acceptable can be determined in co-ordination with the company and print houses. Therefore, the limit may be increased during the future test prints if it feels too strict. But now it will still be in limits that the company approves.

Expert of VTT also accentuated that the absolute colour coordinates (L^* , a^* , b^* , C^* h^*) are difficult to determine, because the uncertainty of measurements, and differences between measurement instruments, may give different results. Therefore, the tolerance in this case plays the significance role than the absolute coordinates. The printer therefore, must evaluate the tolerance between the print and the reference sample. [27]

11 The Next Step

The company's Brand Colour list includes several other colours than Brand Colour. The specification for Brand Colour was only the first step. If every colour of the company's colour palette is to be determined, this thesis gives the basics of specifying process and also the methods. When the above mentioned colours are specified in the same way as Brand Colour, it ensures that the determinations are exactly similar.

The company has decided that reference colour samples will be printed in Pantone. This ensures that colour samples are always equal and also further development co-operation is simpler. The reference colour samples will be sent to printing houses and each printing house takes the LAB-colour measurements by themselves. After that, the results are compared in the company, to see what kind of results are obtained in different houses and if the results correlate with each other.

One thing that came up at the end of project during a discussion with supervisor Nieppola, was how to ensure that in the printing houses the measuring instruments are properly certified. When, for example, the spectrophotometer is sent every year to the manufacturer for calibration, this will ensure that repeatability and correspondence of the measurement instrument are correct. The future next step may then be to consider

how this can be executed in practice. One possible solution might be that printing houses send the certificate of calibration every year.

Reinhard Lindqvist (2010) from KTA-Yhtiö Ltd gave us quick advice about calibration of the measuring instruments. He told that usually the manufactures recommend that instruments are inspected every two years. He also told that in the SpectroEye measuring instrument has a built-in calibration object. The instrument does the calibration itself automatically, when the new measurement is either about to start or periodically, when it is being used. [29]

Lindqvist also told that there are online calibrations. The customer purchases a special calibration card and certification license. When those are connected to the instrument, the customer can get the online report about the condition of the instrument and also, an instrument profile is formed. Because the instrument is individual, the main benefit is that with the instrument, the profile can be seen according to how the instrument sees the colours. This helps to get better measurement results and therefore, the quality control is more reliable. [29]

12 Conclusions

There are several ways to carry out the colour management measurements. This makes it even more challenging to specify an equal guideline for each of them. The main purpose of this study was to ensure that colour remains unchanged during printing process.

Only by specifying the colour it was possible to attain a uniform colour management guideline. Many variables affect the measurements and therefore, measuring must be performed every time as specified. This way the quality of a print product remains exactly the same, regardless of where it is printed. GretagMacbeth SpectroEye is recommended as the measurement instrument, because all the measurements were performed on it and also, to ensure similar measurement results.

Both LAB reference and tolerance values were measured and those were determined both for uncoated and coated surfaces. The density reference and tolerance values were also specified for both materials. Measurements had to be carried out several times to make sure everything was done correctly. For this guideline, there were two measurement times and the final result was combined from those two measurements. For colour specifications the reference colour values were taken from VTT's measurements and tolerance values from 1st measurements.

Creating this guideline would not have succeeded without teamwork. The discussions with printing industry experts gave several points of views to consider. This helped to create uniform and precise specifications for the guideline.

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Appendix 1: Delta Value Equations 1/2 [30]

ΔE (CIE 1976)

The colour difference between a sample colour $L_2a_2b_2$ and a reference colour $L_1a_1b_1$ is:

$$\Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2}$$

ΔE (CIE 1994)

The colour difference between a sample colour $L_2a_2b_2$ and a reference colour $L_1a_1b_1$ is:

$$\Delta E = \sqrt{\left(\Delta L / K_L S_L\right)^2 + \left(\Delta C / K_C S_C\right)^2 + \left(\Delta H / K_H S_H\right)^2}$$

where

$$\Delta L = L_1 - L_2$$

$$\Delta C = C_1 - C_2$$

$$\Delta L = \sqrt{\Delta a^2 + \Delta b^2 - \Delta C^2}$$

$$C_1 = \sqrt{a_1^2 + b_1^2}$$

$$C_2 = \sqrt{a_2^2 + b_2^2}$$

$$\Delta a = a_1 - a_2$$

$$\Delta b = b_1 - b_2$$

$$S_L = 1$$

$$S_C = 1 + K_1 C_1$$

$$S_H = 1 + K_1 C_2$$

$$K_L = \begin{cases} 1 & \text{default} \\ 2 & \text{textiles} \end{cases}$$

$$K_C = 1 \quad \text{default}$$

$$K_H = 1 \quad \text{default}$$

$$K_1 = \begin{cases} 0.045 & \text{graphic arts} \\ 0.048 & \text{textiles} \end{cases}$$

$$K_2 = \begin{cases} 0.015 & \text{graphic arts} \\ 0.014 & \text{textiles} \end{cases}$$

Appendix 1: Delta Value Equations 2/2 [30]

ΔE (CMC)

The colour difference method of the Colour Measurement Committee (the CMC) is a model using two parameters l and c , typically expressed as CMC($l:c$). Commonly used values for acceptability are CMC(2:1) and for perceptibility are CMC(1:1).

The colour difference between a sample colour $L_2a_2b_2$ and a reference colour $L_1a_1b_1$ is:

$$\Delta E = \sqrt{\left(\Delta L/S_L\right)^2 + \left(\Delta C/cS_C\right)^2 + \left(\Delta H/S_H\right)^2}$$

where

$$\Delta C = C_1 - C_2$$

$$C_1 = \sqrt{a_1^2 + b_1^2}$$

$$C_2 = \sqrt{a_2^2 + b_2^2}$$

$$\Delta H = \sqrt{\Delta a^2 + \Delta b^2 + \Delta C^2}$$

$$\Delta L = L_1 - L_2$$

$$\Delta a = a_1 - a_2$$

$$\Delta b = b_1 - b_2$$

$$S_L = \begin{cases} 0.511 & L_1 < 16 \\ \frac{0.040975L_1}{1 + 0.01765L_1} & L_1 \geq 16 \end{cases}$$

$$S_C = \frac{0.0638C_1}{1 + 0.0131C_1} + 0.638$$

$$T = \begin{cases} 0.56 + |0.2\cos(H_1 + 168)| & 164 \leq H_1 \leq 345 \\ 0.36 + |0.4\cos(H_1 + 35)| & \text{otherwise} \end{cases}$$

$$F = \sqrt{C_1^4/C_2^4 + 1900}$$

$$H_1 = \tan^{-1}(b_1/a_1)$$

Implementation Notes:

1. H_1 is in degrees, not radians.
2. If $H_1 < 0^\circ$, add 360° to it.
3. If $H_1 \geq 360^\circ$, subtract 360° from it.
4. In computing H_1 , be careful with the inverse tangent since a could be zero. Instead, use special math functions to do this. In both the Standard C library and Java, this function is called **atan2**. In Microsoft Excel, it is called **ATAN2**. These special functions will compute the proper inverse tangents without needing to worry about "divide by zero" conditions.