

Optimization of grey reproduction in CMYK printing processes

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Grado de Ingeniería de Tecnologías y Servicios de Telecomunicación
Aplicaciones multimedia basadas en procesamiento de la señal
1/2022



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FICHA DEL TRABAJO FINAL

Título del trabajo:	<i>Optimización de la reproducción de grises en procesos de impresión CMYK</i>
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Fecha de entrega (mm/aaaa):	<i>01/2022</i>
Titulación o programa:	<i>Grado de Ingeniería de Tecnologías y Servicios de Telecomunicación</i>
Área del Trabajo Final:	<i>Aplicaciones multimedia basadas en procesamiento de la señal</i>
Idioma del trabajo:	<i>Inglés</i>
Palabras clave	<i>Impresión, calibración, colorimetría</i>
Resumen del Trabajo (máximo 250 palabras): <i>Con la finalidad, contexto de aplicación, metodología, resultados y conclusiones del trabajo</i>	
<p>La impresión de tonos grises es un desafío para casi todas las tecnologías de impresión: muchos factores deben mantenerse bajo control para permitir una reproducción consistente de grises neutros, entre ellos la correlación con el sistema de visión humana. El alcance del proyecto es describir y aplicar el estado del arte del balance de grises neutros y la calibración de reproducción en un proceso genérico de impresión industrial de <i>halftones</i> CMYK de 4 colores. Se aplica un método de calibración de 3 pasos para ser compatible con la norma ISO 12647-2 y lograr una condición de balance de grises neutra, inspirada en el método G7™, centrándose en el caso cuando se parte de una caracterización arbitraria. La prueba se realizó utilizando una prensa industrial HP Indigo sobre papel estucado brillante, calibrada siguiendo las condiciones de impresión FOGRA51 y ajustada para la reproducción del balance de grises utilizando medidas de un espectrofotómetro automático. Se utilizó la fórmula colorimétrica del <i>Grey Index</i> (GI) para evaluar el resultado, respaldada por una evaluación visual en una condición de visualización estándar.</p> <p>Los resultados muestran una mejora de GI de 2,82 de prensa sin calibrar a 1,16 usando la calibración estándar de TVI a 0,61 de la calibración de grises ajustada con precisión, y la evaluación visual concuerda con los resultados. Esta es una demostración de que el método funciona, pero se necesitan más pruebas para validar el proceso y la correlación de la fórmula del Índice de Gray con evaluaciones visuales en más tecnologías de impresión y tipos de sustrato de papel.</p>	

Abstract (in English, 250 words or less):

Printing of grey shades is a challenge for almost all printing technologies: many factors need to be kept under control to allow a consistent reproduction of neutral greys, among them the correlation with human vision system. The scope of the project is to describe and to apply the state-of-the-art of the neutral grey balance and reproduction calibration in a generic 4-colours CMYK halftoned industrial printing process. A 3-steps calibration method is applied to be compatible with ISO 12647-2 standard and to achieve a neutral grey balance condition, inspired from G7™ method, focusing on the case when starting from an arbitrary characterization. The test was made using an HP Indigo industrial press on gloss coated paper, calibrated following FOGRA51 printing condition, and fine-tuned for grey balance reproduction using measurements from an automatic spectrophotometer. The Grey Index (GI) colorimetric formula was used to evaluate the result, supported by visual evaluation on a standard viewing condition.

The results show improvement of GI from 2,82 of uncalibrated press to 1,16 using standard TVI calibration to 0,61 of the fine-tuned grey calibration, and the visual evaluation agrees with the results. This is a demonstration that the method works but more tests are needed to validate the process and correlation of the Grey Index formula with visual assessments in more printing technologies and paper substrate types.

A Nillo, perché aveva ragione.

Many thanks to Elia Nardini of corGae s.r.l. to have provided the usage of the industrial digital printer with paper and materials.

Thanks to HP Inc., in particular to Marc Jansa and Konstantinos Kontonikolas, to have supported my degree journey and to have provided measuring and visual evaluation equipments.

Thanks to Giovanni Daprà, Andreas Kraushaar, Bruno Mortara, Nikolaus Pfeiffer, for the help on bibliography integration.

Thanks to TAGA Italia for support and inspiration.

Abstract

Printing of grey shades is a challenge for almost all printing technologies: many factors need to be kept under control to allow a consistent reproduction of neutral greys, among them the correlation with human vision system. The scope of the project is to describe and to apply the state-of-the-art of the neutral grey balance and reproduction calibration in a generic 4-colours CMYK halftoned industrial printing process. A 3-steps calibration method is applied to be compatible with ISO 12647-2 standard and to achieve a neutral grey balance condition, inspired from G7™ method, focusing on the case when starting from an arbitrary characterization. The test was made using an HP Indigo industrial press on gloss coated paper, calibrated following FOGRA51 printing condition, and fine-tuned for grey balance reproduction using measurements from an automatic spectrophotometer. The Grey Index (GI) colorimetric formula was used to evaluate the result, supported by visual evaluation on a standard viewing condition.

The results show improvement of GI from 2,82 of uncalibrated press to 1,16 using standard TVI calibration to 0,61 of the fine-tuned grey calibration, and the visual evaluation agrees with the results. This is a demonstration that the method works but more tests are needed to validate the process and correlation of the Grey Index formula with visual assessments in more printing technologies and paper substrate types.

Keywords

Printing, CMYK, grey balance, grey reproduction, gray balance, gray reproduction calibration, TVI, Grey Index, Gray Index.

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1. Introduction

1.1. Description of the project

Four colours CMYK (Cyan, Magenta, Yellow, Black) printing is the simplest and most common printing architecture used from most of the home digital inkjet devices, professional digital small and large format printers, industrial printing processes as offset lithography. The intended colours are reproduced using a combination of C, M, Y, K inks, where the black is used to strengthen the darkness areas, in opposition to the light colours that uses only a combination of C, M and Y. From the release of the 2nd version of ISO 12647-2 standard in 2004, all the evaluations, calibrations and tolerances are expressed using the colour space CIELAB (L^* , a^* , b^*), using colorimetric distance formulas CIEDE76 (ΔE_{ab}) and CIEDE2000 (ΔE_{00}). Those colorimetric distance formulas allow the description and communication of the colour accuracy, removing the subjectivity used from centuries.

Neutral grey achromatic colours are a subset of all the possible colours that a printer can obtain. Since the nature of subtractive CMYK printing, grey colours are the most difficult to calibrate and keep under control during the printing process. The reason is partially on the nature of the human vision, that is more sensible in variations on neutral greys than other brilliant colours, and partially on the chemical interaction of C, M, Y inks that need to be extremely balanced to provide a decent result.

The reproduction of neutral grey colours in CMYK printing is done balancing the visual appearance of the entire dynamic range of the chromatic CMY inks (called grey axis), from white to black, and need to be defined in three different domains:

- Neutral grey definition, where the intended colorimetric CIELAB references are defined for the entire grey axis, basing on the substrate and other parameters.
- Neutral grey balance, where the amount (usually percentages) of every device ink channel C, M, Y in the grey axis is defined a priori during the calibration process of the printer. If the system is perfectly calibrated, those percentages should lead to neutral greys,
- Grey reproduction, where the resulting printed greys are compared and evaluated colorimetrically against the targets defined during the grey definition.

The project is focused on industrial CMYK printing processes using halftoned periodic reproduction: it includes offset lithographic, flexographic, screen, and gravure printing, as well as some digital printing processes.

The current version of the standard for offset lithographic printing adopted by the industry all around the world, ISO 12647-2:2013 (15), only suggest a description of neutral grey reproduction, without setting requirements or describing standard processes to achieve it. Inside the ISO 12647-2 there are

only requirements for the ink channels C, M, Y, that are evaluated in the domain of the apparent tone value increase (TVI): following those target values, in most cases the user can achieve a decent grey reproduction, but without any certainty on the result.

In the USA, a method called G7® is widely used by the industry to have a good neutral grey definition, predefined grey balance and to control the grey reproduction (28). The method could be considered a superset of ISO 12647-2 standard.

During the revision process of the ISO 12647-2, started two years ago in ISO/TC130 technical committee (16), following the industry needs, a stronger definition of all the three steps is under consideration, with the intention to be compatible also with the G7 method. At the date of this document, the experts have not agreed about the synthesis of the methods yet.

To achieve a neutral grey reproduction from predefined grey definition and grey balance, the following steps are needed:

1. Achieve the standardized colour gamut adjusting C, M, Y, K primaries, and C+M, M+Y, C+Y secondaries.
2. Adjust the standardized C, M, Y, K tonal value increase curves (TVI)
3. Fine-tune the grey reproduction, keeping the TVI standard tolerances of the step 2

The step 1 and 2 are well known and standardized from the previous edition of the ISO 12647-2 standard, dated 2004. However, standardizing the step 3 is still a challenge even today.

The project is focused on the step 3, the fine tuning of grey reproduction, although the practical implementation started from the step 2 for practical reasons.

After defining the neutral grey axis and using the grey balance from a characterization widely used in Europe, FOGRA51 (4), a print system will be fine-tuned and the grey reproduction evaluated both using the ISO 12647-2 criteria and a new formula called Grey Neutrality Index (GI), published in the 27th Colour and Imaging Conference 2019 by the author (3).

1.2. Justification

Grey balance is one of the big challenges of every CMYK printing system, and every printer manufacturer or printing industry. When the calibration is made following a system or standard already balanced, as the GRACoL reference conditions used in the USA made under G7 conditions, the process is well-defined and known by the market, and tools and processes are available by many suppliers. On the contrary, in Europe, the standard characterizations provided by FOGRA (4) leave the printers free to identify their workflow, and most of the steps are not standardized yet: this is the approach of current ISO 12647-2 (15) standard. Applying some methods used in the USA, adapted to the European FOGRA starting conditions, the project will demonstrate that it is possible to achieve a good neutral grey reproduction condition in a simple and automated way.

1.3. Motivation

Graphic technologies are my passion and my work from the last 18 years, when I entered in graphic arts technology after an early career spent in colorimetric software for paintings.

The challenge of grey reproduction in printing started in XV century also with the work made by Ugo da Carpi (1470-1532) (27), my fellow citizen from Carpi (Modena) in the north of Italy, and has been developed in the modern age by the photographer Ansel Adams (1902-1984) (1) that inspired the previously cited G7 method. I am a big fan of both artists and is a pleasure to add my contribute to this topic.

1.4. Scope

The scope of the degree project is to identify and to apply the state-of-the-art of the neutral grey balance and reproduction calibration in a CMYK printing process. A 3-steps calibration method is applied to be compatible with ISO 12647-2 (15) standard and to achieve a neutral grey balance condition, focusing on the case when starting from a not optimized characterization.

1.5. Objectives

- I. Describe and analyse all the steps that allow a neutral grey calibration in a CMYK printing process.
- II. Identify a process that could be as automated as possible, to be performed by not-skilled users.
- III. Identify a method to communicate the result with a single-number metric.

1.6. Devices

To perform the investigation, three professional devices was used: an industrial press, a spectrodensitometer, and an automatic spectrophotometer.

1.6.1. Printing technology

A CMYK digital press HP Indigo was used to print the samples, thanks to the courtesy of corGae company in Italy. HP Indigo is a digital printer with liquid electrophotographic process that has a transfer blanket like offset lithographic presses. For that reason, the calibration process is almost identical of an offset press and is also faster and cheaper because completely digital driven. The HP Indigo 12000 HD used, shown in Figure 1, is capable to print 3'450 75x53 cm sheets per hour at screened resolutions in the range [175- 290] lines per inch (LPI).



Figure 1 - The HP Indigo 12000 HD of corGae srl, Italy

1.6.2. Measuring equipments

The manual measurements on the printed sheets during the TVI calibration process was taken with an X-Rite eXact spectrodensitometer (5)



Figure 2 - X-Rite eXact™ portable spectrophotometer

Table 1 - X-Rite eXact™ main specifications

Type	45°/0° spectrophotometer
Spectral data	400-700nm at 10nm interval
Aperture	2 or 4 mm
Inter-instrument agreement	Average 0,25 ΔE _{ab} , Max 0,45 ΔE _{ab} on 12 BCRA tiles

Short term repeatability	0,05 ΔE_{ab} standard deviation on white BCRA tiles
Measurement conditions	ISO 13655 M0, M1, M2, M3

The automatic measurements on the charts will be done with a Konica Minolta FD-9 spectrophotometer
(8)



Figure 3 - Konica Minolta FD-9 spectrophotometer

Table 2 - Konica Minolta FD-9 main specifications

Type	45°/0° scan spectrophotometer
Spectral data	380-730nm at 10nm interval
Aperture	3 mm
Inter-instrument agreement	Max 0,3 ΔE_{00} on 12 BCRA tiles
Short term repeatability	0,05 ΔE_{00} standard deviation on white BCRA tiles
Measurement conditions	ISO 13655 M0, M1, M2

1.7. Methodology

Calibration of a printer is a sequential process that does not fit well with Agile methodologies like Scrum. Agile is very efficient when the original requirements are not completely defined, and when it is possible to break the incremental value of the product into independent deliverables.

In this case, we have a well-defined process and sequential actions to achieve the final result of the calibration. The best methodology to manage this project is waterfall, with cues that comes from the Critical Chain Project Management (CCPM) practices.

To accomplish the result, focus need to be maintained on three specific CCPM themes:

- Identify and solve explicit and implicit dependencies
- Accept the identified plan "as is" and spend time to identify uncertainties and possible failure risks
- Use buffers in the critical chain to allow some margin in the operations

Since it is a waterfall project management, the creation of a Work Breakdown Structure (WBS) is crucial, as other tools like GANTT and Breakdown charts.

1.8. Planning

The planning of the activities was made with Microsoft Project software tool, applying the concepts described in section 1.7 above. In the Work Breakdown Structure (WBS) of Figure 4 is possible to see the sequence of the main activities. A prudent buffer of about 30% of the estimated initial work time was added at the end of the project and was re-evaluated periodically. It was critical to get the confirmation of the three slots needed to print the test form, as shown in the Figure 5. Three resources was identified: homework, the press time, and the colour laboratory time. The working calendars was set accordingly with the working hours and the days of availability/unavailability. The project report of Figure 6, generated automatically by Microsoft Project, was be used weekly to track the status that was initially estimated in 205 hours in total.

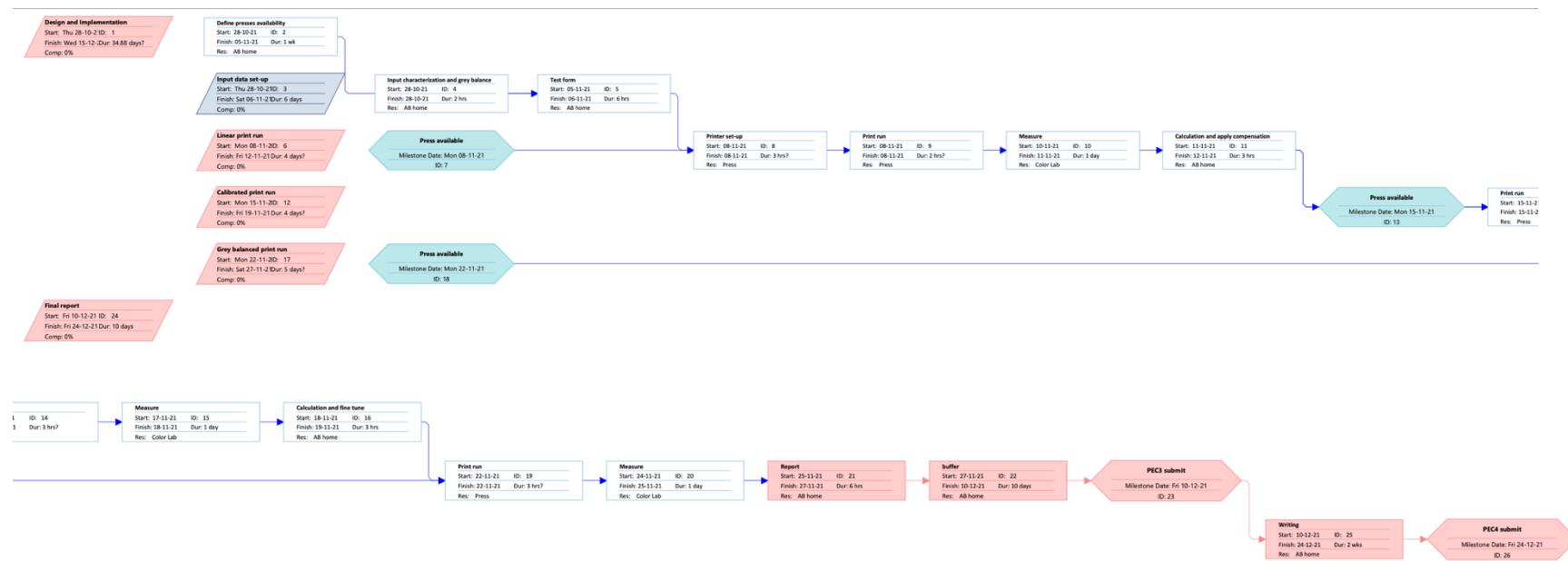


Figure 4 - Work Breakdown Structure

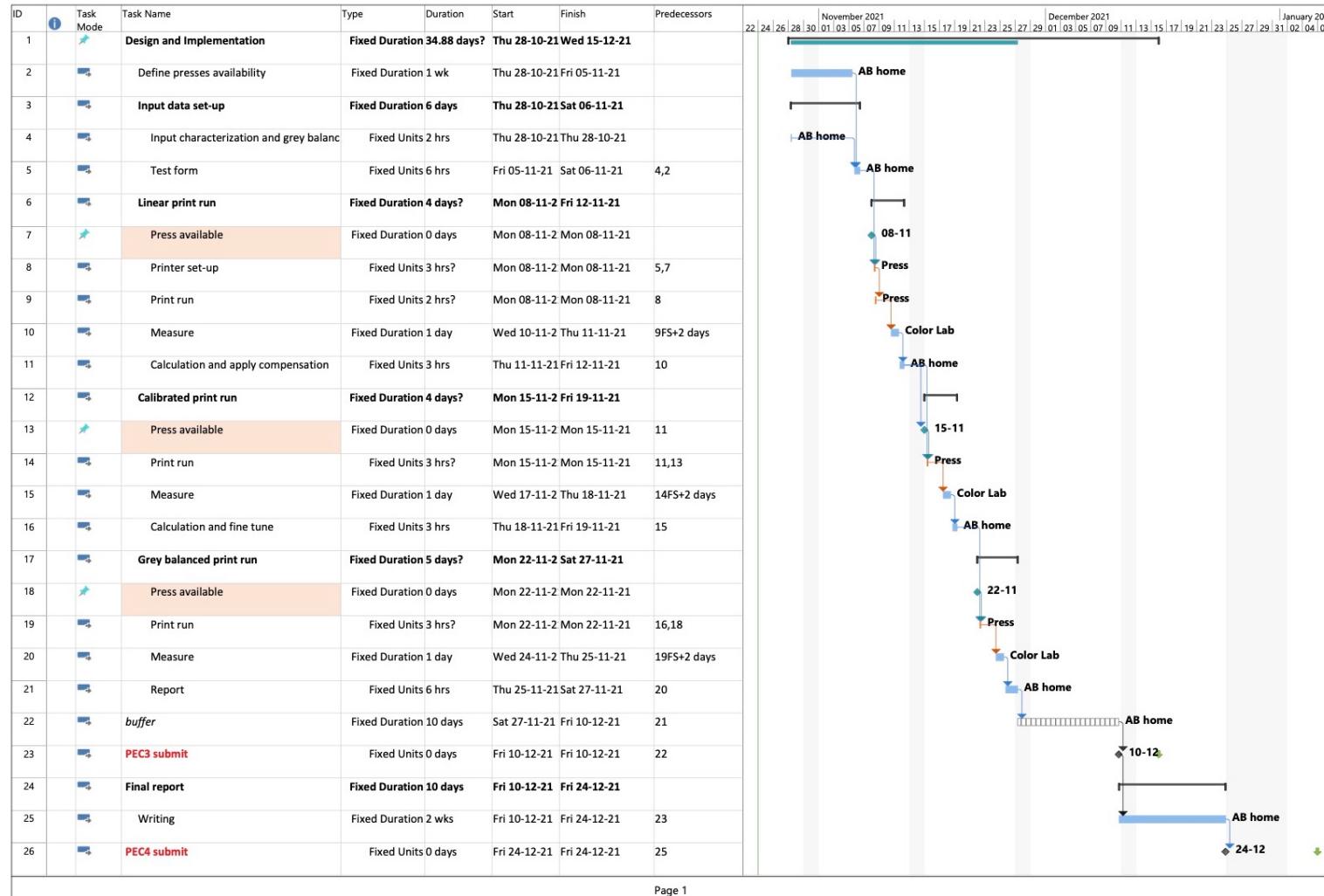


Figure 5 - GANTT chart

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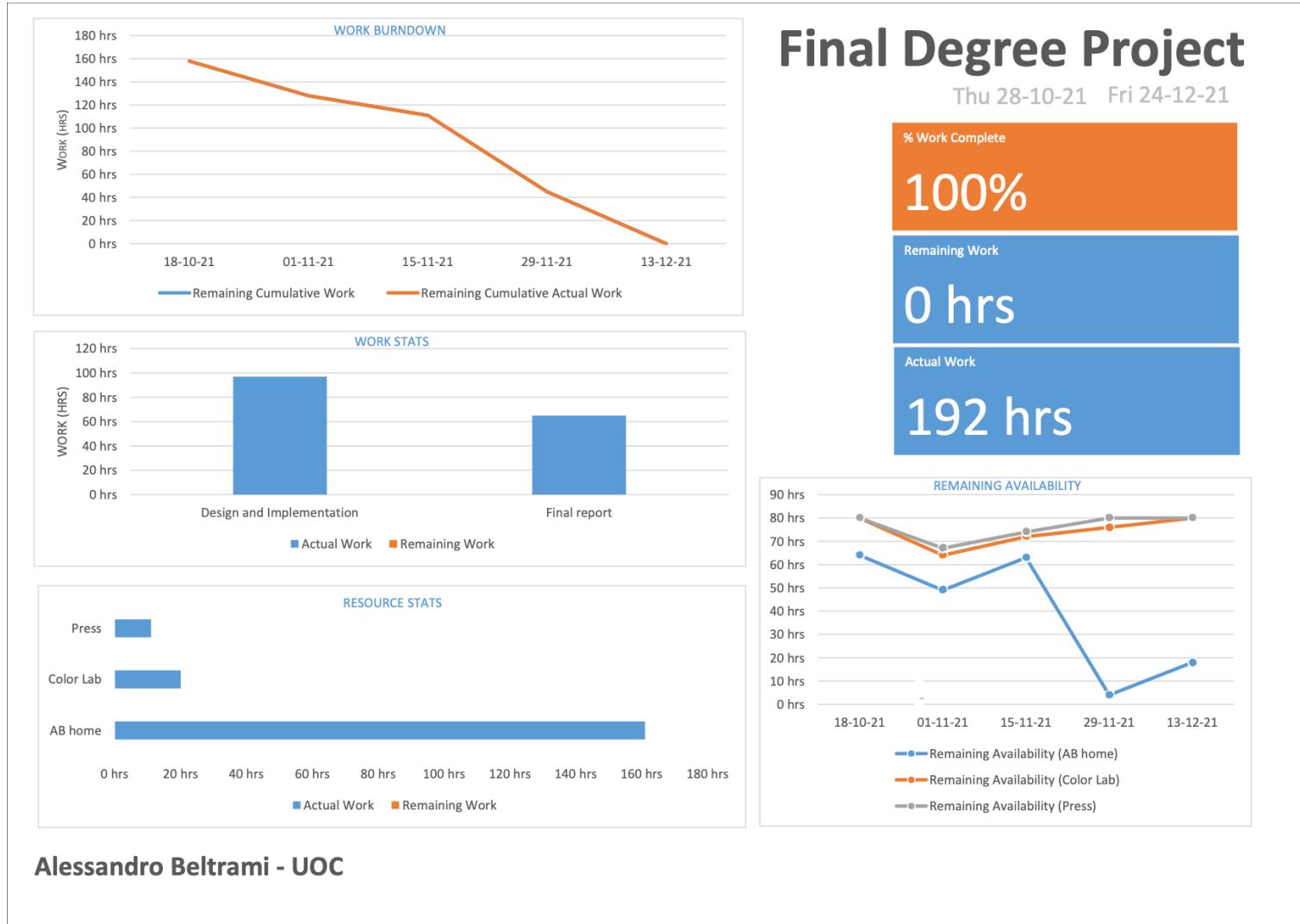


Figure 6 - Project report at the end of the work

1.9. Structure of the rest of the document

The chapter 2 introduces the state-of-the-art of grey reproduction in printing from an historical, mathematical, and industrial graphic technology perspectives.

The chapter 3 contains the design and the implementation of the test, with analytical and subjective evaluations of the results.

The chapter 4 is focused on a review of the results, a retrospective of the methodology used, and possible future works.

2. State of the Art

2.1. Origin of grey printing

Printing is a reproduction technique that was invented around the 220 AD in China, using fabrics and paper, and appears in form of woodcut in the V century both in Japan and in Europe. (2). Until the first years of VI century most of the books or fine art prints that contains images, other than text, was made in Europe only using contours of the elements, without shades of greys or colours, as shown in the example of Figure 7.



Figure 7 - Page from Biblia Pauperum, 15th century

From the beginning, the woodcut printing was competing with the brush painting because it can allow to replicate the same subject many times with few efforts and cost. Brush painting, on the other side, allow an incredible quality and realism on the images at the expense of time and cost need to create a single copy. Today, we can say that brush painting is not scalable.

In early years of 16th century, two different schools start to add shades to woodcut printing. The German school represented by Lucas Cranach and Hans Burgkmair, followed some years later by the Italian Ugo da Carpi, start to investigate the use of shades called *chiaroscuro*. Unless the official attribution of the techniques goes to the Hans Burgkmair with the work represented in Figure 8, the famous painter Giorgio Vasari (1511 - 1574) give the paternity of the technique to Ugo da Carpi because he separated the deep black contour and the grey shade depending on the deepness of shadows, a way that is similar of what the printing industry will use in the following centuries (an example can be seen in Figure 17). The first attempts dated 1510-1511 was lost, and the most ancient reproduction of this technique from Ugo da Carpi is represented in Figure 9 (22), made some year later of Burgkmair works.



Figure 8 - Burgkmair H., Lovers Surprised by Death, 1510



Figure 9 - Ugo da Carpi - Sybil Reading - original woodcut around 1510-15, photo of a reproduction dated around 1520-27

2.2. Photography and the Zone System

The bridge between the ancient works and the modern techniques is the Zone System work formulated by the photographer Ansel Adams in collaboration with Fred Archer in 1939-40. The system was developed mainly to help to find the correct exposure for photographic films, but we are more interested here in the print contrast effect of those exposures. The work is related to the grey reproduction because the introduction of two concepts: the separation between the "shadows" and the "highlights", following by the definitions of a ten-zones scale that allow to simplify the control of the contrast of the grey levels in photographic printings. The main contribution to the grey reproduction of the Zone System was to have identified the need of a scientific method to keep greys under control. (17)

ZONES	0	I	II	III	IV	V	VI	VII	VIII	IX
1. UNITS OF LIGHT	$\frac{1}{2}$	1	2	4	8	16	32	64	128	256
2. EXPOSURE VALUES (EV)	0	1	2	3	4	5	6	7	8	9
3. RELATIVE f/STOPS	F/64	F/45	F/32	F/22	F/16	F/11	F/8	F/5.6	F/4	F/2.8
4. RELATIVE SHUTTER SPEEDS	$\frac{1}{250}$	$\frac{1}{125}$	$\frac{1}{60}$	$\frac{1}{30}$	$\frac{1}{15}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1 sec.	2 sec.
5. RELATIVE ASA	6400	3200	1600	800	400	200	100	50	25	12

Figure 10 - The equivalence of zones, meter readings, f/stops, shutter speeds and ASA numbers (17 p. 31).



Figure 11 - Ansel Adams, The Tetons and the Snake River, 1942, as an example to a perfectly balanced photo that covers all the zones of the Zone System (1)

It is still a challenge even today reproducing with a printing process a photo like the one shown in Figure 11, both on the need to preserve the contrast and to render a neutral grey.

2.3. Physics and colorimetry of grey colours

To understand and describe greys, we need to understand what a colour is or, as Fairchild says "*why is colour*" (7 p. 57).

2.3.1. Colorimetry

Colour is a psychological phenomenon that strictly depends on humans: without a human observer there could not be colour at all. For that reason, colorimetry, the science of the colour measurement and description, take into account the physical properties of the environment as well the psychological properties of the human vision system, composed mainly by the eye, nervous system, and brain. (23 p. 363)

Colour can be described only under the definition of light sources and illuminants, geometry that describe the relationship between the illuminant and the object seen, and human visual response (or a simplification of that). (7 p. 58)

The spectral distributions of illuminants are standardized by the *Commission Internationale de l'Eclairage* (CIE). For graphic arts, the most relevant illuminant is the D50, that represent the natural warm daylight with a correlated temperature of approximatively 5003K. It must be noted that all other industries like inks, plastics, varnishes, etc., use the well standardized D65 illuminant (approx. 6504K).

D50 was chosen in the mid of the past century by photography and graphic arts for due to the viewing of positive transparent film, and the warm yellow/red colour shade of the papers of that age. D50 allowed a more balanced neutral grey appearance than D65 under those conditions; even if today films are rarely used, and the average paper colours have shifted to a cold blue, D50 is maintained in graphic arts standards for legacy reasons.

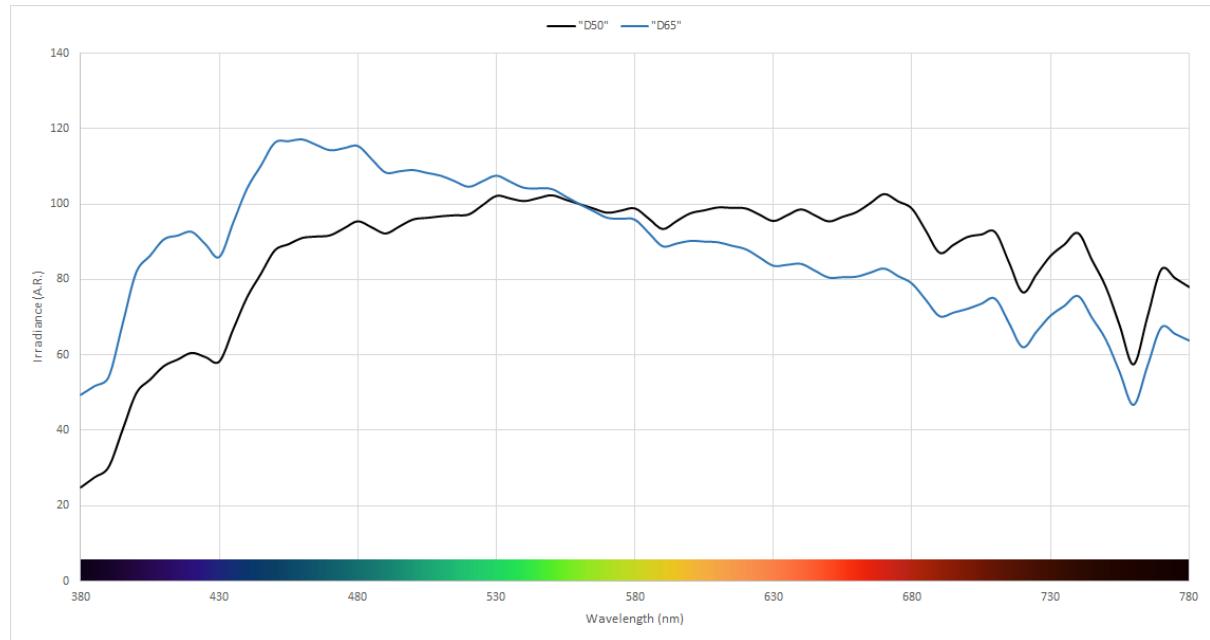


Figure 12 - Comparison of D50 and D65 spectral distributions
from <https://www.waveformlighting.com/color-matching/what-is-d50-for-graphic-arts-printing>

In 1931 the CIE released the 2° standard observer matching functions that, starting from the Wright and Guild experiments, allow to calculate the colours seen in a narrow field view integrated in a tristimulus colour space called XYZ. The functions are shown in Figure 13. Even if in 1964 a more useful 10° standard observer was defined, today used in most industries, graphic arts continue to use the D50/ 2° condition independently of the real viewing field size required by specific application. For example, 2° observer represents well a printer postcard seen at 30 cm from the eyes, but 10° would be more suitable looking a printed billboard in the street. To avoid complexity, D50/ 2° is the only standardized condition of all graphic arts colour calculations.

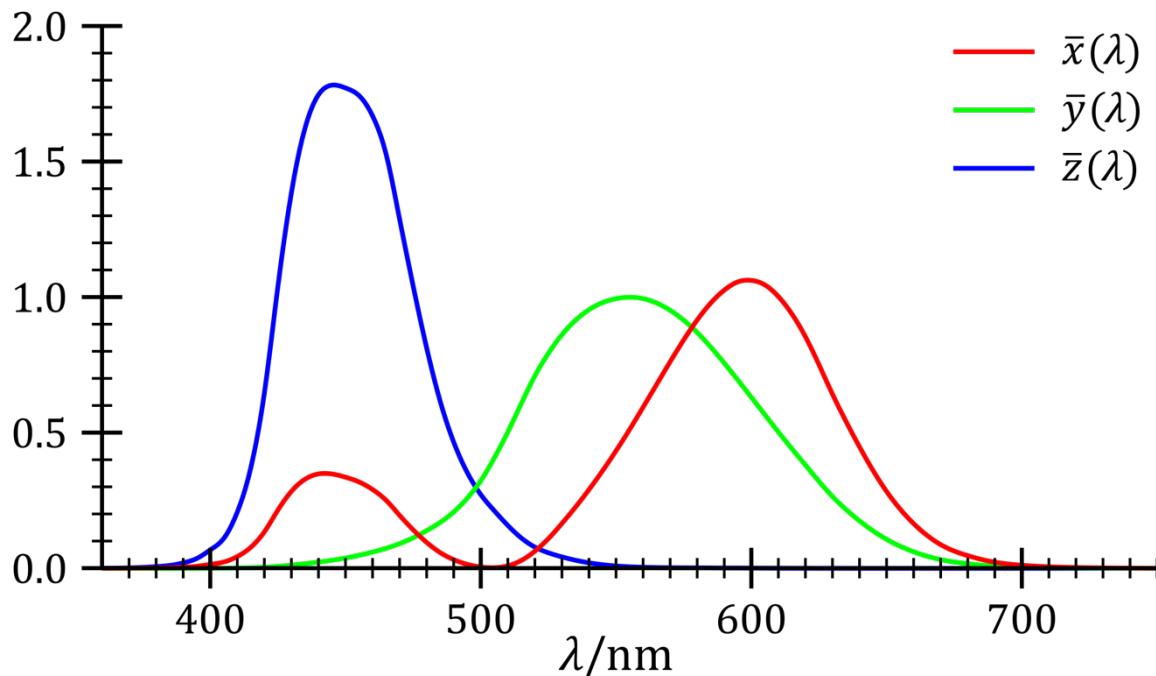


Figure 13 - CIE XYZ 1931 standard 2° observer colour matching functions. From Wikipedia.

In a reflective case, the XYZ values are calculated integrating the spectral reflectance of the object multiplied by the relative power of the illuminant and the matching functions, as shown in Equation 7. The XYZ coordinates fully describe every colour seen by the standard observer but does not contain information about visual appearance. In other words, XYZ colour space is not perceptually uniform, and it is not possible to correlate Euclidean distances with colour differences. For those reasons after many tentative to develop perceptual uniform colour spaces, in 1976 the CIELAB model (also referred as L*a*b*, or simply Lab) emerged as a convergence of the different proposals and is still widely used today in all colour industry.

CIELAB is a three-dimensional colour space where the lightness is expressed by the L* coordinate, and the chromaticity by a* and b* coordinates in an opponent-type system red/green vs. yellow/blue as shown in Figure 14.

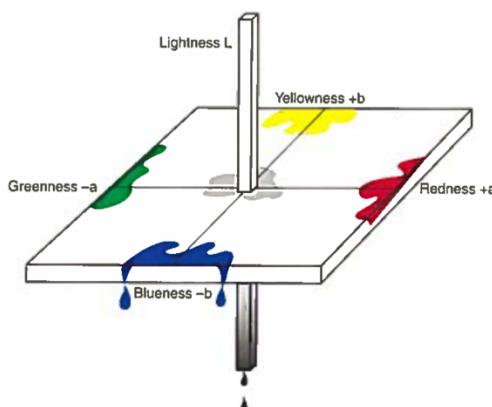


Figure 14 - Opponent coordinate system in CIELAB

To calculate colour differences, two formulas are used in the printing industries: the Euclidean geometric distance shown in Equation 1 and the more complex ΔE_{00} or CIEDE2000 formula developed by Luo, Cui, and Rigg and adopted by CIE in 2001 and later by ISO in several standards. (19)

Equation 1 - The CIELAB colour difference formula

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

The use of CIEDE2000 colour difference formula currently is recommended in all the cases, except when the Euclidean distance has a better correlation with the subtended physical metric, as an example when need to be correlated with ink thickness.

Using XYZ or CIELAB colour spaces is possible to describe all the colours perceived by a standard observer (2° in our case) under a certain illuminant (D50 in our case). Greys colours are contained in these colour spaces.

2.3.2. Chromatic adaptation

The chromatic adaptation of our vision system is the ability to preserve the appearance of object colours under different viewing conditions that are surrounding the object, or pre-exposed. It is a key mechanism for the appearance of grey colours and is a complex interaction of different physical phenomena that overlaps. Here we are more interested in qualitative description of chromatic adaptation, in the context of printing, than a quantitative modelling.

Chromatic adaptation can be observed looking a white piece of paper, for example, under different viewing conditions: even if daylights (like CIE D series) contain more short-wavelength energy than fluorescent or tungsten bulbs, the perceived colour of the paper retains his white appearance. (7 p. 157)

In 1904 Johannes von Kries has formulate the hypothesis that the adaptation made by a specific retinal area modifies the overall sensitivities of the entire tristimulus range through a linear transformation. This assumption is used still today to mathematically apply the chromatic adaptation in many colour spaces, even if the Bradford version is the most used. (29 p. 431)

Equation 2 - Chromatic von Kries adaptation

$$\begin{bmatrix} X_D \\ Y_D \\ Z_D \end{bmatrix} = M \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix}, \quad \text{where } D = \text{destination colour}, \quad S = \text{source colour}$$

The matrix M is a concatenation of matrices that performs three transformations (18):

1. Transform from XYZ into a *cone response domain*, ($\rho\rho, \gamma\gamma, \beta\beta$).
2. Scale the vector components by factors dependent upon both the source and destination reference whites.

3. Transform from $(pp, yy, \beta\beta)$ back to XYZ using the inverse transform of step 1.

For the context of grey reproduction, it is interesting to note that the matrix M is dependent only on the source white reference, and the destination white.

From there, we can define two different viewing conditions: one when the reference is considered the surrounding lighting white, and the second when the reference is considered the substrate white illuminated from that surrounding. It is not possible to define a priori in which context a user will do the evaluation of the print: in most cases our vision system will continuously change the adaptation between the two white points, especially when the substrate white is not so neutral under the surrounding illuminance.

2.4. Background on CMYK printing process colour separation

As we have seen in 2.1, printing is a very old technique of image reproduction, and from there many processes has been invented in more than 2000 years. We focus now on the most used printing process used today for commercials, newspapers, large format, and fine arts: the four-colour CMYK inks printing. Please note that some popular applications, for example most of the food packaging, are using different ink combinations. There is also to note that there are many technological processes that uses CMYK combination, like offset lithographic, flexographic, screen printing, gravure, and many digital technologies. In this work we try to be independent from those technologies, and their implications, as much as possible.

The foundation of CMYK printing process is the colour separation: the division of a coloured image in four separate components corresponding to primary colours cyan (C), magenta (M), yellow (Y), with the reinforce of a black (K) ink. The use of K is necessary in almost all printing processes to achieve stable darker colours, and a better definition of elements like text or line arts.

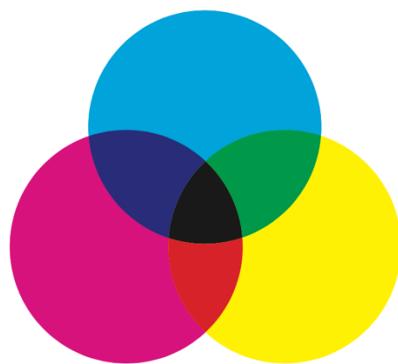


Figure 15 - Subtractive CMY colour model: the combination of C, M, and Y provides a dark grey.
Black is used as fourth ink to reach the black deepness.

Since a specific colour in an image can be defined as a colorimetric XYZ tristimulus (usually RGB, rarely CIELAB, but both can be considered as linear transformations of XYZ) theoretically there is only one CMY combination that match the original colour: the function can be considered a bijection $f: XYZ \rightarrow CMY$, under a theoretical condition that C,M, and Y are pure primaries and able to cover all the colour

space of XYZ. In real printing processes these conditions never happen. and the separation is not a function anymore. That implies that some colours in XYZ domain cannot be represented in CMY codomain, but all colours in CMY image can be represented in the XYZ original domain with only one possible correlation between XYZ and CMY. The XYZ colours that cannot be represented are called out-of-gamut colours, and those that can be represented are called in-gamut colours.

Considering only the in-gamut XYZ' colours, the separation is a bijection $f: XYZ' \rightarrow CMY$, and we will see later that this characteristic is used in the grey calibration process.

Since the use of K, the separated codomain is going from a 3-dimension to a 4-dimension, and the separation becomes a general non-injective non-surjective function:

Equation 3 - In-gamut XYZ' to CMYK separation function is non-injective non-surjective

$$\begin{aligned} \forall cmyk \in CMYK, \text{ could } \exists xyz' \in XYZ' \text{ such that } cmyk = f(xyz'), \text{ and} \\ \forall xyz' \in XYZ', \exists \text{ more than one } cmyk \in CMYK \text{ such that } xyz' = f'(cmyk) \end{aligned}$$

There is an important implication on that: many CMYK combinations can render the same XYZ colour and choosing which of them to use during the separation process requires a defined strategy. In other terms, this strategy defines where is located the image of the separation function in the CMYK codomain.

There are many possible strategies to apply, the most used today is called Grey Component Replacement (GCR) introduced by John Yules in 1940 (30). In a CMY printing, the two predominant inks determine the hue, and the third lesser ink determine its chroma in a negative effect. In effect, the third ink is adding greyness to the result (12). The GCR strategy is to remove the third lesser ink contribution, as a whole or in part, remove the correspondent two dominant inks amount and substitute with a correspondent amount of K ink. Substituting some amount of CMY with some amount of K allow to achieve a more stable printing process, especially in the grey axis, and reach a pure dark black.

Although at the time of the analogue films the GCR formulas was quite straightforward, today with the event of digital images and separations made by software, every supplier has his own customized formula. GCR approach can be conceptualized in a three-step algorithm, first the K is calculated from the in-gamut tristimulus and a set of parameters, and later the CMY are calculated considering the K and again the tristimulus. At the end the CMY and K are combined into the final CMYK values.

Equation 4 - Conceptual GCR calculation steps

$$k = f_{GCR}(xyz', [S]), \quad cmy = f(k, xyz'), \quad cmyk = cmy + k,$$

where $[S]$ is a set of parameters like black ink limit, black width, black curve, ...

Usually, the K amount calculated from a grey colour is higher than the K calculated from a chromatic colour with the same lightness, in that sense the GCR function is adapting to the colour area of the input tristimulus depending on different parameters.

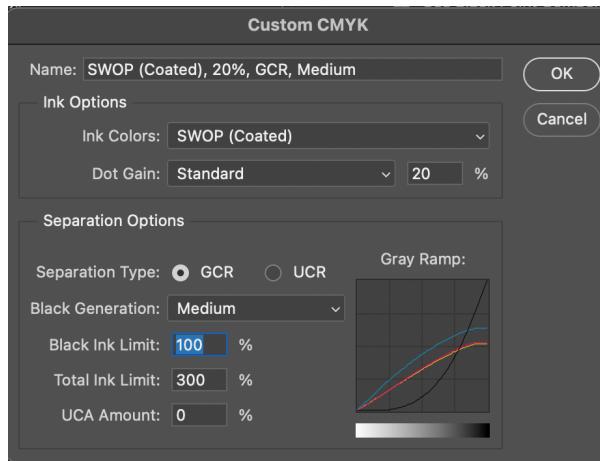


Figure 16 - Example of GCR settings in Adobe Photoshop®



Figure 17 - Greys images converted in CMYK with the GCR settings of the Figure 16, and the four separations. You can see that M and Y have less strength than C, to avoid the brownish effect, and the K channel that contains the replaced CMY content.

Reproduction of grey images in a CMYK printing process can be done theoretically in three ways: using K ink only, using CMY inks only, or using a CMYK combination. Even if it seems counter-intuitive, the use of K ink alone usually does not provide a good image quality for grey images: the result is grainy, even if perfectly neutral (assuming a perfectly achromatic black ink). On the other hands, CMY separations provide smooth images and good image quality, but they are quite unstable during the printing runs. So, the common approach is to use a full CMYK separation using a GCR technique as shown above, balancing image smoothness, detail reproduction, accepting some possible colour change during the production.

2.5. The tone value increase

In the section 2.4 above, the CMYK printing was described independently on the technology used. However, there is an important effect that was described and coded on offset lithographic presses and that is caused mainly by the pression used during this process: the dot gain. With the advent of digital

printing, where there could be no pressure at all, the concept has been maintained and is applicable in those contexts.

Tone Value Increase (TVI), also known as dot gain, is the difference between the tonal value (TV) on the screened film or digital file and the TV of the print. Is specified as a percentage and is a characteristic of all printing processes. The TVI curve depends on the process itself, inks, substrate, and other parameters that can be summarized in a so-called Printing Condition.

Data	20 %	40 %	80 %	100 %
Print				
TVI (%)	10 %	15 %	10 %	0 %

Figure 18 - TVI at 20, 40 and 80%

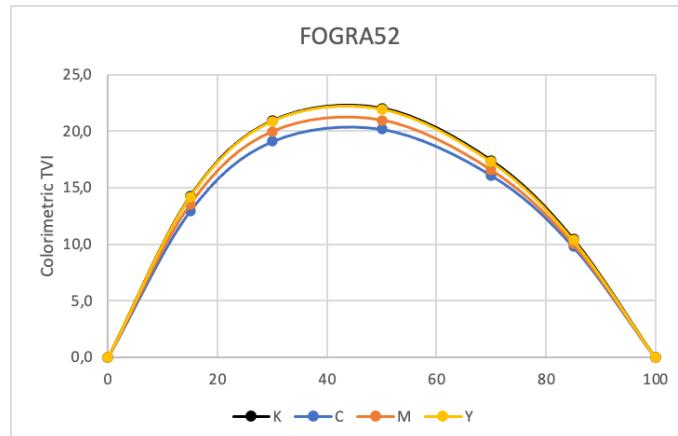


Figure 19 - Ideal TVI of FOGRA52 standard

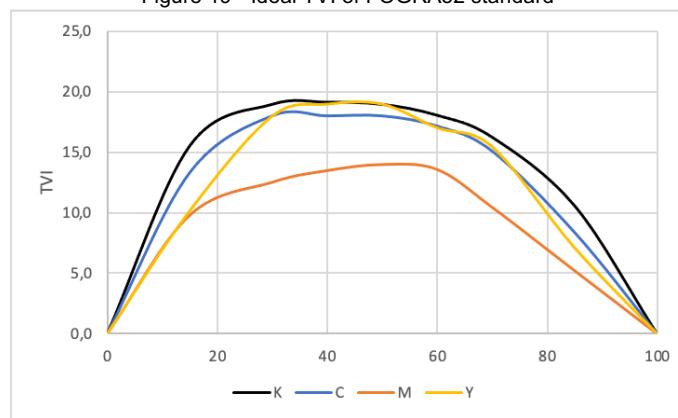


Figure 20 - Real TVI measured in an offset lithographic press

TVI curve is a key player of grey balance, because it is one of the most important parameters that need to be standardized during the print process calibration and need to be kept under control to avoid hue shift, as shown in the example of Figure 21 (6 p. 17)

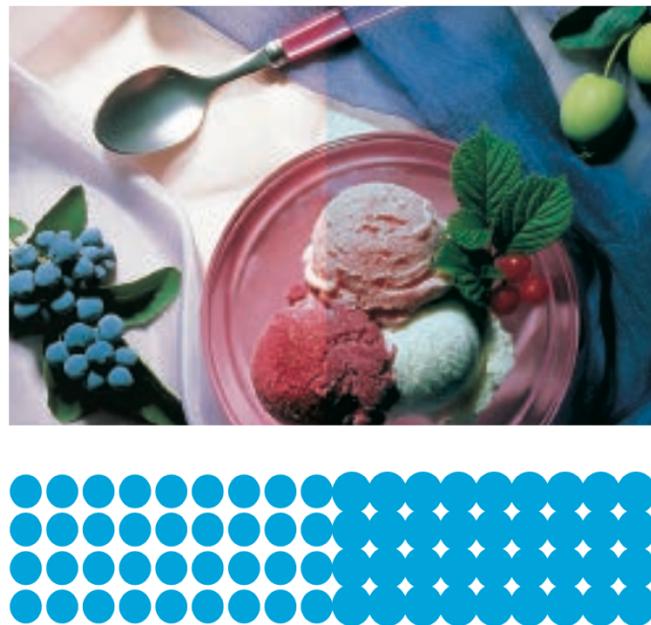


Figure 21 - Effect of abnormal increasing of TVI of cyan in a print result. The right image has a cyan cast.

TVI can be measured in two different ways: from densitometric values and from colorimetric XYZ values. The densitometric TVI is the standard used for many years and is usually referred simply by "TVI" or "Dot Gain". The colorimetric TVI is calculated from XYZ tristimulus and is used when densitometric data are not available or cannot be calculated.

Equation 5 - TVI calculation from densitometric values

$$TVI = 100 \left(\frac{1 - 10^{-(D_T - D_P)}}{1 - 10^{-(D_S - D_P)}} \right) - TV, \quad \text{where}$$

TV is the digital file tone value in 0 – 100 percentage

D_T is the reflectance factor density of the half – tone

D_P is the reflectance factor density of the substrate or paper

D_S is the reflectance factor density of the solid

NOTE: R, G, B density filter need to be selected depending on the ink measured

Equation 6 - TVI calculation from XYZ colorimetric values

$$TVI_C = 100 \left(\frac{X_P - X_T}{X_P - X_S} \right) - TV, \quad TVI_M = TVI_K = 100 \left(\frac{Y_P - Y_T}{Y_P - Y_S} \right) - TV,$$

$$TVI_Y = 100 \left(\frac{Z_P - Z_T}{Z_P - Z_S} \right) - TV, \quad \text{where}$$

TV is the digital file tone value in 0 – 100 percentage

X_TY_TZ_T are the tristimulus values of the half – tone

X_PY_PZ_P are the tristimulus values of the substrate or paper

X_SY_SZ_S are the tristimulus values of the solid

Please note that variations in TVI curve during printing calibration or printing runs does not correlates directly with the visual differences introduced. This is one of the reasons why the two methods proposed in the sections 2.10 and 2.12 below diverge. Despite the different opinions, TVI still be the simplest way to take the dot gain phenomena under control, although it may not be the most accurate.

2.6. Grey in modern printing age

We have seen in the section 2.4 above that most of the grey images are printed using CMYK ink combination, with the K ink that have some contribution to the result, depending on GCR level.

One of the most important research published in modern age was made by Karl Heinz Shirmer in 1955 and published in Germany (25). Shirmer says that the grey reproduced with a printing process made by three colours is not a real grey, because the spectral reflectance is far to be ideally flat, as shown in Figure 22.

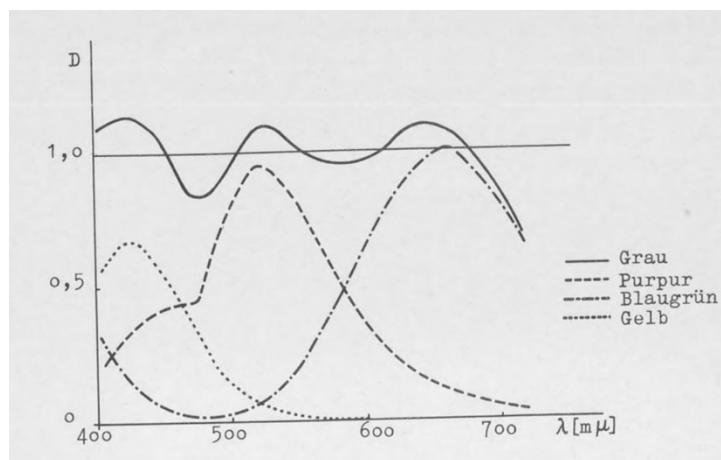


Figure 22 - Spectral density function of a grey composed by three Agfa colorants (25 p. 8)
(note that the wavelengths are wrongly labelled as μm instead nm)

Shirmer also summarize the basis of the grey calibration process, that contains many concepts that are still used today:

- A mixture of C, M, and Y inks in same proportion is not giving a grey because hue shift, typically brown, due to the order in which those inks are printed.
- The explication can be found mainly on some additive behaviour of real subtractive ink-based screened printing process.
- The deviation can be described using a dot gain (today called Tonal Value Increase - TVI - as explained in section 2.5 above) superposition of the different inks.
- The compensation could be calculated linearly in the tone space and has a logarithmic effect in ink density domain, as shown in Figure 23.
- The compensation can be done in the printer or in the original photographic process (today not used anymore, we are doing it on the digital files) with same results.

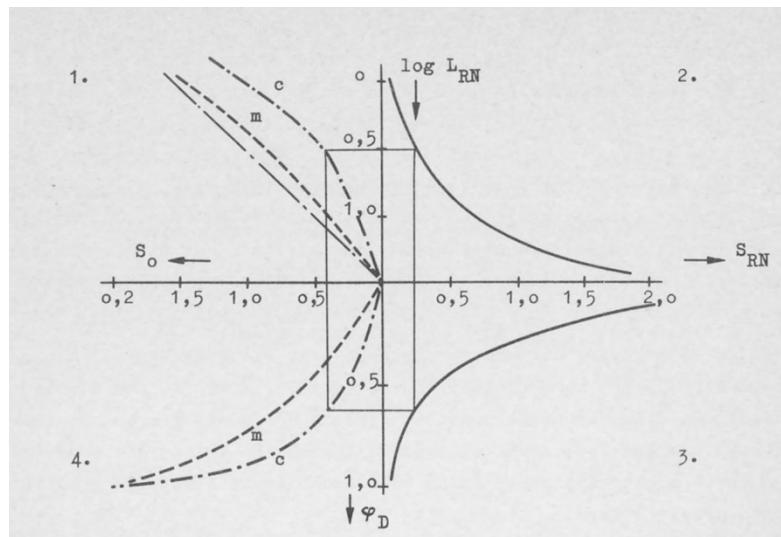


Figure 23 - Schirmer correlation of dot gain curves and logarithmic densities in grey balance (25 p. 31)

The Shirmer's work is very important because is summarizing all the learnings made in those years mainly from USA and Germany, also describing the colour grey reproduction in mathematical terms. Shirmer work was not possible without the Murray model to predict tone reproduction presented in 1936 (20), extended in the year after by Neugebauer for printing processes (21). At that early age, CMYK process was printed using a single ink press, repeating the process four times changing the setup from C, M, Y, to K ink sequentially: that was inefficient, and introduced lot of variability in the final results. From the 1960s till today, grey reproduction using CMYK print processes becomes a very popular topic, due to the increased availability of four-ink presses in all the applications all around the world but is only from early 2000s that the technology allows printing processes stable enough to provide a good grey reproduction. As an example, newspapers in Europe adopted CMYK printing for images less than 15 years ago.

2.7. Definition of grey

When a colour can be defined as "grey"?

The standard definitions found in Oxford dictionary or ISO standards define grey colour as a "colour intermediate between black and white, as of ashes or lead". It is a vague definition, but it introduces first two dependencies: grey depends on white and black references.

To be more precise, we need to define a context and define it in a colorimetric system. Choosing the CIE 1931 standard colorimetric system and pointing to the xy chromaticity diagram of Figure 24, we can say that all the equal-energy stimulus in the centroid of the diagram ($x_E = y_E = 1/3$) are greys, and this include the white and the black.

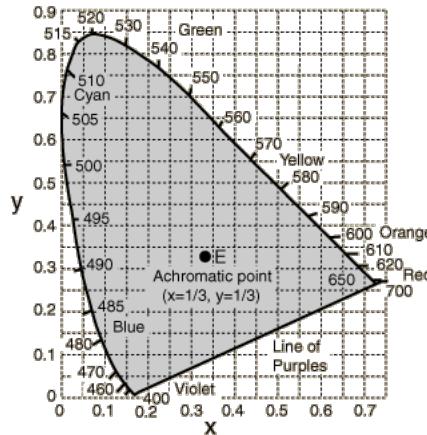


Figure 24 - CIE 1931 chromaticity diagram

The definition above works well in applications like television or digital image encoding, when the only variable is the white point under which XYZ is calculated, called the reference illuminant. Printing on an opaque material, as paper, is considered a reflective case, and from the formulas used to calculate the xy chromaticity is clear the dependency from the reference illuminant and observer chosen:

Equation 7 - Calculation of xy chromaticity coordinates from spectral values

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} X \\ Y \end{pmatrix} \cdot \frac{1}{X + Y + Z}, \quad \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \frac{1}{N} \int_{\lambda} \begin{pmatrix} \bar{x}(\lambda) \\ \bar{y}(\lambda) \\ \bar{z}(\lambda) \end{pmatrix} S(\lambda) I(\lambda) d\lambda, \quad N = \int_{\lambda} \bar{y}(\lambda) I(\lambda) d\lambda$$

where $\begin{cases} \bar{x}, \bar{y}, \bar{z} \text{ are the CiE standard observer functions} \\ S \text{ is the spectral reflectance of the sample} \\ I \text{ is the spectral power distribution of a reference illuminant} \end{cases}$

For graphic arts, the CIE reference illuminant D50 and the 2° observer is defined as a standard for all the colorimetric calculations, as explained in section 2.3.1 above. When the colour has the same energy in XYZ stimulus, can be considered achromatic under the reference illuminant and observer. In this context, all the colours with Y in the range [0, 1] that satisfy the chromatic condition $x = y = 1/3$ are greys.

However, printing means adding inks to a substrate using primary colours, following the subtractive theory. So, in a CMYK printing process the whitest white that is possible to obtain is the substrate (paper) white. This paper white has a specific XYZ colorimetric coordinates under D50/2° condition, that rarely will perfectly match the grey achromatic condition expressed before. We are in a situation in which two different white references conflict in our vision system: the illuminant white reference and the paper white reference. Since is not possible to predict in which condition our eye will adapt, because it depends on many factors like the position of the sample and the amount of unprinted paper area, a common strategy is to consider a compromise between both.

There are different compromises that can be used, for example:

- Grey is a colour that have same chromaticity of the paper

- Grey is a colour that have same chromaticity of a K tone with same luminance
- Grey is a colour with chromaticity that range from that of the paper in the highlights to perfect achromatic in the lowest achievable luminance

The latest one is the best compromise adopted by ISO 12647-2:2013 (15), that also introduces an empirical correction factor of 85%.

Equation 8 - Grey definition as per ISO 12647-2:2013 4.2.8

$$\begin{pmatrix} a^* \\ b^* \end{pmatrix} = \begin{pmatrix} a_p^* \\ b_p^* \end{pmatrix} \left[1 - K \frac{L_p^* - L^*}{L_p^* - L_d^*} \right],$$

where $\begin{cases} L_p^*, a_p^*, b_p^* \text{ is the CIELAB coordinate of the paper} \\ L_d^* \text{ is the CIELAB luminance of the darkest achievable colour} \\ K = 0,85 \text{ is the visual adaptation factor to the paper white} \end{cases}$

The precondition to use the Equation 8 is to know the CIELAB coordinates of the paper and the luminance of the darkest achievable colour; from that point all the a^* and b^* chromatic coordinates can be calculated for every L^* that goes from the paper to the darkest point: the entire grey axis is now well defined.

The use of CIELAB instead the XYZ colour space is preferred because the need to define visual tolerances. Anyway, the transformation from XYZ to CIELAB and vice-versa can be considered as linear (there is a small non-linearity in the formula but can be ignored in this context).

It is important to state that the compromise agreed in the ISO 12647-2 standard is valid for near-neutral papers under D50/2° and is not tested on substrates with high colour chroma (e.g., bright yellows, dark brown, ...) that are also out of scope of this work.

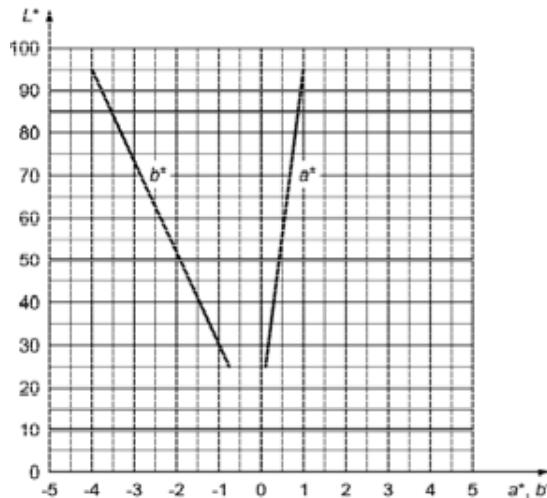


Figure 25 - Example of grey axis of a printing condition with CIELAB coordinates of the paper of [95, 1, -4] and darkest L^* of 25. From ISO 12647-2:2013.

As shown in Figure 25, in the context of the printing condition used in that example all the grey colours rely on the defined grey axis, and what is outside this axis over a certain tolerance cannot be defined

as grey. The axis needs to be considered in three dimensions (L^* , a^* , b^*) but is usually represented with two views a^*/L^* and b^*/L^* for practical reasons. The boundary between what is perceived as neutral grey and what is perceived as a colour is smoothed and depends on the context and the subject reproduced by the image.

Tolerances on the grey axis are usually defined considering geometrical distance in the chromatic plane of CIELAB, as stated by the Equation 9, however there is no agreement on which values can be considered a practical grey chrominance threshold. In other words, there is no agreement when a grey is not considered a neutral grey anymore and start to become a colour. The use of "near-neutral grey" wording used in G7 (10) method does not help.

Equation 9 - Chroma difference formula

$$\Delta C^* = \sqrt{(a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}, \quad \text{where } \begin{cases} a_1^*, b_1^* \text{ is the desired grey chromaticity} \\ a_2^*, b_2^* \text{ is the measured chromaticity} \end{cases}$$

Summarizing the main concept, the definition of the grey in printing is dependent on many parameters: reference illuminant and observer, unprinted substrate white point, darkest achievable colour, and adaptation factor used. The definition still be a simplification as is not considering the context and the cognitive mechanism of memory colours.

2.8. Grey balance in the printing context

Grey balance is the set of C, M, Y, and K values that should allow a neutral grey reproduction in a specific printing condition, so it can be considered a prerequisite for good neutral reproduction in CMYK printing. Without knowing how to achieve the desired grey, it is very inefficient, and almost impossible, to do it with a "try and repeat" process.

It is a direct function of:

- Ink hue of chromatic inks C, M, and Y. In most processes K is achromatic, but in some of them even K has some influence.
- Ink film thickness or density.
- TVI curve of every CMYK ink.

There are other factors that influence the result like: colour sequence during the printing process, ink trapping, screening interferences across colours; those factors are technology dependent.

If the CMYK process inks were perfect colour filters, then equal amount of C, M and Y could be printed superposed and the vision system would receive equal amount of opposite red, green and blue lights.

This result would be seen as a neutral grey, relative to the substrate white point. (9 p. 93)

In real world, pigments that comprise the process colours are not as pure as the theory, and the contamination bring to hue errors. Because the neutral grey requires equal amount of opposite colour lights reflected by the print, the amount of C, M, and Y printed must be adjusted to compensate the hue errors: usually the amount of M and Y need to be reduced, compared to C, as described mathematically by Schirmer (25 p. 22,23,24). An example of hue errors can be seen in Figure 26.



Figure 26 - Example of perfectly neutral grey balance image set (left), simulated brownish hue (centre), simulated bluish hue (right)

Since all the printing process requires a previous calibration, that is made through the printing form exposure or thru digital data, depending on the technology, grey balance can be intended as a precondition or an effect of that calibration.

When the balance is a precondition, fixed CMYK combinations are predetermined, and the role of calibration is to assure that, for those combinations, the result is grey as defined in section 2.7 above. When the balance is an effect of the calibration, the CMYK combinations that allow a grey balance can be found analysing the characterization of that process before the calibration.

Both approaches are valid and has generated the two methods used the first in USA, and the second in Europe, as explained in the section 2.12 below.

2.9. Reproduction of greys in printing

A neutral grey in CMYK printing can be obtained conceptually in three different ways, as anticipated in section 2.4 above:

1. Using a tone composed only of black (K) ink, assuming that the ink is achromatic.
2. Using specific percentages of tones of cyan, magenta, and yellow inks (CMY).
3. Using specific percentages of tones of cyan, magenta, yellow, and black inks (CMYK)

The usage of black ink only is not so common because, even if the grey reproduction is usually colorimetrically perfect and very robust against printing process variations, other image quality attributes like graininess are usually not acceptable.

On the contrary, CMY combinations are instable, because product of three different contributors, but provide a very good graininess and pleasant visual appearance.

For these reasons, in day-to-day work is common to use a mix of the two approaches, and the grey colours are composed by a CMYK tone combination in which, depending on the printing process itself, K can be more or less dominant against CMY contribution.

During the calibration process, and during the process control operations, is a good practice to keep the K as a reference for lightness and hue for CMY ink channels. The control of K channel is done usually independently, and the CMY grey balance is fine tuned to match the neutrality condition under defined tolerances. If CMY is neutral, the assumption is that the same ratio between C, M, and Y mixed with a certain amount of K is also neutral. This is true for printing processes when the K ink is neutral on the entire tone range, as lithographic offset or flexographic, but cannot be true for digital printing processes.

The reproduction of grey in CMYK printing is therefore linked to a grey definition, a grey balance, and a calibration process that allow a grey reproduction.

Grey definition, as shown in section 2.7, is well standardized and accepted all around the world.

Grey balance, on the contrary, is interpreted in a different way depending on the method used, as explained in section 2.8.

Therefore, inevitably, the calibration processes will differ depending on grey balance adopted: when grey balance is a precondition there are more rules to follow, compared to the methods that inherit the grey balance from the result of the calibration.

The first approach that uses a fixed grey balance was codified in the G7® method (10), born in USA, explained in section 2.10 below.

The second approach emerged between the printer manufacturers and printer companies in Germany and more broadly in all Europe: since it is based on the dot gain analysis, it could be called the TVI method and is explained in the section 2.11.

2.10. The G7 method

G7® is a method introduced in 2006 by IDEAlliance association in USA based on the coral work of many US experts, inspired by the work made by Ansel Adams on the Zone System cited in section 2.2 above, also inspired by his research on photographic sensible papers development techniques. G7 name come from the seven grey zones used to control the reproduction in the first version of the standard.

G7 is both a definition of grey scale appearance, and a device independent calibration method for CMYK printing processes using a 1-dimensional curves. (10 p. 4)

2.10.1. Grey definition

The main innovation of G7 is that it defines how a grey scale should appear to the human eye, independently on the printing process. Contrast in highlights is preserved, regardless of the dynamic

range, while darker tone values are compressed or expanded to meet the capabilities or limitation of the printing process. This means that the same image printed on different printing processes with different dynamic ranges will exhibit relatively consistent lightness and perceived contrast.

G7 uses the substrate relative colorimetric Y density called Neutral Print Density (NPD), which value is approximatively equal to the ISO 5 visual status density:

Equation 10 - Neutral Print Density from XYZ

$$NPD = -\log_{10} \left(\frac{Y}{Y_S} \right), \quad \text{where } Y_S \text{ is the luminous reflectance factor of the substrate}$$

NPD allows to use a manual calibration procedure based on fan graph, pencils, and a densitometer, as shown in Figure 27, reducing the needs of sophisticated tools.

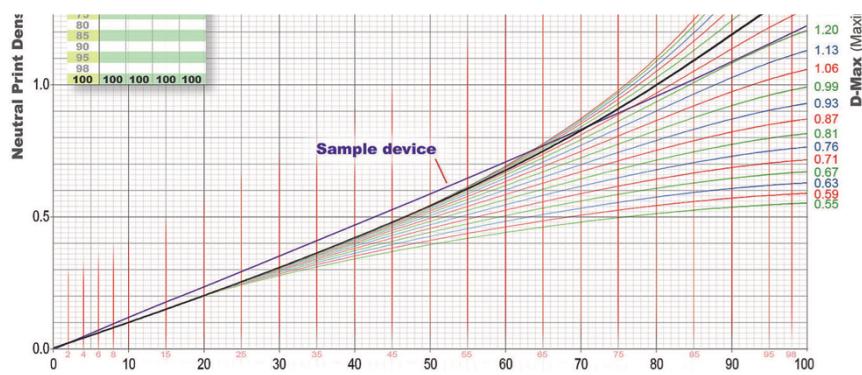


Figure 27 - Typical CMY sample device graph - from G7 How-To

NPD can be calculated also from CIELAB measurements taken by a spectrophotometer, losing the visual fan graph approach, and requiring a spreadsheet or a software. This is the most used G7 implementation today since it is prone to be automated.

2.10.2. Grey balance

G7 uses a unique way to correlate grey balance and grey reproduction and is based on two assumptions: the 3-colour near-neutral tone-scale, and the target NPD curves.

The 3-colour near neutral tone scale is defined as a set of C, M, and Y tone value triplets that have the relationship defined by the Equation 11 (26):

Equation 11 - G7 near-neutral tone scale

$$M = Y = 0.747 \cdot C - 4.1 \cdot 10^{-4} \cdot C^2 + 2.94 \cdot 10^{-5} \cdot C^3,$$

where C is the tone value of cyan in range [0 – 100],

M and Y are the tone value of magenta and yellow

The target NPD curves for CMY and K can be calculated with the formulas provided by the CGATS TR015 paragraphs 5.4 and 5.5 (26), since the formulas are quite complex and out of scope for this document, in the equation below we summarize the dependencies:

Equation 12 - Conceptual function to calculate NPD

$$NPD(TV) = f(Y_D, Y_L, Y_R(TV), Y_C, R_A, R_R),$$

where

Y_D = luminous reflectance factor of the dark end of the black scale

Y_L = luminous reflectance factor of the substrate (paper)

$Y_R(TV)$ = luminous reflectance factor corresponding to the reference NPD curve

Y_C = control point along NPD curve in which the scaling of Y_R is initiated

R_A = actual reflectance range based on the light and dark ends of the tone scale

R_R = defined reflectance ratio that is used to adjust subsequent scaling of the data

The NPD defines only the lightness (L^*) of the references, additional formulas are provided to complete the definition in the chrominance place (a^* , b^*) as shown in the Equation 13.

Equation 13 - G7 CMY near-neutral tone scale colour - from CGATS TR015

$$\begin{pmatrix} a^*(TV_C) \\ b^*(TV_C) \end{pmatrix} = \begin{pmatrix} a_S^* \\ b_S^* \end{pmatrix} \left(1 - \frac{TV_C}{100} \right),$$

where

$a^*(TV_C)$, $b^*(TV_C)$ are the modified chrominance values,

a_S^* , b_S^* are the chrominance of the substrate (paper),

TV_C is the cyan tone value of the 3 – color near – neutral scale

Once the NPD curves are calculated, both the grey balance and the grey definition can be considered well defined.

2.10.3. Calibration

The G7 calibration is made using the NPD metric with a 2-step process:

1. Calibrate the NPD curves of the K and CMY to the reference NPD calculated as explained in the previous section
2. Fine-tune the M and Y curves to achieve a good grey chrominance (a^* and b^*) using the reference calculated with the Equation 13

There are no details about how to calibrate the curves: a reference commercial software and some utility charts are provided, but the mathematics behind it is not publicly shared.

2.11. The TVI method

The calibration method widely used in Europe is based on dot gain calibration and, as explained in the section 2.9 above, does not take grey balance as an input parameter, as G7 does. Since is not uniquely codified, more than a method can be considered a conjunction of best practices that every user can adapt to his needs. Those best practices or recommendations come from the German school tradition, the *Forschungsinstitut für Medientechnologien* (FOGRA) institute and *Bundesverband Druck und Medien* (BVDM) association; the targets and tolerances are also described in the current ISO 12647-2:2013 standard (15).

The starting point of the TVI calibration method of a CMYK printing process is to fix a printing condition where the 100% solid C, M, Y, and K matches under some tolerances with predefined targets. ISO 12647-2 define those target and tolerances in CIELAB values and colour differences, but previous standards used densitometry instead colorimetry. How to reach those targets is technology dependent. To measure the TVI curves (see section 2.5) from the actual printing condition, the printing form or the digital compensation curve need to be set as identity. It means, what it is needed is to measure the natural tonal value increase of every C, M, Y, and K ink without any calibration applied. Usually this is done with a special test file that contains a four-colour scale that allow it, as shown in Figure 28, measured usually with a densitometer, in some cases with a spectrophotometer.

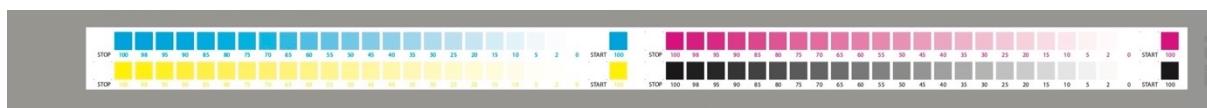


Figure 28 - CMYK TVI calibration scale of a test printing file form - courtesy of TAGA Italia

The objective of the process is to bring measured curves, as shown in Figure 20, to target TVI curves defined by some standard as, for example, the FOGRA52 shown in Figure 19.

The transformation from the measured curve to the target curve is a 1-dimensional problem that need to be repeated for every ink independently: in a CMYK process four different compensation curves need to be calculated.

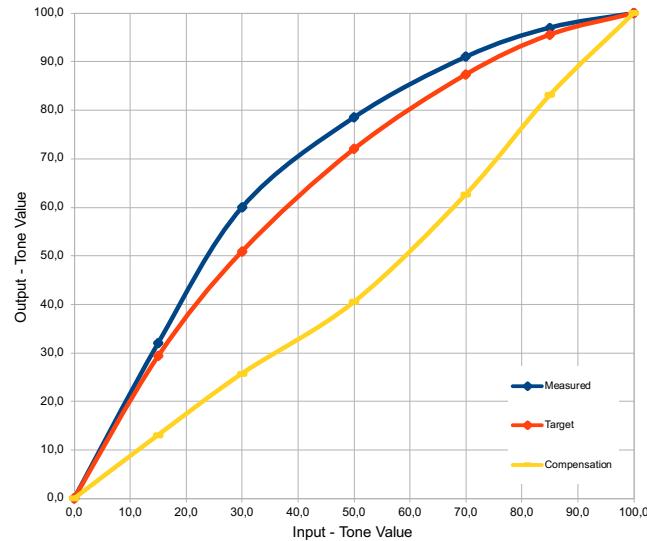


Figure 29 - Example of TVI calibration, shown in TV domain

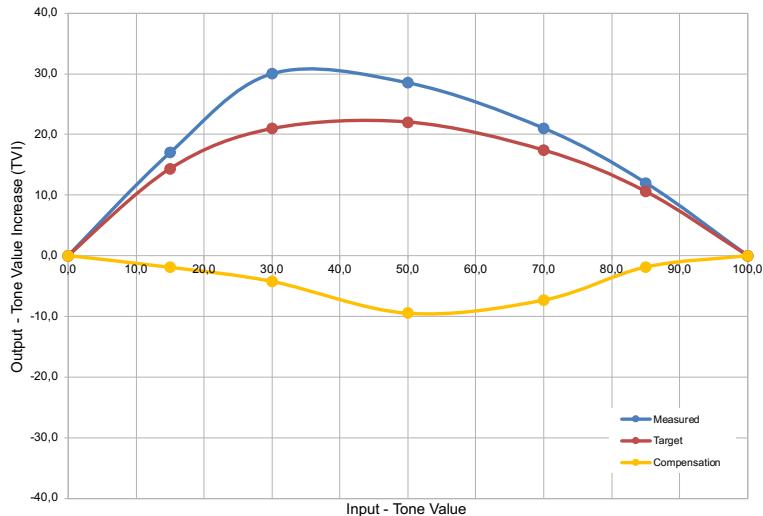


Figure 30 - Example of TVI calibration, same as Figure 29 but in TVI domain

Equation 14 - generic TVI calibration process

$$TVI_F = \text{comp}(TVI_M, TVI_T),$$

where:

TVI_F is the final TVI curve

TVI_M is the measured TVI curve

TVI_T is the target TVI curve

$\text{comp}()$ is the compensation function

We can express the calibration as a generic function that transform the measured TVI curve using a compensation function or curve. This compensation curve needs to be calculated for every ink and is dependent both on measured and target TVI curves, as shown by Equation 14. So, the calibration of a

specific CMYK printing condition to a defined target is in fact the calculation of four different compensation curves, one for each primary colour.

As you can see, all the process is done using densitometric TVI values and is not taking in consideration colorimetry nor the grey definition target to achieve. The calibration is blind to grey reproduction because the objective is different: it is to calibrate the contrast of single ink channels to some standard. The TVI method is able to achieve a decent grey balance only if the CMY inks are well balanced between them, and the natural press dot gain is not introducing big variations in the single TVI curves. ISO 12647-2, the standard that describe the offset lithographic process control, provide normative targets ad tolerances only for TVI curves, adding a spread tolerance intended as the maximum difference allowed between C, M, and Y curves in the 50% mid-tone value. The note 2 of section 4.2.8 of the standard says: "*The grey balance of a given printing process can be used for process calibration and process control as long as the tolerances for tone value increase and mid-tone spread as defined in Table 11 are not exceeded.*" (15)

It means that when following the TVI calibration tolerances, a kind of grey reproduction is possible but need to be controlled using other framework and tools.

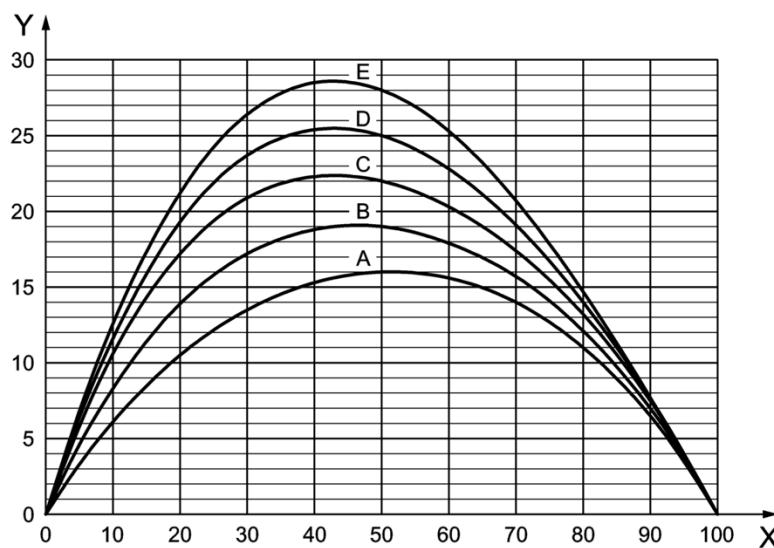


Figure 31 - TVI curves of ISO 12647-2:2013 standard printing conditions

Tone value of control patch	Values in percent	
	Deviation tolerance OK print	Variation tolerance Production print
< 30	3	3
30 to 60	4	4
> 60	3	3
Maximum mid-tone spread	5	5

Figure 32 - The Table 11 of the ISO 12647-2:2013 standard:
TVI tolerances and maximum mid-tone spread for calibration ("OK print" column)

TVI calibration method can be applied in all traditional printing processes like flexographic, gravure, screen printing, with minimal or no changes, and is compatible only with some digital printing process.

For example, it is possible to calibrate an HP Indigo® as shown in Figure 1 with densitometric TVI, when using CMYK press configuration. Other inkjet printing processes requires at least colorimetric TVI measurements and target, as shown in section 2.11, and most of them are calibrated using different methods and metrics.

2.12. Differences between G7 and TVI methods

The differences of the two methods seen in sections 2.10 and 2.11 can be summarized in the Table 3. Since the requirements of the ISO 12647-2:2013 TVI method are wider than G7 tolerance schema, standard TVI calibration can be considered as a basis that allow to achieve G7 grey balance condition.

Table 3 - Differences between G7 and TVI calibration methods

	G7	TVI
Grey definition	Based on NPD reference curves, and substrate	Based on substrate and darkest achievable colour
Grey balance	Fixed: same near-neutral tone scale for all printing conditions and processes.	Variable: depending on the natural inks balance after TVI calibration
Grey reproduction	Normative: weighted luminance and chrominance tolerances ($w\Delta L^*$, $w\Delta C^*$) derived from NPD reference curves metrics.	Informative only: chrominance tolerances (ΔC^*)
Tonal calibration	Based on NPD reference curves	Based on TVI curves
Calibration method	Reference software implementation, or manual charts.	User is free to use whatever method is suitable.
Measurements	Colorimetry (densitometry used only for legacy manual NPD method)	Densitometry (colorimetry necessary only in some digital printing process)
Applicable to digital printing	Yes, the method is process independent	Only when screened CMYK processes

Since G7 method was created with the objective to achieve a good grey reproduction across different printing processes, it is undoubtedly better to achieve it in this context. However, G7 calibrated workflow works well only when the original data to be printed are prepared using G7 grey balance defined in 2.10.2. All the standard printing characterizations used in USA, like SWOP® or GRACoL®, are created on top of G7 grey balance. When the printed data are prepared aiming different characterizations like, for example, FOGRA51 or FOGRA52, the intended grey balance is different, and a colour management

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transformation is required with the risk of introducing errors or inaccuracies. Going from a G7 standard characterization to a custom printing characterization based on G7 grey balance requires minimal changes, and the colour management system could take advantage of that to keep grey reproduction under a precise control. Even if G7 method does not recommend, it is a common practice to print directly G7 standard digital files to a G7 calibrated printer without any colour management, often with good results. This is impossible starting from a characterization that does not underly on G7 grey balance.

At the time of writing, ISO 12647-2 standard is under review by ISO/TC130 committee with the goal to include the main concepts of G7 method, keeping the TVI target and tolerances.

3. Design and Implementation

3.1. Calibration process

The calibration process is designed to fulfil both ISO 12647-2 TVI and G7 target and tolerances and is a tentative to merge the two methods. Particularly, the work wants to identify benefits and possible pitfalls when starting from data prepared aiming a characterization not following the G7 grey balance: FOGRA characterizations are the best candidates because widely used in Europe.

- 1) Input data set-up
 - a) Definition of input data characterization and grey balance
 - b) Preparation or adaptation of a test form that contains all the charts to be measured
- 2) Printer set-up
 - a) Substrate and printer setup
 - b) Targets and tolerances of CMYK solid CIELAB
 - c) Targets and tolerances of CMYK TVI curves
- 3) Linear (uncalibrated) print run
 - a) Achieve solid targets of 1.b
 - b) Measure uncalibrated TVI
 - c) Calculate compensation curve
 - d) Apply compensation curve to printing form or digital data
- 4) Calibrated print run
 - a) Validate calibrated TVI with target and reference of 1.c
 - b) Calculate the fine-tuned grey reproduction for M and Y curves
- 5) Grey balanced print run
 - a) Validate calibrated TVI with target and reference of 1.c
 - b) Validate grey reproduction using different metrics
 - c) Validate grey reproduction visually, comparing results of 3, 4 and 5

The calculation of the TVI compensation curve of the step 3.c will be made transforming TVI to TV curves and describing it with a linear polynomial regression based on least-squared method. Once the TV are described as polynomials, the compensation points can be calculated.

The calculation of fine-tuned grey reproduction will be done with a search method in a LUT of values, as the reference G7 implementations. All the relevant steps are implemented in MATLAB scripts, with intermediate help of Excel files or format-conversion external software.

3.2. Grey definitions

The definition of the grey axis was done following the method standardized in ISO 12647-2:2013 (15) and described in section 2.7 above. The substrate chosen is candidate to match FOGRA51 characterization (4), that is a standard for CMYK lithographic offset printing on coated paper using periodic screen.

Table 4 - Comparison of the substrate with FOGRA51 standard characterization

Substrate	Lecta GardaGloss Coated Paper 150gr/m ²
White point (measured)	$L^*=94,80$ $a^*=1,17$ $b^*=-5,85$
White point (from FOGRA51)	$L^*=95,00$ $a^*=1,50$ $b^*=-6,00$
White point difference	$0,48 \Delta E_{00}$
Darkest achievable colour (from FOGRA51)	$L^*=11,43$

Since the substrate white point is less than $2 \Delta E_{00}$ from the FOGRA51 white point, as suggested by the standard the deviation could be considered production tolerance, and the original FOGRA51 grey axis can be calculated with the formula proposed in the section 4.2.8 of ISO 12647-2:2013 (15). As presented in Figure 33 the grey axis is represented in a^* and b^* projections from $L=95$ to $L=11,43$ as straight black lines.

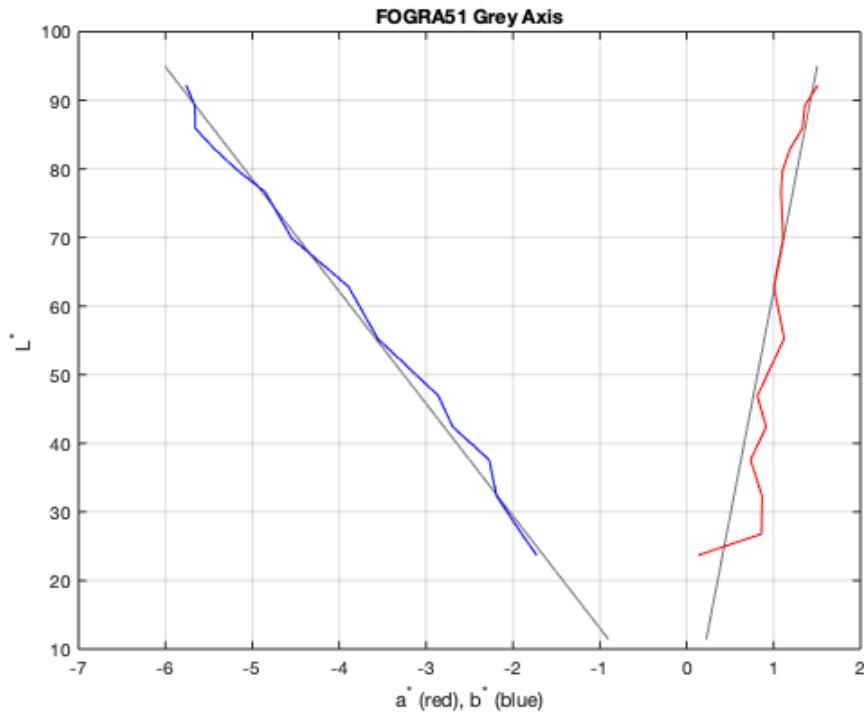


Figure 33 - Theoretical grey axis (black) and the expected reproduction target, considering 8-bit quantization used in TIFF images

The resulting grey axis is shown in Table 5, when the TV column refers to the equivalent K TV in percentage.

Table 5 - FOGRA51_GreyAxis.txt output of MATLAB code Grey_Balance_Extractor.m

TV	CMYK_C	CMYK_M	CMYK_Y	CMYK_K	LAB_L	LAB_A	LAB_B
5	3,53	2,75	2,75	0,00	92,20	1,51	-5,76
10	7,45	5,49	5,49	0,00	89,24	1,36	-5,66
15	11,76	8,63	8,24	0,00	85,93	1,33	-5,66
20	15,69	11,37	10,98	0,00	82,97	1,19	-5,44
25	20,00	14,51	14,12	0,00	79,69	1,10	-5,16
30	23,92	17,65	17,25	0,00	76,62	1,09	-4,85
40	32,55	24,71	23,92	0,00	69,91	1,11	-4,55
50	41,57	32,55	31,76	0,00	62,87	1,00	-3,89
60	51,37	41,96	40,39	0,00	55,25	1,12	-3,55
70	62,35	52,94	51,37	0,00	46,92	0,81	-2,86
75	68,24	59,61	57,65	0,00	42,37	0,91	-2,69
80	74,51	66,67	65,10	0,00	37,59	0,73	-2,27
85	81,57	76,08	74,12	0,00	32,29	0,87	-2,19
90	90,59	88,63	86,27	0,00	26,79	0,86	-1,90
95	97,65	99,22	97,65	0,00	23,67	0,13	-1,73

Using a CMY-only ICC profile created from FOGRA51 characterization (4), is possible to calculate the grey balance in terms of C, M, Y combinations of incremental discrete values of L* gotten from the corresponding L* value of a uniform sampling of K channel with increments of 5% (from 5% to 95% for a total of 15 data points)

The corresponding CMY values, expressed in floating point, are then rounded to 8-bit and the expected L*, a*, b* values are then recalculated. The rationale behind this step needs to be found in the context of the use of a neutral grey calibrated print process: usually the grey neutrality is desired and evaluated printing images. The most common image file format used in professional graphic environments is the 8-bit CMYK TIFF. Moreover, in workflows when the images are provided in 8 or 16-bit RGB, the colour transformations can or cannot be done in floating point or 16-bit: 8-bit is the minimum lower case implemented by the different vendors. Describing and evaluating the grey axis considering 8-bit quantization rounding, allow to calibrate a process considering the worst case of image definition.

The result of the 8-bit rounded grey axes, limited to the luminance range gotten from [5-95%] K, can be seen in Figure 33 expressed by the red and blue lines, and will be our target for grey reproduction.

These steps are implemented in the MATLAB script Grey_Balance_Extractor.m which flowchart is shown in Figure 34.

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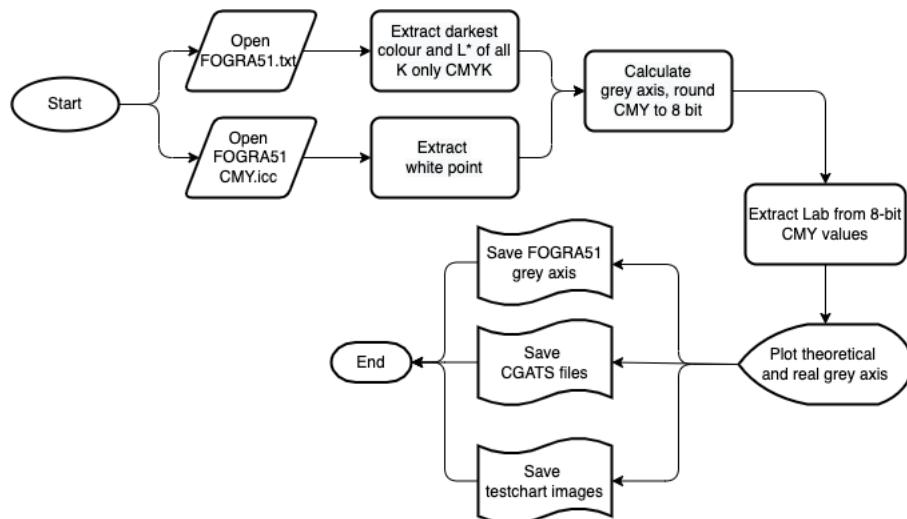


Figure 34 - Flowchart of Grey_Balance_Extractor.m

The script takes in input:

- FOGRA51.txt: FOGRA51 characterization as provided in CGATS file format from FOGRA (4)
- FOGRA51 CMY.icc: ICC CMY profile build from FOGRA51 characterization with a dedicated profiler software
- CIELABD50.icc: synthetic ICC profile needed by MATLAB to perform CMY to CIELAB and CIELAB to CMY transformations
- Grey scale arbitrary steps [5 10 15 20 25 30 40 50 60 70 75 80 85 90 95]
- PS0Coated_v3.icc: official CMYK ICC profile for FOGRA51 characterization, used to verify the data

And the output is made of:

- FOGRA51_GreyAxis.txt: Summary of the CMY balance values and the target CIELABs, as shown in Table 5. Note that the table is defined using CMY values only (K is zero), because one of the assumptions of the entire process is that K channel is not adding chromaticity. This assumption may not be true in all printing processes.
- Test charts and reference CGATS files to print, measure and fine-tune the grey reproduction

3.3. Calibration

The calibration process is the most manual and complex of the entire study because it depends on many details related with the chosen printing technology and available tools. The test was made on the following conditions:

Table 6 - The test printing condition

Printing technology:	Electrophotographic HP Indigo® 12000 HD CMYK printer Screened periodical output 150 lpi (lines per inch)
Spectrophotometers:	X-Rite eXact, X-Rite i1 rev.2 and Konica Minolta FD-9, all ISO 3664 M1 complaints
Substrate:	Lecta GardaGloss coated paper 150 gr/m ²
Software and tools:	Microsoft Excel® for on-site quick validations MathWorks® MATLAB® for preparation and post validation X-Rite i1Profiler® and BabelColor Patch Tool® for testchart preparation BVDM Roman16® evaluation images (24) Adobe Illustrator® for test form preparation Callas pdfToolbox® for final PDF verification

3.3.1. Test form

A 7 pages test form was created considering all the requirements of the printing workflow, the spectrophotometers, and the software used. The creation of the test form needs to take into consideration the maximum printing area of the press, the possible non-uniformity of the printed images, and the limits imposed by the spectrophotometers used. The form was created using Adobe Illustrator™ and the charts were generated by the MATLAB scripts or by commercially available software as, for example, Babel Color Patch Tools™. Images used come from BVDM Roman16 reference images set (24), specifically created for visual assessment of different colour area in printing.

The first pages allow to measure the different characteristics of the print with spectrophotometers, the last pages contain images and are used for visual evaluation and visual comparison.

Optimization of grey reproduction in CMYK printing processes

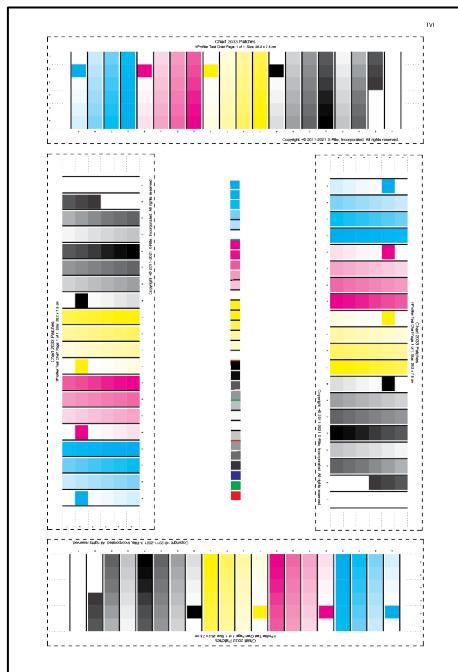


Figure 35 - Test form page 1: TVI calibration page

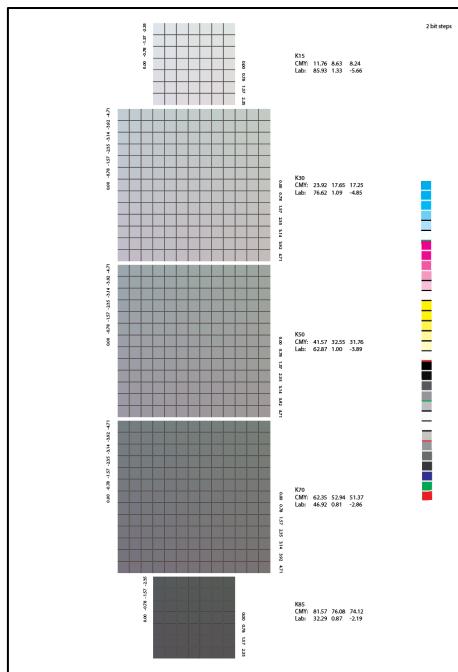
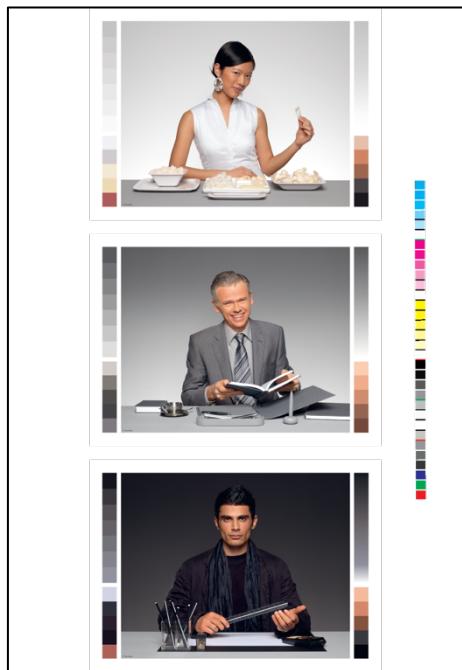


Figure 36 - Test form page 2: grey reproduction calibration page

The TVI page is used in the first step of the calibration and contains charts to measure TVI. To mitigate print homogeneity variability, four charts are printed rotated 90° each one in the page. The central quick chart is used by an Excel sheet to quickly validate the conformance of printing (out of the scope of this document), as the production quality control process establish by the hosting company corGae.



Two versions of three Roman16 (24) images are used to visually evaluate the grey reproduction. All images were separated into 8-bit CMYK TIFF files using a standard FOGRA51 characterization (PSOCoated_v3 ICC profile) using perceptual rendering intent from the original 16-bit RGB images, to simulate a standard reprographic professional process.

The first three images contain near-neutral greys in the highlights, mid tones, and dark tones. The second set is composed by the same images provided in pure black and white RGB: when converted to CMYK the grey reproduction is achieved only if the C,M,Y, and K balance is perfect.



Figure 37 - Test form pages 3,4: Roman 16 images for grey visual evaluation

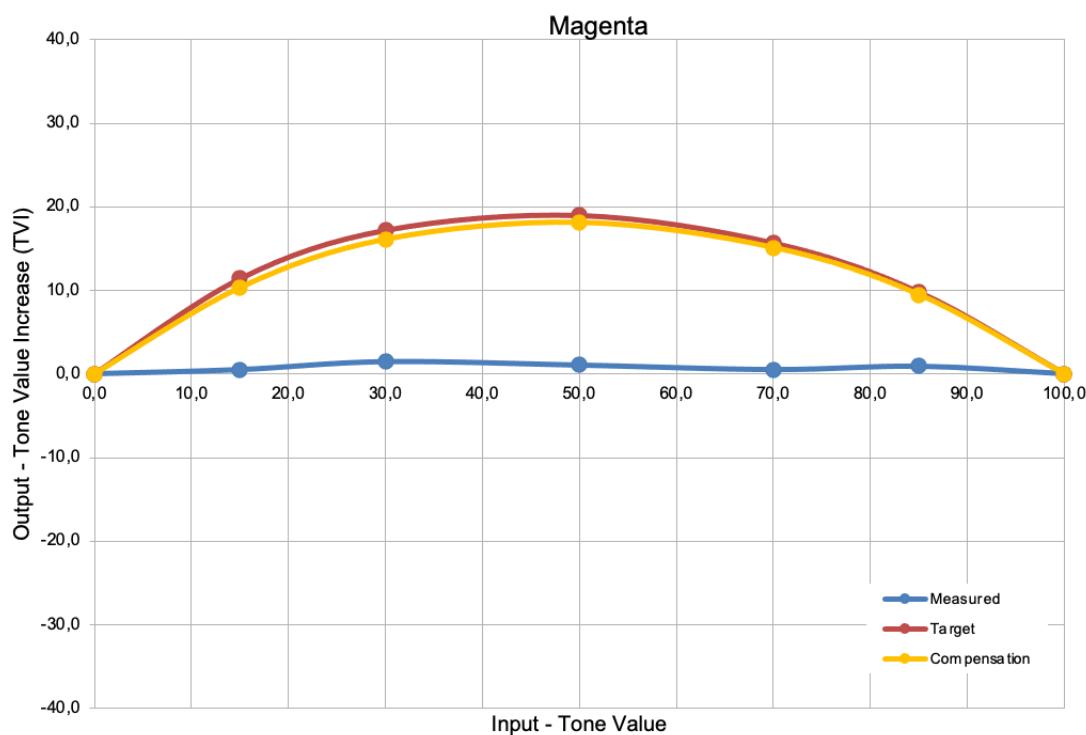
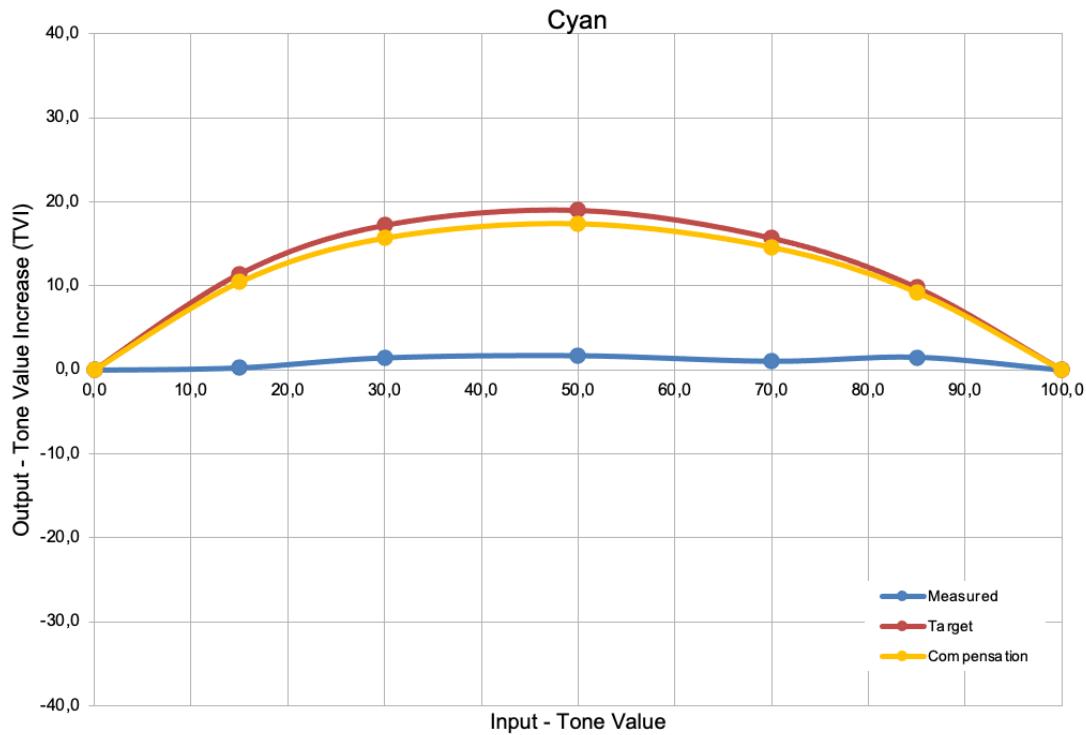


Figure 38 - Test form pages 5,6,7: Roman 16 images for generic visual evaluation

The last pages contain a subset of other Roman16 (24) images to visually validate the effects of the TVI and grey balance calibrations steps. It is not in the scope of the described process to achieve colour coherence in all colour area.

3.3.2. TVI calibration

Following the process described section 2.11 above, the process is first calibrated to the standard ISO 12647-2:2013 TVI curve B (see Figure 31), starting from a linear LUT printing. This step is the precondition both to have the best dynamic contrast and agree with the FOGRA51 calibration. By a grey reproduction point of view, under certain limits every tone calibration fits well as a starting point. The TVI calibration is made with a linear regression made by an Excel file: the process is quite trivial, and the details are out of the scope of the current document. The result is a CMYK LUT (look-up table) that need to be uploaded in the printer workflow and that will be applied to all the further print runs. Please note that the original linear TVI curves reproduction was very close to the desired result and probably all the process would have worked well even without this step.



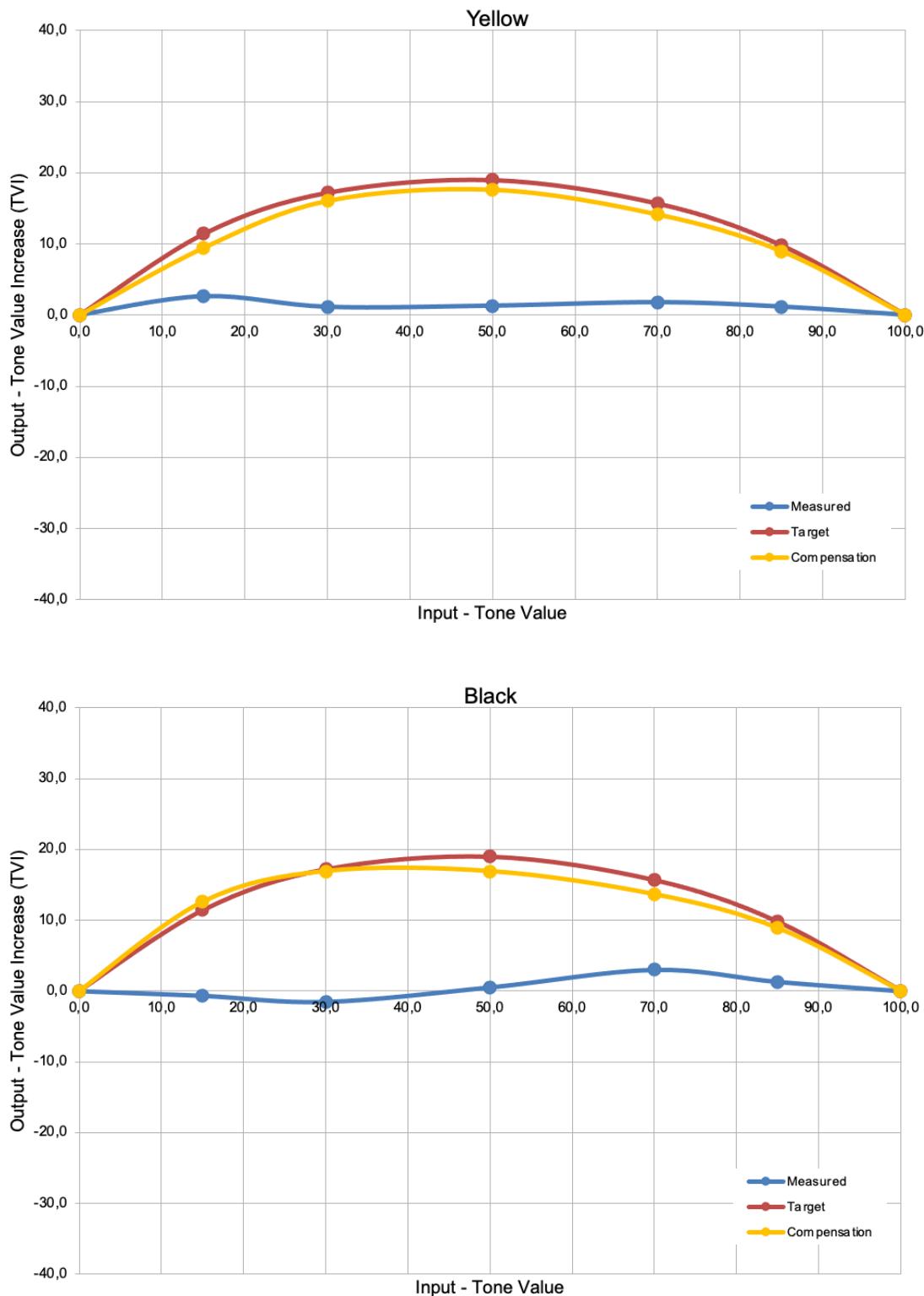


Figure 39 - TVI measured, and correction calculated curve from a linear condition.

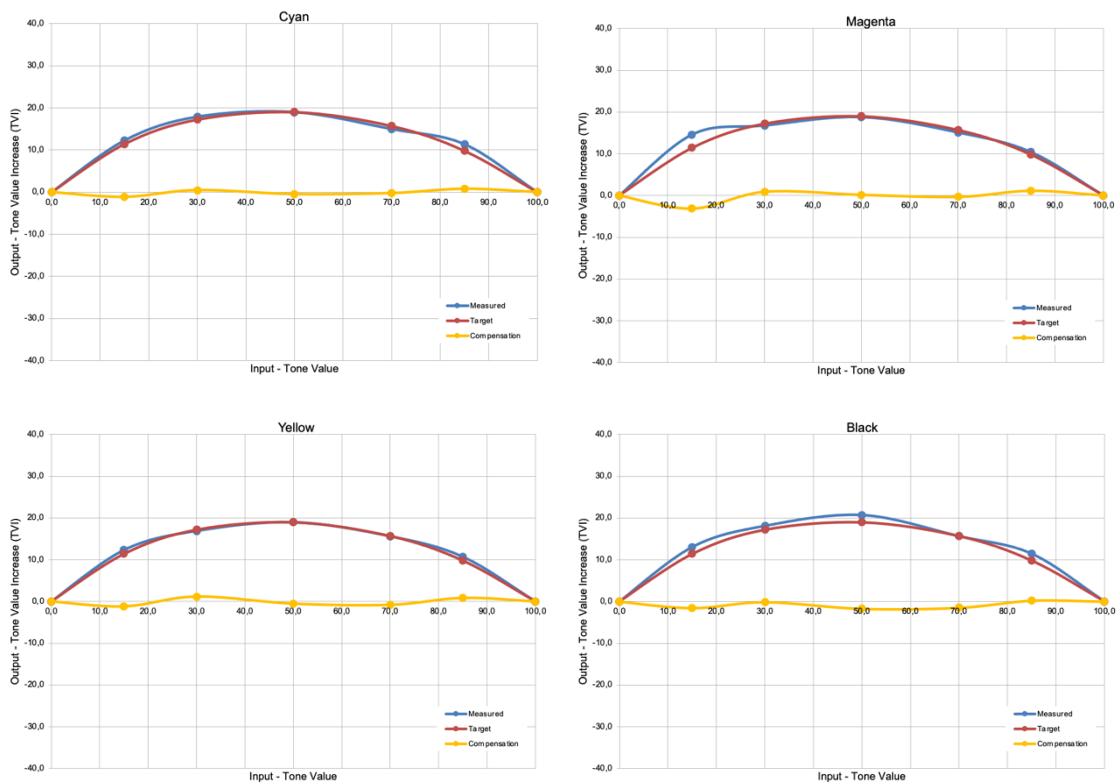


Figure 40 - TVI measured to verify the corrected condition, with residual correction to be applied.
The further correction was not applied because inside the noisy variability of the system.

3.3.3. Grey reproduction fine tuning

Once the printing system is TVI calibrated, is ready to be fine-tuned for grey reproduction.

The process is coded in the `Grey_Finder.mlx` MATLAB script which flowchart is shown in the Figure 41.

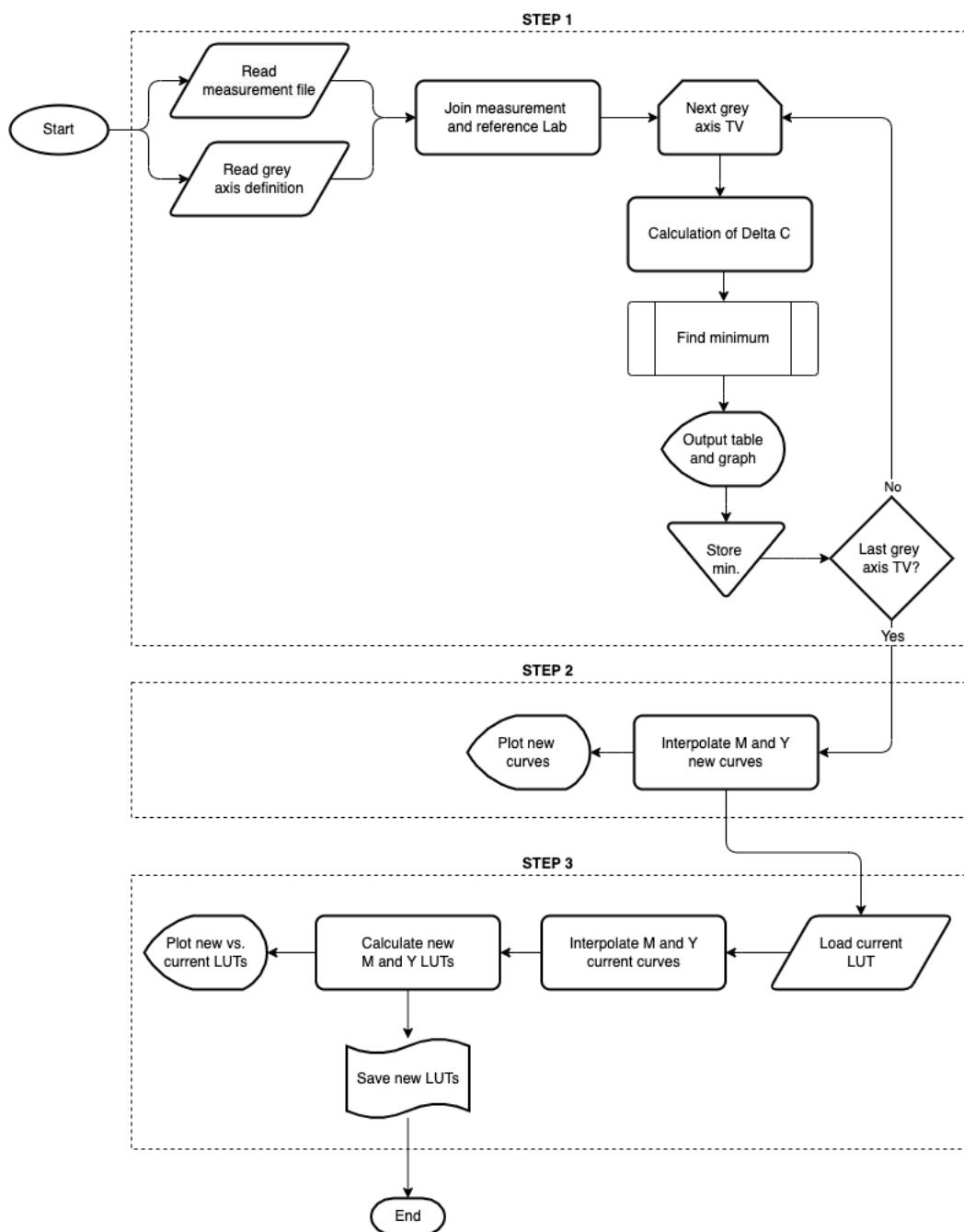


Figure 41 - Flowchart of MATLAB script `Grey_Finder.mlx`

The script takes in input:

- CIELAB measurements of the second page of the test form, combined with the target grey axis values calculated in the section 3.1 above
- Current LUT.xlsx: Current CMYK LUT calculated during the TVI calibration of section 3.3.2

The script provides in output:

- Several graphs to evaluate the calculations
- Calibrated LUT.xlsx: Contains the re-calculated M and Y LUTs that should provide the desired grey reproduction

The steps of the fine tuning are:

1. Find the 5 neutral points keeping C fixed, and moving only M and Y
2. Calculate the M and Y correction curves in the entire tone range using a spline interpolation
3. Calculate the new M and Y LUTs applying the correction to the TVI calibrated LUTs

STEP 1: Find the neutral points

To understand this step, it is important to analyse how the chart of Figure 42 is done. Five charts are generated automatically by the script as described in Figure 34, chosen as arbitrary points in the entire tonal range. As a best practice the samples 15, 30, 50, 70, and 85 are chosen from the Table 5. Every one of these charts, of dimension of 7x7 or 13x13 patches, contains a central patch that represent the identified CMY combination: in theory it should provide the ideal CIELAB value. Around every patch, the M and Y channel are incremented in a range of +/- 3 steps for the lighter and the darker, and +/- 5 steps for the mid-range tones. Every step contains increment of 2 bits (0,78% TV).

Since the C channel is constant for every chart, the result is a hue variation that goes from less to more magenta in x direction, and less or more yellow in y direction. If the grey reproduction were perfect, the central patch of every chart will match exactly the CIELAB values calculated. In practice this never happens, and the fine tuning is made finding the patch of every chart that has the lowest delta with the target value.

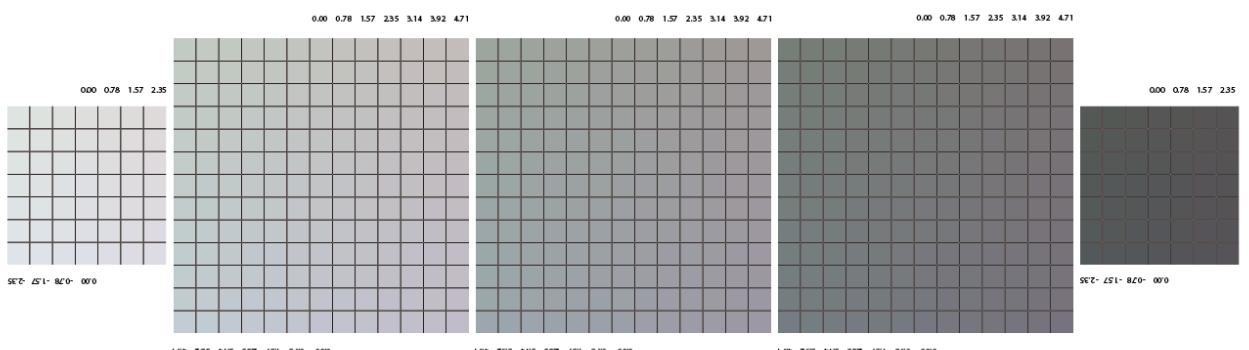


Figure 42 - The five grey reproduction charts

For the five TV points the result of the finding is an increment/decrement of the M and Y values of a specific value.

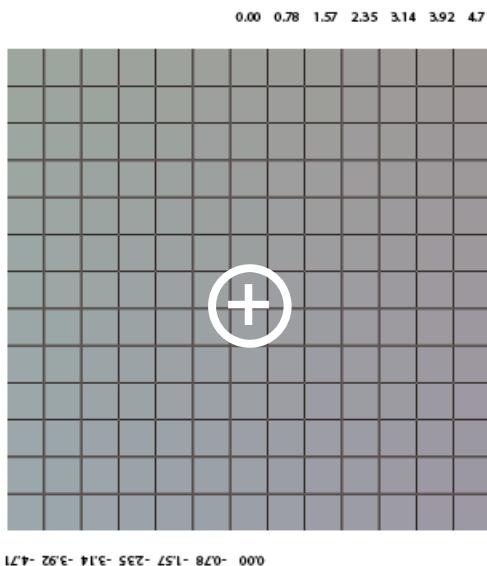


Figure 43 - Example of perfect grey reproduction - the central patch has the lower delta vs. target CIELAB value: no M and Y correction needed.

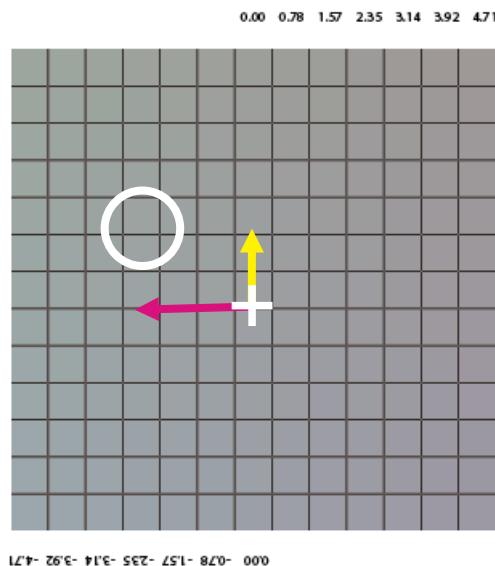


Figure 44 - The enhanced patch has the lower delta vs. target CIELAB: requires M correction of -2,35 and Y correction of +1,57 (simulated example)

NOTE: that process was originally described by G7™ method (10 p. 10).

The resulting table of the calibration test made, as calculated by the script Grey_Finder.mlx:

Table 7 - Original and fine-tuned grey balance

1 C	2 M	3 Y	4 NEW_M	5 NEW_Y
0	0	0	0	0
11.7647	8.6275	8.2353	7.0588	9.0196
23.9216	17.6471	17.2549	16.0784	19.6078
41.5686	32.5490	31.7647	32.5490	32.5490
62.3529	52.9412	51.3725	53.7255	52.1569
81.5686	76.0784	74.1176	76.0784	75.6863
100	100	100	100	100

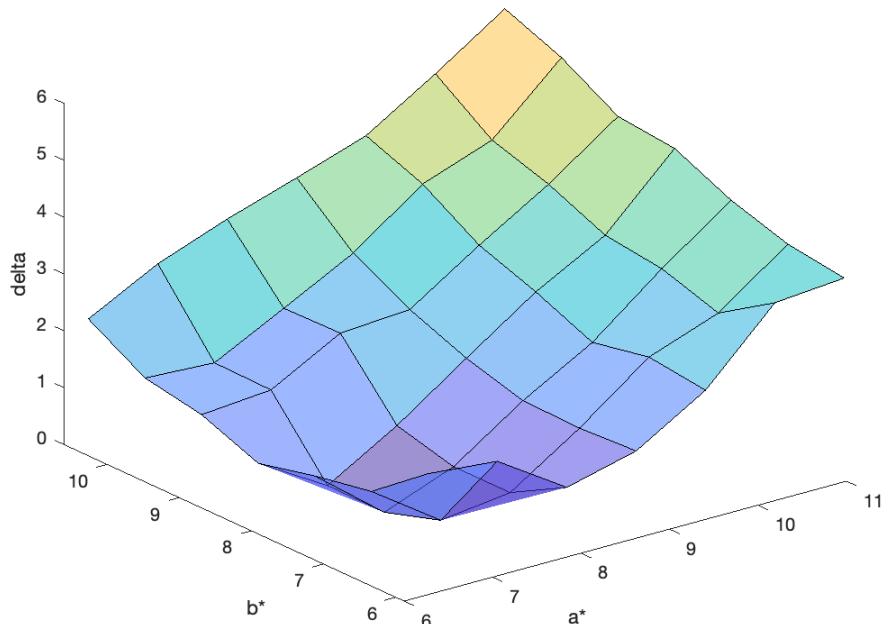
The column C,M,Y of the Table 7 are the original grey balance selected points from Table 5, the NEW_M and NEW_Y values represent the changes needed to fine-tune the grey balance in order to achieve a good grey reproduction. Since this step does not involve interpolations, at least for the five selected points the result should be exactly as expected.

Following the output of the intermediate calculations of the scripts:

Find keypoint chart K 15

ctable = 49x8 table

	CMYK_C	CMYK_M	CMYK_Y	CMYK_K	LAB_L	LAB_A	LAB_B	...
1	11.7600	6.2700	5.8800	0	86.5000	1.3300	-7.7600	
2	11.7600	7.0600	5.8800	0	85.9500	1.8000	-8.3600	
3	11.7600	7.8400	5.8800	0	85.5800	2.5100	-8.6300	
4	11.7600	8.6300	5.8800	0	84.9700	3.1900	-8.7300	
5	11.7600	9.4100	5.8800	0	84.5500	3.8200	-8.7900	
6	11.7600	10.2000	5.8800	0	84.1800	4.7100	-9.0100	
7	11.7600	10.9800	5.8800	0	83.7400	5.6400	-9.1900	
8	11.7600	6.2700	6.6700	0	86.2300	0.9100	-7.1200	
9	11.7600	7.0600	6.6700	0	85.7100	1.6500	-7.0800	
10	11.7600	7.8400	6.6700	0	84.8800	2.2700	-7.5200	
11	11.7600	8.6300	6.6700	0	84.0900	3.1000	-7.7300	
12	11.7600	9.4100	6.6700	0	83.7300	4.0600	-8.0200	
13	11.7600	10.2000	6.6700	0	83.0400	4.5400	-8.1300	
14	11.7600	10.9800	6.6700	0	82.6200	5.5200	-8.6900	
⋮								



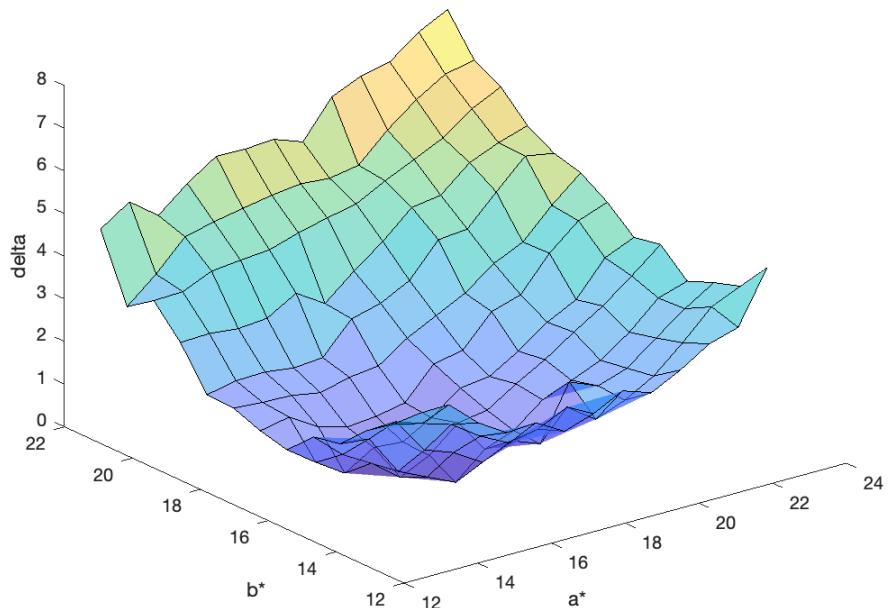
C=11.76 M=7.06 Y=9.02 delta=0.20

Optimization of grey reproduction in CMYK printing processes

Find keypoint chart K 30

ctable = 169x8 table

	CMYK_C	CMYK_M	CMYK_Y	CMYK_K	LAB_L	LAB_A	LAB_B	...
1	23.9200	12.9400	12.5500	0	76.8400	0.1900	-9.1900	
2	23.9200	13.7300	12.5500	0	76.1000	0.8300	-9.7300	
3	23.9200	14.5100	12.5500	0	75.6200	1.2800	-9.2300	
4	23.9200	15.2900	12.5500	0	75.5100	1.6400	-9.7700	
5	23.9200	16.0800	12.5500	0	74.9100	2.3700	-10.1000	
6	23.9200	16.8600	12.5500	0	74.7800	2.4700	-10.0600	
7	23.9200	17.6500	12.5500	0	74.2800	2.7300	-10.0300	
8	23.9200	18.4300	12.5500	0	74.4800	3.2500	-9.5700	
9	23.9200	19.2200	12.5500	0	73.7200	4.1200	-10.1000	
10	23.9200	20.0000	12.5500	0	73.3400	4.3600	-10.3100	
11	23.9200	20.7800	12.5500	0	73.1200	4.9300	-10.1100	
12	23.9200	21.5700	12.5500	0	72.6300	5.4100	-10.4000	
13	23.9200	22.3500	12.5500	0	72.2800	5.5500	-10.7200	
14	23.9200	12.9400	13.3300	0	78.1900	0.8500	-7.7400	
⋮								

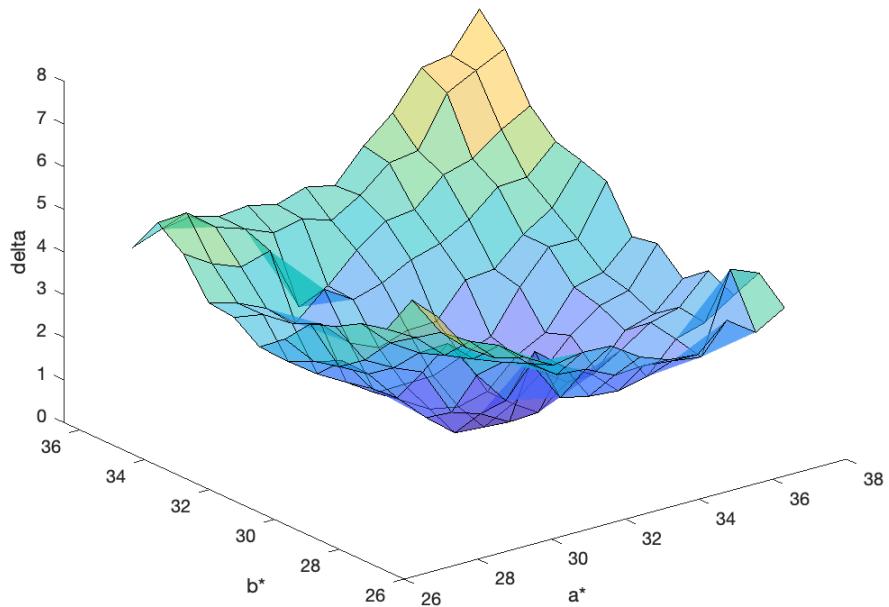


C=23.92 M=16.08 Y=19.61 delta=0.34

Find keypoint chart K 50

ctable = 169x8 table

	CMYK_C	CMYK_M	CMYK_Y	CMYK_K	LAB_L	LAB_A	LAB_B	...
1	41.5700	27.8400	27.0600	0	66.3600	-0.8100	-7.0900	
2	41.5700	28.6300	27.0600	0	65.7700	-0.1200	-7.6500	
3	41.5700	29.4100	27.0600	0	65.5900	0.5800	-7.9100	
4	41.5700	30.2000	27.0600	0	65.1500	0.5600	-7.7200	
5	41.5700	30.9800	27.0600	0	65.0500	1.2600	-7.8100	
6	41.5700	31.7600	27.0600	0	64.7500	1.5400	-7.6200	
7	41.5700	32.5500	27.0600	0	64.2600	2.0200	-7.7500	
8	41.5700	33.3300	27.0600	0	63.5900	2.6000	-7.3900	
9	41.5700	34.1200	27.0600	0	62.9300	2.8400	-8.1000	
10	41.5700	34.9000	27.0600	0	61.9400	3.6200	-8.3600	
11	41.5700	35.6900	27.0600	0	61.5300	4.4400	-8.8800	
12	41.5700	36.4700	27.0600	0	61.2200	4.7000	-8.8300	
13	41.5700	37.2500	27.0600	0	60.9700	5.4100	-9.4100	
14	41.5700	27.8400	27.8400	0	64.4000	-1.5100	-7.6700	
⋮								



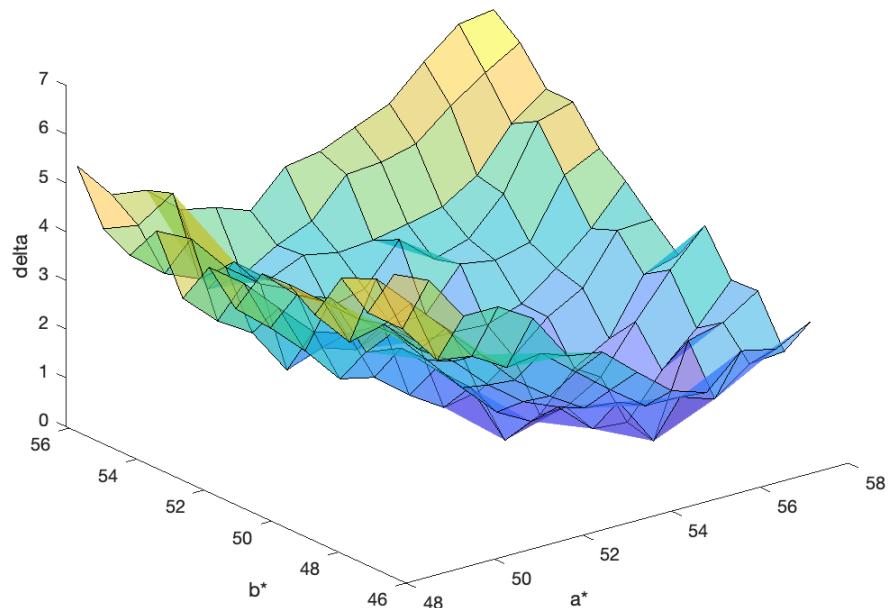
C=41.57 M=32.55 Y=32.55 delta=0.29

Optimization of grey reproduction in CMYK printing processes

Find keypoint chart K 70

ctable = 169x8 table

	CMYK_C	CMYK_M	CMYK_Y	CMYK_K	LAB_L	LAB_A	LAB_B	...
1	62.3500	48.2400	46.6700	0	49.0200	-3.6100	-5.7800	
2	62.3500	49.0200	46.6700	0	49.4200	-2.1300	-6.2800	
3	62.3500	49.8000	46.6700	0	48.9100	-2.0900	-6.1800	
4	62.3500	50.5900	46.6700	0	48.4800	-0.9000	-6.2700	
5	62.3500	51.3700	46.6700	0	47.8200	-0.2900	-6.3600	
6	62.3500	52.1600	46.6700	0	47.5600	0.5300	-6.2600	
7	62.3500	52.9400	46.6700	0	46.9200	1.4100	-6.9400	
8	62.3500	53.7300	46.6700	0	46.6700	1.5200	-7.0400	
9	62.3500	54.5100	46.6700	0	46.5600	1.4900	-7.3500	
10	62.3500	55.2900	46.6700	0	46.0100	1.8600	-7.5800	
11	62.3500	56.0800	46.6700	0	46.0600	2.8000	-7.9900	
12	62.3500	56.8600	46.6700	0	45.4900	4.1400	-7.9500	
13	62.3500	57.6500	46.6700	0	45.3000	4.0500	-8.1300	
14	62.3500	48.2400	47.4500	0	48.7500	-2.9600	-4.8300	
⋮								

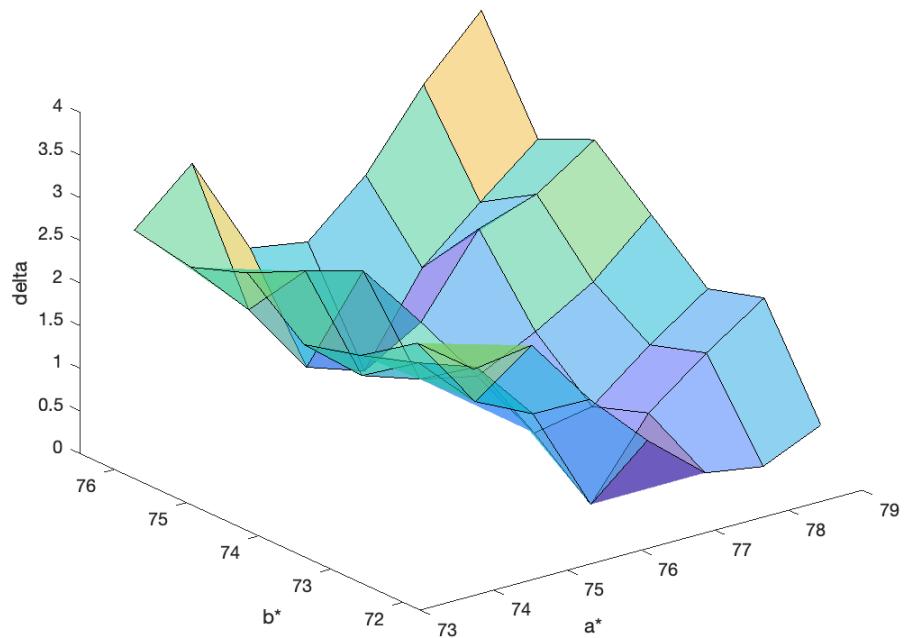


C=62.35 M=53.73 Y=52.16 delta=0.06

Find keypoint chart K 85

ctable = 49x8 table

	CMYK_C	CMYK_M	CMYK_Y	CMYK_K	LAB_L	LAB_A	LAB_B	...
1	81.5700	73.7300	71.7600	0	32.5300	-1.2900	-3.3500	
2	81.5700	74.5100	71.7600	0	32.4700	-1.1000	-4.5200	
3	81.5700	75.2900	71.7600	0	33.5800	-0.1700	-3.7500	
4	81.5700	76.0800	71.7600	0	33.2900	1.0700	-3.9400	
5	81.5700	76.8600	71.7600	0	32.6900	1.8000	-4.3600	
6	81.5700	77.6500	71.7600	0	32.3500	2.6300	-4.9100	
7	81.5700	78.4300	71.7600	0	32.0600	3.2400	-5.3200	
8	81.5700	73.7300	72.5500	0	34.0800	-1.1000	-3.4200	
9	81.5700	74.5100	72.5500	0	33.8500	-0.3900	-3.2400	
10	81.5700	75.2900	72.5500	0	33.4400	0.2300	-2.6400	
11	81.5700	76.0800	72.5500	0	32.9900	1.1100	-2.6900	
12	81.5700	76.8600	72.5500	0	32.3300	1.8500	-3.4300	
13	81.5700	77.6500	72.5500	0	31.4000	2.3300	-3.7900	
14	81.5700	78.4300	72.5500	0	31.2600	2.8100	-4.1000	
⋮								



C=81.57 M=76.08 Y=75.69 delta=0.21

STEP 2: Calculate correction curves

The corrections calculated in step 1 are not practical: it means that the original LUT calculated for TVI calibration in section 3.3.2 need to be changed, as an example, from M=17,6741% to M=16,0784%. But the calibrated LUT was introduced in the workflow only in steps of 5% and this pivot points are not available. For that reason, the entire M and Y LUTs need to be recalculated in the same range of the of the TVI calibrated LUTs, to allow an easy change in the workflow software.

To do so, starting from the five known points, new correction curves for M and Y are interpolated. The method used is the spline interpolation, that allow the curve to pass exactly for the known points.

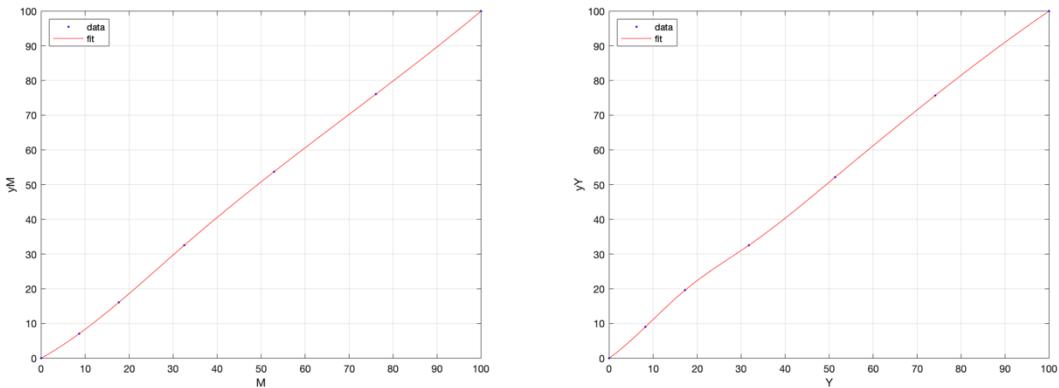


Figure 45 - Grey reproduction fine tuning step 2 correction interpolated curves for M (left) and Y (right)

The R^2 of this interpolation is 1,0 because the spline piecewise method used.

STEP 3: Calculate calibrated LUTs

The same interpolation method is applied to the original LUTs, and now that all the LUTs can be expressed by functions, the next step can be mathematical described as:

$$M_{new} = M_{LUT}(M_{corr}(TV)), \quad Y_{new} = Y_{LUT}(Y_{corr}(TV))$$

where:

TV is the original tone range [0 – 100] in step of 5,

M_{corr}, Y_{corr} are the correction curves of the Figure 45,

M_{LUT}, Y_{LUT} are the current LUTs after TVI calibration process,

M_{new}, Y_{new} are the new calibrated LUTs

The result of the process can be seen both in the Figure 46 and Table 8 below, please note that the C LUT has not changed:

Optimization of grey reproduction in CMYK printing processes

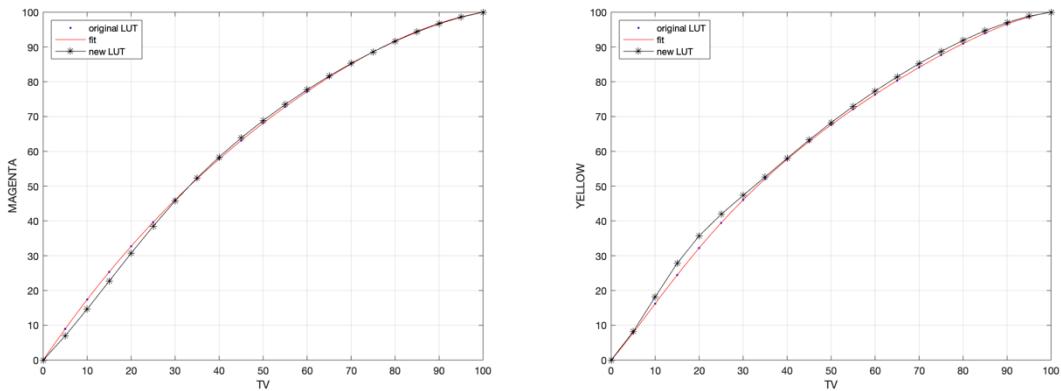


Figure 46 - Calibrated M and Y LUTs graphs

Table 8 - Calibrated M and Y LUTs

TV	LUT_C	LUT_M	LUT_Y	LUT_K	NEW_LUT_M	NEW_LUT_Y
0	0	0	0	0	0	0
5	9.2140	8.9469	7.8531	10.5031	6.9580	8.1865
10	17.6699	17.3944	16.2137	19.5926	14.6495	18.1539
15	25.4693	25.3140	24.4401	27.5614	22.6820	27.8059
20	32.6984	32.7140	32.2183	34.6473	30.7148	35.6962
25	39.4304	39.6224	39.4244	41.0408	38.4710	41.9020
30	45.7271	46.0764	46.0402	46.8928	45.7371	47.3264
35	51.6400	52.1152	52.1023	52.3217	52.3738	52.6625
40	57.2108	57.7759	57.6723	57.4189	58.3798	58.0287
45	62.4721	63.0906	62.8188	62.2533	63.8477	63.2645
50	67.4472	68.0850	67.6078	66.8744	68.8546	68.2593
55	72.1504	72.7771	72.0963	71.3141	73.4599	72.9454
60	76.5866	77.1765	76.3284	75.5880	77.7100	77.3254
65	80.7512	81.2840	80.3327	79.6954	81.6397	81.4207
70	84.6302	85.0908	84.1194	83.6191	85.2697	85.2332
75	88.1994	88.5787	87.6784	87.3250	88.6061	88.7438
80	91.4250	91.7195	90.9773	90.7619	91.6399	91.9159
85	94.2628	94.4746	93.9601	93.8606	94.3447	94.6961
90	96.6589	96.7956	96.5476	96.5357	96.6745	97.0310
95	98.5496	98.6240	98.6396	98.6863	98.5555	98.8472
100	100.0000	100.0000	100.0000	100.0000	100.0000	100.0000

3.4. Evaluation of grey reproduction

The evaluation of grey reproduction is done by the MATLAB script Grey_Evaluation.mlx, which flowchart is shown in

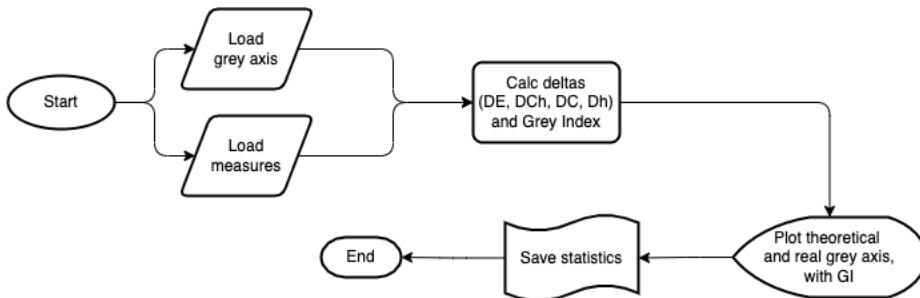


Figure 47- Flowchart of MATLAB script Grey_Evaluation.mlx

Measuring the chart of Figure 42, after printing using the calibration LUTs of the Table 8, the five central patches are extracted, and the new calibrated grey axis is built. The graph is compared against the original FOGRA51 grey axis calculated in Table 5.

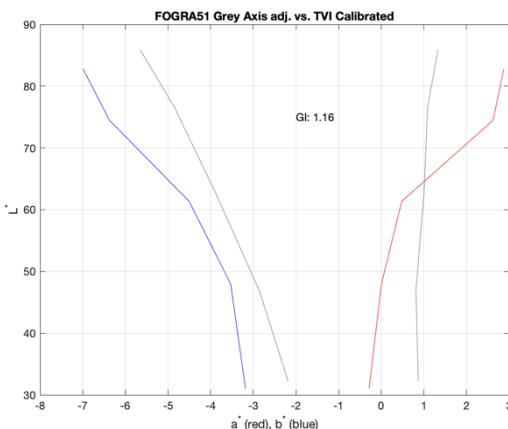


Figure 48 - Measured grey axis after TVI calibration
(section 3.3.2)

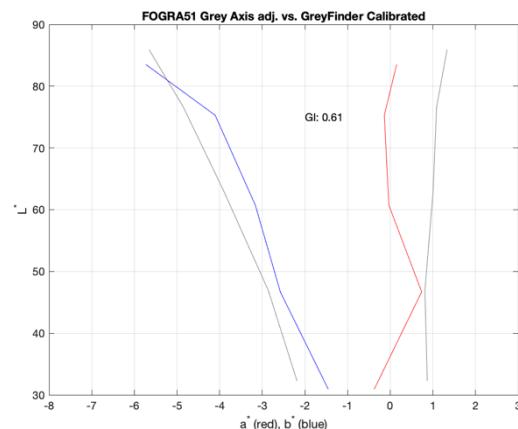


Figure 49 - Measured grey axis after grey balance optimization (section 3.3.3 STEP 3)

The grey axis shown in Figure 49 has the values of the table below:

Table 9 - Calibrated grey reproduction and statistics

TV	C	M	Y	Ref. L*	Ref. a*	Ref. b*	Meas. L*	Meas. a*	Meas. b*	ΔE_{00}	ΔCh
15	11,76	8,63	8,24	85,93	1,33	-5,66	83,52	0,15	-5,73	2,32	1,19
30	23,92	17,65	17,25	76,62	1,09	-4,85	75,29	-0,14	-4,10	2,08	1,43
50	41,57	32,55	31,76	62,87	1,00	-3,89	60,74	-0,03	-3,16	2,43	1,27
70	62,35	52,94	51,37	46,92	0,81	-2,86	46,70	0,74	-2,58	0,34	0,29
85	81,57	76,08	74,12	32,29	0,87	-2,19	30,92	-0,38	-1,45	2,21	1,44

3.4.1. Grey Index

A tentative to summarize a grey axis deviation was proposed by the author in CIC27 conference addressing a different use case: when an ICC profile is verified against $a^*=b^*=0$ grey axis (3). The premises remains valid also on the current use case, when print results need to be compared with a calculated target grey axis. As reported in the paper, "*There are two different grey neutrality deviances (one in chroma and the other in hue angle) that we can observe and, to simplify the evaluation process, we created a single index that can combine together those deviations.*". Current standards provide different formulas to evaluate the distance of an axis point against a reference, like the CIE chromaticness difference (ΔCh), but there isn't a standardized way to summarize those distances with a single metric.

Proposed Grey Index formula is catching both the constant average deviation in chroma, and the variation of hue differences. Those variations in hue at different points in the grey axis may create an undesired rainbow effect, when the lack of neutrality span in different regions of the chromatic a^*b^* plane (red, yellow, green, blue) across the axis. GI is zero when the grey axis perfectly matches the target axis in the chromatic plane, ignoring lightness differences. One possible tolerance to evaluate grey neutrality is consider $GI \leq 1$.

One hypothesis is that when the deviation is constant, if there aren't other visual references in our field of view usually our vision system can adapt to the neutral shade and the result is perceived as neutral. When the rainbow variation is present, with or without neutral references in the field of view, our visual system is not able to adapt, and the result is particularly annoying.

NOTE: I have not found studies or research to support this hypothesis: it will be the subject of future experiments.



Figure 50 - Neutral images (left) vs. simulated greenish deviation (centre), and simulated rainbow hue variation effect (right)

Optimization of grey reproduction in CMYK printing processes

Equation 15 - Grey Index equation - from (3) corrected with the usage of absolute value of chroma differences, not present in the original formula because ΔC_{ab}^* was always positive in the original use case.

$$GI = \overline{abs(\Delta C_{ab}^*)} \cdot \left[\frac{\sigma(\Delta h_{ab})}{2\pi} + 1 \right]$$

where

$\overline{abs(\Delta C_{ab}^*)}$ is the average of all chroma differences absolute values,

$\sigma(\Delta h_{ab})$ is the standard deviation of all hue angles differences, in radians

Table 10 - Evolution of GI during the calibration steps

	Linear LUT	TVI calibrated LUT	Grey optimized LUT
GI	2,82	1,16	0,61

The Grey Index after the TVI calibration was 1,16 and drop down to 0,61 after the grey reproduction fine tuning. Even if the TVI calibrated condition was quite good, the fine-tuned LUTs have provided better neutrality.

3.5. Visual Evaluation

Three different steps are evaluated under a standard ISO 3664:2009 P1 viewing condition: the linear printing before all calibration process, the TVI calibrated prints and the grey fine-tuned prints.



Figure 51 - Visual evaluation of grey shades: linear printing (left), TVI calibrated images (centre), grey fine-tuned images (right)

With the premise that is not easy to take a photo that represents colorimetrically the perception of a printed matter seen in a standardize lighting condition, some consideration on the samples of Figure 51 can be noted:

- The uncalibrated linear printing (left) is too light. This is consistent with the very low TVI (almost 0) measured at the beginning of the process and shown in Figure 39. Anyway, the starting grey reproduction colour shift was not completely wrong, compared to other printing systems, with a greenish shade.
- The TVI calibrated print (centre) has the right contrast between mid-tones, lights, and shadows: it's a proof that the TVI correction LUT was applied. The grey balance is quite good especially in the darkness but has a red shade in the lights. The visual perception agrees with the grey reproduction calculation shown in Figure 48.
- The grey calibrated print (right) has a better neutrality. There are no visible shades and the conjunction of three photos seems homogenous. This agrees with the grey reproduction calculation shown in Figure 49, and the Grey Index improvement seen in section 3.4.1 above.

Optimization of grey reproduction in CMYK printing processes



Figure 52 - Visual evaluation of pastel colours: linear printing (left), TVI calibrated images (centre), grey fine-tuned images (right)

Analysing other colours, it can be seen that there is a big difference from the linear printing to the other conditions, but very marginal changes due to the grey fine tuning compared with the TVI calibrated images. Even if the LUT changes affected all the mid-tones of all the colours, as the colours become more saturated our vision system loses the ability to see the differences introduced.

4. Conclusions and future work

4.1. Conclusions

The tested process has demonstrated to work successfully when the starting condition, after TVI calibration, is almost neutral and can be optimized. Probably if the starting point had been too close to the target, the grey reproduction fine tune process would be less effective and would have introduced more noise shown as over-correction. On the contrary, if the starting point had been too far away, a less efficient 4 or 5-step calibration workflow would have been necessary.

The pros of the method are:

- It could be completely automated since it relies only on colour measurements and algorithms.
- Having a strong grey definition allows specific process control during production.
- The Grey Index can be used as a metric to identify the effectiveness of the grey reproduction fine tuning.
- In a significative number of workflows and use cases, the proposed method allows to print digital CMYK images already prepared for FOGRA51 standard condition without using an ICC colour conversion. The result will be perceptually coherent in the grey axis and all the pale colours; the more saturated colours will have deviations depending on the CMYK primary and secondary differences against the selected characterization.

The cons are mainly related to the practical implementation of the method:

- It requires an accurate and repeatable spectrophotometer, likely automated, with average of at least 3 charts to identify and correct measurement outliers. Previous test made with a handheld manual spectrophotometer, and single-chart measurement, failed because low measurement accuracy.
- In digital printing processes when the use of a LUT is not necessary, it adds extra complications compared to the straightforward use of ICC profiles. Precisely for this, the test was made on a HP Indigo® technology that uses LUTs that mimic the traditional offset lithography plate LUT concept.
- The grey reproduction fine tuning method is not taking care about the lightness (L^*) deviations introduced, that can lead to a worse perceived contrast in some cases.

Another approach used in the industry is to calibrate the printer ignoring the neutral grey reproduction and leave all the grey reproduction to the colour management usually made through ICC profiles (11). ICC profiles architecture treats greys as well as other colour areas without specific focus: it is responsibility of the ICC profiler software to implement the strategy to deal with it. The creation of an ICC profile is usually a one-step operation, with no real control of intermediate calculations: using today's technology is providing a good result in many use cases, but the impossibility of controlling the result in a fine way does not make it suitable for critical applications. Starting to set up a workflow with a solid grey definition allows the user to have everything under control and to easily fine-tune the system or apply stringent process control tolerances.

4.2. Future work

There are several areas for improvement in the field of grey reproduction in CMYK industrial printing, looking both on the efficiency and effectiveness of the calibration processes:

- A 1-step calibration process could be possible, using similar strategy of ICC profiles internal table creations. To be demonstrated the level of accuracy that is possible to achieve.
- Considering multiple calibrations on different paper substrates of the same printing system, a machine learning system could be implemented to predict the corrections to make depending on the characteristics and the colour of the substrate.
- TVI metric still widely used in the industry, but CTV (Colour Tone Value) formula is under standardization. In the domain of the grey reproduction topic it shouldn't have much impact but further evaluations are necessary.
- The colour difference formulas used to evaluate grey neutrality are all based on CIE 1931 colorimetric system (29 p. 130-176). Different approaches as CAT02 chromatic adaptation over CIELAB, or RLAB, or CIECAM02 could be explored (7 p. 301).
- Further work is necessary to test the GI metric in different conditions and correlate it with visual assessment in order to define practical tolerances to use in process or quality control flows. To do so, psychophysical experiments need to be performed to correlate physical measurements and perceptions. (7 p. 38-55)

Ultimately, there is a need of more data gotten from different paper substrates and printing processes, measured in controlled conditions. The complexity is that the level of accuracy needed is in the same range of the accuracy and inter-instrument agreement, or consistency, of most used spectrophotometers: mixing measurements from different experiments or sites prevents a direct comparison between them.

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Annexes

Annex A: Terms and Definitions

1. CHARACTERIZATION

Relationship between input/output device-dependent and device-independent values. (13)

2. CIELAB COLOUR SPACE

Rectangular opponent-type colour space derived from non-linear transformations of the 1931 CIE XYZ system and expressed by the colour coordinates L^* , a^* , b^* approximately uniform with respect to colour differences, where L^* represents relative lightness, a^* represents redness or greenness and b^* represents yellowness or blueness. (13)

3. CIE STANDARD ILLUMINANTS

Illuminants A, D50, D65, etc., defined by the CIE in terms of relative spectral power distribution. (13)

4. COLOUR CHARACTERIZATION TARGET

Standard colour reference used for establishing the relationship between a printed image and the input values of that image. (13)

5. COLOUR SEPARATION

Act of separation by which a multi-coloured original is split into the separate colour files or films associated with the printing colorants for process colour printing. (13)

6. COLOUR SPACE

Geometric representation of colours in space, usually of three dimensions (13)

7. CONTINUOUS TONE

Image that has not been screened and has infinite tone gradations between the lightest highlights and the deepest shadows. (13)

8. CONTRAST

- Subject contrast refers to relative difference between the amount of light reflected by the "highlights," or bright areas, of the subject and the "shadows," or darker areas. This difference is measured with a reflected-light meter. (17)
- Print contrast (also called tonal separation) is the ability of the film and printing paper to render a visual distinction between close tonal values. (17)
- Relationship or degree of tonal gradation between the lightest and darkest area in a original or reproduction (13)

9. CONTROL PATCH

Area produced for control measurement purposes. (13)

10. CONTROL STRIP

Array of control patches. (13)

11. DENSITY

Weight of tone or colour in any image, measurable by a densitometer. (13)

12. DOT PERCENTAGE

Percentage of an area covered by half-tone dots of each colour, ranging from 0 % to 100 % (13)

13. GREY COMPONENT REPLACEMENT (GCR)

Removing appropriate amounts of individual colorants that together are equal to grey and replacing these multiple colorants with an appropriate amount of black. (13)

14. GREY BALANCE

Set of tone values for cyan, magenta and yellow that are expected to appear as an achromatic grey under specified viewing conditions when printed using the specified printing conditions.

15. GREY REPRODUCTION

Set of colorimetric values of the print that appears as an achromatic colour under specified viewing conditions if printed under specified printing conditions to be used for process control. (14; 2)

16. GREY SCALE

Series of grey levels between white and black.

17. GRADATION

Staged change in tones from highlight to shadow. (13)

18. HALF-TONE

Image composed of dots which can vary in screen ruling (number per centimetre), size, shape, or density, thereby producing tonal gradations. (13)

19. LINE ART

Image that has no tonal gradation. (13)

20. MEDIUM BLACK POINT

Lowest luminance neutral that can be produced by an imaging medium in normal use, measured using the specified measurement geometry. (13)

21. MEDIUM WHITE POINT

Neutral colour with the highest luminance that can be produced by an imaging medium in normal use, measured using the specified measurement geometry. (13)

22. MID-TONE BALANCE CONTROL PATCH

Half-tone control patch, containing all three chromatic process inks, used for assessing the balance between the inks in which the cyan tone value is normally in the range between 40 and 60 and the magenta and yellow tone values are selected to approximate an achromatic colour. (13)

23. PRIMARY COLOUR

Unitary colours from which all other colours are created (in additive and subtractive colour theory. (13)

24. SECONDARY COLOUR

Colour produced by the mixture (either additive or subtractive) of two primary colours. (13)

25. TONE

Degree of lightness or darkness in any given area of an image. (13)

26. TONE VALUE (TV)

Proportional printing value encoded in a data file and interpreted as defined in the file format specification. (13)

27. TONE VALUE INCREASE (TVI) - ALSO CALLED DOT GAIN

Difference between a tone value on the print and the tone value on the half-tone film or in the digital data file. (13)

28. UNDER COLOUR REMOVAL (UCR)

Removing appropriate amounts of individual colorants that together are equal to black and replacing them with an appropriate amount of black. (13)

Annex B: Curriculum Vitae

When finished the technical bachelor's in computer science, in early '90s, I had the opportunity to follow the evolution of multimedia applications from the first commercial devices, as Commodore CDTV and Philips CD-I developer, to 3D and VR applications on PCs running Microsoft Windows some year later. In 1995 I have co-founded a software house that created colorimetric software for paint industries, now part of Datacolor Inc., USA. In 2003 I started consulting activities for standardization and certification of printing processes, and workflow custom software, for primary industries like Tetra Pak (Sweden), GlaxoSmithKline (UK), UTECO (Italy), Ricoh (Italy), Konica Minolta (Italy, Switzerland, Japan), Canon (Italy), Komori (Italy), SACMI (Italy), and Jet-Set CEFLA (Italy). I moved in Sant Cugat (Barcelona) and joined HP Inc. in 2017 as R&D Engineer and Program Manager, focused on colour and image quality processes. I give my contribution to the standardization community in ISO/TC130 Graphic Technology committee from 2009, before as Italian head of delegation, now representing Spain. I'm also member of ICC International Colour Consortium representing HP Inc., Past President of Technical Association of Graphic Arts TAGA Italia, and member of IEEE for many years.