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Method Article

A step-by-step method for predicting the spectrophotometric response of a carded fabric composed by differently colored raw materials

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A R T I C L E I N F O

Method name:
Spectrophotometry
Reflectance factors
Colour mixing
Predictive assessment
Method for predicting the spectrophotometric response of a carded fabr iccomposed by differently colored raw materials

A B S T R A C T

The comparison of the finished product's color to the color demanded by a client or provided by a catalogue is one of the most critical steps of the production of carded fibers. This is currently determined by calculating the colorimetric distance between the finished article, which is made by mixing some colored raw fibers to achieve a homogenous color, and the desired one. When this colorimetric distance exceeds a value specified by the customer, the recipe must be modified to close the gap between the end product's color and the required one. The above mentioned trial and error procedure used to determine the appropriate quantities of colored fibers for achieving a desired final color of a fiber lacks a computer-aided tool to assist colorists. Therefore, it is a bottleneck in the process of creating carded fabrics. The present work offers a novel method for predicting the spectrophotometric response of a carded fiber based on the spectrophotometric response of the raw components used to make the fiber. The method is described step-by-step.

- The method is applicable to predict the spectrophotometric response of a fabric composed by any number of pre-colored fibers.

Specifications table

Subject Area:	
More specific subject area:	*Textile Engineering*
Method name:	*Method for predicting the spectrophotometric response of a carded fabric composed by differently colored raw materials*
Name and reference of original method:	*Furferi, Rocco, and Lapo Governi. "Prediction of the spectrophotometric response of a carded fiber composed by different kinds of coloured raw materials: an artificial neural network-based approach." Color Research & Application 36.3 (2011): 179-191.*
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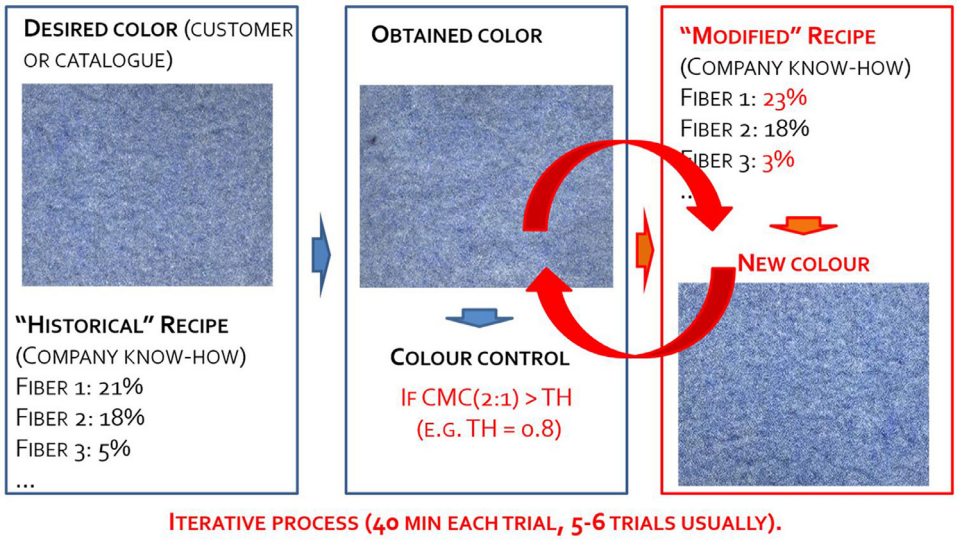

Fig. 1. Current trial and error approach. Each iterative test is highly time-consuming.

Method details

Background

One of the most impacting phases in the production of fabrics is the dyeing process. This requires chemicals, energy and water for wet processing, consequently releasing toxic pollutants into the environment and contributing to the emission of carbon dioxide. An excellent method for decreasing the need for dyeing while also giving new life to discarded textiles is to make yarns out of fibers produced from waste fabrics. In such a case, the favored approach for the processing of yarns is the so-called "recipe-based mixing," i.e. the practice of mixing a variety of uniformly colored fibers in various amounts.

Currently, textile firms conduct color mixing based on their expertise: when a desired color (i.e. the so-called color target) is requested, the colorist usually begins checking the company storehouse for appropriately colored fibers to be blended according to a given formula. In effect, modern businesses are supplied with databases where spectrophotometric pre-colored fiber information is stored along with suggested percentages to be used to achieve a specified color target. In other words, textile industries have "historical" formulas that can be used to produce a final "blend" (using processes such as combing, painting, roving, spinning or carding [1]). Whenever a blend is made, colorists usually perform an instrumental comparison with respect to the color target to determine the color difference. Such a comparison is tested under a variety of standard illuminants such as D65 or TL84 [2] using multiple color spaces such as *CIELAB* or *CMC(2:1)*.

More often than expected, the result achieved by combining the fibers is very different from the reference, even though companies adopt a "consolidated" recipe. In fact, when calculated using a spectrophotometer, the color differences between the recipe-based reflectance factors and the spectrophotometric response of the reference in terms of CIELAB and CMC(2:1) distances may be greater than 0.6-0.8 [3]. As a result, the original recipe must be modified to meet the required color, demanding the creation of numerous samples in order to decrease the difference in color between the blend formed by mixing the raw components and the desired one.

As each trial requires time-consuming manufacturing and measuring procedures, this trial and error approach is a bottleneck of the entire fabric manufacturing process, as shown in Fig. 1.

Several approaches for the evaluation of color matching of dyed fibers are in literature, roughly divided into two categories: theoretical methods and Artificial Neural Networks (ANNs) based methods.

- Theoretical methods are primarily based on the widely known Kubelka-Munk (K-M) [4] theory, which is typically used to analyze diffuse reflectance spectra obtained from samples that are weakly absorbed. These approaches allow spectral reflectance prediction for a mixture of components (colorants) that characterized by coefficients of absorption K and dispersion S. Unfortunately, owing to the irrationality of the additivity assumption, two constant Kubelka-Munk functions contribute to problems in practical use, rather than the K-M turbid medium theory itself [5]. When fiber blends are obtained by applying colorants to a base, K-M is a valid option; but it appears to fail when fabrics are obtained by combining pre-colored fibers together. Several studies relating to the tristimulus matching algorithm based on the Stearns-Noechel (S-N) model [6] (and its implementations [7]) have been proposed to predict formulas for matching a given color norm by mixing pre-dyed fibers in order to address these limitations. While the theoretical approaches described above provide excellent results for predicting the color of turbid media, they can lead to improper results in predicting the reflectance factors of mixtures obtained by mixing pre-colored fibers.

- ANNs-based methods prove to provide a reliable and very practical strategy to assist the colorist in color matching. This is shown in [8], where a transfer function is calculated by connecting the color spectrum obtained by a linear combination of the spectra of and component with the measured reflectance values of the first attempt blend. For blends composed of more than 15 components, the method proved to be successful since the average color difference between the expected spectra and the actual carded fiber spectra is less than 0.55 for the CMC(2:1) tolerance method for an experimented collection of blends. The key drawback is that the solution suggested is only reliable for 5% variants of a recipe and uses only a single material (e.g. wool).

Both theoretical and ANN-based approaches demonstrated a certain degree of reliability when dealing with the forecasting of the spectral response. However, several issues remain unsolved so far to render the use of these methods in the industrial practice. First, such experimental approaches are not easily integrated into industrial practice since they require the use of complex algorithms which usability for Companies is often not affordable. Furthermore, since textile companies always create a first-attempt fabric using their historical recipe it is possible to have an additional information i.e. the actual spectrophotometric response of at least one blend (whose reflectance values are often "near" to the reference ones); this information could really help the forecasting system in performing more accurate estimation of the spectrophotometric response of the blended yarn, but is not considered in literature studies assessing color matching.

Method objectives

The main aim of the present work is to propose an appropriate method for reliably assessing the spectral response of a blend once a recipe is provided and textile experts create a first-attempt blend. The method relies on a theoretical approach used for the prediction of reflectance factors obtained by mixing the same kind of differently colored raw material. The method, described step-by-step in order to allow its replication by researchers working in textile field, is a modified version of the one proposed in [9].

Required Equipment

The method requires the use of a reflectance spectrophotometer working in the wavelength range from 400 to 700 nm, possibly with step of 10 nm. The spectrophotometer is required to provide the value of light reflectance using a scattered light measurement in SCE (Specular Component Excluded) mode. The scan has to be carried out with a neutral white background using an 8 deg angle between the light source and the fabric. A white calibration of the spectrophotometer is required at the beginning of data acquisition.

The spectrophotometer is required to be connected to a PC to store data in the form of a 31 elements vector representing the reflectance values vs. the wavelength for an examined fabric. To ensure adequate robustness and representativeness of results, the use of the largest measuring area of the spectrophotometer is suggested (typically equal to 25.4 mm).

Statement of the problem

- Let $p_i(\lambda)$ be the spectral reflectance factors of the i^{TH} of the n components composing a carded fabric: $i = 1, 2, \dots, n$.
- Let, then, α_i be the percentage of each component (wool, cotton, linen or other fibres) composing the blend.

As widely recognized in literature, in case of subtractive mixing, a "blend mixing" spectrum $R(\lambda, \alpha_i,)$ can be defined as follows:

$$R(\lambda, \alpha_i) = 10\exp\left[\sum_{i=1}^{n} \alpha_i(\log_{10}(p_i(\lambda))\right] \tag{1}$$

In Eq. (1), λ indicates the wavelength, varying in the range [400 – 700 nm]. The size of vectors $p_i(\lambda)$ and $R(\lambda, \alpha_i)$ varies depending on the number of wavelengths sampled to acquire the raw material spectrum. Typically, such a value is equal to 1×31.

Of course, the following equation must be satisfied:

$$\sum_{i=1}^{n} \alpha_i = 1 \tag{2}$$

The vector $\mathcal{A} = [\alpha_i,\ i = 1 \dots n]$ is the so-called "recipe".

- Now, let $R_s(\lambda)$ be the actual spectral reflectance factors of the blend obtained by mixing the components $p_i(\lambda)$ according to a given recipe. The general relationship between $R(\lambda, \alpha_i)$ and $R_s(\lambda)$ may be stated by the following formula:

$$R_s(\lambda) = \mathfrak{F}(R(\lambda, \alpha_i)) \tag{3}$$

Accordingly, once the transfer function $\mathfrak{F}$ is evaluated, it is possible to calculate the spectral reflectance factors $R_s(\lambda)$ of the blend obtained by mixing its components following a given recipe i.e. once parameters α_i and the vectors $p_i(\lambda)$ are provided.

In the ideal case, like for instance in the mixing of coloured light or of perfectly homogeneous dyes, the transfer function $\mathfrak{F}$ is linear. For this reason the relationship between $R_s(\lambda)$ and $R(\lambda, \alpha_i)$ becomes:

$$R_s(\lambda) = \delta \cdot R(\lambda, \alpha_i) \tag{4}$$

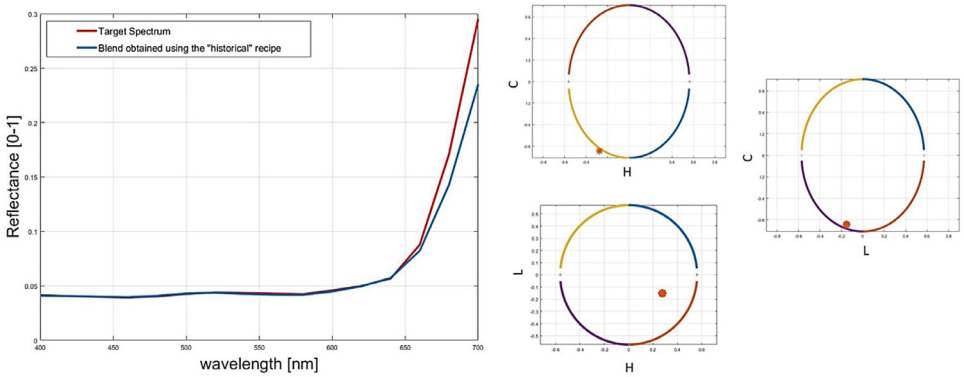

Fig. 2. Comparison between target spectrum ($R_s(\lambda)$) and blend obtained using the "historical recipe" ($R(\lambda, \alpha_i)$) for a given blend.

Where: $\delta = costant$. As widely known, for light mixing $\delta = 1$.

Unfortunately, Eq. (4) is not suitable for the evaluation of the spectral reflectance factors of carded fabrics, as stated in the literature and further demonstrated in industrial practice. This can be seen, for instance, in Fig. 2 where a comparison between $R_s(\lambda)$ and $R(\lambda, \alpha_i)$ is provided with reference of a sample tested by authors. From the spectrophotometric measurement, it is in typically possible to retrieve the LCH ellipsoid [8], whose centre represents the LCH value for the target spectrum and whose axes represents a given tolerance value (here equal to 0.6) for the color comparison. By way of example, Fig. 2 shows the projections of the LCH ellipsoid on the HC, HL and LC planes and the orange star in figure represents the coordinates LCH of the blend obtained by using the given recipe. As depicted in Fig. 2, the obtained blend does not respect the tolerance value in terms of CH values, being outside of the CH ellipse.

In fact, unlike paint formulations or mixing of light, because they remain separate entities on a macroscopic scale, it is not possible to obtain full homogenization of textile fibers. Because of incomplete mixing, this means a non-linear transformation of spectral values. In more depth, Eq. 4 is true in special cases where opaque or transparent fibers are mixed without overlap. In real cases, this condition is not guaranteed since a clear overlap characterizes fabrics. According to Figure 1, subsists a strong difference between the two set of spectral reflectance factors. For this reason, in order to estimate the spectrophotometric response of a mixed blend, a method for evaluating the transfer function $\mathfrak{F}$ is required.

Step-by-step Method

1. Determine, using the equipment described above, the spectral reflectance factors of all the components composing the carded fabric. This allows determining the n $p_i(\lambda)$ spectral responses.
2. Evaluate the "blend mixing" spectrum $R(\lambda, \alpha_i,)$ using Eq. 1. This can be easily afforded since the parameters α_i, i.e. the percentage of each component composing the blend are known.
3. Assume that Eq. 3 can be approximated by the Hadamard product (element wise) between a function $\Phi(\lambda)$ (depending only on wavelength) and the "blend mixing" spectrum $R(\lambda, \alpha_i)$. This results in the following equation:

$$R_S(\lambda) \cong \Phi(\lambda) \cdot \ R\left(\lambda, \alpha_i\right) \tag{5}$$

4. Process, by carding machine, a blend exactly composed by the n pre-colored fibers, mixed according to percentages α_i. This allows to determine the vector $R_S(\lambda)$.
5. Estimate, by using Eq. 5, the vector $\Phi(\lambda)$. By using this simple step it is possible to determine a good approximation of the transfer function $\mathfrak{F}$ proposed in Eq. 3.
6. Evaluate colour difference between $R_S(\lambda)$ and $R(\lambda, \alpha_i)$. This can be performed by using *CMC(2:1)* color distance $\mathbf{DE_{CMC(2:1)}}$ [10] usually provided by the software accompanying the spectrophotometer. In case the acquisition deice only provides the spectral responses, CMC distance can be evaluated according to [11]. a) In case the colour distance is lower than a pre-set threshold value (e.g. 0.6) the procedure stops and $R_S(\lambda)$ can be considered sufficiently close to the desired spectral response and the recipe has not to be changed. b) In case the colour distance is equal or higher than the pre-set threshold value, the recipe has to be changed to meet the required standard. Therefore, step 8 is required.
7. In current practice, when the CMC(2:1) distance exceeds the threshold, colorists have to guess which of the pre-colored fibers should be reduced or increased in terms of percentage (i.e. how parameters α_i can be changed) to obtain a blend whose colour is more resembling the target. As already mentioned, this involves a number of trial and error steps since for any variation of α_i steps from 4 to 7 should be repeated. In this method, this time-consuming phase is avoided by proceeding as follows.
    a) Provide a first-attempt modified recipe, by choosing new α_i values. In this step, the colourists usually adopt minimal variations of the original recipe based on the LCH ellipsoid, to obtain a blend closely resembling, in terms of colour, the desired target. By way of example, referring to Fig. 2, colourists need to raise the C and H values i.e. to render

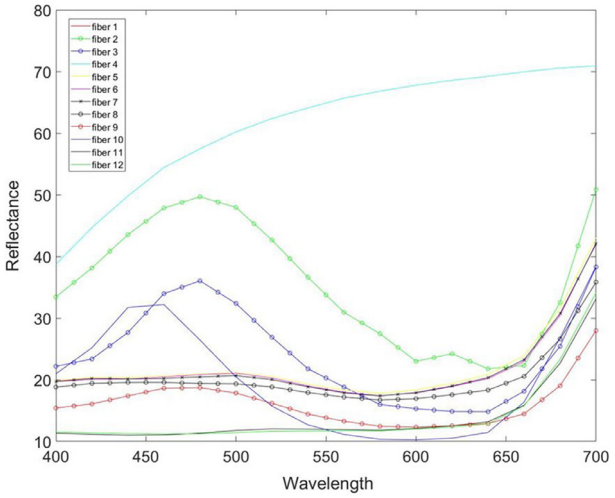

Fig. 3. Spectral response of the pre-colored wool fibers composing the original blend for the considered case study.

the blend lighter and greyer; this can be carried out by adding more grey lighter fibres. Accordingly, the modification on the recipe, i.e. the modification of α_i values, is guided by such considerations; the percentage of a lighter fiber, for instance, are raised while, at the same time, darker fibers are reduced. It is important to underline that, according to current practice, the modifications on the recipe should respect the following condition: $|\Delta\alpha_i| \leq 5\%$.

b) Once the first-attempt recipe is selected and the new blend is obtained, evaluate, using Eq. 5, a new "blend mixing" spectrum $R_N(\lambda, \alpha_i)$.

c) Evaluate, using the transfer function $\Phi(\lambda)$ the spectrophotometric response of the blend obtained by mixing the fibers with the new recipe, according to the following Equation:

$$R'(\lambda) \cong \Phi(\lambda) \cdot R_N(\lambda, \alpha_i) = \frac{R_S(\lambda)}{R(\lambda, \alpha_i)} \cdot R_N(\lambda, \alpha_i) \tag{6}$$

$R'(\lambda)$ is estimated without the need of physically carding a new blend and, since it is evaluated mathematically, it can be instantaneously evaluated.

Repeat step 6 using $R'(\lambda)$ instead of $R_S(\lambda)$.

As described above, step 8 can be repeated a number of times until the *CMC(2:1)* color distance is reduced below the pre-set threshold. This iterative process is not time-consuming since the only parameters to be changed are the n α_i values.

9. Physically create the new blend according to the last modified recipe, obtained in step 8a.
10. Determine actual spectrum $R^a(\lambda)$of the new blend and compare it, in terms of *CMC(2:1)* color distance, with the spectral response of the target. If such a color distance is lower than a given threshold (commonly in the range [0.6-0.8]), the modified recipe is successful in reliably replicating the target blend.

The final result of the method consists of a new recipe to be adopted for obtaining a given blend. The modified theoretical approach demonstrates its effectiveness under the condition that the percentage of the colored materials composing the blend is subjected to changes comprised in the range ± 5%. This means that the optimal recipe to obtain a desired color (i.e. the reference spectrum) has to be searched within modified recipes with $|\Delta\alpha_i| \leq 5\%$. This condition is acceptable for Textile companies in most of their cases since the modified recipe does not differs from the original ones more than 5% for each component. This restriction is because for every (little) modification of the recipe, the transfer function $\Phi(\lambda)$ is presumed to remain constant, but this cannot be respected with high variations on the recipe.

Method validation

To provide an example of the application of the method, a blend composed by 12 pre-colored wool fibers is here defined. The acquisition equipment consists of a Hunterlab Ultrascan VIS reflectance spectrophotometer with above-mentioned specs. Fig. 3 shows the spectrophotometric response of the 12 fibers composing the original blend.

The original recipe is as follows: $\mathcal{A} = [0.027,\ 0.046,\ 0.068, 0.094,\ 0.034,\ 0.056, 0.234, 0.228,\ 0.114,\ 0.012, 0.057,\ 0.038]$.

The threshold for color distance is set equal to 0.6.

The original recipe does not allow to meet the standards since the *CMC(2:1)* distance exceeds the given threshold (see Fig. 3) (Fig. 4).

Table 1
Results, in terms of CMC(2:1) distance obtained for three variations of the original recipe.

Fabric id.	Number of pre-colored components	Original Recipe (%)		$DE_{CMC(2:1)}$	First variation of the recipe (%)		$DE_{CMC(2:1)}$	Second variation of the recipe (%)		$DE_{CMC(2:1)}$	Third variation of the recipe (%)		$DE_{CMC(2:1)}$
32-R126A	12	$\alpha 1$	2.7	0.64	$\alpha 1$	2.6	0.38	$\alpha 1$	2.6	0.27	$\alpha 1$	2.7	0.24
		$\alpha 2$	4.6		$\alpha 2$	4.4		$\alpha 2$	4.2		$\alpha 2$	4.3	
		$\alpha 3$	6.8		$\alpha 3$	6.6		$\alpha 3$	6.7		$\alpha 3$	6.8	
		$\alpha 4$	9.4		$\alpha 4$	9.2		$\alpha 4$	9.4		$\alpha 4$	8.9	
		$\alpha 5$	3.4		$\alpha 5$	3.2		$\alpha 5$	3.2		$\alpha 5$	3.0	
		$\alpha 6$	5.6		$\alpha 6$	5.5		$\alpha 6$	5.4		$\alpha 6$	5.6	
		$\alpha 7$	23.4		$\alpha 7$	24.6		$\alpha 7$	25.6		$\alpha 7$	26.6	
		$\alpha 8$	22.8		$\alpha 8$	22.1		$\alpha 8$	21.5		$\alpha 8$	20.6	
		$\alpha 9$	11.4		$\alpha 9$	11.1		$\alpha 9$	10.7		$\alpha 9$	10.4	
		$\alpha 10$	1.2		$\alpha 10$	1.1		$\alpha 10$	1.2		$\alpha 10$	1.2	
		$\alpha 11$	5.7		$\alpha 11$	5.9		$\alpha 11$	6.3		$\alpha 11$	6.3	
		$\alpha 12$	3,8		$\alpha 12$	3,6		$\alpha 12$	3,5		$\alpha 12$	3,5	

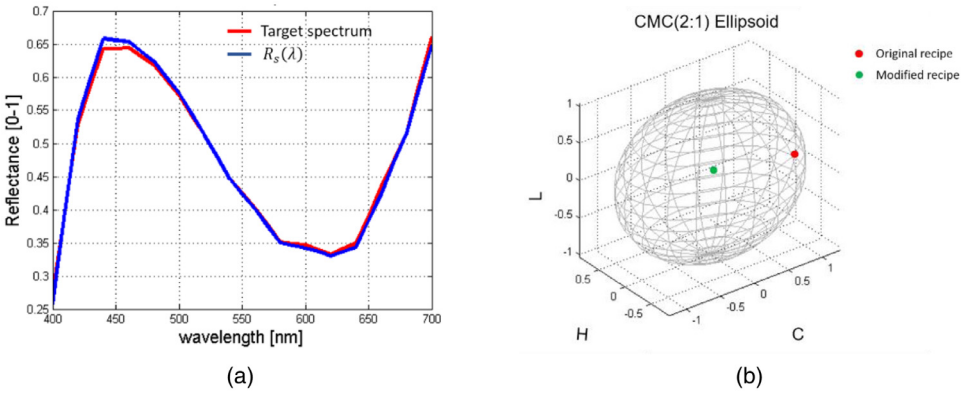

Fig. 4. a) Comparison between $R_s(\lambda)$ and target spectra for the exemplificative blend; b) position, in the CIE CMC(2:1) ellipsoid built based on target spectrum, of original and target recipe.

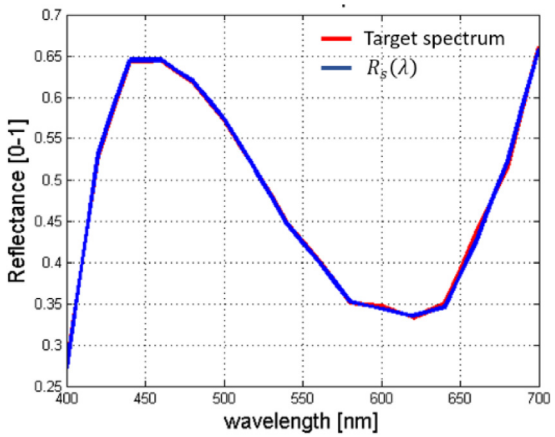

Fig. 5. a) Comparison between $R_s(\lambda)$ and target spectra for the modified blend (third recipe).

Therefore, colorists tested three different variations of the recipe as listed in Table 1 in order to reduce color distance, assessed according to the proposed method. Third variation of the recipe is as the one to create the blend, which resembles the desired standard. For each test the term $DE_{CMC(2:1)}$ indicates the CMC(2:1) colorimetric distance between the predicted spectrophotometric response and the measured one. Measured against the target blend spectral response $R_S(\lambda)$, the actual spectrum of the new blend $R^a(\lambda)$ resulted, for such a recipe, equal to 0.24 (see Fig. 5).

Declaration of interests

X The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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