Industrial Research on Evolution and Prediction of Hardwoods Color

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Color prediction in dyed wood is a difficult task since it involves the analysis of light propagation through a complex media where scattering and absorption processes are present. Kubelka-Munk based models are usually proposed to make those predictions. Here, an oak wood color prediction tool is presented with the Kubelka-Munk theory and self-learning procedures as the basis of the model. Color prediction lies on the joint contribution of both the dying material and the wood substrate, each characterized by their previously obtained colorimetric and spectral properties. An identification of wood and dyes through the study of their optical properties is shown from which the necessary parameters are obtained for the different applications. The model allows to predict with good accuracy the resulting color in wood through the $L^*C^*h^\circ$ coordinates when mixing either water or solvent based dyes in different proportions for dying a wood substrate. Furthermore, the influence of applying dyes mixture by either hand with a brush or machine with a roller coating, and also that of varnishing are studied.

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1. INTRODUCTION

A huge variety of situations in physics involve light propagation in media with significant scattering and absorption. Consequently, approaches to this problem are quite different, depending on the area, from astronomy[1] or colloids[2] to industries like paper[3, 4], paints[5], color printing[6], plastics[7], ceramics [8], textiles [9] or even the food industry[10]. A good review of the advances and physical approaches introduced during the 20th century can be found in [11, 12].

The transport of light through wood [13] has also been an area of interest since finished wood distinctive appearance is commercially important. Wood has always been a highly prized construction material for its strength properties combined with a relatively low density and the ease with which it can be cut, carved, bent, etc. However,freshly cut wood is not a common option, being very often dried and finished in some way before use. The finished wood has a characteristic appearance with its spatial and color variation, that is due to a multitude of factors, including the nature of the wood (type, age, cut orientation), the storage conditions (temperature and humidity), the physical processes undergone (the mechanics of the cut and sanding) and the finishes applied to it (oils, dyes, varnishes, and their combinations). The whole process of light transportation that gives rise to the reflectance and color of wood is a combination of surface and volume effects that makes the modeling of the optical behavior a very complex task. However, among all the factors, the finish is probably the most influential on the overall color and the one in which the models can most efficiently work.

Modeling light propagation in wood being a complex problem, the most general approach, i.e. solving the RTE (Radiative Transfer Equation)[14], is not practical. However, there are other ways of dealing with the problem of surface reflectance that have proved very useful, as well as reliable and easy to apply, like the bidirectional flow models [11]. Two or four-flow models [15, 16], can be considered good theoretical frameworks to address the problem of surface spectroscopy.

The success of the two-flux theory known as Kubelka–Munk's (K–M) [5] is based on three aspects: (i) the required assumptions are very simple (homogeneous medium, isotropic scattering, bidirectional diffuse light flux, and no lateral boundaries nor specular reflection), (ii) their solutions are fundamentally correct (the RTE reaches equivalent solutions for isotropic scatters), and (iii) its main result, the so called K–M function, is broadly known and applied. This last result directly relates the reflectance of a material surface with the ratio K/S, being K and S the absorption and backscattering coefficients, respectively, both reciprocal lengths. This reflectance is often noted as R_∞, because it is valid for specimens that are thick enough as to totally hide the substrate underneath. Of course there are other important and more generalistic developments under the general name of K–M theory [17, 18].

The past developments and applications of bidirectional models have created a solid basis for the development of a color–prediction model for wood. This basis is very important since, as mentioned previously, different processes can considerably alter the final color of the wood in an unexpected way, making it difficult to obtain or reproduce an specific appearance. Today, the mechanisms for achieving a desired color on a surface that undergoes changes through various finishing processes, are essentially empirical. Hence, the predictive capacity is based exclusively on the experience achieved by a learning process based on trial and error. In this work, a wood color prediction model based on colorimetric and spectral properties of the wood and the colorants used is presented. The model allows to predict objectively the resulting color in wood given with $L^*C^*h^\circ$ color coordinates, when applying different dyes mixture with a color variation less than the intrinsic variation of natural wood. In this model, numerical tools are used, based on the K–M theory and self-learning procedures that help to improve the precision of the prediction provided by the light transport theory adapted to the wood.

In Sections 2 theoretical framework of this work will be presented. Kubelka-Munk theory is mentioned with the color matching and dyes mixture problems. In Section 3 the material and the experimental methods used in the study are described. The results of the different parts of the study are presented in Section 4. An identification of wood and dyes by the study of their optical properties is shown, obtaining the necessary parameters for the different applications.This characterization of the materials is essential for the color prediction on wood. In the section the prediction model is also explained. Furthermore, some interesting results are shown such as the influence of applying dyes mixture by hand with a brush or by machine with a roller coating and the influence the varnished. Finally, Section 5 presents a summary and the main conclusions of this work.

2. THEORETICAL MODEL AND CALCULATIONS

A. Kubelka-Munk Theory

Kubelka-Munk model[19] is a quite simple two-flux bidirectional model of light propagation. It assumes an opaque layer that is parallel to a supporting substrate plane (assumptions [3, 11] and references therein). With its result for the spectral reflectance in the visible range, the color of opaque materials can be predicted. The important role of light propagation (the volume affects surface color), means that each component of the visible spectrum has to be associated to an absorption coefficient K, and a scattering coefficient S, both wavelength-dependent magnitudes. In practical terms it means that each dye in the sample has to be well known, as well as its concentration and the thickness (X) of such layer. All of them takes part in forming an specific color.

The Kubelka-Munk model provides an expression for the total reflectance R_t , i.e., the fraction of the incident light reflected by the specimen placed in optical contact with a given substrate.

$$R_t = \frac{(1 - aR_g) \sinh bSX + bR_g \cosh bSX}{(a - R_g) \sinh bSX + b \cosh bSX} \quad (1)$$

, where $a = 1 + K/S$, $b = \sqrt{a^2 - 1}$ and R_g is the substrate reflectance . This equation is commonly found in the literature in terms of coth [3] [11]. It may be shown that in the limit of infinite thickness, Eq. (1) reduces to the well-known Kubelka-Munk function R_∞

$$\lim_{X\to\infty} R_t \equiv R_\infty = a - b = 1 + \frac{K}{S} - \sqrt{\left(\frac{K}{S}\right)^2 + 2\left(\frac{K}{S}\right)} \quad (2)$$

or

$$\frac{K}{S} = \frac{(1 - R_\infty)^2}{2R_\infty} \quad (3)$$

Making use of Eq. (1) the dye film thickness is:

$$X = \frac{1}{2bS} \ln \left[\frac{R_T (a - b) + R_g (a + b) - 1}{R_T (a + b) + R_g (a - b) - 1} \right] \quad (4)$$

Another important equation for color formulation is the additive of absorption and scattering contributions of each component in a mixture, a dependence that was already proposed in the early developments of the model [20]:

$$\frac{K(\lambda)}{S(\lambda)} = \frac{\sum c_i K_i(\lambda)}{\sum c_i S_i(\lambda)} \quad (5)$$

,where $K(\lambda)$ and $S(\lambda)$ are the absorption and scattering coefficients of the mixture, c_i the concentrations of each dye and $K_i(\lambda)$ and $S_i(\lambda)$ the absorption and scattering coefficients of each dye.

A.1. Color Matching

Color matching problem involves, first, predicting the spectral reflectance of any known dye mixture. This requires characterizing the starting dyes, i.e. the coefficients $K_i(\lambda)$ and $S_i(\lambda)$, and, obtaining the overall $K_i(\lambda)/S_i(\lambda)$ (Eq. (3)) provided that all concentrations are known. Secondly, color matching also involves an inverse problem, i.e. finding the necessary mixture to obtain a specific spectral reflectance. Again, this requires characterizing the starting dyes and solving an undetermined system of equations to obtain the concentrations.

The color of various mixtures of dyes applied on any substrate have to be predicted with the Eq. (1) and Eq. (5). For that, the absorption and scattering coefficients of each dye has to be known, as well as the reflectance of the substrate.

A.2. Dyes mixture

The total reflectance when a quantity of dyes mixture is applied on the substrate has contributions from both the substrate and the dyes mixture. It is known that the reflectance cannot be added, however K/S is additive. Therefore, the color of dye mixtures applied on any substrate can be predicted with Eq. (1) and Eq. (5). Hence, knowing each dye absorption and scattering coefficients and substrate reflectance the dyes mixture final color is predicted. Figures 1 and 2 show the color variation, assuming the Standard Illuminant D65 and 2° Standard Observer of 1931, when applying an increasing thickness of two and three dyes mixture (white circle, square and star) on a substrate (white rhombus). Depending on the concentration of each dye, different range of colors can be obtained.

B. Spectrophotometry and colorimetry

From the spectral reflectance and transmittance functions computed with a propagation model, CIE-XYZ tristimulus values can be computed assuming a standard illuminant and a standard observer [21], so that the color presented by a sample either in reflectance or transmittance can be numerically located in a color space. XYZ color coordinates can then be converted to $L^*a^*b^*$ color coordinates (L^* being the luminosity), which allow for the calculation of the chroma C^* and the hue h°.

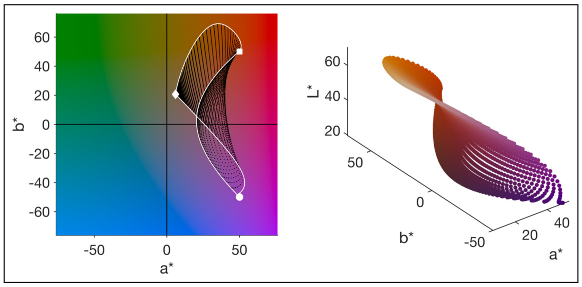

Fig. 1. Color space range obtained applying an increasing film thickness of two dyes mixture (white circle and square) on a substrate (white rhombus).

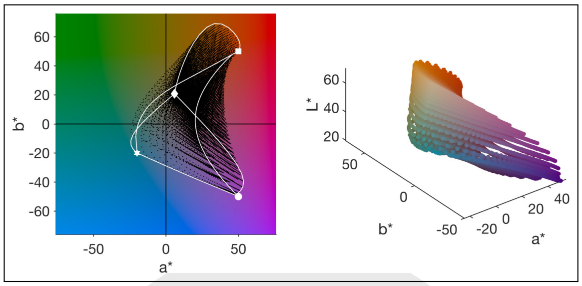

Fig. 2. Color space range obtained applying an increasing film thickness of three dyes mixture (white circle, square and star) on a substrate (white rhombus).

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (6)$$

$$h^\circ = \arctan\left(\frac{b^*}{a^*}\right) \quad (7)$$

The color difference is calculated with the formula ΔE_{00} improved in 2000 where lightness inaccuracies are fixed [22]. Currently, it is the most accurate CIE color difference algorithm available.

3. SYSTEM COMPOSITION AND EXPERIMENTAL METHODS

A. Material description

For this study, oak wood provided by Wood Manners company was used. This type of wood is divided into different selections according to the knots and the homogeneity of the color. The selections are Exquisite, Elegant, Classic and Modern (see Fig. 3).

Fig. 3. Factory's wood selection (from left to right): Exquisite, Elegant, Classic and Modern.

Furthermore, before dye mixture application the wood undergoes a sanding process. The sanding can be light, medium or intense according to the intensity and depth of the different nylon and steel brushes used. The light sanding is required to have wood's pore a bit open, and for that the wood undergoes first a steel brush and then a nylon brush with little depth. When wood's pore has to be more open, the medium sanding is used, which is done by passing the wood through a steel brush with double pressure or depth and through the nylon brush. Finally, the intense sanding leaves the pore open using the steel and the nylon brush with double pressure or depth. Then a standard sanding is applied to leave the upper part flat. On the other hand, dyes dissolved in water and solvent were used to stain the hardwood. The colors available to mix were blue, yellow, orange, red and black for solvent-bases dyes and blue, yellow, green, red, black and white for water-based dyes. These products were also provided by Wood Manners company.

B. Experimental procedure

B.1. Measure method

The color of the wood samples was measured once the dye applied had dried (*infinite* thickness), since the color varied in the drying process. The measurements were made at different points of the wood sample, thus, the results of the measurements showed a point cloud, providing information of the color variation in the sample. The number of points selected varies from 10–20 depending on the samples size. Hence, the average color and its dispersion were obtained for each sample, and the study is based on it.

The measurements of the surface reflectance was performed with a Konica Minolta CM-2300d spectrophotometer, within an approximately 8 mm diameter spot. From the reflectance the color coordinates were calculated assuming the D65 Standard Illuminant and the 10º Standard Observer from 1964.

B.2. Material characterization method

It is necessary to know the absorption and scattering properties of each isolated dye, in order to be able to separate the effects of the substrate and those of each dye and to be able to predict colors of mixtures (see A.2). Therefore, substrate and dyes physical parameters that characterized the materials had to be identified.

The substrate was characterized obtaining the reflectance values (R_g) and the ratio between the absorption (K) and the scattering (S) coefficients. Before this characterization an analysis of how sanding affects the color.

Dyes were characterized identifying the K/S ratios of each one based on the product concentration (c) · uptake of dye (g) thus the reflectance can be predicted as a function of concentration of dyes mixture applied on wood and the uptake of dye by wood in g/m^2 .

In the characterization the same method was applied with all the dyes. Five solutions with different concentration of dyes were prepared on water or solvent and they were applied on wood with different amount of solution (different uptakes). As a result, several samples were obtained with varied concentrations and uptakes. Once the dye was dried the relation between K/S ratios and the product c · g was adjusted, using the samples reflectance.

4. RESULTS

A. Characterization/Parametrization of Materials

The following section shows results obtained in the identification of the materials (wood and dyes) using their optical properties. The characterization of the substrate and dyes is explained, where the necessary parameters for color prediction were obtained. In addition, a study of the influence of sanding, a brief analysis of the influence of applying dyes mixture by hand with a brush and by machine with a roller coating and an approximation of applied dye's film thickness on the substrate by industrial machines are presented.

A.1. Substrate (Wood)

The spectral reflectance of 4 wood selections (see Fig. 3) and 3 types of sanding (light, medium and intense) were analyzed. The reflectances measured before and after sanding do not show significant differences (see, e.g., Fig. 4). Figures 5 and 6 show the color coordinates before and after sanding. In the figures it is also observed that there is no significant difference in wood color when it is sanded.

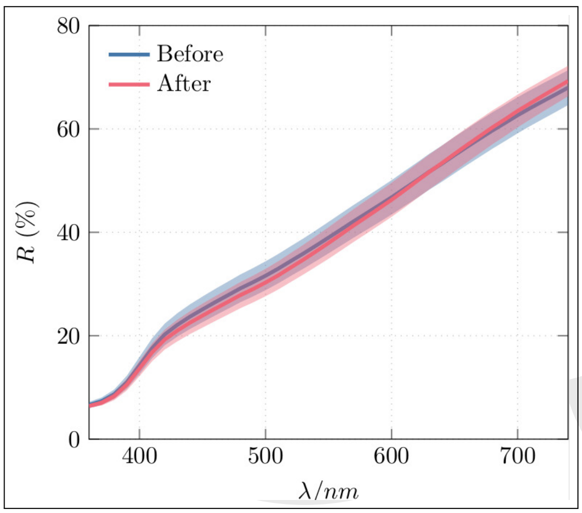

Fig. 4. Spectral reflectance of wood samples before and after medium sanding.

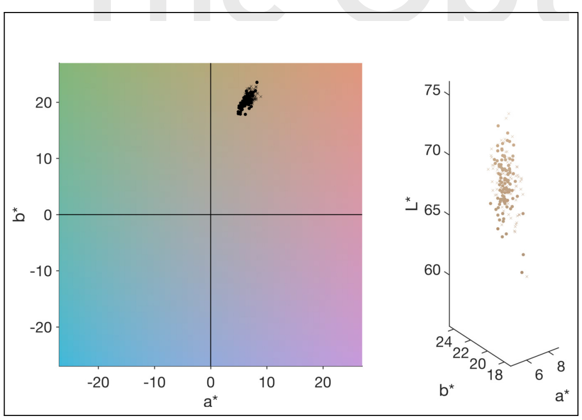

Fig. 5. Color coordinates $L^*a^*b^*$ of wood samples before (points) and after (crosses) medium sanding.

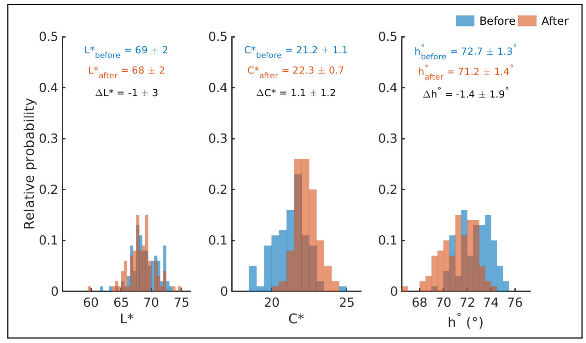

Fig. 6. Relative probability histograms of color coordinates $L^*C^*h^\circ$ of wood samples before and after medium sanding.

The spectral reflectance values of the 4 selections are shown in Figure 7. In the results a smooth growth trend as the wavelength increases is appreciable.

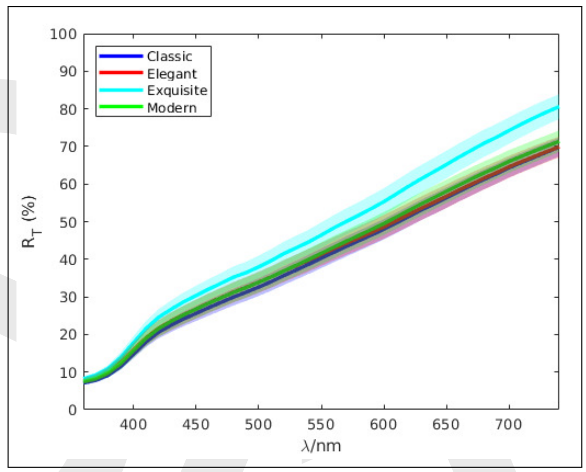

Fig. 7. Spectral Reflectance of different substrate selections: Exquisite, Classic, Elegant and Modern.

In Figure 8 the color coordinates $L^*a^*b^*$ of the substrates are shown. Hence, wood color coordinates can be summarized with the values $L^* = 71 \pm 2$, $C^* = 21 \pm 1$ and $h^\circ = 73.7 \pm 1.5^\circ$.

A.2. Pigments and colorants

The spectral reflectance of 11 dyes at different concentrations and uptakes was measured. The concentrations of dyes in the mixture usually do not exceed 10% of the proportion since the colors obtained normally are similar to the wood. In the study, this proportion was increased for solvent-based dyes, but the mixture of dyes never exceeded 30% of the total proportion. In the case of water-based dyes mixtures, the proportion was lower as it forms a film in the wood. Regarding uptake of dye, the range was usually between 15-25 g/m^2 although a higher range of between 10-40 g/m^2 was reached in order to expand color prediction model values. As an example, the reflectances for the solvent-based red dye are shown in Figure 9.

From the results it was observed that the function that best described the relationship between K/S and the product $c \cdot g$ was an exponential function, $(K/S) = a(c \cdot g)^b$. A fitting was made for each dye obtaining values of the spectral parameters a and b (one value for each wavelength) for each dye that would predict the reflectance based on the applied dye. As an example,

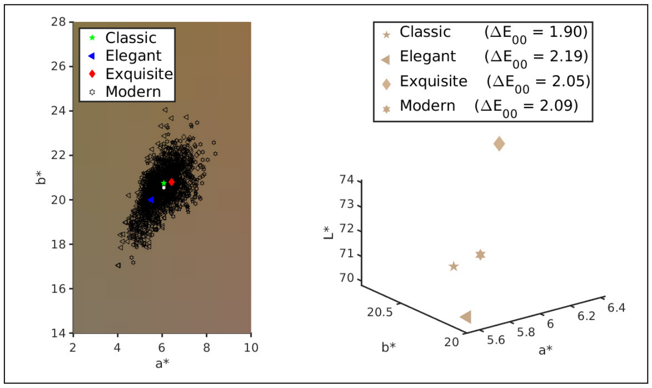

Fig. 8. Color coordinates $L^*a^*b^*$ of 4 wood selections. On the left, the $a^* - b^*$ plane is shown, where all measurements made with the spectrophotometer for each type of substrate are shown, with its average. On the right, each substrate selection is presented in the $L^*a^*b^*$ color space.

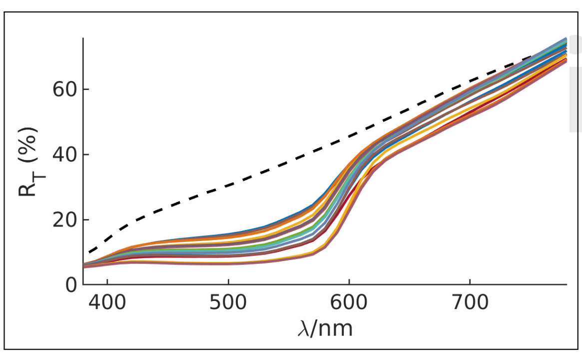

Fig. 9. Spectral reflectance of solvent-based red dye at different concentrations and uptakes.

Figure 10 shows K/S of solvent-based red dye as a function of the product $c \cdot g$ for a value of λ, with its best fit function parameters.

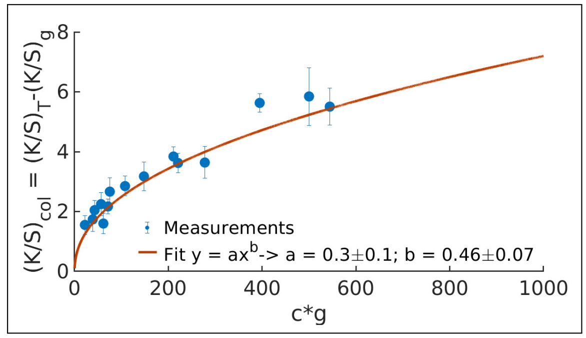

Fig. 10. Solvent-based red dye's (K/S) ratio as a function of the product $c \cdot g$ for a value of λ. The best fit for the data with its corresponding parameters is also shown.

B. Influence of applying dyes mixture by hand with a brush or by machine with a roller coating

In this study samples were made by hand using a brush with an uptake and a particular mixture and then they were replicated by machine using the roller coating. In the first study, a comparison was made between water-based dyes and solvent-based dyes. Two different concentrations were chosen, one per type of dye, and 5–6 samples were stained. Figures 11 and 12 show the results for water-based and solvent-based dyes, respectively. The color varies in the case of water-based dyes, while it may considered the same for solvent-based dyes, when applied by hand with a brush or by machine with the roller coating.

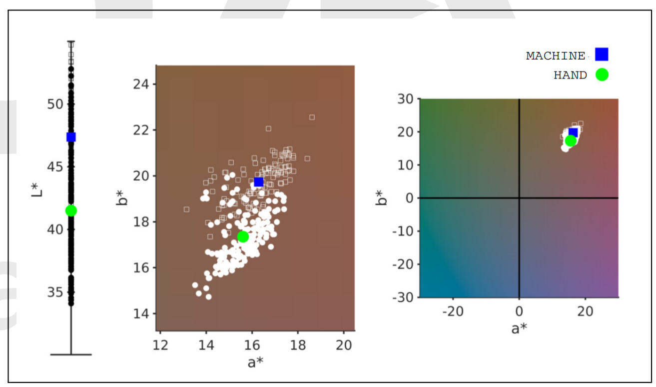

Fig. 11. $L^*a^*b^*$ color coordinates of samples stained with water-based dyes. Points show measurements of 6 samples applying dyes mixture by hand using the brush and squares show measurements of the 6 remaining samples applying dyes mixture by a roller coating in the machine.

In a second study, the solvent-based dyes were mixed with water-based white pigment since there is no white color in solvent-based dyes. In general, solvent- and water-based pigments are not miscible. However, when the solvent is a hydro-alcohol and dyes are used in very low ratios, the mixture is not so unstable. In addition, the constant movement of the fluid in the machines prevents it form separating. The same analysis was performed by adding the white dye and it was shown that the final color was similar when the samples were stained by

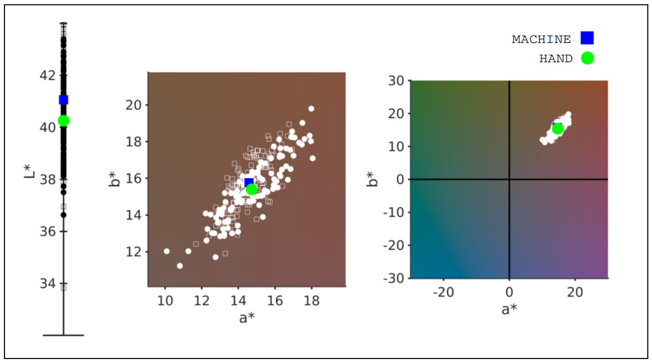

Fig. 12. $L^*a^*b^*$ color coordinates of samples stained with solvent-based dyes. Points show measurements made on 6 samples made by hand using the brush and squares show measurements of the 6 remaining samples made by a roller coating in the machine.

hand with a brush or by machine with a roller coating (see Fig. 13).

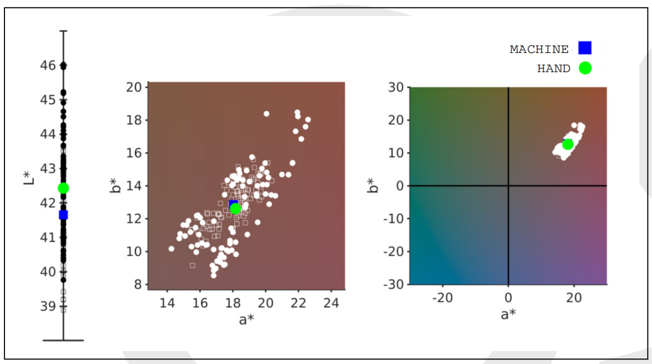

Fig. 13. $L^*a^*b^*$ color coordinates of samples stained with a mixture of a solvent-based dye and a water-based white pigment. Points show measurements made on 6 samples made by hand using a brush and squares show measurements of the 6 remaining samples made by machine using a roller coating.

B.1. Estimation of the dyes film thickness

The thickness measurement turned out to be very complicated, because the dye penetrates the wood. Once the absorption and scattering properties and the substrate reflectance of each dye are known, the thickness of the applied dye with the industrial rollers can be estimated from the total reflectance measurements, using Eq. (4). On average, the applied dyes film thickness is approximately $10\,\mu$m.

Figure 14 shows the comparison between the experimentally measured spectral reflectance and the theoretical estimates obtained for different thicknesses. It can be seen that theoretical curve for $X = 10\,\mu$m is the one that best fits the experimental curve.

C. Color prediction model

It is possible to obtain a prediction of the resulting colors by mixing different colorants in different proportions, and applying them on a wooden substrate, once substrate and dyes are characterized. However, the formulation of the problem in terms of a single expression for $(K/S)_{mix}$ is not a straightforward task,

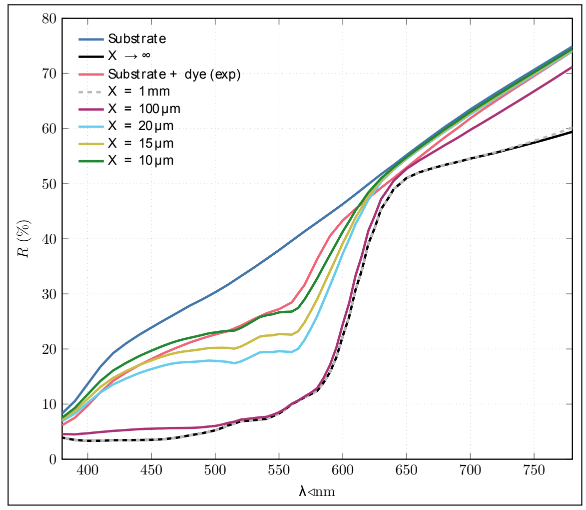

Fig. 14. Experimentally measured spectral reflectance of the water-based red dye and theoretical estimates obtained for different thicknesses. Substrate reflectance is shown as a reference.

since the pigment data are specific properties of the material –i.e. properties defined for every point in the layer volume– while the substrate properties are located underneath, and its importance depends on the thickness and pigment concentration of the layer above. An empirical approach was proposed for this case, in terms of an addition of coefficients:

$$\left(\frac{K}{S}\right)_{\text{mix}} = \left(\frac{K}{S}\right)_{\text{g}} + \sum_{i=1}^{11}\left(\frac{K}{S}\right)_i, \tag{8}$$

where

$$\sum_{i=1}^{11}\left(\frac{K}{S}\right)_i = \sum_{i=1}^{11} a(c\cdot g)^b \tag{9}$$

being a and b the spectral-dependent parameters whose fit was described in section A.2. According to Eq. (8) the substrate term becomes relatively less important for highly absorbing pigments.

Hence, different regions in the color space will be covered depending on mixed dyes, dyes concentration and uptake. The intrinsic variability of the color will be shown with the point cloud. It is important to emphasize here that, from the absorption and scattering properties of stained wood, it is possible to obtain color coordinates by the reflectance through Eq. (3) (the thickness will be *infinite* since it is measured on dry pigment).

The validation process, comparing theoretical and experimental results, was satisfactory. However, the prediction needs an improvement in order to obtain more accurate predictions.

Therefore, a self-learning method has been added to the prediction model based on the samples recollected and connections found among all the data.

C.1. Database

For the construction of an improvement model for color prediction, all the possible information was collected, creating a database.

Figure 15 shows $L^*a^*b^*$ color coordinates of all the samples used in the prediction model improvement process. Some of them were obtained by hand dying with a brush in the laboratory (small points) and the rest were made in the company's machine with a roller coating (big points). As it is observed, small dots (samples by hand) encompass big ones (samples by machine), therefore, the prediction model will be more accurate since most of the predictions will not use extrapolation method.

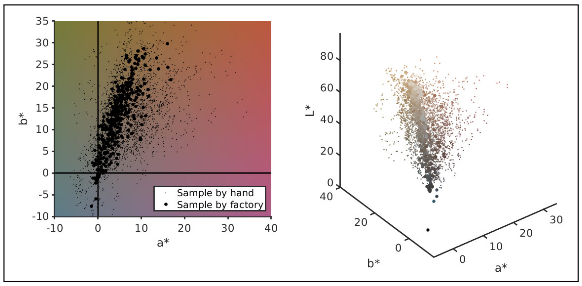

Fig. 15. $L^*a^*b^*$ color coordinates of all samples used in the prediction model improvement process, those obtained from the laboratory by hand application (small points) and from the factory (big points).

C.2. Self-learning method

The method used to improve the prediction model is based on a simple linear regression, since a high linear correlation is appreciable between color coordinates (L^*, C^* and h°) obtained with the prediction model and those obtained experimentally. In Figure 16 the mentioned linear relation is observed for the three color coordinates.

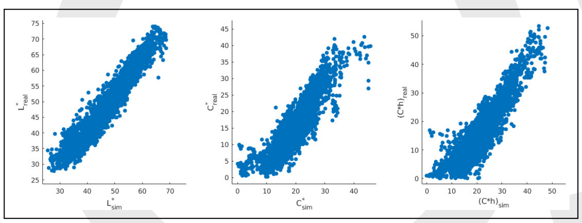

Fig. 16. Linear correlation between the L^*, C^* and h° color coordinates obtained with the prediction model and those obtained experimentally.

C.3. Prediction software operating method

The reflectance of the target color is introduced in the program. The target color is compared with all the samples saved on the database calculating color differences with the ΔE_{00} formula. The program will choose 3–8 samples with the minimum value of ΔE_{00} and with each sample will follow the instructions below:

- If $\Delta E_{00} < 1$ it will choose dyes concentrations and uptakes of this sample from the database as a good prediction for the target color matching. Hence the concentration and uptake of the sample will be shown in the screen.
- Else ($\Delta E_{00} > 1$) It will take dyes concentrations and uptakes of the database sample as a starting point in the prediction. The program will vary this concentrations of dyes and uptakes automatically in small quantities calculating the new color coordinates of dyes mixture and the color difference with the target. The color coordinates of the modified concentrations will be calculated using the prediction model mentioned at the beginning of section 8, improved with the simple regression model. That is, it will calculate the color coordinates as the sum of K/S of each dye– calculated using the product $c \cdot g$– and then apply a change with linear regression.

  The program will continue varying the concentrations in a prescribed way until the color difference ΔE_{00} is minimized. Finally, the concentrations and uptakes with the minimum ΔE_{00} will be saved and shown in the screen.

D. Varnish Influence in wood color

In a first study, different shades from the factory sample collection were used to get an initial idea of the influence of varnish. Table 1 shows a summary of the absolute changes in the $L^*C^*h^\circ$ coordinates as well as the color differences ΔE and ΔE_{00} when applying varnish on these different shades.

Table 1. Absolute changes in the $L^*C^*h^\circ$ coordinates and color differences ΔE and ΔE_{00} when applying varnish on the different shades.

Hue	ΔL^*	ΔC^*	Δh° (°)	ΔE	ΔE_{00}
Brut Nature ($L^* > 60$)	-7 ± 2	7.2 ± 1.0	-2.0 ± 1.0	10.3 ± 1.5	6.9 ± 1.5
Clear ($L^* > 60$)	-3.6 ± 1.8	4.4 ± 1.1	-1.6 ± 1.3	6.0 ± 1.0	3.9 ± 0.9
Moscatto ($L^* < 60$)	0.8 ± 1.8	0.5 ± 1.0	-0.6 ± 1.1	1.9 ± 1.2	1.7 ± 1.0
Zaha Gris($L^* < 60$)	-3.2 ± 1.4	0.5 ± 1.4	0.8 ± 1.4	3.6 ± 1.2	3.3 ± 1.1
Zaha Negro ($L^* < 40$)	0 ± 2	-0.2 ± 1.3	7 ± 5	2.2 ± 1.3	2.0 ± 1.0

As a result, it can be seen that the luminosity (L^*) always decreases when applying varnishes, i.e., the color becomes darker. In the case of saturation (C^*) , the behavior varies according to the luminosity. In light shades materials ($L^* \gtrapprox 70$), the saturation increases; in dark shades materials ($L^* \lessapprox 40$), on the contrary, the saturation decreases.

Finally, the hue (h°) remains unchanged in most cases, the variation is negligible in comparison to the intrinsic variation of the wood itself.

In a second analysis, 80 samples stained with the dyes used in the factory were studied. Different dyes were added in the mixtures, covering the largest color space available with the 80 samples. The results are shown in figures 17 and 18.

Figure 17 shows the relationship between the L^*C^*h color coordinates of unvarnished samples and their differences, $\Delta L^*, \Delta C^*$ and Δh , comparing with the color obtained when varnishing the samples. The same conclusions deduced from the Table 1 can be drawn.

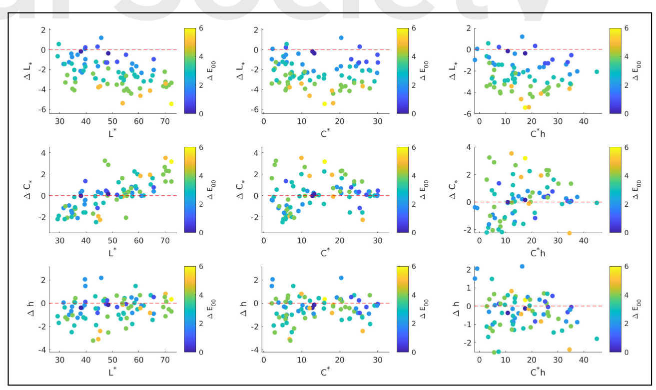

Fig. 17. Color differences , $\Delta L^*, \Delta C^*$ and Δh, of varnished and unvarnished samples as a function of the coordinates L^*C^*h of the samples before being varnished. Dots color indicate the color difference, $\Delta E00$, between the two samples.

Figure 18 shows the relation between the L^*C^*h color coordinates without varnishing and varnishing. From this figure it can be concluded that the varnish influence could be predicted with a simple regression model.

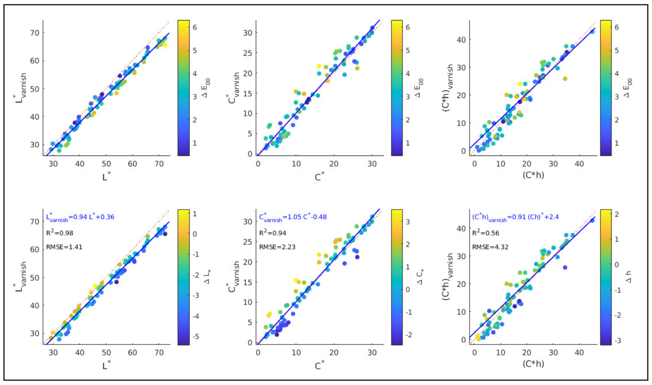

Fig. 18. L^*C^*h coordinates of the samples before and after being varnished. Color dots indicate the color difference, ΔE_{00}, between the two samples.

5. CONCLUSIONS

Color prediction tool in oak wood with considerable precision, given the intrinsic variation of the wood, is presented showing all the steps and its results. The model allows to predict the resulting color when mixing different dyes in different proportions and applying them on an oak wood substrate. Therefore, empirical method applied has been replaced by an objective model , i.e., it is not necessary to prepare real physical samples.

Another application of the widely used Kubelka-Munk formalism has been presented, where the main result known as Kubelka Munk function has been the principal tool in the development of the predictive model. The color prediction is based on the sum of the contributions of each material applied and the substrate. Therefore, an identification of the absorption and scattering properties of each dye and the substrate was made to separate the effect of each one and develop the model. The characterization of dyes is based on best fitting for the results obtained in practice. Therefore, the fitting function could vary when using another type of dye or when applying the same dye on another substrate.

The prediction model based on light propagation is not precise enough because some technical aspects that could affect have not been taken into account. In this article a self-learning method were used to achieve a more precise prediction. The combination of a simple linear regression allowed to improve the precision of the color prediction, achieving a color difference less than the intrinsic color variation of wood. However, it should be mentioned that the prediction is not accurate in the entire color space, for some color areas it works better than for others. Therefore, as a future line of research it would be convenient to carry out a microscopic study of the wood. This research would provide information about the behavior of dyes when penetrating the wood such as the depth, where it goes or the chemical reactions between dyes and wood components. It is known that when a water-based dyes mixture is applied grain rising appears and this can also influence on the resulting color. This color changed caused by chemical reactions are not characterized by Kubelka -Munk theory.

All the samples used for the research and development of the prediction tool were also useful. This information have create a database that allows the automation of the color prediction, since it establish as a starting estimation close to the objective.

Another important result on wood color prediction is to know the approximate applied dyes film thickness on the substrate since it helps know in advance what thickness will normally be applied by the machine's roller.

An interesting addition to these results is the analysis of the difference of applying dyes mixture by hand with the brush or by machine with a roller coating. It can be seen that when a color is replicated by machine with the roller coating, after being matched by hand dying with brush, can disperse depending on the dyes used.

Another aspect that has been examined is the influence of varnish. It is concluded that luminosity and saturation are the color coordinates that change in the process. Moreover, it has been observed that in light colors the difference is more significant than in dark ones. The importance of final solution is that it can be quantified with a simple prediction model.

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