UNIVERSITÀ DEGLI STUDI FIRENZE
DIEF DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

METHODS FOR PREDICTING SPECTRAL RESPONSE OF FIBER BLENDS

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re-vip reverse engineering, virtual and rapid prototyping

COLOR IN TEXTURE AND MATERIAL RECOGNITION

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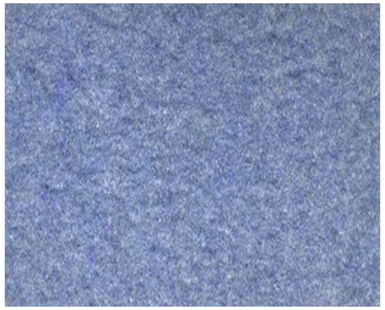
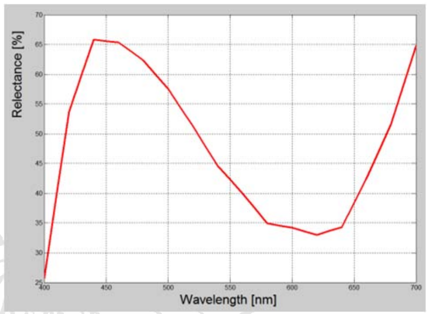
Background_1

One of the key phases in producing textile fabrics is the "recipe-based mixing"

Desired colour
(customer or catalogue)



Spectrophotometric measurement



Pre-coloured fibers
(Store)

"Historical" Recipe
(Company know-how)
Fiber 1: 21%
Fiber 2: 18%
Fiber 3: 5%
…
Carding Machine

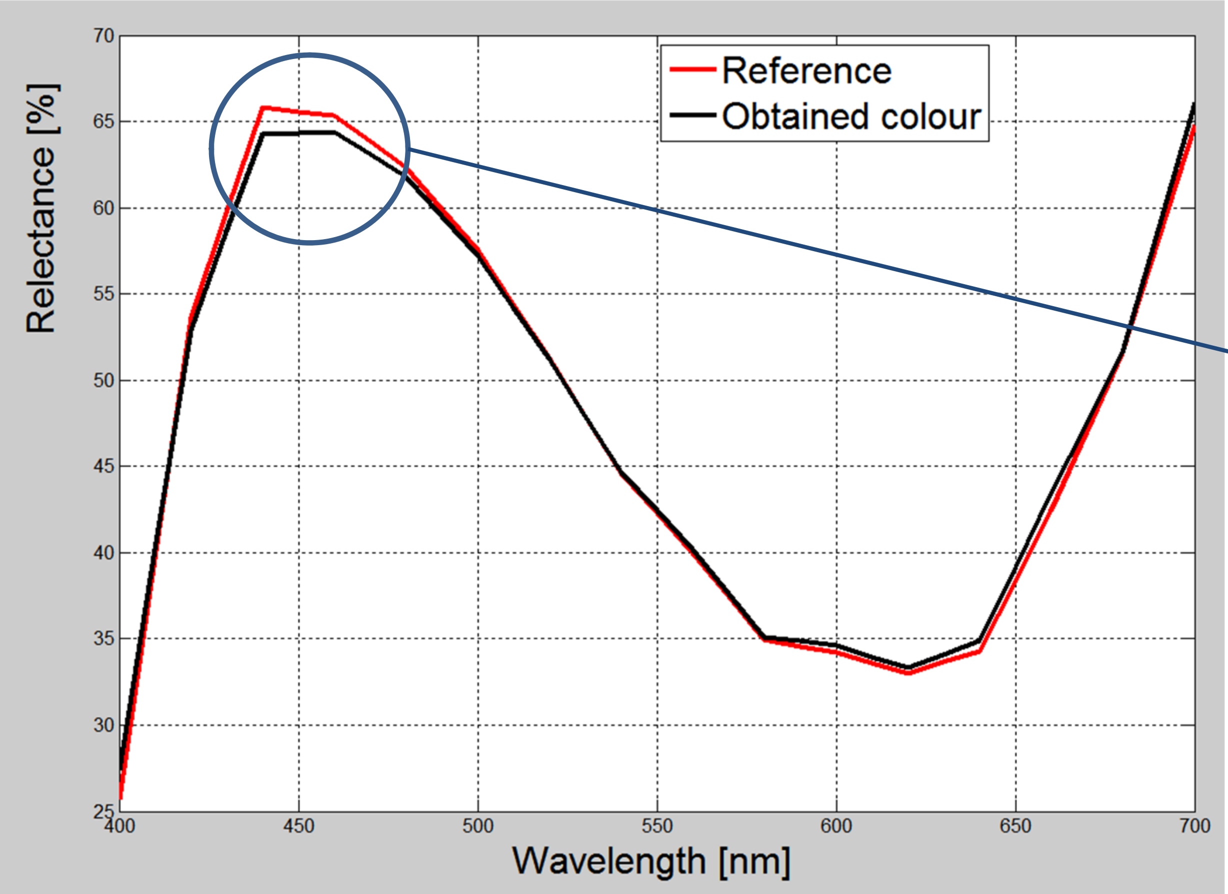
Obtained colour
(using recipe)

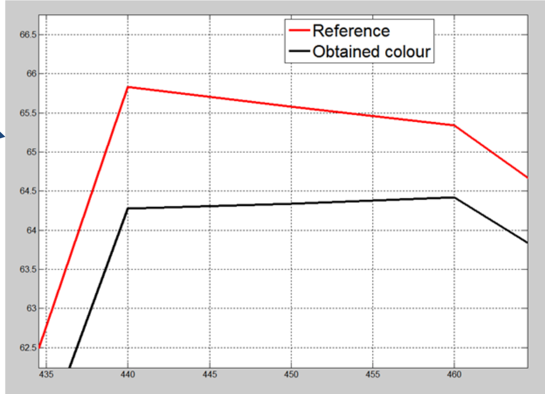
Colour control

If CMC(2:1) < TH
(e.g. TH = 0.8)

BACKGROUND_2

MOST TIMES, UNFORTUNATELY, THE RESULT OBTAINED BY MIXING THE FIBERS MAY BE VERY DIFFERENT, IN TERMS OF SPECTROPHOTOMETRIC DISTANCE, FROM THE REFERENCE:



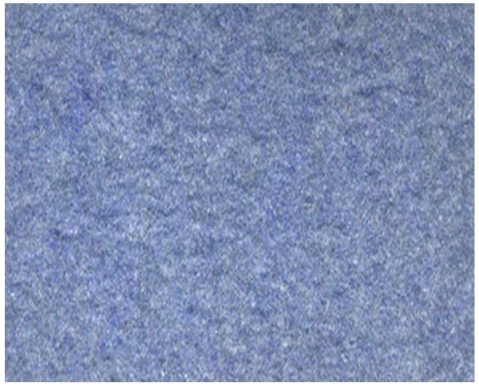


CMC(2:1) = 1.3

BACKGROUND_2

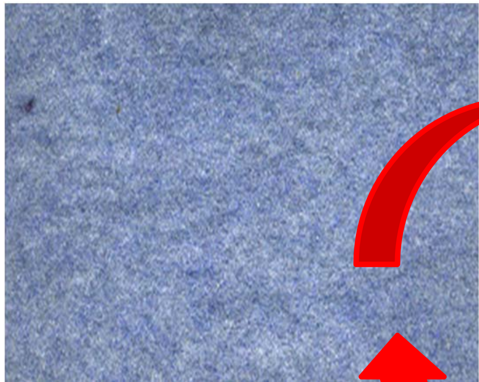
THE COLOURISTS HAVE TO CHANGE THE ORIGINAL RECIPE TO REDUCE THE COLORIMETRIC DISTANCE BETWEEN THE OBTAINED BLEND AND THE DESIRED ONE

DESIRED COLOUR
(CUSTOMER OR CATALOGUE)



"HISTORICAL" RECIPE
(COMPANY KNOW-HOW)
FIBER 1: 21%
FIBER 2: 18%
FIBER 3: 5%
...

OBTAINED COLOUR



COLOUR CONTROL

IF CMC(2:1) > TH
(E.G. TH = 0.8)

"MODIFIED" RECIPE
(COMPANY KNOW-HOW)
FIBER 1: 23%
FIBER 2: 18%
FIBER 3: 3%
...

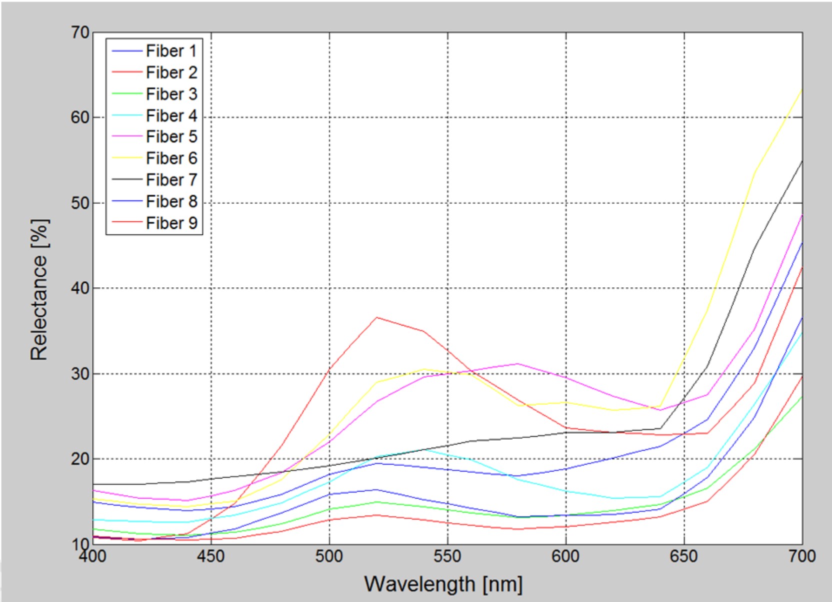
NEW COLOUR

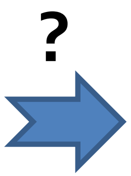
ITERATIVE PROCESS (40 MIN EACH TRIAL, 5-6 TRIALS USUALLY).

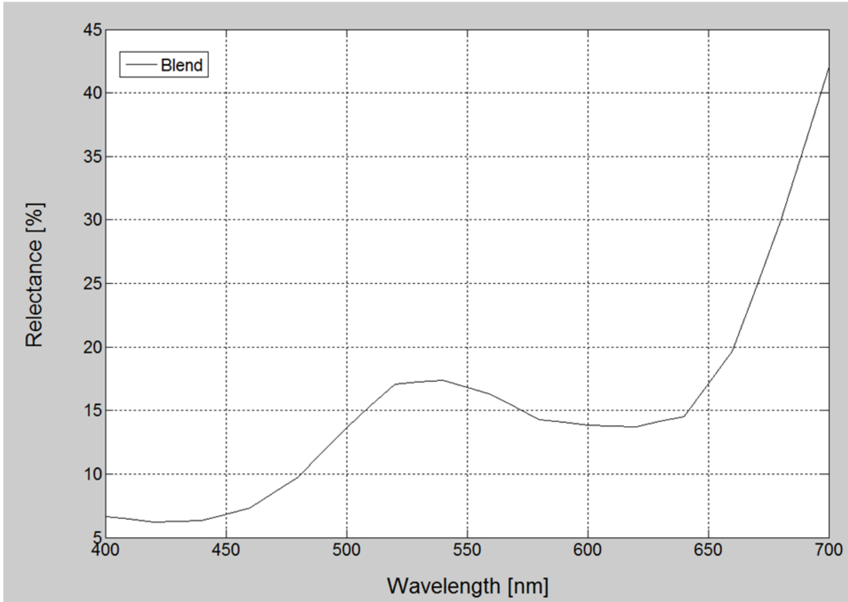
RECIPE PREDICTION PROBLEM

A RELIABLE COMPUTER-BASED SPECTRUM FORECASTING COULD HELP IN CHANGING THE RECIPE IN REAL TIME SIMPLY BY USING A PC!

THE PROBLEM TO BE SOLVED CONSISTS OF A RELIABLE FORECAST OF THE BLEND SPECTRAL RESPONSE ONCE THE REFLECTANCE FACTORS OF ITS COMPONENTS ARE KNOWN.







FIBERS SPECTRA

BLEND SPECTRUM

STATEMENT OF THE PROBLEM

FROM A THEORETICAL POINT OF VIEW THE PROBLEM MAY BE STATED AS FOLLOWS:

Transfer Function

$$\boxed{\boldsymbol{R_F}(\lambda)} = \boxed{\mathcal{F}}\left(\boxed{\mathrm{A}}, \boxed{\boldsymbol{p}_i(\lambda)}\right)$$

Spectral reflectance factors of the fabric obtained by mixing the components

Recipe
$\mathrm{A} = [\alpha_1, \alpha_2, \ldots, \alpha_n]$ with $\sum_{i=1}^{n} \alpha_i = 1$

Spectral reflectance factors of the *i*th component of a fabric

IF $\mathcal{F}$ IS PREDICTABLE, IT IS POSSIBLE TO EVALUATE THE SPECTRAL REFLECTANCE FACTORS OF A FABRIC $\boldsymbol{R_F}(\lambda)$ GIVEN THE PARAMETERS α_i AND THE VECTORS $\boldsymbol{p}_i(\lambda)$!!

STATE OF THE ART_1

SEVERAL COMPUTER-BASED APPROACHES HAVE BEEN PROPOSED IN LITERATURE DEALING WITH COLOUR MIXING. E.G.:

KUBELKA-MUNK (K-M) THEORY

STATES A CORRELATION BETWEEN THE K-S RATIO (ABSORPTION/SCATTERING) OF A BLEND (MIX) AND THE K-S RATIO OF SINGULAR COMPONENTS TO BE MIXED TOGETHER PLUS THE SUBSTRATE

$$\left(\frac{K}{S}\right)_{\lambda,mix} = \underbrace{\boxed{\left(\frac{k_{\lambda,t}}{s_{\lambda,t}}\right)}}_{\text{SUBSTRATE}} + \underbrace{\boxed{\alpha_1\left(\frac{k_{\lambda,1}}{s_{\lambda,1}}\right) + \cdots + \alpha_n\left(\frac{k_{\lambda,n}}{s_{\lambda,n}}\right)}}_{\text{COMPONENTS}}$$

SUBTRACTIVE MIXING

DEFINES A SUBTRACTIVE COLOR MIXING SPECTRUM :

$$\boldsymbol{R_S}(\lambda,\alpha_i) = \exp\left(\sum_{i=1}^{n} \alpha_i \boldsymbol{d}_i(\lambda)\right)$$

$$\boldsymbol{d}_i(\lambda) = -log_{10}(\boldsymbol{p}_i(\lambda))$$

ANN-BASED METHODS

COLOUR MIXING IS ADDRESSED BY TRAINING ANNS TO FIND A TRANSFER FUNCTION BETWEEN INPUT SPECTRA AND TARGET ONE.

STATE OF THE ART_2

KUBELKA-MUNK (K-M) THEORY – LIMITS (FOR THIS APPLICATION)

$$\left(\frac{K}{S}\right)_{\lambda,mix} = \boxed{\left(\frac{\boldsymbol{k_{\lambda,t}}}{\boldsymbol{s_{\lambda,t}}}\right)} + \alpha_1\left(\frac{k_{\lambda,1}}{s_{\lambda,1}}\right) + \cdots + \alpha_n\left(\frac{k_{\lambda,n}}{s_{\lambda,n}}\right)$$

1. VALID PREDICTION OF THE COLOUR OF A MIXTURE OF PIGMENTS DEPOSED ON A SUBSTRATE
2. (5-6 PIGMENTS MAX)

3. IN BLENDS OBTAINED BY MIXING FIBRES THE DEFINITION OF "SUBSTRATE" IS QUITE WEAK SINCE UNLIKE FABRICS DIPPED IN DYE BATH (WHERE A "MONOCHROME" SUBSTRATE IS DYED), THE FINAL PRODUCT IS OBTAINED MIXING PRE-COLOURED FIBRES.

SUBTRACTIVE MIXING – LIMITS (FOR THIS APPLICATION)

1. VALID PREDICTION OF THE COLOUR OF A MIXTURE OF PIGMENTS BUT **COMPLETELY UNRELIABLE PREDICTION FOR FIBER BLENDS** (IS NOT POSSIBLE TO OBTAIN A COMPLETE HOMOGENIZATION OF TEXTILE FIBERS BECAUSE THEY REMAIN SEPARATE ENTITIES ON A MACROSCOPIC SCALE)

ANN-BASED METHODS – LIMITS (FOR THIS APPLICATION)

1. REQUIRES HUGE DATASETS FOR TRAINING

AIM

IMPLEMENTATION OF TWO PRACTICAL METHODS FOR ACCURATE ESTIMATION OF SPECTROPHOTOMETRIC RESPONSE OF A TEXTILE BLEND COMPOSED BY DIFFERENTLY COLOURED FIBRES

1ST METHOD: BASED ON KUBELKA-MUNK (K-M) THEORY

2ND METHOD: BASED ON SUBTRACTIVE MIXING

THE TWO **PROPOSED** METHODS HAVE A COMMON STARTING POINT:

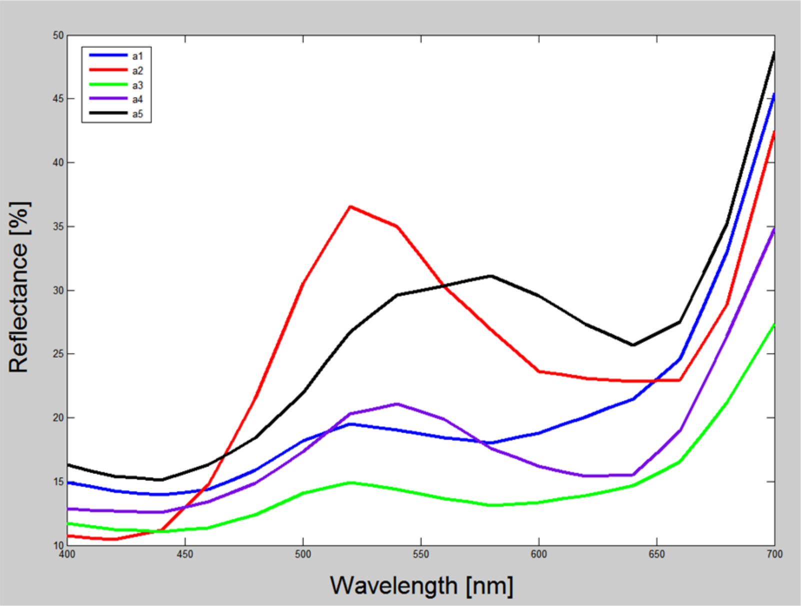
COLORISTS WORKING IN TEXTILE COMPANIES ALWAYS CREATE A FIRST-ATTEMPT BLEND USING THEIR HISTORICAL RECIPE

THIS HELPS **A LOT** IN PERFORMING THE COLOUR PREDICTION

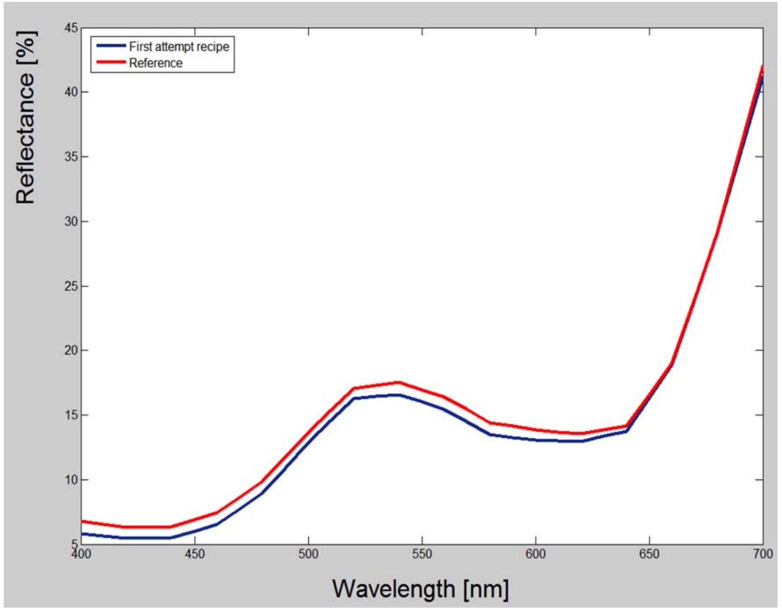
PROPOSED APPROACHES – STARTING POINT

THE METHODS START WITH THE KNOWLEDGE OF:

1. SPECTRUM OF EACH COMPONENT



2. REFERENCE AND FIRST ATTEMPT REFLECTANCE



3. ORIGINAL RECIPE

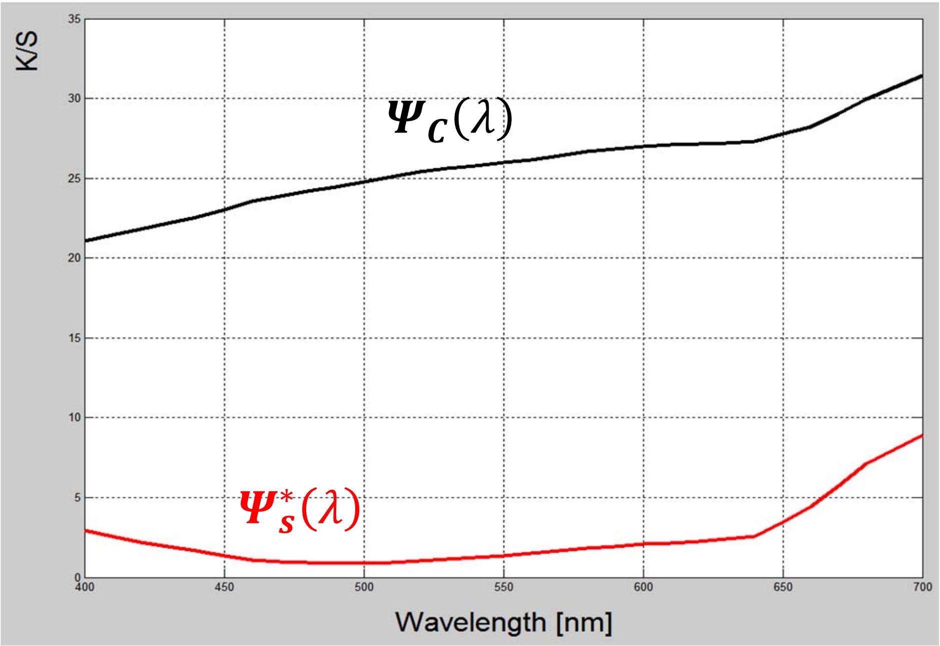
$$A = [\alpha_1, \alpha_2, \dots, \alpha_n] \quad \text{with} \ \sum_{i=1}^{n} \alpha_i = 1$$

K-M-BASED APPROACH_1

THE KNOWLEDGE OF THE SPECTRAL RESPONSE OF FIRST-ATTEMPT BLEND ALLOWS TO EVALUATE A "K-S RATIO OF AN EQUIVALENT FABRIC SUBSTRATE" $\Psi_s^*(\lambda)$

$$\boxed{\boldsymbol{\Psi}_{\boldsymbol{s}}^*(\lambda)} = \left(\frac{K}{S}\right)_{\lambda,mix} - \left\{\alpha_1\left(\frac{k_{\lambda,1}}{s_{\lambda,1}}\right) + \cdots + \alpha_n\left(\frac{k_{\lambda,n}}{s_{\lambda,n}}\right)\right\} = \boxed{\boldsymbol{\Psi}_{\boldsymbol{F}}(\lambda)} - \boxed{\boldsymbol{\Psi}_{\boldsymbol{C}}(\lambda)}$$

K-S RATIO OF AN IDEAL EQUIVALENT FABRIC HAVING THE SAME REFLECTANCE VALUES OF THE ACTUAL ONE <u>BUT</u> OBTAINED USING A DYE DIPPING PROCESS



K-S RATIO FROM FIRST ATTEMPT RECIPE

COMBINATION OF WEIGHTED K-S RATIOS OF FIBER COMPONENTS

K-M-BASED APPROACH_2

UNDER THE HYPOTHESIS THAT THE TURBID MIXING MECHANISM OF FIBERS ONLY SLIGHTLY CHANGES BY VARYING THE ORIGINAL RECIPE…

$\boldsymbol{\Psi}_{\boldsymbol{S}}^{*}(\lambda)$ IS ASSUMED **CONSTANT** FOR A GIVEN FABRIC

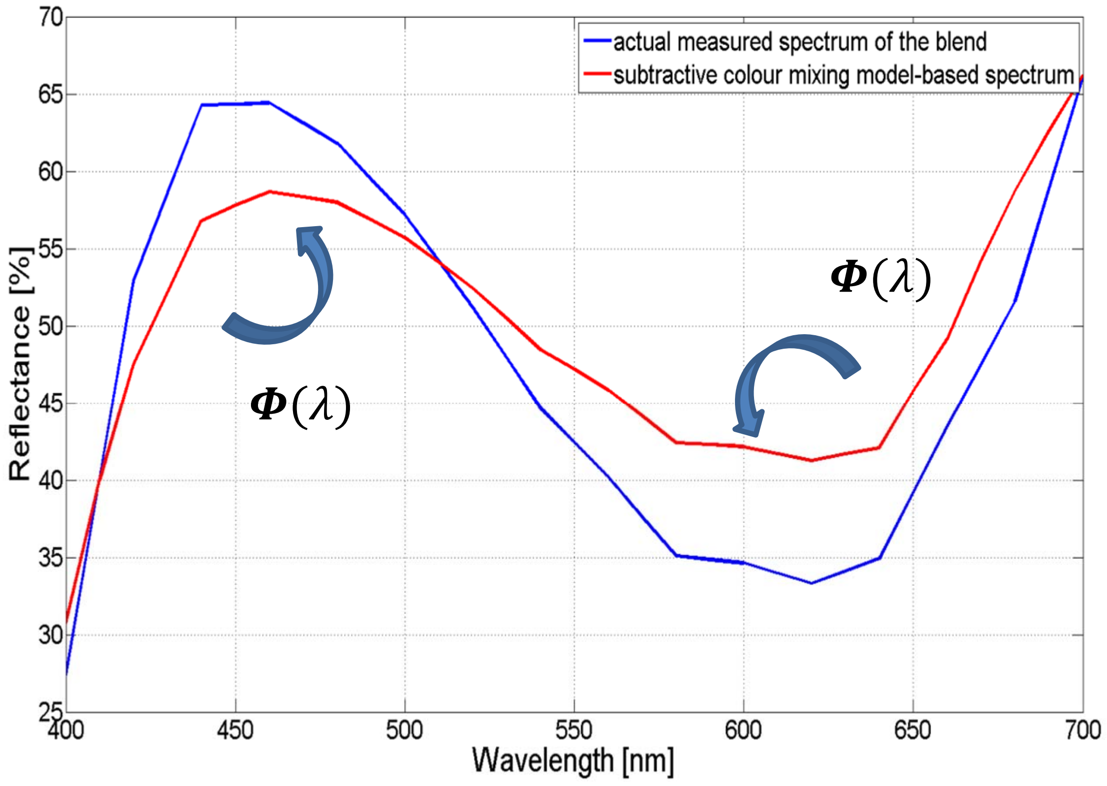
K-S RATIO FOR ANY GIVEN VARIATION OF RECIPE

$$\begin{cases} \boxed{\psi_{Fnew}(\lambda)} = \psi_S(\lambda) + \overline{\psi}_C(\lambda) \\ \psi_{Fnew}(\lambda) = \dfrac{\left(1 - R_F(\lambda)\right)^2}{2R_F(\lambda)} \end{cases} \Rightarrow R_F(\lambda)$$

PREDICTED SPECTRUM USING METHOD 1

SUBTRACTIVE MIXING-BASED APPROACH_1

AS MENTIONED ABOVE, THE SUBTRACTIVE COLOUR MIXING IS NOT ABLE TO PROVIDE A GOOD PREDICTION OF THE BLEND REFLECTANCE: **IT IS, RATHER, A ROUGH APPROXIMATION**



A WAVELENGTH-DEPENDANT FUNCTION $\Phi(\lambda)$ HAS TO BE DEFINED

$\Phi(\lambda)$: DIFFERENCE BETWEEN FIRST ATTEMPT RECIPE AND THE SPECTRUM OBTAINED USING SUBTRACTIVE COLOUR MIXING EQUATION.

SUBTRACTIVE MIXING-BASED APPROACH_2

THE $\boldsymbol{\Phi}(\lambda)$ FUNCTION IS EASILY EVALUATED AS FOLLOWS:

$$\boldsymbol{\Phi}(\lambda) = \frac{\boxed{R_F(\lambda)}}{\boxed{R_S(\lambda, \alpha_i)}}$$

$R_F(\lambda)$ → **FIRST ATTEMPT RECIPE SPECTRUM**

$R_S(\lambda, \alpha_i)$ → **SUBTRACTIVE COLOUR MIXING SPECTRUM**

UNDER THE HYPOTHESIS THAT THE FUNCTION $\boldsymbol{\Phi}(\lambda)$ **REMAINS CONSTANT** FOR ANY SMALL VARIATION OF THE ORIGINAL RECIPE, THE FINAL PREDICTED SPECTRUM FOR ANY VARIATION OF RECIPE $\boldsymbol{R}*_F(\lambda)$ **IS EVALUATED AS FOLLOWS:**

$$\boldsymbol{R}_{Fnew}(\lambda) = \boldsymbol{\Phi}(\lambda) \cdot \boldsymbol{R}_{Snew}(\lambda, \alpha_i)$$

**PREDICTED SPECTRUM
USING METHOD 2**

TEST AND RESULTS_1

IN ORDER TO TEST THE PROPOSED METHODS:

- 40 FABRICS COMPOSED ACCORDING TO RECIPES CHARACTERIZED BY MORE THAN 8 DIFFERENTLY COLOURED FIBRES;
- THREE CYCLES THROUGH THE CARDING MACHINE IN ORDER TO OBTAIN A HOMOGENEOUS COLOUR;
- ACQUISITION SYSTEM CONSISTING OF A BENCH ON WHICH A HUNTERLAB ULTRASCAN VIS REFLECTANCE SPECTROPHOTOMETER IS PLACED AND CONNECTED TO A PC;
- 8 DEGREE ANGLE BETWEEN THE LIGHT SOURCE (D65 ILLUMINANT) AND THE SAMPLE;
- **PREDICTED SPECTRA USING THE TWO PROPOSED APPROACHES COMPARED WITH THE ACTUAL MEASUREMENT OF THE REAL FABRICS OBTAINED USING THE MODIFIED RECIPES.**
- **RESULTS ALSO COMPARED WITH LITERATURE METHODS (ANN-BASED)**

TEST AND RESULTS_2

		CMC(2:1) distance from reference (actual fabric with modified recipe)			
Sample	Number of components	K-M-based approach	Subtractive mixing-based approach	Theoretical approach [1]	ANN-based approach [1]
1	10	0.7121	0.5770	0.7753	0.6944
2	11	0.3821	0.2804	0.7266	0.2801
3	10	0.4797	0.4496	0.7117	0.3881
4	8	0.1283	0.1285	0.4243	0.1302
20	10	0.8827	0.8726	1.0210	0.5315
21	10	0.5548	0.5291	0.9782	0.544
22	12	0.4002	0.3832	0.4231	0.2885
23	12	0.4993	0.4293	0.6752	0.4157
24	14	0.5024	0.5102	0.8893	0.3971
30	20	0.9992	0.9892	1.2132	0.8878
31	18	1.0924	1.0280	1.3238	0.9232
32	20	1.0821	0.9321	1.4272	0.8872
33	9	0.4234	0.3992	0.8728	0.4193
34	10	0.5892	0.6092	0.8253	0.6131
For all 40 samples	Mean value	0.5633	0.5260	0.7886	0.4761
	Median value	0.5080	0.4738	0.7589	0.4438
	Max value	1.0924	1.0280	1.4272	0.9982
	Min value	0.1283	0.1285	0.4231	0.1058

TEST AND RESULTS_3

AS EXPECTED, THE ANN-BASED METHOD PROVIDES BETTER RESULTS IN PREDICTING THE ACTUAL COLOUR OF THE BLEND (AVERAGE CMC(2:1) DISTANCE LESS THAN 0.48)

BUT IT REQUIRES **TRAINING**

THE TWO PROPOSED METHODS DO NOT REQUIRE TRAINING AND:

- PERFORM WELL WITH A COLOUR DISTANCE AVERAGELY EQUAL TO 0.5633 (K-M-BASED)AND 0.5260 (SUBTRACTIVE MIXING-BASED).
- THE MEDIAN VALUE OF CMC(2:1) DISTANCE IS LOWER THAN 0.51 FOR BOTH METHODS.
- PREDICT ALSO SPECTRUM FOR HIGH NUMBER OF COMPONENTS

(DISTANCE INCREASES BUT STILL LOWER THAN 1.2)

PERFORMANCE IS ACCEPTABLE FOR MOST TEXTILE COMPANIES WORKING IN THIS FIELD

BOTH METHODS PROVE TO BE EFFECTIVE IN BLEND MIXING SPECTRUM PREDICTION!

CONCLUSIONS

TWO METHODS FOR PREDICTING THE SPECTRAL RESPONSE OF A FABRIC OBTAINED BY MIXING PRE-COLOURED FIBRES HAVE BEEN PROPOSED:

1. THE FIRST IMPLEMENTS A MODIFIED VERSION OF THE KUBELKA-MUNK TWO CONSTANT APPROACH
2. THE SECOND USES A ROUGH PREDICTION BASED ON A SUBTRACTIVE COLOUR MIXING MODEL TO BUILD A TRANSFER FUNCTION BETWEEN THE SPECTRAL RESPONSES OF THE RAW MATERIALS AND THE EXPECTED REFLECTANCE FACTORS OF THE BLEND.

METHODS PROVE TO BE EFFECTIVE AND FURTHER TESTS WILL BE PERFORMED THANKS TO THE HELP OF AN ITALIAN COMPANY (NEW MILL S.P.A., PRATO)

FUTURE WORKS AND IMPLEMENTATIONS

IN CASES WHERE THE PREDICTION IS NOT SO ACCURATE A PRACTICAL SOLUTION UNDER IMPLEMENTATION IS TO CREATE A SECOND-ATTEMPT FABRIC TO BE USED AS THE NEW REFERENCE FOR THE PROPOSED METHODS.

THIS ALLOWS TO STRONGLY REDUCE THE COLOUR DISTANCE BETWEEN THE PREDICTED SPECTRUM AND THE ACTUAL ONE (THIRD-ATTEMPT FABRIC)

		CMC(2:1) distance from reference (actual fabric with modified recipe)		**CMC(2:1) distance from reference (actual fabric with second-attempt modified recipe)**	
Sample	Number of components	K-M-based approach (using first-attempt recipe)	Subtractive mixing-based approach (using first-attempt recipe)	K-M-based approach (using second-attempt recipe)	Subtractive mixing-based approach (using second-attempt recipe)
30	20	0.9992	0.9892	0.3234	0.2998
31	18	1.0924	1.0280	0.3562	0.3223
32	20	1.0821	0.9321	0.2903	0.2237

FURTHER TESTS ARE OBVIOUSLY REQUIRED!

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