Feasibility Study of the Reflective Properties of Façade Materials for Architectural Lighting Design

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***Abstract*—The paper presents a detailed feasibility study carried out before the design stage of the architectural lighting of the building of the Faculty of Electrical Engineering. The reflectance coefficients of all the surfaces of the building are measured and statistically verified. The bidirectional reflectance distribution functions of three basic surfaces are also measured. The color coordinates of the surfaces are matched to the color coordinates of the light of the flood lights chosen for realization of the lighting concept.**

Keywords—feasibility study for architectural lighting, color characteristics of surfaces, color coordinates of light

I. Introduction

The visual impression of a building, observed during the night depends on its form and the way it is illuminated or in other words the lighting composition is defined by the architectural composition [1, 2]. That does not mean that when architectural lighting is designed, its aim is to repeat the daytime vision of the object. On the contrary when a façade is illuminated, its architectural merits and specifics should be highlighted, thus creating a pleasing and original night view.

There are, of course, some basic principles that should be followed. First of all it should be estimated weather the building is symmetrical or asymmetrical. If it is symmetrical, the symmetry should be highlighted with light and the light composition should also be symmetrical. Also the presence of metrical elements should be noted – they give the opportunity for rhythmical light composition. The distribution of the luminance on the surface of the illuminated object should also be considered. The color impression from the illuminated object should also be considered and depends on their color, the spectrum of light, the distance from which they are observed, their size, color and luminance of the environment type of the used light sources and the presence of stray light (for example from street lighting).

The color of the facades can be estimated if the spectral composition of the light sources and the spectral reflectance characteristics of the façade materials are known. When large objects are observed from angle greater than 30”, color shifts can be noted. The adaptation processes also influences the color impression from the observed object. The realization of the wanted lighting effects suggests serious study of the specific situation.

The object of the current paper is the twelfth educational block of the Technical University of Sofia. Its architecture cannot be estimated as “remarkable”, except for the entrance – fig. 1. In this case the idea is to highlight with lighting its volume and the architectural elements of the entrance – the columns, signs, dome.

Fig.1 Façade of the twelfth educational block of TU – Sofia

Some basic principles exist when it comes to architectural lighting. The first classical concept for artistic lighting of buildings is the so called general lighting or flooding the object with light. This principle is not appropriate for the building under consideration, because it makes the object “loose” its volume, and the aim here is to highlight the volume. The second principle is to use localized lighting – the preferred principle for the twelfth educational building of TU- Sofia, because of the opportunity to highlight specific architectural elements and the volume of the building at the same time minimizing the lighting pollution. The third principle is to use combination of localized and general lighting. The fourth principle is to use color in the lighting design in order to achieve dynamic night view. The fifth principle is that of contour or silhouette lighting which aims to highlight the physical boundaries of the building. Artistic lighting can be realized also by means of decorative glowing elements.

The angle of incidence of light on the surface determines the presence or absence of shadows and its fracture. For flat surfaces this angle should be between 0 and 60°. When the surface of the façade is with rough fracture this angle should be chosen more precisely – it should be highlighted with light but without its roughness throwing shadows on the surface.

The colonnades are always preferred elements to be highlighted. This is possible in three basic ways – by one side lighting, front lighting or two side lighting of the elements.

II. Preliminary Measurements

A. Reflectance and lighting

Measurement The visual effect of the illuminated objects is formed by the light, reflected by them. The buildings’ facades are built with a variety of building materials. According to their structure and coloring, they reflect in a different way the incident light.

The reflective properties of the different materials can be described with:

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- Their reflectance coefficient ρ – the ratio between the reflected luminous flux Φr and the whole luminous flux falling on the surface Φ [3]:

$$\rho = \Phi r/\Phi \qquad (1)$$

- Their bidirectional reflectance distribution function (BRDF), which presents the distribution of the reflected light in characteristic planes – fig. 2:

$$fr=(dL_r(\theta_i,\varphi_i,\theta_r,\varphi_r))/(dE_i(\theta_i,\varphi_i)),\ sr^{-1} \qquad (2)$$

where dLr is the reflected radiance, dEi is the irradiation of the surface, θr is the zenith reflectance angle, φr is the azimuth angle of reflectance, θi is the zenith angle of incidence of the radiation, φi is the azimuth angle of incidence of the radiation.

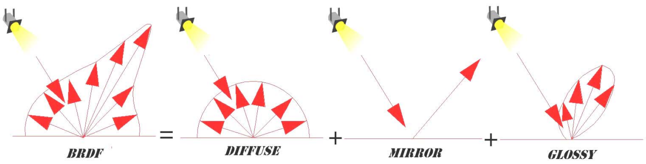

Fig. 2 BRDF of a surface, that has diffuse, mirror and glossy components

When the reflection is diffuse, the BRDF is always a circle, no matter what the incident angle of light on the surface is. Diffuse reflectance is available when the surfaces have roughness, which size is bigger than the wavelength of light – for example – gypsum.

When the roughness of a given surface is with size smaller than the wavelength, mirror reflectance is observed.

Ideal diffuse or mirror reflection do not exist in the real life. Most often the reflectance of the surfaces is mixed. That is why investigation of the BRDF of the façade surfaces is important.

Another consideration that must be taken into account is the positioning of the light source against the surface. If the surface is illuminated frontally, its fracture is muted and it looks almost smooth. On the contrary is the surface is illuminated sideways its relief is highlighted and if the light falls on the surface by a very small angle, it is highly prominent [4].

The perceived color of the façade materials at night also depends on the spectrum of the light sources, their correlated color temperature, their color rendering index and by the light, emitted by street luminaires or other light sources near the object.

B. *Measurement of the reflectance coefficients of different materials, used for the façade of the 12th educational block of TU - Sofia*

The current paper presents the results of all preliminary measurements needed for architectural lighting design of the twelfth educational block of the Technical University of Sofia.

The reflectance coefficients have been measured by means of colorStiker. For every surface at least ten measurements have been carried out and have been statistically analyzed.

In order to obtain the BRDF of the main surfaces – white gypsum façade and grey colonnades the experimental setup shown on Fig. 3 is used.

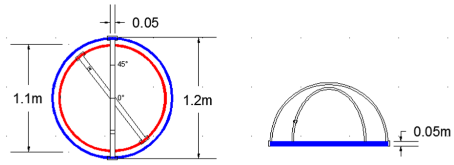

Fig. 3 Gonioreflectancemeter for measurement of BDRF

In order to obtain the color characteristics of the light sources in terms of correlated color temperature, color rendering and spectrum, a specific measuring device MK350S Spectrometer is used.

III. Reflectance coefficients, BRDF and colorimetric measurement

A. *Measurement of the reflectance coefficients of the main surfaces*

The reflectance coefficients of the materials used for the buildings' façade have been measured and the experimental results are shown in tables below. The greatest part of the façade of the building is covered with white diffuse gypsum based plaster – Fig. 3a. Fig. 3b shows the color coordinates of the plaster in the CIE xyY color space.

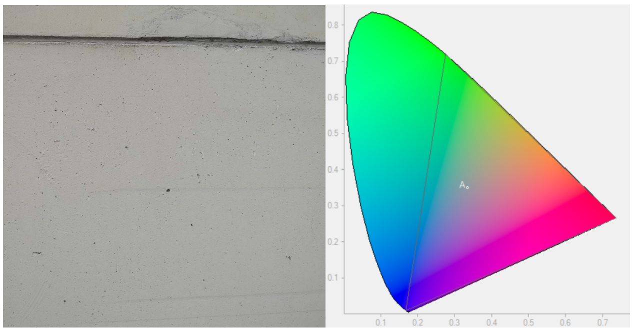

Fig. 3 a) Gipsum based plaster – white, diffuse, b) CIE xyY color coordinates of the plaster

The average reflectance coefficient is calculated to be ρ = 84% and the colour coordinates of the plaster are given in Table 1 both as CIE RGB and CIE xyY colour spaces. The measured data is statistically analysed and the results are given below the measured values.

Another part of the façade of the building of the Faculty of Electrical engineering that characterizes its architecture is the metal cover of the edges of the building and window frames. Its average reflectance coefficient is ρ = 5%. The surface of this material is shown on fig. 4a) and its color coordinates in the CIE xyY colour space – on fig. 4b). Table 2 is dedicated to the experimental measurement of the color coordinates of the surface and their statistical analysis.

TABLE 1 EXPERIMENTAL RESULTS AND DESCRIPTIVE STSTISTICS OF THE MEASURED COLOR COORDINATES OF THE PLASTER IN RGB AND XYY COLOUR SYSTEMS

Sample number/ Descriptive statistics	R	g	b	x	y
1	225	218	201	0,33	0,35
2	226	218	201	0,33	0,35
3	225	217	200	0,33	0,35
4	225	217	200	0,33	0,35
5	225	218	202	0,33	0,35
6	225	216	198	0,33	0,35
7	224	216	198	0,33	0,35
8	226	217	199	0,33	0,35
9	224	215	197	0,33	0,35
10	226	217	201	0,33	0,35
Mean	225,1	216,9	199,7	0,33	0,35
Standard Error	0,23	0,31	0,52	0,00	0,00
Median	225	217	200	0,33	0,35
Mode	225	217	201	0,33	0,35
Standard Deviation	0,74	0,99	1,64	0,00	0,00
Sample Variance	0,54	0,99	2,68	0,00	0,00
Kurtosis	-0,73	-0,16	-1,09	-	-2,57
Skewness	-0,17	-0,61	-0,35	-	-1,19
Range	2,00	3,00	5,00	0,00	0,00
Minimum	224,0	215,0	197,0	0,33	0,35
Maximum	226,0	218,0	202,0	0,33	0,35
Sum	2251,0	2169,0	1997,0	3,30	3,50
Count	10,0	10,0	10,0	10,0	10,0
Confidence Level(95,0%)	0,53	0,71	1,17	0,00	0,00

Fig. 4 a) Metal coating of the edges of the building and window frames, b) color coordinates of the coating in CIE xyY colour space

The colonade at the front entrance of the building considered is another element, that is distinctive and interesting and should be highlighted by means of architectural lighting. The columns are covered with grey metal coating – fig. 5a) with reflectance coefficient ρ = 69%. The colour coordinates of the cover are given in table 3 and their visualization at the CIE xyY colour space - on fig. 5b).

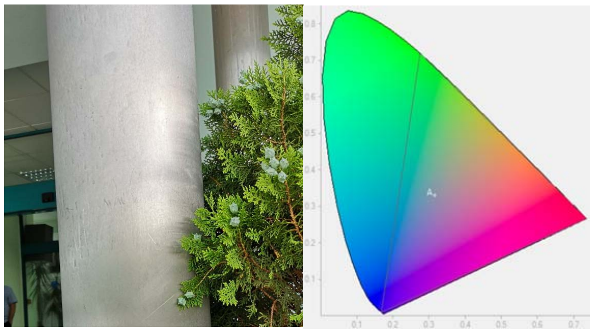

Fig. 5 a) Metal coating of the columns at the entrance of the building b) color coordinates of the columns at CIE xyY color space

TABLE 2 EXPERIMENTAL RESULTS AND DESCRIPTIVE STSTISTICS OF THE MEASURED COLOR COORDINATES OF THE COATING IN RGB AND XYY COLOUR SYSTEMS

Sample number/ Descriptive statistics	R	g	b	x	y
1	5	81	93	0,22	0,29
2	24	85	96	0,22	0,29
3	0	71	84	0,2	0,28
4	0	71	84	0,2	0,28
5	0	71	84	0,2	0,28
6	0	70	83	0,2	0,28
7	0	71	84	0,2	0,28
8	0	71	84	0,2	0,28
9	0	71	84	0,2	0,28
10	0	71	84	0,2	0,28
Mean	2,9	73,3	86	0,204	0,282
Standard Error	2,40	1,65	1,44	0,00	0,00
Median	0	71	84	0,2	0,28
Mode	0	71	84	0,2	0,28
Standard Deviation	7,58	5,21	4,55	0,01	0,00
Sample Variance	57,43	27,12	20,67	0,00	0,00
Kurtosis	8,81	2,36	2,10	1,41	1,41
Skewness	2,94	1,90	1,86	1,78	1,78
Range	24	15	13	0,02	0,01
Minimum	0	70	83	0,2	0,28
Maximum	24	85	96	0,22	0,29
Sum	29	733	860	2,04	2,82
Count	10	10	10	10	10
Confidence Level(95,0%)	5,42	3,73	3,25	0,01	0,00

The colonade at the front entrance of the building considered is another element, that is distinctive and interesting and should be highlighted by means of architectural lighting. The columns are covered with grey metal coating – fig. 5a) with reflectance coefficient ρ = 69%. The colour coordinates of the cover are given in table 3 and their visualization at the CIE xyY colour space - on fig. 5b).

Fig. 5 a) Metal coating of the columns at the entrance of the building b) color coordinates of the columns at CIE xyY color space

TABLE 3 EXPERIMENTAL RESULTS AND DESCRIPTIVE STSTISTICS OF THE MEASURED COLOR COORDINATES OF THE COLUMNS IN RGB AND XYY COLOUR SYSTEMS

Sample number/ Descriptive statistics	**R**	**g**	**b**	**x**	**y**
1	228	226	228	0,31	0,33
2	232	231	234	0,31	0,33
3	240	240	245	0,31	0,32
4	230	226	228	0,31	0,33
5	231	228	230	0,31	0,33
6	236	234	236	0,31	0,33
7	222	218	218	0,32	0,33
8	218	216	217	0,31	0,33
9	221	218	219	0,31	0,33
10	221	220	222	0,31	0,33
Mean	227,9	225,7	227,7	0,311	0,329
Standard Error	2,29	2,48	2,85	0,00	0,00
Median	229	226	228	0,31	0,33
Mode	221	226	228	0,31	0,33
Standard Deviation	7,23	7,83	9,01	0,00	0,00
Sample Variance	52,32	61,34	81,12	0,00	0,00
Kurtosis	-1,03	-0,61	-0,20	10,00	10,00
Skewness	0,21	0,48	0,58	3,16	-3,16
Range	22	24	28	0,01	0,01
Minimum	218	216	217	0,31	0,32
Maximum	240	240	245	0,32	0,33
Sum	2279	2257	2277	3,11	3,29
Count	10	10	10	10	10
Confidence Level(95,0%)	5,17	5,60	6,44	0,00	0,00

On the two sides of the building's façade there is architectural highlight of the windows with brick construction – fig. 6 a) with reflectance coefficient ρ = 13%. The colour coordinates of the bricks are given in table 4 and on fig. 6 b).

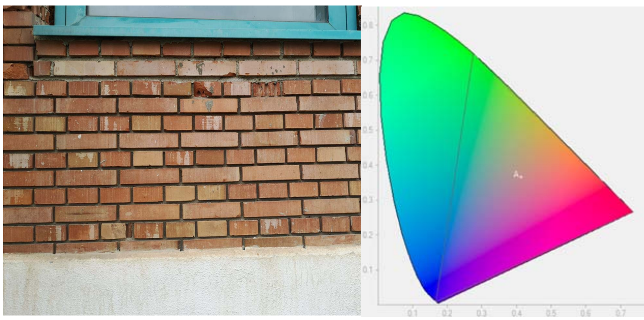

Fig. 6 a) Brick highlight of the side windows, b) color coordinates of the bricks at CIE xyY color space

TABLE 4 EXPERIMENTAL RESULTS AND DESCRIPTIVE STSTISTICS OF THE MEASURED COLOR COORDINATES OF THE BRICKS IN RGB AND XYY COLOUR SYSTEMS

Sample number/ Descriptive statistics	**R**	**g**	**b**	**x**	**y**
1	162	107	86	0,34	0,36
2	162	116	93	0,4	0,37
3	157	114	90	0,4	0,37
4	153	106	86	0,41	0,36
5	158	115	92	0,4	0,37
6	160	117	93	0,4	0,37
7	167	118	93	0,41	0,37
8	153	102	79	0,42	0,37
9	159	114	93	0,4	0,36
10	149	98	76	0,42	0,37
Mean	158	110,7	88,1	0,4	0,367
Standard Error	1,67	2,20	1,98	0,01	0,00
Median	158,5	114	91	0,4	0,37
Mode	162	114	93	0,4	0,37
Standard Deviation	5,27	6,95	6,26	0,02	0,00
Sample Variance	27, 8	48,2	39,2	0,0	0,0
Kurtosis	-0,12	-0,76	0,04	6,77	-1,22
Skewness	-0,11	-0,80	-1,14	-2,38	-1,04
Range	18	20	17	0,08	0,01
Minimum	149	98	76	0,34	0,36
Maximum	167	118	93	0,42	0,37
Sum	1580	1107	881	4	3,67
Count	10	10	10	10	10
Confidence Level(95,0%)	3,77	4,97	4,48	0,02	0,00

Another plaster, that characterizes the façade of the educational building of the Faculty of Electrical Engineering – TU – Sofia is the mosaic plaster at its base, shown on fig. 7a). It has an average reflectance coefficient ρ = 27%. The colour coordinates of the mosaic plaster are given in table 4 and their visualization at the CIE xyY colour space - on fig. 7b).

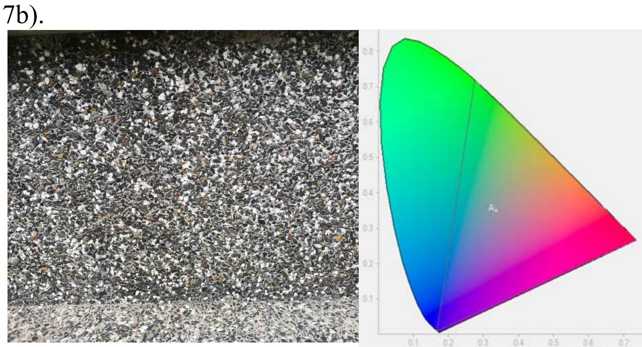

Fig. 7a) Mosaic plaster at the base of the building's façade, b) color coordinates of the plaster in CIE xyY colour space

TABLE 4 EXPERIMENTAL RESULTS AND DESCRIPTIVE STSTISTICS OF THE MEASURED COLOR COORDINATES OF THE PLASTER IN RGB AND XYY COLOUR SYSTEMS

Sample number/ Descriptive statistics	R	g	b	x	y
1	95	95	91	0,32	0,34
2	112	106	101	0,33	0,34
3	127	123	116	0,33	0,34
4	122	118	111	0,33	0,34
5	122	120	115	0,32	0,34
6	119	116	110	0,32	0,34
7	144	144	140	0,32	0,34
8	128	125	119	0,33	0,34
9	110	106	98	0,33	0,35
10	134	127	117	0,33	0,35
Mean	121,3	118	111,8	0,326	0,342
Standard Error	4,30	4,29	4,28	0,00	0,00
Median	122,00	119,00	113,00	0,33	0,34
Mode	122,00	106,00	#N/A	0,33	0,34
Standard Deviation	13,61	13,56	13,52	0,01	0,00
Sample Variance	185,12	184,00	182,84	0,00	0,00
Kurtosis	0,74	0,74	1,36	-2,28	1,41
Skewness	-0,34	0,18	0,57	-0,48	1,78
Range	49,00	49,00	49,00	0,01	0,01
Minimum	95,00	95,00	91,00	0,32	0,34
Maximum	144,00	144,00	140,00	0,33	0,35
Sum	1213,0	1180,0	1118,0	3,26	3,42
Count	10,00	10,00	10,00	10,00	10,00
Confidence Level(95,0%)	9,73	9,70	9,67	0,00	0,00

B. Measurement of the BDRF of the main surfaces

Since the experiment for measurement of the BRDFs of the surfaces is hard and time-consuming procedure, it is only made for some of the façade elements – gypsum based plaster, metal coating of the outer edges of the building and columns. The results are given for position of the photodetector at 5° from the surface.

The gypsum based white façade plaster shows almost diffuse reflectance characteristics – fig. 13

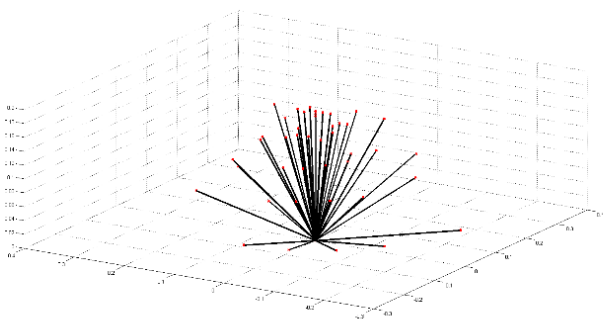

Fig. 13 BRDF and indicatrices of reflection of white gypsum based plaster

The BRDF of the metal coating of the edges of the building also show almost diffuse reflectance characteristics – fig. 14, while the columns have also a mirror component – fig 15. The mirror component is not a concern, because it is at an angle, at which no observers will be present, so glare is not probable.

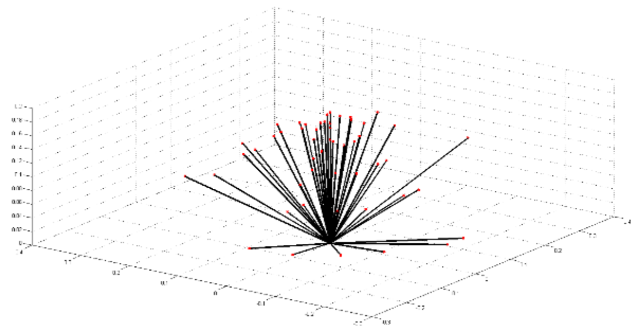

Fig. 14 BRDF and indicatrices of reflection of the metal cover of the outer edges of the building

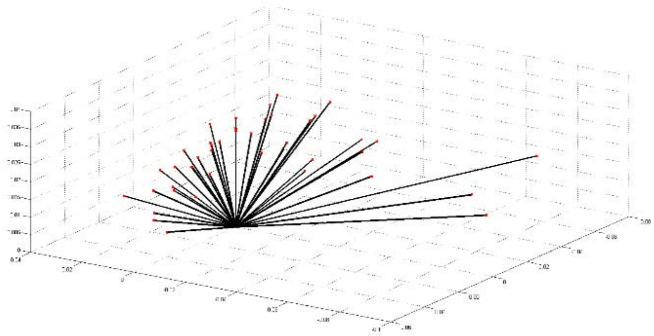

Fig. 15 BRDF and indicatrices of reflection of the metal coating of the columns

C. Measurement of the color characteristics of the flood lights, chosen for illumination of the surfaces

When it comes to architectural lighting, it is important that the reflective characteristics of the object are matched to the color characteristics of the light sources. Considering this rule for the architectural lighting of the object under consideration flood lights with the following color coordinates are experimentally chosen:

- Blue-green with x=0.1651, y=0.3503;
- Green with x=0.1833, y=0.7007;
- Red with x=0.6905, y=0.3061;
- Blue with x=0.1579, y=0.1530;
- White with x=0.3307, y=0.3695.

IV. ANALYSIS OF THE RESULTS AND CONCLUSIONS

The current paper aims to show the process of the preliminary measurements and investigations, needed for architectural lighting design. It is a complicated process that should be very precisely done in order to have a close match between design and realization. These investigations do not exclude the process of the "on site" experiments that have to be done before the implementation of the design, but makes them shorter and easier. The reflective characteristics of the different surfaces of an object are measured and by means of analysis and on site experiments are best matched to available floodlights.

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