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To cite this article: C D Galaanu 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **586** 012016

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# Lighting systems calculations for heritage buildings

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**Abstract.** The heritage buildings generate specific problems for electrical installations, with supplementary request from lighting systems. The continuous trends towards modernization are traditionally in conflict with the conservation of the architectural details. This major constraint must be considered for new circuits, but also for luminaire, when retrofit is the main approach. After the esthetical considerations, the engineering approach raises a problem in connection with the dimensioning methods. For heritage buildings, the lighting systems must cover infinity of situation, very different from classical designing methods, based on Utilization Factor or Direct Illumination Calculus for orthogonal situations. An original method of calculation is proposed, based on analytical geometry, useful for any orientation of the working plane. Even this method has important limitations, generated by the specifically architectural details, and a lighting simulation is necessary. Based on DIALuxEVO7, specific methods are presented. The importance of results interpretation is also underline.

## 1. Introduction

The heritage buildings are a subject of a continuous evolution, together with the society. The main parameter that imposes the rhythm of the evolution is the energy consuming, in relation with the price of the energy. All others phenomenon could be placed in the second place: comfort level and safety, water management, diversity of pollution involved and so on. Under the general research agenda of historic buildings and energy efficiency, in [1] one discover the importance of the field: “To refurbish historic buildings on a sustainable basis implies that environmental, economic as well as social and cultural aspects are taken into account. The interdisciplinary knowledge needed to handle these aspects has called for increased research activity. This demand has been reflected in several calls from the Joint Programming Initiative (JPI), as well as the EU’s Seventh Frame-work Program and Horizon 2020. Several successful recent projects have focused on the refurbishment potential in historic buildings. Most of them have been characterized by topics regarding technical measures, careful passive solutions and the conversion to fossil-free energy sources.” Until now, this approach was the only one. But in the same paper [1], a strong affirmation was found: “There are significant differences between the modelled (theoretic) and actual energy performance of buildings in general. The difference between the calculated energy consumption and the actual energy consumption can exceed 100% in extreme cases. User behavior is considered to be the main reason behind this significant gap between the actual and predicted energy performance of buildings.” These discover are stronger than energy methodology [2], serving as a starting point for new considerations.

Another gap between calculation methods and the specificity of heritage building is available in [3], where the natural lighting was analyzed together with artificial lighting and thermal comfort: “It is not easy to select the optimal window system that provides buildings the best balance between solar energy transmission and transmission of daylight. Several calculation methods have been developed to guide engineers and architects to choose a right solution of window system, that results in good indoor climate low energy consumption and overall visual comfort. Light availability analysis characterizes every daylight system, determining several factors such as site latitude, urban context, prevailing



seasonal climatic conditions (temperature, solar irradiation, solar altitude, clear sky probability), building orientation, building openings, etc.”

In [3], the complexity of ancient building is again demonstrated: “the 3D model of the Hall of Two Hundred was carried out taking into account all geometric and architectural characteristics of the building, its walls, its furnishings and the outside urban context. The present furniture (consisting of 60 seats fixed at a base upright, and wooden benches along the two walls without windows) were modelled with a simplifying geometry, disregarding ornaments and inlays, the monumental marble ornaments at the south doors, but attributing the specific thermo-physical, optical, photometric and colorimetric properties to each different surface. Protrusions of the coffered ceiling were disregarded, but their surface was modelled by an equivalent surface built using the average weighted value of the reflective coefficient of multiple surfaces. These simplifications were assumed because of RAM capacity of the computer used and computational time reduction, guaranteeing the quality of the results with a system of a higher number of simulation points.”

All these arguments underline the complexity of possible calculation required by the ancient buildings. The lighting systems are in a continuous modernization, due the solid state “revolution”, and the calculus methodology must be reconsidered.

The ancient buildings raise also a classical problem, a conflict between the newest technology and the condition of no architecture modifications. The solution imposes the Wi-Fi technology and IoT [4] for intelligent evacuation guidance systems for improving fire safety (introducing intelligent fire safety), or photoluminescent way finding [5].

The wide range of problems rise from lighting methods in heritage buildings covers also the fresco structural problem [6] or regarding the spectral damage for lighted museum paintings [7] or [8]. The spectral composition has not only negative effect, but also a positive one, as a tool to enhance faded colors of museums artefacts [9].

Of all these obvious problems, the specificity of calculations problems for lighting systems in heritage building are the most surprising. In figure 1 one presents such example:



**Figure 1.** Lighting optimization for arches and vaults in Cotroceni Palace, Bucharest

The specificity of lighting configuration from Fig.1 is the surface that must be optimized: not the working plane (horizontal), but the curves one, from arches and vaults. In the same category one has dome illumination, with artificial or natural lighting. The main problem will be to find a way to represent somehow the results, not only in qualitative manner (false colors) but in quantitative manner, in association with a calculation surface.

## 2. New calculation method for direct illumination

The classical methodology for direct illumination from a luminaire is available in a classical monographic book [10, 196-198], but huge limitations are known, being applicable only for horizontal or vertical surfaces. A historical building has many other situations, where classical approach is not useful. A new method, presented by the author in [11], is based on analytical geometry. The geometrical considerations are presented in Fig.2, and the method could be extended for any other shapes, considering dedicated software, as MATLAB (see below).

The calculation surface is generated similar with a mesh, by the points:

$X1, X2, \dots, XI, \dots, XMAX$  where  $NX$  is the number of values;

$Y1, Y2, \dots, YJ, \dots, YMAX$  where  $NY$  is the number of values;

$Z1, Z2, \dots, ZK, \dots, ZMAX$  where  $NZ$  is the number of values.

The ration of these vectors will be constant, but not necessary:

$$\begin{aligned}\Delta X &= \frac{X_{MAX} - X_1}{N_X - 1} \\ \Delta Y &= \frac{Y_{MAX} - Y_1}{N_Y - 1} \\ \Delta Z &= \frac{Z_{MAX} - Z_1}{N_Z - 1}\end{aligned}\tag{1}$$

In this point on calculates the projection in horizontal plane of the vertical ratio increment (figure 2):

$$\Delta ZO = \Delta Z \times \text{ctg} \alpha\tag{2}$$

The classical methodology supposes that the angles could be measured, but one propose to calculate  $\beta$  angle in horizontal plane, between intersection of the mesh and horizontal plane with the OX axis:

$$\beta = \text{atg} \frac{X_{MAX} - X_1}{Y_{MAX} - Y_1}\tag{3}$$

The vertical ratio for the considered mesh:

$$ZOT = \Delta ZO \times (N_Z - 1)\tag{4}$$

The X, Y, Z coordinates for current calculus point I, J, K:

$$\begin{aligned}X_{I,J,K} &= X_1 + (I - 1) \times \Delta X + \Delta ZO \times (k - 1) \cos \beta \\ Y_{I,J,K} &= Y_1 + (J - 1) \times \Delta Y + \Delta ZO \times (k - 1) \sin \beta \\ Z_{I,J,K} &= Z_1 + \Delta Z \times (k - 1)\end{aligned}\tag{5}$$

With these coordinates one calculates the current distance between every calculation point and luminaire position:

$$DPO_{I,J,K} = \sqrt{(X_{I,J,K} - XC)^2 + (Y_{I,J,K} - YC)^2}\tag{6}$$

The angle  $\gamma$  is defined in vertical plane, between optical axis of the luminaire and current calculation direction, respectively on which the light intensity will be produce the direct illumination. The lighting



$$\gamma = \text{atg} \frac{DPO_{I,J,K}}{ZC - Z_{I,J,K}} \quad (7)$$

In horizontal plane on define angle  $\omega$ , between the projection of the luminous ray and the calculation point ( $DPO_{I,J,K}$ ) and  $OX$  axis:

$$\omega = \text{atg} \frac{Y_{I,J,K} - YC}{X_{I,J,K} - XC} \quad (8)$$

The angle  $\omega$  could be useful for weighted average between those two lighting intensity  $I(\gamma)_{I,J,K}^{long}$  and  $I(\gamma)_{I,J,K}^{transv}$ , respectively:

$$I(\gamma, \omega)_{I,J,K} = \frac{I(\gamma)_{I,J,K}^{transv} \times \omega + I(\gamma)_{I,J,K}^{long} \times (90 - \omega)}{90} \quad (9)$$

For illumination calculus is necessary the angle between light intensity  $I(\gamma, \omega)_{I,J,K}$  and the normal on the surface  $Z$ . This is the point where the classical theory wasn't capable to generate solution. Using vector algebra, the normal on the surface  $Z$  could be described using angles  $\alpha$  and  $\beta$ :

$$\vec{N} = N_x \vec{X} + N_y \vec{Y} + N_z \vec{Z} \quad (10)$$

Where

$$\begin{aligned} N_x &= \cos \alpha \sin \beta \\ N_y &= \cos \alpha \cos \beta \\ N_z &= \sin \alpha \end{aligned} \quad (11)$$

For the current calculus point ( $I, J, K$ ) one obtains the direction from luminaire to this point:

$$\vec{D}_{I,J,K} = X_{I,J,K} \vec{X} + Y_{I,J,K} \vec{Y} + (ZC - Z_{I,J,K}) \vec{Z} \quad (12)$$

And now the angle between luminous ray and the normal on the surface  $Z$ :

$$\cos \theta = \frac{N_x X_{I,J,K} + N_y Y_{I,J,K} + N_z (ZC - Z_{I,J,K})}{\sqrt{N_x^2 + N_y^2 + N_z^2} \sqrt{X_{I,J,K}^2 + Y_{I,J,K}^2 + (ZC - Z_{I,J,K})^2}} \quad (13)$$

With all these elements, the direct illumination could be calculated for a maintenance factor  $M_f$ :

$$E_{I,J,K} = M_f \frac{I(\gamma, \omega)_{I,J,K} \cos^3 \theta}{(ZC - Z_{I,J,K})^2} \quad E_{I,J,K} = M_f \frac{I(\gamma, \omega)_{I,J,K} \cos^3 \theta}{(ZC - Z_{I,J,K})^2} \quad (14)$$

For multiple luminaires, the effect is additive.

For the first moment, the complexity of the calculus impose to use some general programming language (as MATLAB), but DIALux are expected to give important advantages, offering a complete lighting simulation. Surprisingly, for the ancient buildings, even DIALux EVO7 has some limitations.

### 3. Arches Modeling In Dialux Evo7

The continuous development of DIALux EVO7 software is a professional solution, for interior and exterior lighting systems. Modeling architectural details is not a problem, grace to the importing facilities from AutoCAD and 3DS. Building the model is not the subject of this paper, but interpreting the results is a different item. In figure 3 one presents such lighting model, for a fresco, situated in a niche. This niche generates the supplementary problems, additional to those impose to the visibility of the art paining: contrast of luminance, reflections, uniformity and so.

The problems occur due the lack of the cylindrical calculation surface (or spherical) in DIALux EVO. The cylinder is realized by elements, and for every element it is possible to have any results (average



**Figure 3.** The Sabin Balaşa fresco, lighting solution study in Lost Steps Hall, Palace of University “A.I. Cuza” from Iaşi

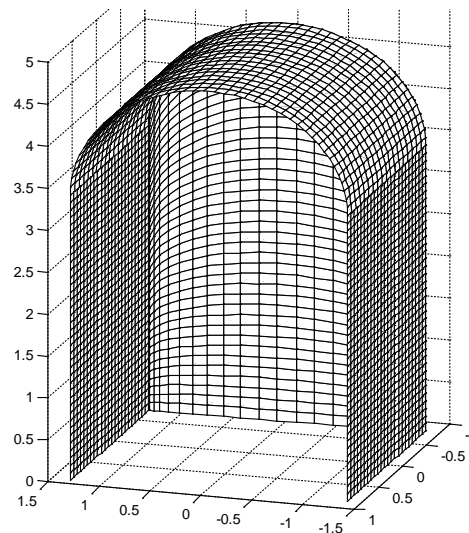
illumination, minimum, maximum value, luminance also). In Fig.3 one of these cylindrical elements is highlighted. In the author’s opinion, it is very difficult to analyze the results on an arch, especially when one imposes high accuracy of the model, using minimum 60 cylindrical elements for a single arch. Again, it is possible to analyze element by element, but the entire luminous situation is impossible to be obtained.

### 4. Arches modeling in Matlab

The author’s functions for direct illumination based on previous method for generalized surfaces bring the possibility to analyze the results on any surfaces, using general graphical function from MATLAB, as surface, mesh or contour. All these functions could associate the results to a plane surface, giving

the possibility to interpret the final global configuration. Demonstrating this, the next example will give the main direction about mesh generation and result visualization.

Mesh generation refers to four main surfaces (as in figure 4), the front surface (the fresco), the superior arch, and two lateral rectangular surfaces.



**Figure 4.** Mesh generated for The Sabin Balaşa fresco (Figure 3)

Mesh generation is the most important phase in building the numerical model. To understand how the superior arch mesh is generated, some lines from MATLAB coding are presented, with some comments:

```
R=1.35; % Fresco dimension: 2,70m wide
for j=1:19, for i=44 % elements for Y axis, elements for X axis
    Xarch(j,i)=R*cos((i-1)*pi/43);
    Yarch(j,i)=1.6/2-(j-1)*1.6/18; % 1.6m is the deepening
    Zarch(j,i)=3.4+R*sin((i-1)*pi/43); % 3.4m is the high of lateral wall
end, end
```

The vertical surface for the fresco is generated in similar way:

```
for j=1:39, for i=1:24 % number of elements for vertical dimension, for horizontal ratio
    Xfresco(j,i)=R*cos((i-1)*pi/23);
    Yfresco(j,i)= -.8;
    Zfresco(j,i)=(3.4+R*sin((i-1)*pi/23))/38*(j-1);
end, end
```

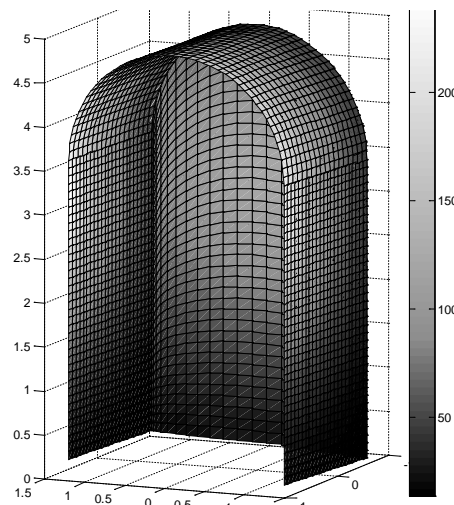
After these surfaces, two rectangular surfaces are generated directly, with mesh grid function, obtaining the mesh as in figure 4. In this point, illumination level is ready to be calculated.

## 5. Arch lighting modelling in Matlab

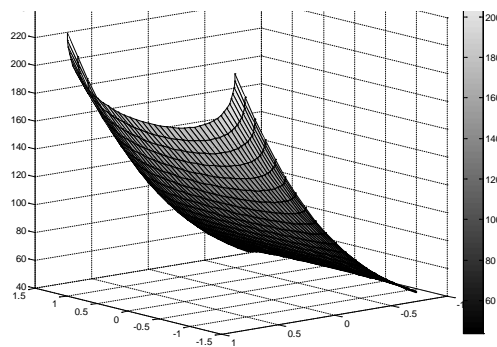
The author's function for illumination calculus, applied to the surfaces previous generated, will give the direct and reflected illuminance, as a first step in designing the lighting solution for fresco visibility. A qualitative visual effect could be observed in figure 5, in grey colour map. For the arch area, a special analysis could be realized using function *surf* (*Xarch*, *Yarch*, *Earch*) where illumination level *Earch* is used as a vertical parameter for visualized surface in figure 6. Other functions are available for data analysis, as *contour*.

In this moment the calculated data for the arch zone could be analyzed in a unitary matrix, as seen in figure 6, in total contrast with the situation from DIALux EVO7, as seen in figure 3.





**Figure 5.** Illuminance level (lux) for a symmetrical lighting source with light intensity of 350 cd situated at (0; 1.6; 3)



**Figure 6.** Illuminance level (lux) for arch zone from Fig.5, in a separate representation.

Using mesh generation for any other architectural details, the heritage building could be analyzed in details using MATLAB functions, and for the general lighting simulations the DIALux EVO will generate trustable results.

## 6. Conclusions

The lighting systems for heritage buildings rise specific problems in connection with preservation of architectural details, with retrofit problems and introduction of new circuits without visual aggression. Using this, other objectives could be solved, as the stability of natural dyes under light emitting diode lamps [12], the strategic objective being the enhancing the appreciation and preservation of archaeological heritage [13] and even the effect of natural light [14]. An unexpected problem, generated by the lighting design for arches, vaults and domes could be solved using vector algebra, implemented by the author in some original MATLAB function, and the results could be analyzed more efficient comparing with DIALUX EVO7. The disadvantage of DIALux is the impossibility to define calculation surfaces other than plane surfaces. The paper presents a general method for lighting design, useful for particular architectural details from heritage buildings.

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### Acknowledgments

This research was supported by UEFISCDI grant PCAI-163CI, contract PN-III-P2-2.1-CI-2018-0965 for imaging measurement of correlated color temperature, grant SILUM-219CI, contract PN-III-P2-2.1-CI-2018-1287 for imaging measurement of luminance, grant MAXLUM-256CI, contract PN-III-P2-2.1-CI-2018-1490 for simultaneous imaging measurement of correlated color temperature and luminance.