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Small lighting luminaires for illumination applications

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Abstract: The application of solid-state light sources in luminaires creates a new quality in illumination design works. In a confrontation with a commonly used but relatively unattractive flood method, the use of small-size luminaires allows one to present an illuminated architectural object in a more attractive way in the evening and at night. In this case, it is possible to apply the principles of illumination described in the literature, especially the principle of height amplification and the principle of depth amplification. The conceptual work of illumination with the use of a large number of small-size luminaires does not require the use of supporting graphical tools, but the specification of actual lighting equipment using only polygonal samples in this case is not possible. The paper presents selected issues of the key stages of the completed work. Using specialized computer software, a geometric model of the architectural object has been developed, facade materials have been parameterized, models of small-size illuminating equipment have been selected and, finally, calculations of luminance distribution on illuminated surfaces have been carried out. As a result of computer work, luminance distributions and photorealistic visualizations of illuminations from defined main directions of observation were obtained. The Lubomirski Palace in Przemyśl is an example of the architectural object indicated for detailed works.

Key words: computer visualization, illumination, LED light sources, luminance distribution

1. Introduction

A key element of illumination projects is to create the most attractive presentation of buildings in the evening and at night [1,2]. Apart from a considerable area of freedom of light setting on the illuminated facades of buildings, there are literature recommendations limiting the negative effects of illumination on the environment (light immission), building users and traffic safety in the vicinity of illuminated buildings [3,4]. In addition, a number of useful techniques are used in practice, aimed at zonal illumination of the facade and highlighting the play of light and shadow on elements of ornamentation of buildings (the desired differentiated distribution of luminance on the facade). Then, in aesthetic perception, the illuminated building is perceived more spatially and becomes more visually attractive. The implementation of this goal involves a set of light-technical features used in the design of luminaires for illumination and their appropriate placement and aiming. Luminaires for illumination are located closer to the facade, often on cornices, in window recesses or other elements of facade design [5]. The distinguishing feature of this type of lighting luminaires installation is the installation of luminaires between the illuminated building and the observers of the illumination. It is different in the application of the flood lighting, where the luminaires illuminate the building within its contours and their installation is performed at a considerable distance from the building behind the observers [6,7]. A certain, simplified form of illumination considered is the illumination of the building with the light of road lighting fixtures, especially decorative lighting located in the vicinity of the building and elements of the building's own lighting.

An example of this type of pseudo-illumination (partial, unattractive illumination by street lamps) with the spot registration of luminance values L_p is shown in Fig. 1. The recorded exem-

Fig. 1. An exemplary illustration of flood lighting distribution on the front facade of the building

plary luminance levels are too low for proper display of the building, and the cloister illumination is non-uniform. This contradicts the recommended principle of illumination consistency.

It is, therefore, expected that for buildings with extensive facade geometry, luminaires should be mounted relatively close to the facade [8]. A way to meet the above postulate is to use small outline luminaires working with LED sources. The small dimensions of luminaires are conducive to their easy location and installation within the facade and matching the color of the luminaire bodies to the color of the facade significantly reduces their exposure during the daytime. Possibilities of application of the indicated equipment for illumination purposes have been presented using a simulation design method, in relation to a real building – the Lubomirski Palace in Przemyśl (Fig. 2) [9, 10].

Fig. 2. View of the southern facade of the Lubomirski Palace in Przemyśl

The palace is a facility designated for detailed work that meets the expectations for specification of illumination equipment including small LED luminaires. There are very good conditions to create zone illumination for all facades: a large number of deep window recesses and wide window sills. There are also no restrictions on the installation of ground-mounted luminaires along the facade. An additional advantage is the fact that the building is not illuminated and its facade is in good technical condition.

2. Specifics of light ray distribution in a system of small luminaires

Until relatively recently, luminaires for illumination were equipped exclusively with sodium and metal halide light sources. The optical elements dedicated to forming the luminous flux distribution of discharge sources are single or multi-curved reflectors. Both the discharge sources, with relatively small overall dimensions, and the reflector systems with the required beam angle, guaranteeing the effective transformation of the light beam, form the total starting conditions for the construction of luminaire bodies. Thus, classically, luminaires for illumination equipped with a reflective optical system and discharge light sources are successfully used for flood light distribution, where the luminaires are located at a considerable distance from the illuminated building. The illumination has then the character of contour lighting, and the light distribution of luminaires for illumination is characterized by considerable dispersion of the light beam formed in one part by the reflector and in the other part emitted directly from the source.

An alternative method of illumination is the zone method, in which luminaires are expected to be installed in the space between the observer and the building being illuminated. In this case, these are usually elements of the architectural design of the building: cornices, window recesses, etc., as well as existing or added columns that provide access for electrical power and assembly.

It is expected, especially during daylight hours, that luminaires mounted within the facade will be as little visible to observers as possible. This can be partially achieved by painting their bodies the same color as the facade. However, the most effective solution is to use luminaires with small body dimensions. In this case, it would be necessary to use LED light sources with a small light-emitting surface (very favorable conditions for forming a beam) and a small-size, lenticular optical system. The light-optical system of LED luminaires should enable the effective illumination of relatively large zone areas of the facade by locating the luminaires close to the facade. The term "effective illumination" should be understood as an equalized luminance distribution with an appropriate value and expected size of the spot of light on the facade.

For the purpose of the detailed study, an analysis of lighting conditions using small luminaires was conducted. The following figure – Fig. 3 – shows a model situation in which a luminaire for illumination (O) is installed on a cornice at a distance (a) from a section of porous facade with a height (b) and a reflectance (ρ) from the wall. The luminaire was directed at the top edge of the facade, through which the optical axis of the luminaire (O) passes.

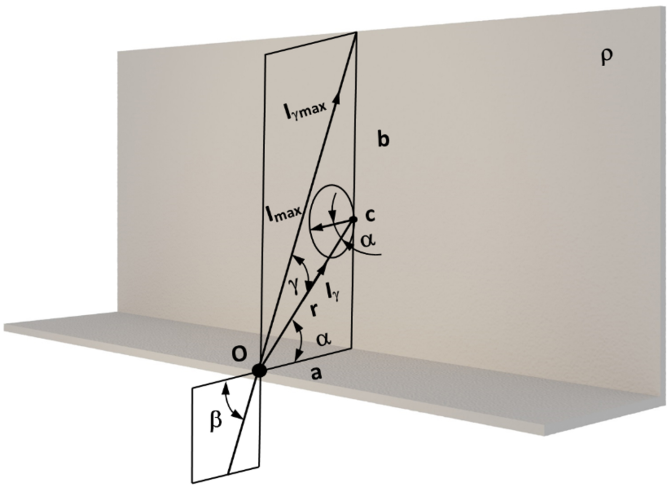


Fig. 3. A model system including the luminaire O, located in the immediate vicinity of a fragment of the facade

Light rays emitted from the luminaire (O), falling on elementary facade surfaces, produce illuminance on them. For example, the illuminance E will appear on the elementary surface (c) of the facade, according to the relation:

$$E = \frac{\phi}{S}, \tag{1}$$

where: ϕ is the luminous flux incident on the elementary surface (c), S is the elementary facade surface (c).

Some of the luminous flux will be reflected from the facade, and the facade will become a secondary light emitter. The reflected luminous flux ϕ_ρ, will be related to the facade reflection coefficient ρ:

$$\phi_\rho = \rho\phi\,. \tag{2}$$

Facade surfaces are porous for the most part, so we assumed, when analyzing the nature of the expected distribution of the luminous flux of the luminaire, that according to the Lambert law, the elementary rays will be reflected from the sample elementary surface (c) of the facade. In the analytical description of the phenomenon of light reflection from the facade, mirror reflection was not taken into account. This is due to the fact that in illumination practice, directing the light beam toward the reflective surface in a mirror-like manner will create an undesirable risk of reflective glare when light rays run from top to bottom, whereas directing the light upward will not allow one to achieve the recommended average luminance levels on the facade. Also, directional-diffuse reflection was not taken into account due to the fact that the dominant group of historical buildings has almost exclusively facades that respond according to Lambertian reflectance. The light distribution of the beam reflected from the facade according to the Lambert law is a cosine distribution, which is described by the relation:

$$I_\alpha = I_{\max}\cos\alpha\,, \tag{3}$$

where: I_α is the luminous intensity I in the direction α, $I_{\max}$ is the maximum luminous intensity of the beam reflected from the elementary surface (c), α is a plane angle between the normal n to the elementary surface (c) and the direction of light rays.

Thus, the luminous flux reflected from the elementary facade surface (c) can be expressed using the sine Formula [11]:

$$\phi_\rho = \rho\phi = 2\pi\int_o^{\pi/2} I_\alpha \sin\alpha\,\mathrm{d}\alpha = 2\pi\int_o^{\pi/2} I_{\max}\cos\alpha\sin\alpha\,\mathrm{d}\alpha = \pi I_{\max}\,. \tag{4}$$

The luminance L of the elementary surface (c), reflecting the elementary rays according to the Lambert law, is constant in all directions, so it can be calculated by knowing the maximum luminance $I_{\max}$ and the area of the elementary surface (c):

$$L = \frac{I_{\max}}{S}\,. \tag{5}$$

By combining the above relations, it is possible to determine the luminance L of the elementary surface (c) of the facade related to the reflectance ρ and the illuminance E on that surface:

$$L = \frac{I_{\max}}{S} = \frac{\rho\phi}{\pi S} = \frac{\rho E}{\pi}\,. \tag{6}$$

On the other hand, the illuminance E on the elementary surface (c) can be expressed by a relation representing the inverse square of the distance:

$$E_C = \frac{I_\gamma}{r^2} \cdot \cos\alpha\,, \tag{7}$$

where: r is the section between the luminaire (O) and the elementary surface of the facade, I_γ is the luminous intensity in the direction of the angle γ.

It is possible to simultaneously replace the angle α with the formula:

$$\alpha = \beta - \gamma\,. \tag{8}$$

Referring to Fig. 1, the section r and angle α can be expressed by the formulas:

$$r = \frac{a}{\cos\alpha} \quad \text{and} \quad \alpha = \arctan\frac{b}{a} - \gamma\,, \tag{9}$$

where: b is the height of the facade fragment, a is the distance of the luminaire from the facade, γ is the angle of light rays towards the elementary surface of the facade (c).

Using the above two relations, the illuminance at the facade elementary surface (c) can be described as follows:

$$E_C = \frac{I_\gamma}{a^2} \cdot \cos^3\left(\arctan\frac{b}{a} - \gamma\right). \tag{10}$$

Finally, by replacing the illuminance parameter E of the elementary surface (c) with the formula for the luminance L of this surface, the following relation is obtained:

$$L_C = \frac{\rho \cdot I_\gamma}{a^2 \cdot \pi} \cdot \cos^3\left(\arctan\frac{b}{a} - \gamma\right). \tag{11}$$

This expression allows one to calculate the distribution of luminance on subsequent elementary surfaces of the facade according to the assumed angular luminous intensities of the luminaire (O), emitted towards these elementary surfaces. In other words, it is possible to analyze the distribution of luminance on the facade depending on the luminous intensity curve of the luminaire illuminating the facade fragment under consideration.

In the field of illumination, it is expected that the luminance distribution on the facade will be as even as possible, also under conditions where luminaires are located close to the facade. As can be seen in Fig. 1, this is not an easy task because the spatial angle of the luminous flux emitted towards the facade includes extremely short and long r sections. The only possible and correct way to do this is to adjust the light distribution curve of a small luminaire to its close location relative to the facade and to aim it properly. This task would not be feasible if part of the luminous flux of the luminaire is emitted directly from the light source without optical shaping. In structural solutions with solid-state light sources, the entire luminous flux of the LED source is converted by the lenticular system.

The suitability of three characteristic types of luminaire distributions intended to be installed close to the facade was evaluated. These are: the concentrated distribution with the angle of the maximum luminous flux $\gamma_{\max} = 0°–15°$ and the luminous intensity curve shape factor $K \geq 3$, the deep distribution with the angle of the maximum luminous flux $\gamma_{\max} = 0°–30°$ and the luminous intensity curve shape factor $2 \leq K < 3$ as well as the diffuse distribution with the angle of the maximum luminous flux $\gamma_{\max} = 0°-35°$ and the luminous intensity curve shape factor $1.3 \leq K < 2$. Figure 4 illustrates the shapes of the above luminous intensity curves.

The directions of the emitted light I_γ in the angular range $\gamma = 0°-80°$ were determined by making the following irregular division of the angle γ: 0, 2, 4, 6, 8, 10, 20, 30, 40, 50, 60, 70 and 80 degrees. This division allowed a more accurate representation of the luminous intensity curve of the concentrated distribution. It was also assumed that the luminous intensity values of the presented curves will refer to the maximum luminous intensity of 1, common to all distribution curves. Such a way of presenting selected distribution curves of illuminating luminaires is due to the fact that with the close position of the luminaire in relation to the illuminated surface, there is a need for even illumination of the entire facade, especially its upper part, farthest from the luminaire. It is into this zone that the axis of the maximum luminosity is directed. Of course, the three characteristic light curves presented in Fig. 4 will illuminate with the same intensity the zone of the facade corresponding to the direction of the maximum light radiated, but more intensively the subsequent regions of the facade, located closer to the location of the luminaire. In this case, the fluxes of the luminaires whose distributions are illustrated in Fig. 4 will vary.

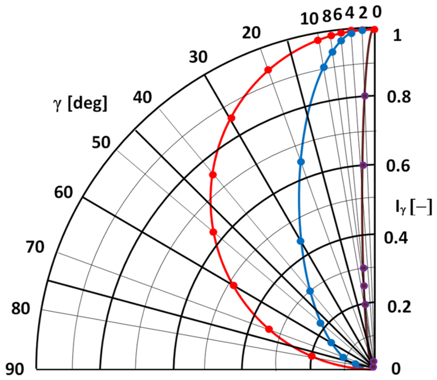


Fig. 4. Curve shapes for the concentrated, deep and diffuse luminous intensity distribution

Therefore, it is beneficial to link the luminance of a given zone of the facade, represented by a specific point (C) on the facade, with the luminance of that zone by a mathematical relation. This is shown in the form of the last presented relationship.

By using the last presented mathematical relations, the luminance was determined at the facade points corresponding to the directions γ of the emitted elementary beams of the luminous flux. It is expected that as the luminous flux concentration of the luminaire increases, the luminance distribution across the facade will become more uniform. The results of the calculations are presented in Fig. 5.

As expected, the luminaire with the concentrated distribution realizes the most favorable luminance distribution on the facade. Obviously, the most uniform luminance distribution was not achieved. However, literature sources indicate that a difference between the smallest and largest value of the luminance distribution on the facade in the ratio of 1:2 is allowed [12]. In this

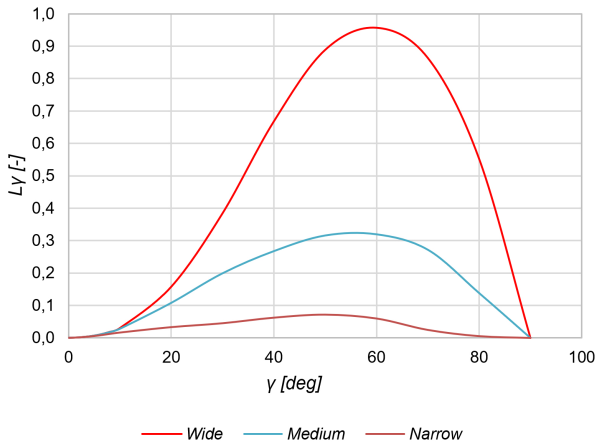


Fig. 5. Luminance distribution on a fragment of the facade depending on the light distribution of the luminaire

respect, the result obtained is satisfactory. The use of luminaires with deep and diffuse distribution for zonal illumination will only make sense if the luminaire is at a significant distance from the facade. Otherwise, unattractive local facade overexposure will occur at the bottom of the facade in the immediate vicinity of the luminaires. For illumination of the entire facade, including the horizontal dimension, linear small luminaires with the concentrated distribution can be used. In this case, the resulting uniform luminance distribution in the vertical axis will be transferred to the horizontal axis along the elevation. To confirm the obtained results of the analysis, sample point and linear digital models of small luminaires were implemented into a virtual environment with a model representing a real building.

3. Simulation of illumination with equipment specification

The use of advanced simulation methods is necessary during the design of complex illuminations, especially zonal ones. Elements of computer graphics are also successfully applied in other fields of technical sciences [13]. The classic approach of field trials may involve only illumination of fragments or may involve relatively simple illuminations involving a small amount of illumination equipment. Commercially available computer tools sufficiently represent the physical phenomena of the path of light rays and the interaction of light rays with obstacles [13, 14]. They allow multivariate analyses of the selection of luminaires with different luminous flux distributions, their arrangement and targeting, and finally, for visualizations of the illumination and luminance distributions on facades [15]. 3D Studio MAX graphics software was used for the simulation work. In the course of the analysis, a geometric simulation model of the building was initially developed, taking into account the need for precise representation of its spatial form and details. It necessitates the luminaires to be close to the facade. The result of the work is illustrated in Fig. 6.

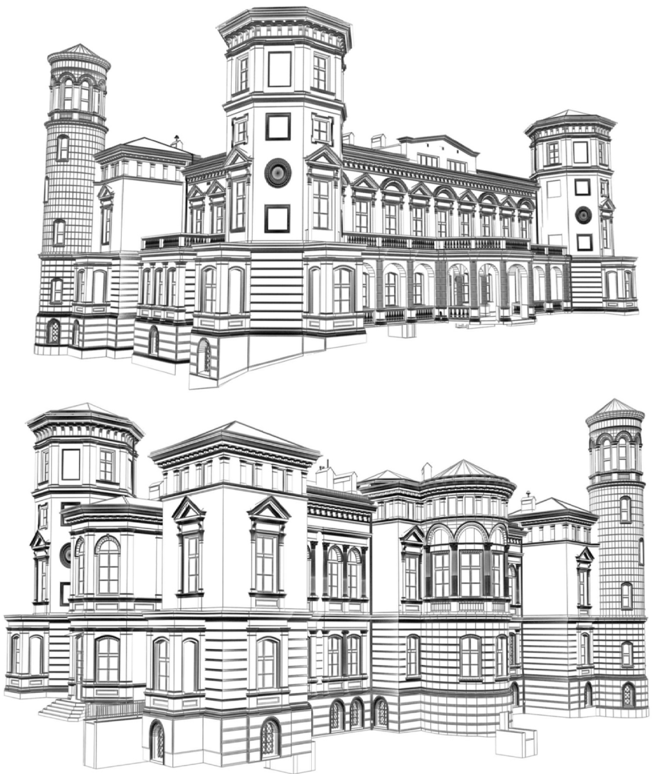


Fig. 6. Visualization of the geometric form of the Lubomirski Palace
with an assumed high scale of detail projection

The adopted high accuracy scale of the geometric model is particularly important for the location of small luminaires close to the facade. The shape and size of shadows created by elements of architectural decor are closely related to the distance of floodlights from the facade. Moreover, for the zones of the building (in the present analysis, these are the cloisters of the northern facade), where the phenomena of multiple reflections occur, the accuracy of mapping the geometry of the zone directly affects the values of luminance distribution inside it. Figure 6 shows a section of the column head model in addition to the edge views of the geometric model of the southern and northern facades. The illustration confirms the high quality of the computerized spatial mapping of the building.

In the next stage of computer modelling of the facility, the values of the reflectance of the materials covering the facade were defined. These parameters were determined on the basis of the applied method of measuring the reflectance, using the measurement of the illuminance of the light stream falling on the facade and reflected from it. The measurement was made on parts of the facade of the real building.

As already mentioned, window recesses, cornices and cloisters of the building are natural places where small lighting luminaires can be located. The digital files of the light distribution of the selected luminaires in a modeling environment were used at the level of computer modeling [17]. Easy access to large online databases of models of small illumination luminaires allows us to freely choose different types of luminaires. Examples of pre-qualified equipment solutions are illustrated in Fig. 7.

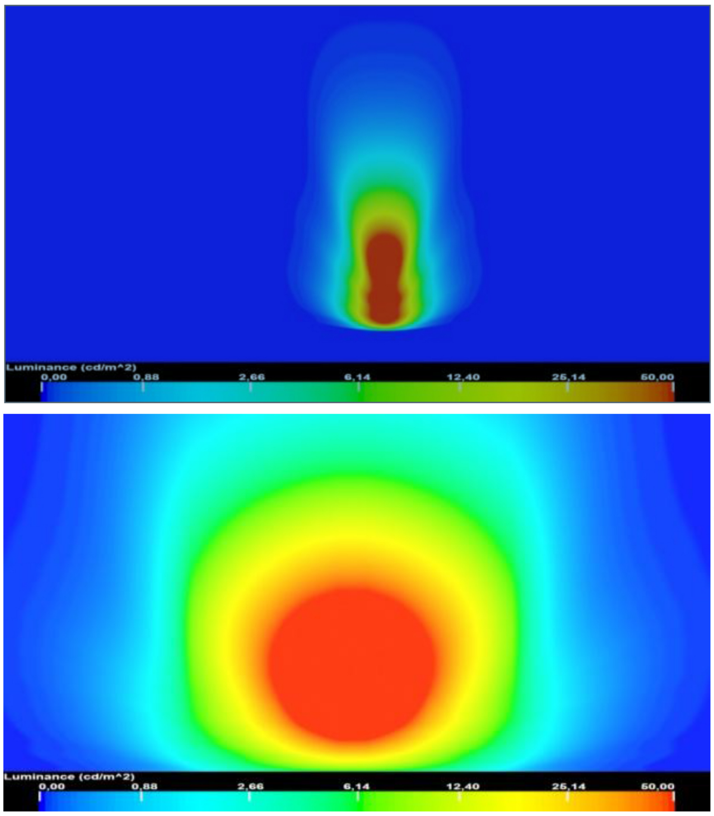
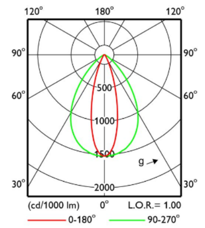
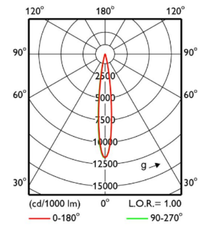
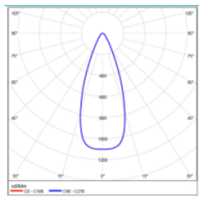
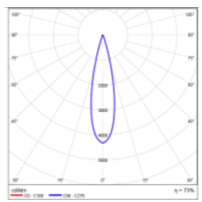
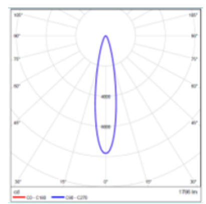


Fig. 7. Illustration of the luminance distribution of exemplary small luminaires with rotationally symmetric and symmetric distribution in two mutually perpendicular planes

One of the presented solutions is a small linear luminaire particularly suitable for illumination of facade zones with installation on cornices. The second example is a luminaire with rotationally symmetric distribution used for accent lighting. In both cases, an analysis of the luminance distribution on the illuminated surface indicates that the luminaires installed close to the facade cause excessive illumination on a single fragment of the facade. This is the disadvantageous effect of the short path of light rays, travelling from the light source along the optical axis of the luminaire to the facade. Although the value of axial light intensity decreases with distance according to the inverse square law, in the end an aesthetically unpleasing intense spot of light is created on the facade. This phenomenon was reduced by adjusting the optics of the luminaires and, where possible, by slightly moving the luminaires away from the facade. Due to the size of the building, a variety of illumination equipment was put together based entirely on small

LED luminaires. Linear luminaires with two mutually perpendicular planes of symmetry of luminous flux distribution and luminaires with rotational-symmetrical solid of light distribution were specified. An exemplary list of linear and spot luminaires selected for illumination is presented in Table 1 [17].

Table 1. Selected small luminaires used for the illumination of the Lubomirski Palace in Przemyśl

No.	**Luminaire angle**	**Quantity**	**Power [W]**	**Luminous flux [lm]**	**Dimensions [mm]**	**Photo of the luminaire**	**Luminous intensity distribution curve**
1	10°×60°	82	5	221	69°×305×71		
2		65	10	475	69°×305×71		
3		8	20	950	69°×610×71		
4	8°	36	30	1 168	271°×163°×175		
5	40°	2	51	1 598	430°×150		
6	23°	4	27	1 115	290°×133°×113		
7	21°	12	509	1 786	180°×318°×124		

Taking into account the literature recommendations for illumination, dozens of models of floodlights were placed in the close vicinity of all facades of the building. Three levels of luminaire location were assumed: the first is the ground level, the second corresponds to the level of the first story and the third is the top level of the building. For the first level of the location, the illumination fixtures are spaced 80 to 100 cm from the facade. The remaining luminaires, installed on cornices, balconies and window recesses, are spaced 60 to 15 cm from the illuminated surfaces. The aiming points of each group of luminaires were analyzed individually for the best optical effect, taking into account the need to reduce the emission of light through the windows to the interior of the building. The luminous intensity distributions of the luminaires were chosen taking into account the specific geometric features of the facade and the scale of light absorption by the facade material. All luminaires used are facing upwards, thus avoiding the risk of direct glare. In order to graphically present the arrangement of illumination equipment, the principle was adopted that the place of luminaire installation is marked with the beginning of the vector, and its aim with the arrowhead. The proposed placement, aiming, and grouping of luminaires are illustrated in Fig. 8.

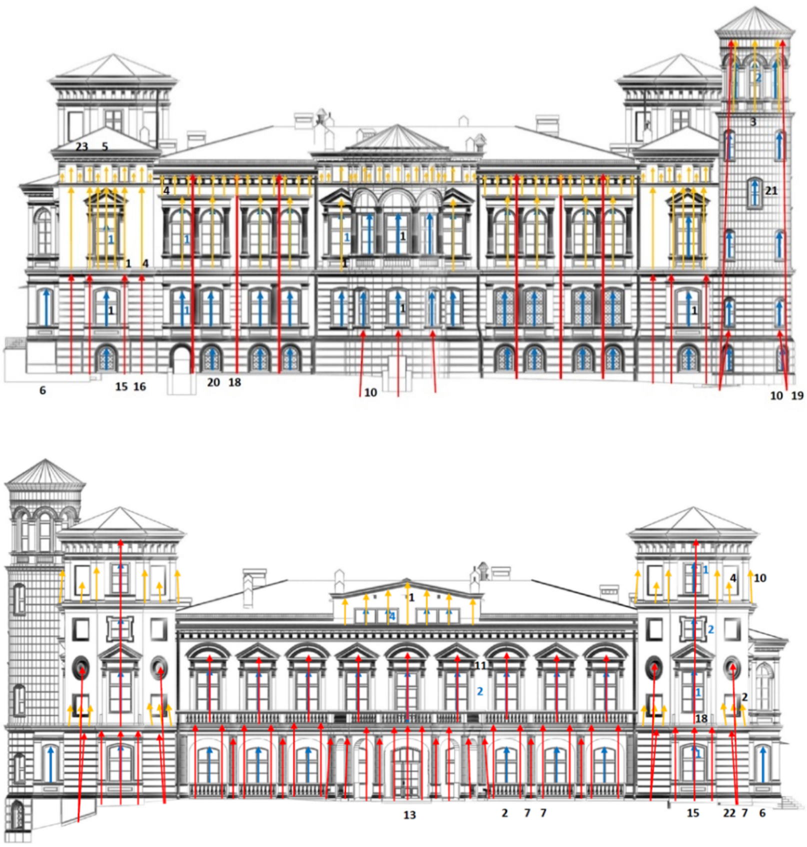


Fig. 8. Indicated places of installation and positioning of small illumination equipment on the northern and southern facades

Due to the need to illuminate the facade of the building on the first-floor level, LED in-ground luminaires were used. Such a solution guarantees full illumination of the entire facade, but it should be noted that in this case it is necessary to analyze the documentation describing the course of underground water supply, gas, electricity, sewage lines etc., within the vicinity of the building. Sometimes there are also difficulties locating in-ground luminaires in the vicinity of facades due to nearby greenery or access roads. No such difficulties were encountered in the case under consideration.

4. Results of numerical calculations

As a result of the finally adopted concept of illumination of the building and photometric calculations performed, surface luminance distributions on all facades and pseudo-realistic visualizations were obtained. The numerical calculations took into account both the direct component of the elementary rays emitted from the LED sources and the component of the luminous flux reflection. It was dictated by the existence of deep window recesses and cloisters. Although taking the component of reflection into account increases the time required to obtain the results of the luminance distribution on the facades, at the same time it eliminates the risk of erroneous results of the luminance distribution values in the window recesses. The analysis of the luminance distribution took into account literature recommendations of average luminance levels for background luminance (in the analyzed case, the Lubomirski Palace is located in a magnificent park and is not affected by intense ambient light). The impact of the roadway decorative lighting surrounding the building was also considered in the analysis conducted. The obtained results of the simulation calculations are given in Fig. 9.

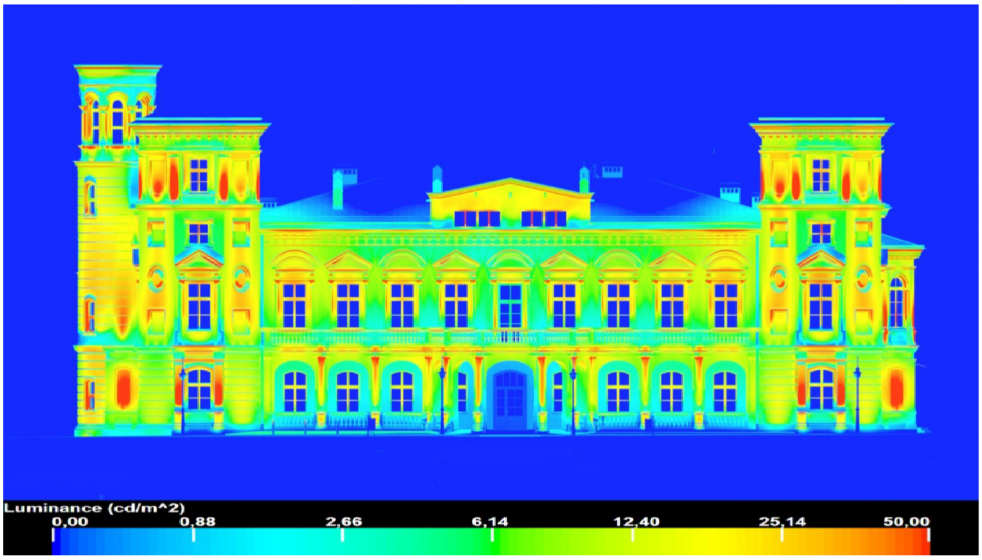


Illustration of the luminance distribution on the illuminated southern and northern facades

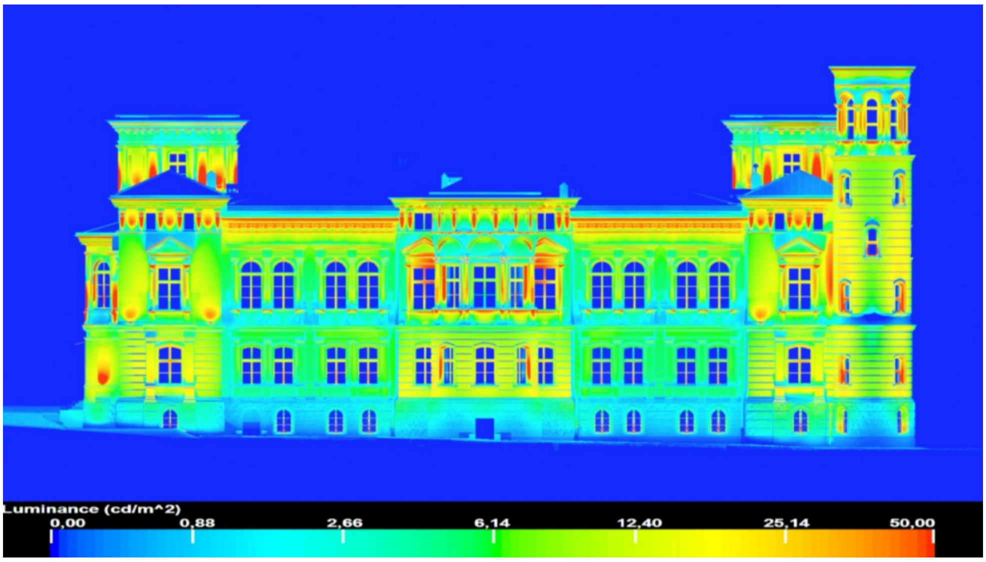


Fig. 9. Illustration of the luminance distribution on the illuminated southern and northern facades

Presentation of the results of simulation work in the form of luminance distribution on the facades is a necessary action, allowing one to evaluate the obtained contrast between the average luminance of the background and the illuminated facades. Analysis of the luminance distribution on the facade is helpful in verifying the obtained lighting effects in terms of compliance with the principle of height or depth amplification, and indirectly enables the assessment of the scale of light immission in the building's surroundings. However, it does not provide a basis for aesthetic evaluation of the illumination in the form of light-shadow play on the illuminated facades of the building. In this case, it is necessary to generate a visualization of the illumination. In the illumination under consideration, LED sources with a color temperature of 2 700 and 3 000 K were proposed for use. This choice is based on literature recommendations to match the color temperature of LED sources to the dominant color of the plaster on all facades. Computer visualizations of the illumination are provided in Fig. 10. According to the authors of the study, the concept of illumination and specified small lighting equipment made it possible to realize attractive decorative lighting. Elements of architectural design were highlighted, thanks to which the geometric form of the Lubomirski Palace was effectively emphasized. The presented visualizations confirm the validity of the selected zone illumination, and the use of small luminaires allowed for trouble-free installation within the close vicinity of the facade. Of course, the resulting aesthetic effect is one of several key factors to consider. Not to be overlooked is the issue of the cost of purchasing and installing lighting equipment, the cost of operating the illumination system, etc. [16].

Fig. 10. Visualization of the illumination of both facades of the Lubomirski Palace using small luminaires

5. Conclusions

The luminance distributions on facades obtained as a result of computer simulations as well as visualizations allow one to draw several conclusions of general nature. The high usability of small luminaires with LED sources for illumination purposes has been confirmed. It applies both to the ease of locating the equipment within the building and to the luminance distribution parameters achieved. This type of installation will significantly reduce the level of light emission into the building through the windows. The dispersed distribution of the illumination equipment also gives additional possibilities for the arrangement of the illumination. It will be possible to sequentially divide the illumination system into festive and of everyday use. For special occasions, it will be possible to fully illuminate the building from all directions, both from far and near. Under the conditions of daily exposition, it will be possible without difficulty to illuminate only the characteristic elements of the building or to illuminate the palace only from selected directions. The only possible impediment to the realization of practical illumination may be the need for possible conservation consultations regarding the locations of the luminaires and the method of running the power supply installation within the facade. Theoretically, it is possible to use small-size luminaires for flood illumination, but then it would be necessary to use batteries of luminaires due to the much greater distances of light rays from the luminaires to the illuminated surfaces. In such a case, it is more advantageous to use individual luminaires of higher power. In addition, directing the light beam from a greater distance significantly reduces the optical effect of chiaroscuro play, making the illumination less attractive. For this reason, the variant of flood illumination using small-sized luminaires was not implemented in the simulation work.

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