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Selected Issues on Material Properties of Objects in Computer Simulations of Floodlighting

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Abstract: This paper addresses issues with computer simulation involved in designing illumination for architectural structures. In particular, the reflectance and transmittance of materials were studied with respect to their influence on luminance values, thus directly the power levels for luminaires applied under particular projects. Raster images derived from digitally processed daytime pictures were used to precisely define material properties. Bitmaps were tested with regard to measuring and editing materials with a widely used graphic application. A real architectural object, the Basilica of the Dormition in Jerusalem, served as the test object. A floodlighting design was performed following a complete analysis of all electrical and photometric parameters. Luminance distributions were analysed comprehensively. Hence, the data allowed for an assessment of the lighting design compliance with guidance given by International Commission on Illumination (CIE) for floodlighting objects and its required standards. The floodlighting utilization factor of the lighting solution developed was also verified, as it is the input parameter for evaluating not only the energy efficiency for the installed lighting system, but also the impact it has on the surroundings, in this case, the project that is to be implemented.

Keywords: lighting technology; floodlighting; reflectance and transmittance; floodlighting utilization factor; computer simulation of lighting

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1. Introduction

Floodlighting has always been aimed at enhancing night images of architectural objects [1–5]. Computer simulations have assisted floodlighting design for more than a quarter of a century [6–11]. Simulations help to present the designers' illumination visions [12]. Usually, they are performed with rendered photorealistic pictures [13,14]. Controlled outdoor tests are carried out equally often [15,16]. Unsurprisingly, both methodology and software applications used to perform such designs have enjoyed a steady and dynamic growth [17–19]. While designing is vital to find the prospective illumination purpose, not only in terms of aesthetic values [20] but also in terms of achieving compliance with required technical standards, and to account for economic factors, including the operating cost of the lighting system [21].

Technical issues include, among others, finding luminance distribution for the floodlighted façades, direct glare risk assessment, selecting lighting equipment to be deployed to eliminate light pollution, and economic factors related to the floodlighting system to be installed, operated, and maintained [22–25].

Hence, photorealistic visualisations of the illuminated structures are to be set directly against the luminance distribution values, and indirectly against the locations where luminaires are to be installed or light distribution systems to be applied, and against their power. The last parameter is the key element concerning the plans for the floodlighting system exposition time, and, in a wider perspective, to the system maintenance and operation costs. Once at the design and simulation stage, it is essential to realise that the proper approach to finding the right parameters for reflectance and transmittance of façade materials under consideration shall be of major importance, while determining power for particular luminaires. A direct and linear relation between the reflectance and luminance values is critical to answering why this should be the case. Unfortunately, to reproduce material properties accurately remains a complex task. Quite often it is related to colour variability, which is particularly true for historical objects. As the construction materials age, irregular colour changes tend to occur; such changes are difficult to measure and must be incorporated into photometric calculations. Under standard numerical simulations for objects to be illuminated, constant colour values are assigned to specific surfaces by averaging over a given field, and as such they by definition do not accurately represent the actual conditions. Hence, the correctness of calculations may be significantly affected.

2. Relation between Reflectance Value and Light Source Power

As noted, to properly select power for luminaires, we need to know reflectance and transmittance characteristics of the surface façade materials. Let us assume a luminaire Z of power P and luminous efficacy η to radiate towards the elementary façade surface dS the luminous flux Φ within the solid angle dω (Figure 1). An individual ray from such a beam incident onto point A of the elementary surface dS, once reflected from it, is scattered at all angles within the surroundings. For porous façade materials, such as brick, sandstone, travertine, or plaster, the reflected rays are scattered under the Lambert's, or near-Lambert's cosine law [26]. It provides the first quality characteristics of the reflected light. This reflection is depicted at the surface β as the circle envelope tangent at the point A of the surface dS. The light reflected in this manner allows for observing the floodlighted object from all angles, with the luminance remaining constant according to Formula (1), despite the cosine dependence of the reflected luminous flux intensity upon the observation angle:

$$I_\alpha = I_{max} \cos\alpha \quad (1)$$

where I_{max} is the maximum luminous intensity of the surface in the normal direction and α stands for the angle between the normal n perpendicular to the surface dS and the observation direction k.

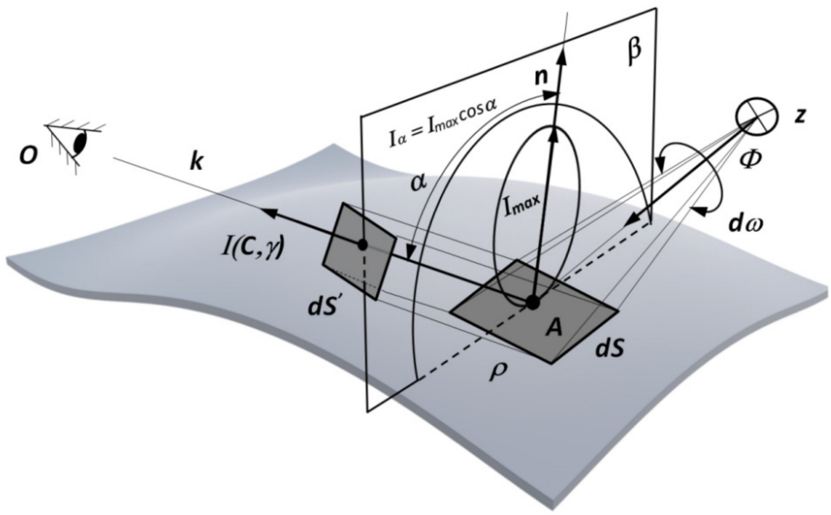


Figure 1. Graphic representation of the elementary ray reflection from a porous surface, compliant with Lambert's cosine law.

A quantitative feature of the luminous flux reflected towards the observer can be described by reflectance ρ. The widely known sine Formula (2) is applicable in this case, provided the analytical dependence $I_\alpha = f(\alpha)$ is known and spatial luminous intensity distribution is of rotational and symmetric character. Here both conditions are met:

$$\phi_\rho = 2\pi \int_o^{\pi/2} I_\alpha \sin\alpha d\alpha = 2\pi \int_o^{\pi/2} I_{max} \cos\alpha \sin\ \alpha d\alpha = \pi I_{max} \quad (2)$$

where ϕ_ρ is the luminous flux reflected from the elementary surface dS.

Taking into account the incident flux, Φ can be written as (3):

$$\rho\phi = \pi I_{max} \quad (3)$$

Thus, the illuminated façade becomes a secondary radiator, seen by the observer O as bright, or to be precise, seen as its luminance distribution. The surface luminance is constant in all directions; hence, it might be calculated from Formula (4) with maximum luminous intensity I_{max} and the surface of the element dS known.

$$L = \frac{I_{max}}{S} \quad (4)$$

On the other hand, the luminous flux emitted from a luminaire depends on its power according to Relation (5):

$$\phi = \eta P \quad (5)$$

where P is the luminaire power and η denotes its luminous efficacy.

By substituting one into the other, we arrive at Relation (6):

$$L = \frac{I_{max}}{S} = \frac{\rho\phi}{\pi S} = \frac{\rho\eta P}{\pi S} \quad (6)$$

With Formula (6) it is clearly seen that reflectance ρ may directly influence the value of the reflecting surface luminance, and that it is interrelated with the source power.

Though the luminance distribution over the given surface can be obtained from the actual travel of the elementary rays to the luminaire, via reflection towards the observer, it can also be generated by applying a simulated environment [27]. Still, in both cases, luminance distribution analysis is not limited solely to the floodlighting domain, and it can be performed under studies on luminance distribution at the light surfaces, diffuse lenses, lenticular optical systems, and any other surfaces, e.g., roads [28–32].

3. Reflectance Properties of the Façade Materials for Objects to Be Floodlighted

Architectural structures with façades both clear in their geometrical form and with hardly varying reflectance provide the least complex cases of objects to be illuminated. A simulation model for such an object is then relatively easy to construct, as the reflectance and transmittance for the façade materials are simple to project. Selected luminaire models are incorporated into a design-simulated environment and placed as required by the specific floodlighting methodology. The numerical simulations for calculating photometric parameters provide not only photorealistic visualisation of the illumination under design, but also the luminance distribution at the façade surface related to the given input reflectance values. The following step is to check the design compliance with guidance from the International Commission on Illumination (CIE) [33,34]. Hence, the luminance distribution assessment at the floodlighted façade has a direct impact upon selecting the proper power of luminaires, and on the energy efficiency of the designed floodlighting.

The majority of designs, regretfully, face difficulties related to façades covered with various materials of roughness levels, varying from place to place due to grinding, or with a variety plaster colours applied, which is particularly true for typically rich ornamentation of Baroque architecture.

A computer visualisation of the Basilica of Santa Maria Maggiore pediment is shown as an exemplary case study (Figure 2). Here, the reflectance variability occurs in zones at three levels. First, the colour of the light reflecting surface (see the part of belfry plinth of the surface S_1 and reflectance ρ_1) is concerned. In the concerned case, individual façade zones follow in principle a two-colour scheme. For other solutions, then definitely more complex colour schemes may be adapted.

Figure 2. Diversity of materials in the pediment coverage (wiz. Pajda D.).

The second factor that affects the way light is reflected from the façade is its surface porosity level (see the column part of surface S_2 and reflectance ρ_2). The porosity may vary within one type of material, i.e., due to its mechanical grinding, or through a range of materials such as plaster, tile or sheet roofing, travertine cladding. The façade dirt gathering mechanism, that is dust and dirt capability of settling on a porous surface, is closely related to this factor.

There is also the third complementary factor that involves the material porosity scale: environmental dirt intensity within the surroundings, along with gravity or other active environmental factors such as wind, related to the pollutants' capacity to settle. Typically, nooks and crannies of the façade, cornice flattenings, window and ornament recesses, northerly oriented walls, etc. are the first to gather dirt (see the part of ornamentation with the surface S_3 and the reflectance ρ_3). Hence, it should be noted that high variability in reflectance and transmittance may occur even within a single façade and its individual zones.

Polygonal measurements of the façade performed on the actual object, and/or examination of façade materials samples already at the planning stage, i.e., prior to introducing these parameters into the computer model, are highly recommended. The light reflectance is obtainable from indirect measurements with calibrated illuminance and luminance meters applied. Unfortunately, these measurements are often subject to a permit for temporary traffic shutdown, or need to engage teams specialised at height measurements, etc., so practically they are not always likely to be performed. When unable to meet such requirements, designers need to apply approximate reflectance values for a given material. Therefore, it is of crucial importance, either to reliably estimate the impact that the approximated transmittance and reflectance parameters may have on the accuracy of finding proper power for luminaire equipment to be selected, or to search for alternative findings on façade reflectance by computer simulations.

This paper tests the suitability for applying raster images to determine input reflectance and transmittance parameters for computer simulations. Bitmaps derived from daytime photographs, taken in different lighting conditions of the object subject to design, are used for this purpose by taking advantage of their graphical transformations.

With the reflectance at the accessible façade spot, where illuminance is measurable, the reflectance at each point/pixel of the map can be computed with software based on a raster image transformation. The average value of this photometric parameter for the whole material can also be determined.

To meet the objective of this study, computer simulations for the actual object to be floodlighted, according to the approved design procedure, were performed. The luminaire equipment defined by photometric files (luminous intensity distribution files) was used. The files represent the spatial luminous intensity distribution. Individual rays incident on the multitone colour surface produce specific illuminance at the particular point/pixel. Knowing the reflectance of each mapped point/pixel, the luminance is calculated and a visualisation image is built.

4. Methodology and Tools

Development of a computer simulation for floodlighting, regardless of the applied tool, can be divided into several stages [13]. The most important stages regarding analytical issues are listed below, namely:

- Geometric modelling of the object to be illuminated;
- Measuring and defining reflectance and transmittance of materials;
- Developing floodlighting concepts;
- Photometric calculations.

Though geometric modelling consumes most of the time [35], it is not the stage that determines technical reliability and compliance of the design. Developing a conceptual floodlighting and performing reliable photometric calculations have been shown and proven to be vital. Notwithstanding, even following all details of the art of design does not necessarily provide the correct results. Most standard software accounts for processing the photometric calculations on the basis of illuminance. The calculations are not too complex; thus, many applications may run correctly. Still, the human eye does not respond to this photometric parameter. It reacts solely to the luminance. Hence, it is the only technically correct parameter that can help to assess architectural floodlighting quality. All standards and technical reports on outdoor lighting define the luminance [33,34,36,37]. For floodlighting objects, the *Guide for Floodlighting* developed by International Commission on Illumination (CIE) proves to be the essential reference. Thus, it is important to meet CIE recommendations both in the designed and implemented projects, and to determine that the luminance values are compliant. Hence, in the process of designing any floodlighting scheme, defining materials has secondary importance; therefore, it cannot be achieved without a geometric model in place.

Nevertheless, few parts of computer simulation software include photorealistic simulation, which is crucial for designing the floodlighting necessary for presenting luminance distribution results. To make luminance values reliable, the software needs to include reflectance and transmittance calculations of the materials from which the structure is built. For objects uniform in colour and structure, the problem is easy to overcome as designers are able to easily find the required reflectance and transmittance values for the materials within the project. Otherwise, for objects with great variety in materials, the problem of accurately defining their reflectance and transmittance characteristics needs to be solved. As intended, we applied raster images for dedicated material bitmaps in order to test such an approach to solving this issue. Bitmaps have been obtained from daytime photographs. As the objects are not uniformly lit, both with regard to geographic directions and atmospheric conditions, the bitmaps have been adjusted to each other in terms of geometry and colour tone. To test the reliability of the changes introduced, simulations in daylight were performed for the conditions identical to the ones at the time when the picture had been taken. Provided that no difference between the pictured and visualised object is noticeable, the material properties were considered reliable, i.e., defined properly.

Under our study, Autodesk 3ds Max 2021 software was selected to track the impact of reflectance and transmittance for the materials, as defined above, on the level of the object luminance variability. The software was found unique and met the floodlighting design requirements. Specifically, while generating photorealistic simulations, the data necessary for photometric calculations, i.e., luminaires luminous intensity distribution data, and data on reflectance and transmittance of the materials, were derived from bitmaps. Hence, luminance analysis for all designs developed with this software was available.

5. Selection of Actual Objects for Detailed Study on Defining Façade Reflectance

Selecting an object as an actual template and meets expectations concerning research on issues related to the reflectance parameter remains the key element prior to the simulation stage of the study.

For this project a structure, located in Jerusalem, Israel, of great historical, religious, and touristic significance. The site is the Dormition Abbey and the Basilica of the Dormition, located on a hill south of the Old City walls, near the Cenacle and the Tomb of David (Figure 3).

The present basilica is the fourth church built on the site. The first was an octagonal church, built around 382 by Emperor Theodosius the Great, and transformed later, around 415, into a five-nave basilica called Hagia Sion. The church was burnt by the Persians in 614, later rebuilt, and subsequently destroyed again in 966 and 1009. Then, around 1110, the Crusaders erected a three-nave temple at the site called Sancta Maria in Monte Sion, which was destroyed by Muslims in 1219. In 1342, it was again rebuilt by the Franciscans, who were expelled by the Muslims in 1523.

During his journey to the east, German Emperor William the Second purchased a part of Mount Zion from the Turkish Sultan in 1898, to build a monastery and a new, towering temple dedicated to the care of Catholic pilgrims from Germany. The church was consecrated in 1906 and remains cared for by German Benedictines [38].

The church was to resemble the Aachen Cathedral. It was built of white sandstone in Romanesque-like style. The basilica is shaped as a rotunda with four towers and buttresses, enveloped within a Greek cross outline. A chancel with an apse is attached to the rotunda on the east side. The massive bell tower and the rotunda with its conical pitched roof and dormer windows make the entire complex appear to be a medieval fortress.

The oval shape of the main part of the church is not accidental, since its task was to reflect the events commemorated there, such as the washing of the apostles' feet, the Last Supper, Pentecost, and Mary's passing from earthly life. The oval tends to be frequently used in religious architecture if the structure is to commemorate exceptionally important events or theological truths. White sandstone, so-called Jerusalem stone, is associated not only with a customary style, which over centuries turned into a building requirement for all Jerusalem, but also in order to preserve the character of golden Jerusalem. The stone may be found in many varieties, polished and unpolished, and stylised as Herodian stone in the form of a rectangular stone block with regular narrow, shallow-dressed margins surrounding the central panel (Figure 4).

Figure 3. The Basilica seen from the north.

(**a**) (**b**)

Figure 4. View of polished (**a**) and unpolished (**b**) single-cut white sandstone.

The bossage used by the Romans was to emphasize the powerful character of the building, as due to chiaroscuro the wall built that way seemed more monumental than one that is simply flat. Apart from the historical reference, the roughness of the stone reminds that the Church is a community of imperfect people—sinners.

It was architect's intention for the abbey to allude to Arabic Islamic architecture by applying, especially in the arches, a colourful pattern of alternating red and white stones, called also ablaq technique, typical and popular in Islamic architecture.

As seen from the perspective of people climbing Mount Zion, the temple block bears the resemblance to a boat prow, which obviously is a reference to the most commonly associated church image.

Although very unlikely the architect's intention, a widespread belief among the inhabitants of Jerusalem, retold and spread gladly by tourist guides, heralds the church tower with the clock faces. When seen from a certain perspective, it resembles either the head of a Prussian warrior, or Kaiser Wilhelm himself, with the dome resembling the helmet and the clock faces the eyes.

Analysis of all building materials reveals Lambertian or near-Lambertian surfaces to have been used for exterior façades and roof cladding. Fortunately, materials used for rotunda roofing sheets, apse stone cladding, turrets, and belfry, and, similarly, the polished and porous sandstone blocks, are easily distinguished by their surface colour. Clear discoloration in the guttering areas and window recesses, smaller in scale in comparison to discoloration at the rotunda north side, most likely due direct influence of wind carrying dust and small debris, are also observed. It means that at the stage of constructing a computer model for the object concerned, where specific and reliable reflectance values are to be assigned to each material applied in façades, zone analysis for the façade materials needs to be carried out. For the study under consideration, mainly due to difficult access to the higher parts of the object, polygonal reflectance measurement for individual materials is impossible. This is usually the case with monumental objects, slender in shape. Preliminary attempts have been made to solve the problem by applying computer graphics with augmented reality elements included, but at present they are not very effective [39].

Therefore, to precisely design the floodlighting methods and to reliably define luminance levels for the façades, in compliance with the values recommended by specialists, proves to be a very difficult task. Such a limitation may also imply large error margins for the estimated luminaires power to be applied within the project. Last but not least, it may also cause differences between simulated visualisation and the final, actual aesthetic effect of the floodlighting, which are difficult or impossible to accept. The architectural object selected provides all the elements necessary for detailed examination under this study; in particular, its façade shows sufficient variability in structure.

Therefore, the object selected is definitely one that is exemplary for testing the adopted methodology.

6. Floodlighting Method and Its Evaluation concerning Observation Distance

The Basilica of the Dormition of the Blessed Virgin Mary belongs to a small group of landmarks and widely known from Jerusalem panorama pictures. The monastery and basilica complex are located near the existing southern section of the Old City walls, in the vicinity of the Gate of David, more commonly called the Zion Gate. The basilica is located in the southwestern part of the city on Mount Zion, which lies in a picturesque area bordering to the east the Tyropeon Valley and the Hinnom Valley to the south and west. To the north, it borders the densely developed old city. While evaluating the feasibility of the basilica illumination study, the first steps were concerned with assessing its visibility from the key observation directions that coincide with intense tourist traffic zones, both in the evening and at night.

The directions envelope the monastery complex immediate surroundings, crossed with pedestrian and motor traffic routes, an intermediate zone slightly farther from the basilica, which corresponds to the average observation distance of the site, e.g., the westward observation field from the eastern slope of the Gehenna/Hinnom Valley, and longer observation distances from locations far from the site, such as the Mount of Olives (Figure 5).

To carry out the object visibility analysis, that is, to find spots from where architectural details and structural facade materials are possible to identify, three observation zones were introduced, depicted above as three concentric circles; specifically, a blue zone within the basilica immediate vicinity, a red zone enveloping its relatively close vicinity, and a brown zone featuring farther observation directions. For clarity, the ring sections only are shown in the figure. The outer radius of each ring zone was determined by observations as the maximum distance limit from where design details and/or material textures remain distinguishable.

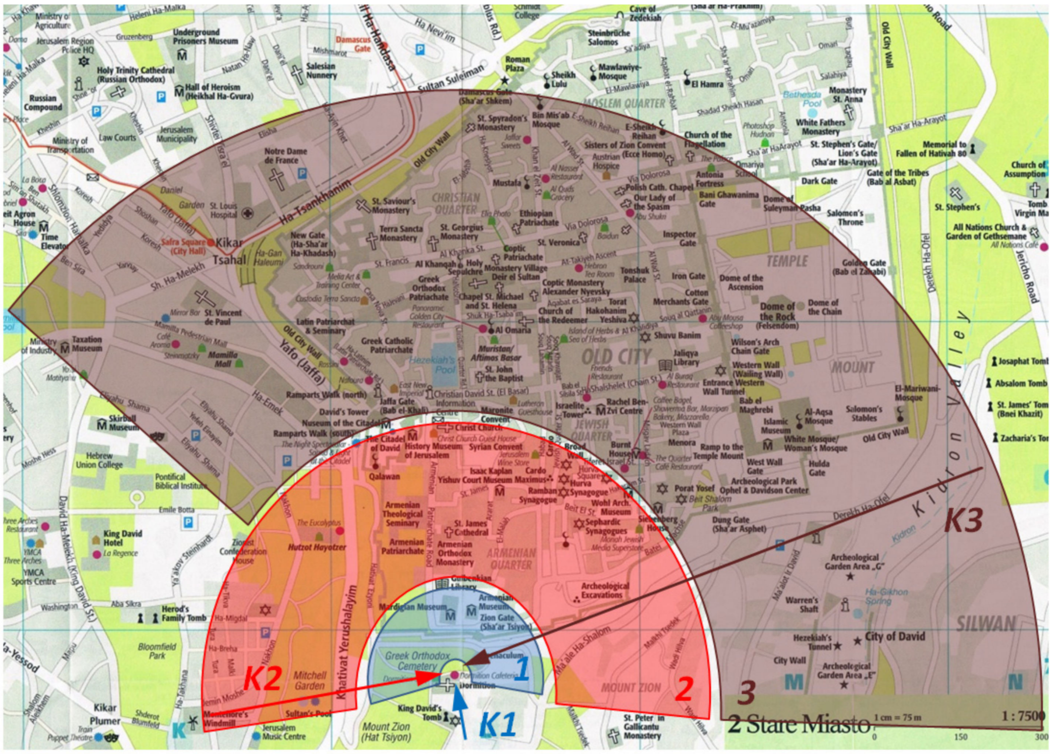


Figure 5. Object visibility zones and directions [40].

The outer radius of the inner ring is equal to circa 450 m; it covers partly the local street network, and includes K1 characteristic close observation directions, i.e., the viewing terrace area of the Tomb of David (Figure 6). Within this densely developed zone, outline visibility of the site is severely limited by tall buildings. A relatively short observation distance allows for a visual identification of architectural details of the site, in particular, details of the façade's rich and diverse geometric structure. Thus, a zone illumination method could be applied, and luminaires could be installed relatively close to the façade at a few elevated levels, to achieve the required and attractively enhanced chiaroscuro effect.

However, this solution would undoubtedly mean execution of effective antivandalism protection measures for the lighting equipment, along with obtaining conservation officer consultancy/permission for anchoring luminaire elements into the façade.

Another maximum limit for observation distance of approximately 1100 m envelopes the central ring outer outline radius with the exemplary observation direction K2, towards Gehenna/Hinnom Valley slope with the Montefiore windmill (Figure 7).

Within this zone due to high walls of the old town, up to 12 m, the lower parts of the basilica are not visible from the northern observation direction. Similarly, other site observation directions within the intermediate visibility zone are limited concerning the full outline of the site. Nevertheless, the potential of basilica exposition is greater at dusk and night, as the visibility area tends to be extended and covers the more intense pedestrian traffic area. Importantly, within the intermediate observation zone, unlike the close perception zone, full identification of architectural details is precluded. Therefore, the zonal illumination method is disregarded and the planar method is favoured.

Within the last ring, the city zone encapsulating far observation directions, e.g., the direction from the Mount of Olives (K3) (Figure 8), have been set.

Only the basilica outline can be seen in the distant observation directions, with relatively good visibility. The proposed planar method for illuminating the site with appropriately balanced luminance distribution, allows for achieving acceptably high positive contrast in relation to the background, which includes both the sky and other illuminated objects. Therefore, to keep illumination coherent at the macroscale, it definitely seems well founded and practical to follow illuminating methods selected for the neighbouring objects, such as the floodlighted fragments of the old town walls or the Hurva Synagogue illumination. At present, as seen in the Jerusalem view presented in Figure 9, the basilica, despite being the predominant panorama feature, is engulfed by darkness; the basilica site is marked with an arrow on the image.

Figure 6. A close, exemplary south direction (K1) of site observation.

Figure 7. An exemplary intermediate west observation direction (K2) of the site.

Figure 8. Exemplary distant, east observation direction (K3) of the site.

Figure 9. Distant, exemplary east observation direction (K3) at night, photo: Oliwia Papatanasis.

The method selected offers several advantages. In particular, it minimises the need for installing luminaires in the façade proximity, requiring them to be anchored in the wall at only few places, and in comparison to the zonal method, it produces a short specification for illumination equipment to be installed. It must be noted, however, that due to a longer luminaires–basilica distance, the challenge to limit light pollution will arise [41]. Contemporary attempts to provide effective technical means for limiting this phenomenon, such as installing dedicated screens on individual spotlights, are in progress. Such a solution limits, to some extent, the entire luminaire luminous flux available for floodlighting. Other systems, such as adaptive optics systems that shape the entire luminous flux to the required form, have not yet been implemented. Trial implementations in the indoor lighting environment have been reported [42].

The analysis presented above, for various observation directions and distances from the object, provided the basis for defining zones for the dedicated scheme that illuminates the basilica, and for finding the recommended illumination method, either planar, accent, or mixed. Explicitly, by recognising the widest possible exposure of the object to a potentially significant number of observers, the upper part of the rotunda, and the bell tower, were assigned for floodlighting with a planar method.

7. Results and Discussion

With respect to its geometry, the Basilica of the Dormition of the Blessed Virgin Mary in Jerusalem is not easy to model numerically. A relatively large number of architectural details, richly variable in shapes, provide a significant challenge. Time required to develop an accurate geometric model has been estimated as several hundred hours of labour. A geometric representation of the basilica, seen from a close observation direction, is depicted in Figure 10. The direction is consistent with the K1 for the blue zone shown in Figure 5.

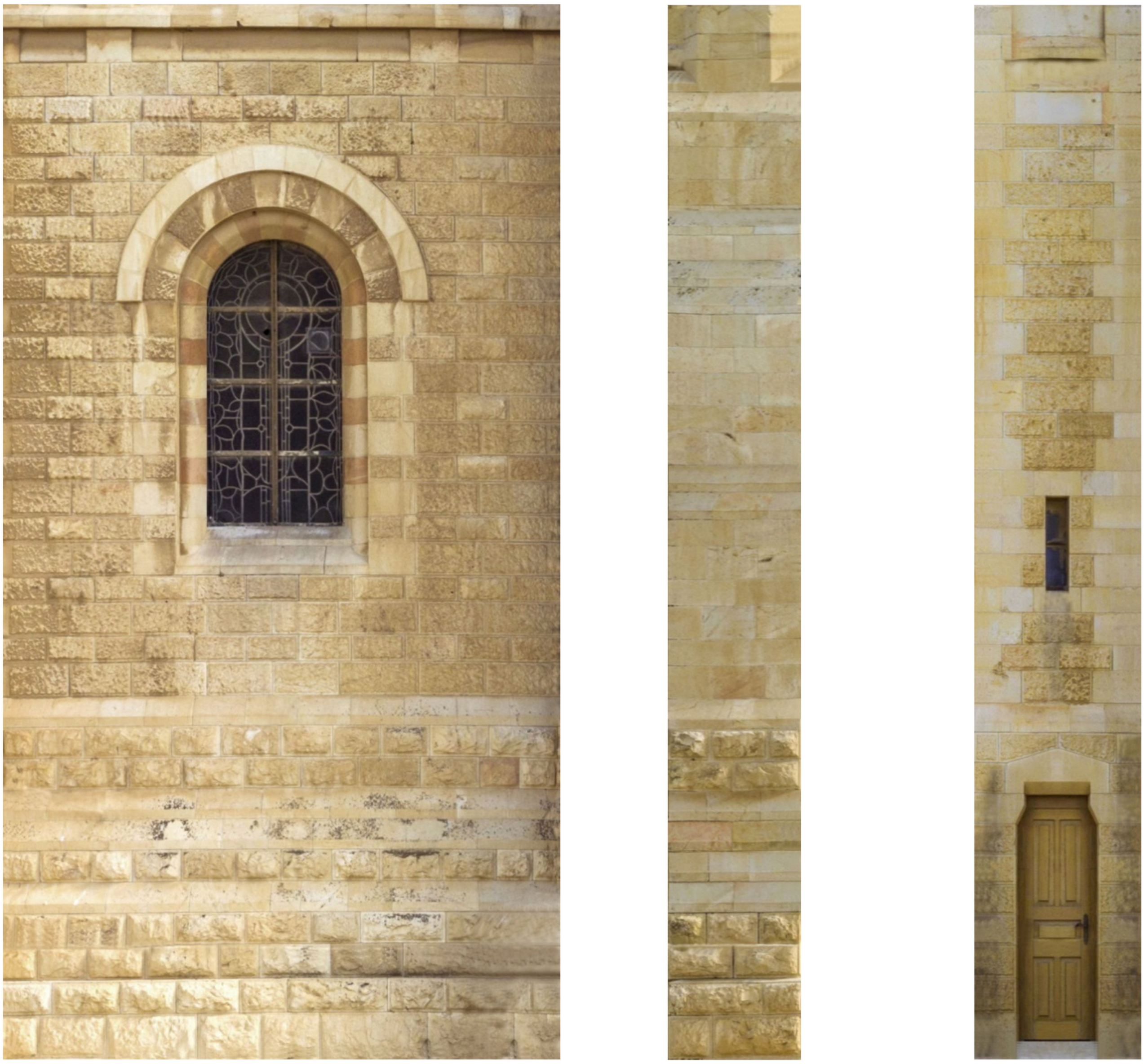
Figure 10. A geometric model of the Basilica of the Dormition of the Blessed Virgin Mary on Mount Zion in Jerusalem.

7.1. Defining Reflectance Properties of Materials from Raster Images

As noted earlier, the geometric model developed completes solely the first stage of the design works. Though it is a laborious stage, it does not necessarily lead to reliable luminance calculations. The basilica is built from diffusive materials that display a great variety of colours. Such a variety is feasible for defining in a standard representation, i.e., by assigning specific colours to the respective basilica parts. Hence, in the methodology adopted, the materials were defined on the basis of daylight pictures and computerised bitmaps corresponding to specific parts of the façade. The procedure for developing a bitmap for the tower is shown in Figure 11. A picture of the detail under consideration is taken first (Figure 11, step 1), and it provides an input to raster image processing software to be geometrically transformed in order to eliminate perspective effects and find the correct aspect ratio (step 2). Next, effects such as sunlight shadows, or shadows cast by various external elements, i.e., here electrical wires, are to be reduced by means of spectral transformations capable of accommodating various light conditions at the time when pictures of particular elements of the façade (step 3) had been taken. The final step is to assign each bitmap to a specific surface representing the part of basilica under consideration (step 4). The whole set of bitmaps for the basilica and the tower was developed that way. Selected examples of these bitmaps are shown in Figure 12.

Figure 11. Steps for developing a bitmap corresponding to the basilica tower surface.

Computer software that allows for defining bitmap-based reflectance and transmittance of materials typically calculates average and maximum values for reflectance or transmittance. Figure 13 shows Autodesk 3ds Max 2021 Material Editor with the read section highlighted for reflectance and transmittance of materials. For the Dormition of the Blessed Virgin Mary Basilica, only the reflectance was subject to analysis, as there are no transparent materials to be illuminated. Still, the way the parameters are defined holds. It should be noted that material properties defined this way, i.e., as based on photographs, could be highly erratic and proper care should be taken to avoid it. For example, for a picture of a white wall, the raster image is represented by a hue with a value of 255 for each RGB component, so it leads to a perfect white with a reflectance of 1 (Figure 13a). The software then indicates an anomaly with a red or blue value for overrated and underrated parameters, respectively. It is up to designers to rely on the real measurements rather than the values yielded by software. In Figure 13b, the average and maximum values of the coefficient are shown for the bitmap that was developed. They correspond to the part of the basilica tower depicted in Figure 11.



(**a**) (**b**) (**c**)

Figure 12. *Cont*.

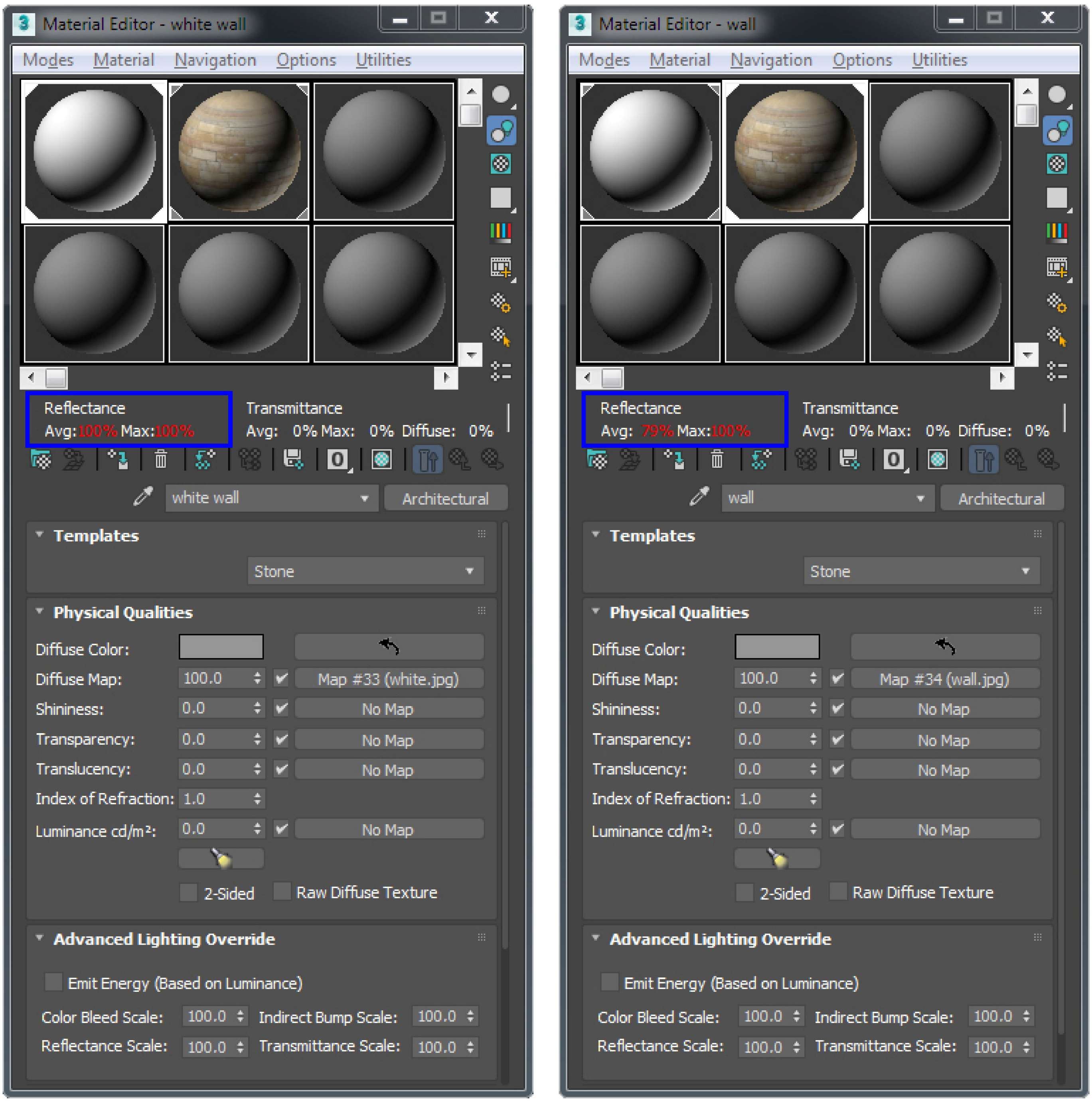
(d) (e)

Figure 12. Exemplary material bitmaps for (**a**) the main rounded wall of the basilica rotunda, (**b**) the buttress separating the rotunda rounded walls, (**c**) the surface of the rotunda side turrets (one of six bitmaps), (**d**) the tower dome, and (**e**) the tower in the part under the terrace.

The observed average reflectance value for the actual material picture of one of the basilica walls reaches 79% (0.79), which is obviously overestimated. The correct average value of the reflectance for this material is 43% (0.43). The overestimation is rooted in colour-based calculations of the value, with white colour (RGB = 255/255/255) assumed as the maximum (100%). Hence, the reflectance is overrated by 54% and, if left uncorrected, it would result not only in a computation error. Under the project to be implemented, the luminance values would be lower than the ones assumed by designers and yielded by further computer simulations. This case is risky, and should be accommodated for by installing additional lighting equipment, which is unlikely to be kept under control as most likely luminaires are already installed, at least partly. The designer finds this very uncomfortable, as it is a mistake that led to poor lighting. The costs related to installing additional luminaires cannot be ignored. Typically, it all results in oversized luminance, as it is difficult to select a proper luminaire to the one already in place, in order to achieve the required level of illumination. Quite often it is not possible at all. Moreover, luminance level that is too high involves installation of increased power, so the illumination project is less energy efficient than it could have been.

The illumination of the Basilica of the Dormition is incorporated into the lighting system of the city of Jerusalem. These floodlighting projects, by definition, need to be integrated into the surroundings and interrelated with other objects to be illuminated, so luminance oversizing by no means takes place. As the Jerusalem objects can be seen from distant observation points due to their location, it is clear that they are perceived as a whole. Hence, the floodlighting designs must be interconsistent. Uncontrolled luminance, whether oversized or undersized, is therefore a risk to be avoided at all cost.

Two approaches to the issue are most typical. The first is to reduce the bitmap brightness with a raster graphics editing program. This, unfortunately, is not very convenient, as many attempts are required to introduce such corrections. The second, a more convenient and a faster one, is to use the reflectance scale correction factor, available for the material type from Architectural in the Advanced Lighting Override (Figure 14). It facilitates defining the percentage of the initial reflectance calculated from the bitmap (54%).



(**a**) (**b**)

Figure 13. Material Editor of Autodesk 3ds Max 2021 software with the reflectance and transmittance reading section highlighted: (**a**) material defined as a white bitmap and (**b**) material defined by means of a multicolour bitmap.

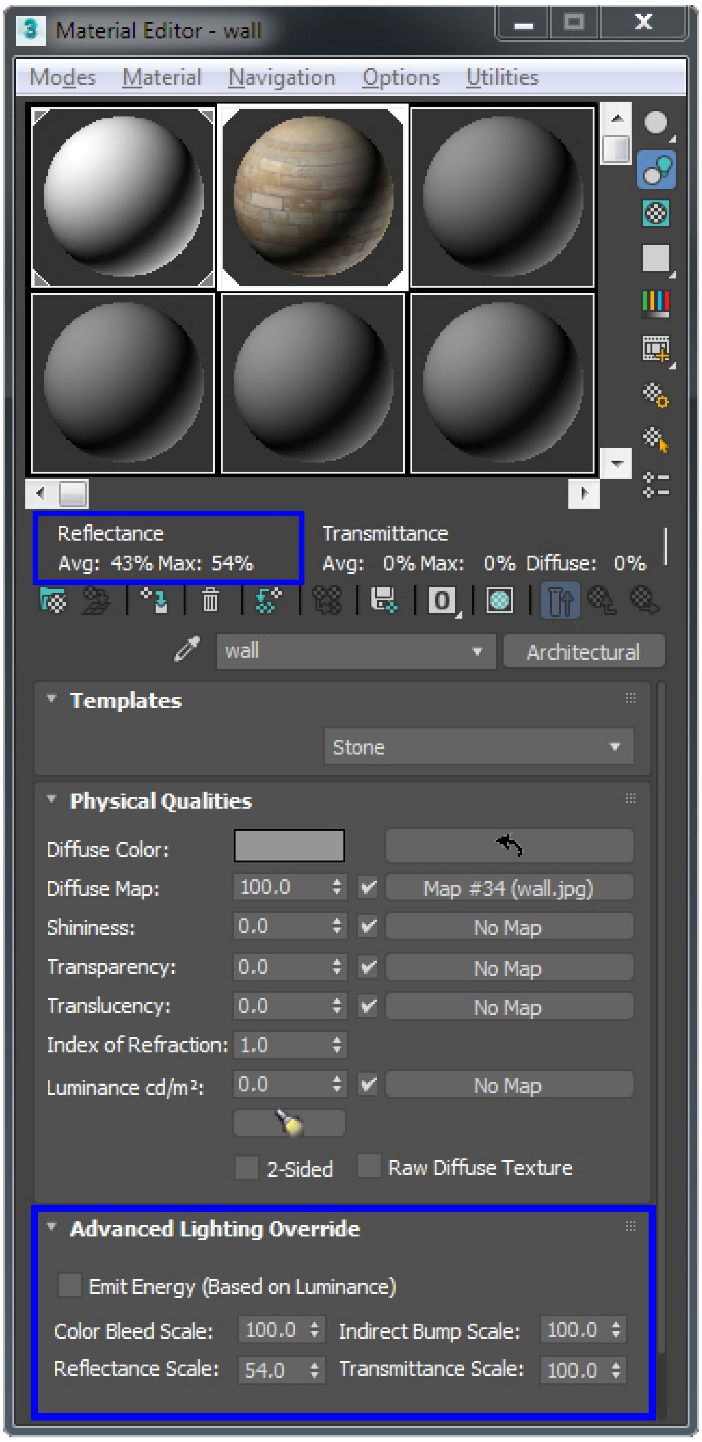


Figure 14. Reflectance correction by means of reflectance scale parameters under Autodesk 3ds Max software.

7.2. Reliability Verification for Defining the Reflectance Properties of Materials

Typically, in architectural structures a large variety of materials is used. For the Basilica of the Dormition of the Blessed Virgin Mary, 62 materials were defined; each definition strictly followed the procedure for creating bitmaps and correcting reflectance parameters. The luminance for each material within the lighting system under design, however, could then be assumed reliable in terms of the real value once the design is implemented; an intercorrelation analysis for all materials is recommended to be carried out. The illumination of the object causes complicated light and shadow interaction to occur. Hence, the luminance levels tend to vary between particular elements, and due to these variations material errors are likely to escape even the most careful designer's eye. The unintended material errors in turn bias the results obtained for the direct component of illuminance and for luminous flux multiple reflections alike.

Therefore, this procedure for defining material properties was checked against analysis where natural, daylight conditions and uniform lighting were applied. Several simulations were run with the object location, geographic directions, cloud cover, and time of the day defined. Figure 15 shows simulations for daylight conditions, with overcast and clear sky, Figure 15a,b, respectively. The images presented are collages of visualisations with daylight photographs taken under the same conditions. With no noticeable differences between the modelled image and the photo, the process for defining the reflective properties of the materials can be considered correct.

(**a**) (**b**)

Figure 15. A collage of the basilica daytime photograph with its visualisation based on the geometric model under the same lighting conditions for (**a**) an overcast sky and (**b**) a clear sky.

7.3. Computer Simulated Floodlighting

Illumination designs developed with all the preliminary works performed are technically correct and visually attractive. As accentuating basilica architectural details is of no importance with regard to being recognisable to distant observers, and in accordance with the design assumptions, the planar method was selected to illuminate the Dormition Basilica of the Blessed Virgin Mary in Jerusalem. From distant observation points, particularly from the third zone, the observer is able to identify the basilica either by its outline or as the average luminance for a given direction. Obviously, when defining the average luminance level for any object, guidance and standards should be taken into account; the latter ones are defined with regard to the brightness of the zone the object is located within. Night photos of Jerusalem (Figure 9) show intense ambient lighting. The International Commission on Illumination recommends for such cases the luminance of at least L_{av} = 12 cd/m^2 [33], whereas more recent reports on environmental light pollution recommend a maximum value of 25 cd/m^2 [34]. The preliminary design assumptions were to apply light warm in colour (3000 K), as Jerusalem is lit primarily with warm light. The areas, streets, and partly architectural structures are illuminated with high-pressure sodium luminaires.

Warm colour illumination is therefore also advisable due to its moderate exposure at the city skyline (temperature is increased to 3000 K compared to 2000 K, which is provided by a high-pressure sodium light source). Feasible spots on the basilica walls and within its surroundings were used to install luminaires. A collage-visualised illumination of the object, as seen from the observation direction within the second zone is shown in Figure 16. It corresponds to the point and direction denoted as K2 in Figure 5.

Figure 16. Floodlighting designed for point and direction K2 within the second observation zone.

Floodlighting the basilica, despite the applied planar method, which by definition seems to optically flatten the objects, remains attractive for observations. Diverse lighting equipment applied, both with regard to luminaires power and the luminous flux distribution, allowed for achieving luminance levels that do not disturb clear perception of basilica shapes.

7.4. Analysis of Results Based on False Colour Visualisation

Prior to the luminance analysis, a computer visualisation is just an attractive picture. As photorealistic as the picture may seem, which is true for the one shown in Figure 16, it provides none of the technical data on the lighting system to be applied. Perception depends both on the medium that it is depicted on and the environment the medium is placed within. Therefore, the only proper way to analyse illumination is to validate its technical luminance analysis, which is attainable either numerically or with false colour images technique [27]. Both techniques have their advantages and disadvantages [13], although for farther observational directions, image-based assessment appears to be sufficient and relatively quick to perform. Figure 17 shows the luminance distribution calculated for the K2 observation direction within the second observation zone. It is deductible that the average luminance levels of the object lie within the range of several cd/m^2. A thorough luminance analysis of the raster image yields 13.47 cd/m^2, so it can be concluded that the design assumptions are met and the design is not oversized.

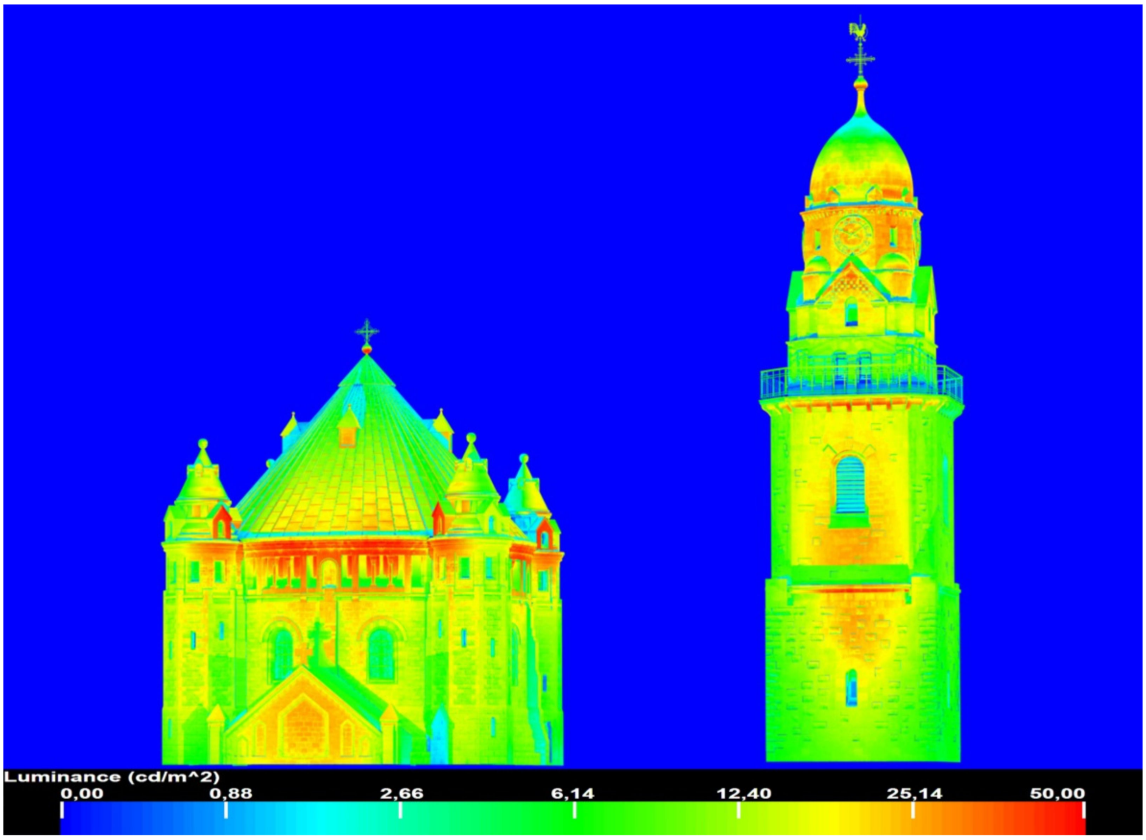


Figure 17. False colour luminance distribution for K2 observation direction.

7.5. Energy Analysis and Floodlighting Utilization Factor

The floodlighting design for the Basilica of the Dormition of the Blessed Virgin Mary in Jerusalem was implemented with electroluminescent light sources (light emitting diode—LED) luminaires. The lighting equipment, applied under the project, is listed and specified in Table 1. The total installed power P = 4.08 kW. For such a large and extensive facility, the project is considered energy efficient. Nevertheless, the floodlighting utilization factor (FUF) is required for its verification.

Table 1. The specification for the lighting equipment applied under the floodlighting design for the Basilica of the Dormition of the Blessed Virgin Mary in Jerusalem.

Luminaire Power P [W]	Light Source Luminous Flux ϕ_0 [lm]	Colour Temperature T [K]	Luminaire Luminous Flux ϕ_L [lm]	Luminaire light Output Ratio LOR [%]	Max. Luminous Intensity I_{max} [cd]	Half Beam Angle $\delta_{1/2}$ [deg]	Quantity [pcs.]
162	23,050	3000	17,518	76	23,742	50	6
162	23,050	3000	18,210	79	177,411	14	14
84	9550	3000	6588	69	24,209	58/12	10

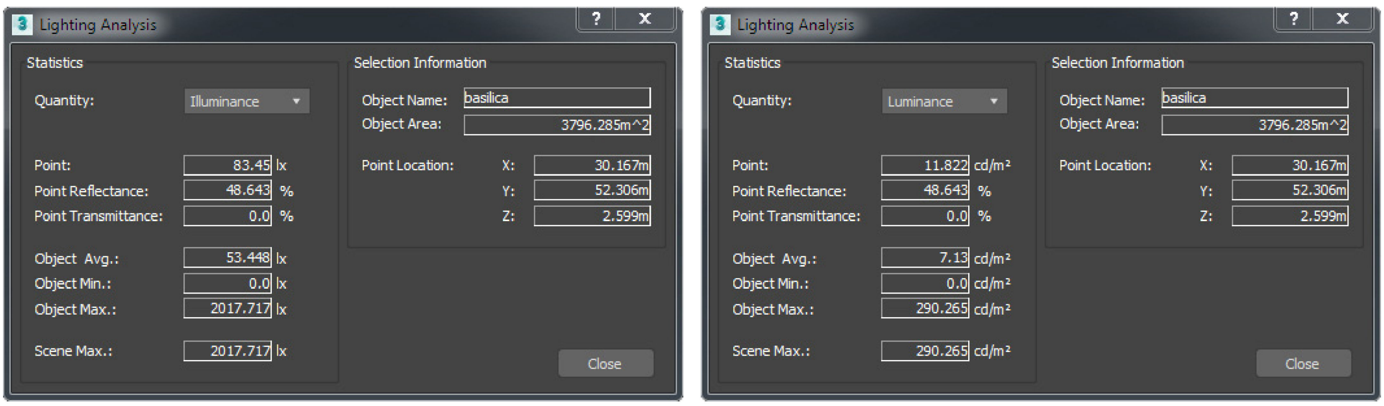
Many approaches are applied to perform floodlighting utilization factor calculations [24]. Each approach yields correct results. For the basilica, as its geometric model was developed and Autodesk 3ds Max software was applied, it was decided to perform the calculations with lighting analysis, available in the radiosity calculation algorithm software. The average illuminance and luminance levels on the object are calculated and surface area is provided. This set includes all the data required to determine the floodlighting utilization factor according to Formulas (7) and (8):

$$\mathrm{FUF} = \frac{\phi_u}{\phi_{t0}} \cdot 100\% \quad (7)$$

$$\phi_u = E_{av} \cdot S \quad (8)$$

where FUF is the floodlighting utilisation factor, ϕ_u is the luminous flux performing the average illuminance E_{av} on the object, ϕ_{t0} is the luminous flux of all light sources installed in the luminaries used to illuminate the object, E_{av} is the average illuminance level on the object, and S is the surface area of the object.

As shown in Figure 18, the Lighting Analysis function in Autodesk 3ds Max software, the area (Object Area) of the illuminated basilica façades reads S = 3796.285 m^2. Most certainly it is overestimated, though it is difficult to estimate by how much. The average illuminance performed on the object yields E_{avg} = 53.448 lx (Figure 18a). This value in turn seems underestimated. Overestimated surface area and underestimated average illuminance levels result from the assumed geometrical model, as it incorporated interpenetrating planes, which definitely increased the basilica surface area. Additionally, at the interpenetrated planes, zero illuminance and luminance is calculated, which results in the underestimated mean value of these photometric parameters. Yet, the geometric model is irrelevant for floodlighting utilization factor calculations. As the area increases, the illuminance decreases, so the floodlighting utilization factor calculated from Formulas (7) and (8) remains the same. For floodlighting utilization factor calculations, following its principal definition, only the direct component of the illuminance is taken into account. Thus, it cannot serve as the base for calculating the average luminance of the object, and the result shown in the measurement window (Figure 18b) is simply wrong. Hence, it shall be recalculated with multiple reflections from the basilica façade included, and with raster image analysis showing the incorporated luminance distribution (Figure 17).



(**a**) (**b**)

Figure 18. Lighting Analysis tool showing: (**a**) illuminance measurement and (**b**) luminance measurement and surface area measurement for the floodlighting design provided by Autodesk 3ds Max software.

Under the design considered, 30 LED luminaires were used, with the total luminous flux of the light sources of ϕ_{t0} = 556,500 lm. The useful luminous flux that performs the average illuminance E_{avg} = 53.448 lx is therefore equal to ϕ_u = 202,904 lm. Incorporating this data to Formulas (7) and (8), the illumination efficiency is calculated at 37%. For this value, the luminaire light output ratio (LOR) was taken into account. As shown in Table 1 LOR is equal to 76%, 79%, and 69%. Floodlighting utilization factor at the level of 40% is considered high for the planar method, which means the design developed seems energy efficient. Additionally, the floodlighting utilization factor itself is not sufficient to fully assess the energy efficiency of the lighting solution. Concerning sustainability, low electricity consumption, and environment friendly aspects, the design provides a compromise between the technically viable illumination for the basilica and the lighting effect achieved. As we deal with a historic building, whose structure needs and deserves special care, solutions where luminaires are to be mounted onto the façade were ruled out. Also luminaires should be located at places hardly accessible to third parties. Unfortunately, a negative impact on the environmental light pollution and higher glare are typical for the planar floodlighting method. Under specific weather conditions, glow around the site may also occur. Still, with prevailing Jerusalem weather, as it is typically clear and dry, the risk is low. With all these aspects in mind, the luminaires and their positioning were set to keep the emitted light beam focused as much as possible on the basilica. Unfortunately, illuminating the object from a distance means applying luminaires of higher power than for local installation, i.e., on the façade of the object, which automatically affects the floodlighting utilization factor.

8. Further Works

The geometrical model developed for the basilica and the tower is the first stage of work aimed at reconstructing the Byzantine, Crusader, and Modern basilicas. They are to be performed with computer photorealistic visualisation techniques, animation, and virtual reality (VR). Daylight and artificial lighting algorithms are used to calculate lighting parameters. The correct representation of the reflectance and transmittance of materials is the key issue to obtain correct and realistic results under the project.

9. Conclusions

The illuminance and luminance levels obtained for specific floodlighting designs are highly sensitive to reflectance and transmittance of materials. It is typical for designers processing computer-simulated lighting calculations to determine reflectance and transmittance parameters precisely with regard to their value, but in reckless disregard for reality. An average value is provided for different parts of façades. It is, however, worth remembering that these values are of general character, i.e., the surface material, in each of its elementary parts, may be far different in colour, which directly affects the reflectance value. Hence, defining this parameter based on a single numerical value happens to be critically imprecise. As the research has shown, a practical solution is to use material bitmaps derived from daytime pictures. Developing illumination concepts for architectural structures, following this design procedure, is neither simple nor quick. In addition to the effort and time spent on constructing the geometric model, the design process needs to be completed with stages related to digital image processing. Although at present it is a challenge, digital image processing techniques keep evolving, as we may observe it with each new application for mobile phones. In our opinion, raster images are already applied in practice to defining reflectance and transmittance parameters for materials; their practicality in that respect will only grow.

Nonetheless, as shown by the exemplary floodlighting design for the Basilica of the Dormition of the Blessed Virgin Mary in Jerusalem, there is currently no alternative solution that would allow for obtaining a technically correct design and to analyse its floodlighting utilization factor, i.e., the parameter that specifies the luminous flux practical use, and thus also electrical energy consumption.

To develop the design presented in the paper, a total of circa 400 labour-hours were needed. Has it been worth the effort? We believe that for historically or religiously important sites, development time should not be a matter to consider when deciding which design method to chose. The potential consequences of applying underestimated/overestimated reflectance properties are grave, as miscalculations not only affect the floodlighting effect, but may also result in oversized luminance, hence unnecessary energy consumption, if underestimated parameters are applied.

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