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An Evaluation of Annual Luminous Exposure from Daylight in a Museum Room with a Translucent Ceiling

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Abstract: The current study investigates the issue of computer-aided daylight evaluation in a museum room with a dropped translucent ceiling. In this type of room, daylight is admitted through classic windows located in the facade and then distributed in the plenum, which is located above the exhibition space and transmitted through the translucent ceiling into the museum room. This illumination method enables guiding daylight deep into the room, excluding the impact of direct solar radiation. The presented study is based on data obtained through computer-aided daylight simulation by DeLuminæ (DL-Light, ver. 11.0.9) software using the Radiance software for all calculations and real weather data for Wroclaw, Poland. A museum room of 12 × 12 m with three different heights of the plenums was simulated to establish an optimal relation of the width to height plenum ratio. Next, the annual exposure in K lx·h/year was calculated, as sensitive works of art may be subjected to damage caused by light exposure. To further reduce illumination, the simulation of an automatic shading system in the form of horizontal louvers was performed. The system was activated when certain illumination values were detected by the sensor on the building's roof.

Keywords: museum daylight; daylight simulation; Radiance

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1. Introduction

All exhibition/museum rooms require adequate lighting. The use of daylight in exhibition space is a special challenge, as this type of lighting is a subject of high variability over time and is also largely influenced by the architectural form of a room and the location of openings. When daylight is introduced into an exhibition space, its quantity and quality should be checked for each hour of the year, as daylight is a damaging factor for most artworks, the most important of which is fading. Daylight can also be a source of potentially harmful UV radiation for works of art [1]. The optimal illuminance level in an exhibition room should be enough to allow visitors to admire the works of art, while at the same time limit potentially harmful effects. As addressed by Leccese et al., "the key concern (. . .) is to balance conservation requirements and exhibition needs" [2]. One of the best summaries of this complicated situation with many trade-offs is given by Lucchi, who writes that "the needs for artwork conservation and human comfort are opposite" [3] and emphasize that the methodology should consider the opposite requirements of damage reduction and enhancement of visual comfort. Many preventive conservation measures are also undertaken to protect the works of art [4].

According to Fathy et al., the daylight intensity control is considered "a main challenge of daylighting design that hinders its use in exhibitions" [5]. However, daylight is the most appropriate way to illuminate exhibits when it comes to color reproduction. As Fathy et al. state, "most of the exhibits have been created under the natural light whereas, artificial lights prevent visitors to observe the tiny details of the artwork" [6]. Therefore, in certain situations, risks are taken in bringing the daylight into exhibition spaces to ensure adequate color reproduction. The positive effects are not limited to improved color reproduction but are also economical by lowering the energy consumption for artificial lighting and thus reducing the carbon footprint of an exposition.

One of the possible ways of bringing the daylight into the exhibition rooms is illumination from above. If the intense sunlight is adequately managed, roof opening is an effective and comprehensive way to illuminate works of art. The most commonly used systems of direct zenithal lighting (skylights and dormers) require illumination attenuation, which is performed by the use of blinds or louvers. However, it has to be said that in the case of art displays, this method may not be sufficient because it does not exclude the effects of direct sunlight operating on the surface of the artwork, some bright patches of daylight are inevitable. For this reason, light-diffusing shades, curtains, or materials that are light-permeable/translucent but not transparent are a much better solution.

The idea of scattering the light over the exhibition space is not new. Since ancient times, light-permeable fabric has been used to scatter light coming from above in rooms and open spaces. The velarium—an awning stretching over an ancient theatre—was used to avoid creating glare and limit the direct sunlight illumination reaching the spectators [7]. There are scientific reports considering the use of velarium in the Colosseum [8] and the Amphitheatre in Pula [9]. The team of d'Ambrosio Alfano et al. also discussed the acoustic role of velarium in "Teatro Grande" in Pompeii and the "Teatro Romano" in Benevento [10], while Ramzy reported the biophilic qualities of velarium as a tool of increased air circulation [11]. In 20th century century many museum buildings have been upgraded using different types of light-scattering dropped ceilings. In Museum Boijmans Van Beuningen in Rotterdam, "matt glass panels were placed" [12] below the skylight to make the light diffused. In Italy, since 1950, many museums have been rebuilt using the textile velarium or translucent dropped ceilings usually made of glass. Most recent publications report velarium being used in the Pinacoteca di Brera in Milan (arch. Vittorio Gregotti, Piero Portaluppi) where skylights were replaced by "glass-chamber and UV-filters" [13]. The Sant'Agostino Museum in Genova and Castelvecchio Museum in Verona are also lit by natural light; translucent ceilings are used in many modern buildings. The buildings of the Beyeler Foundation in Basel (RPBW) and the High Museum Expansion in Atlanta, 2005 (arch. Renzo Piano Building Workshop) feature light-redirecting systems that are installed above the translucent roof, while in the case of Harvard Art Museums Renovation and Expansion in Cambridge, 2014 (arch. Renzo Piano Building Workshop) a skylight with translucent louvers are installed.

Typologically, velarium and its contemporary successors are installed to diffuse the light that is coming from above, usually from a skylight (or through the opening of the atrium). This solution is effective, but frequently, very high values of illumination are recorded regardless of the light scattering layer, especially in the case of direct solar radiation coming from above (the highest value of illumination detected by the roof sensor in the presented test room was 88,495 lx). Therefore, the presented paper addresses a different solution, in which the daylight is admitted through translucent clerestories (side openings placed higher in the wall, above eye-level), distributed in the plenum, and transmitted through the translucent dropped ceiling into the room. In this solution, the effect of direct solar illumination is excluded, as the roof is opaque. The analyzed solution shows some affinity to the ancient velarium but can also be associated with anidolic non-imaging optic systems (*an*: meaning "without", and *eidolon*: meaning the "image" in Greek) [14] and other light redirecting systems, (e.g., a light-shelf).

So far, limited attention has been paid to daylight evaluation in a new type of museum room—the one with a plenum illuminated through clerestory windows and a translucent dropped ceiling. In this type of exhibition room, daylight is admitted through translucent windows located in the façade (b), and then distributed in the plenum (f), which is located above the exhibition space, and transmitted through the translucent ceiling (d) into the exhibition room (every ray of light is scattered twice or even three times depending on the number of the panes of glass that are used). This illumination method enables guiding daylight deep into the room, excluding the impact of direct solar radiation, and guarantees a more even distribution of daylight. The schematic of the test room is presented in Figure 1.

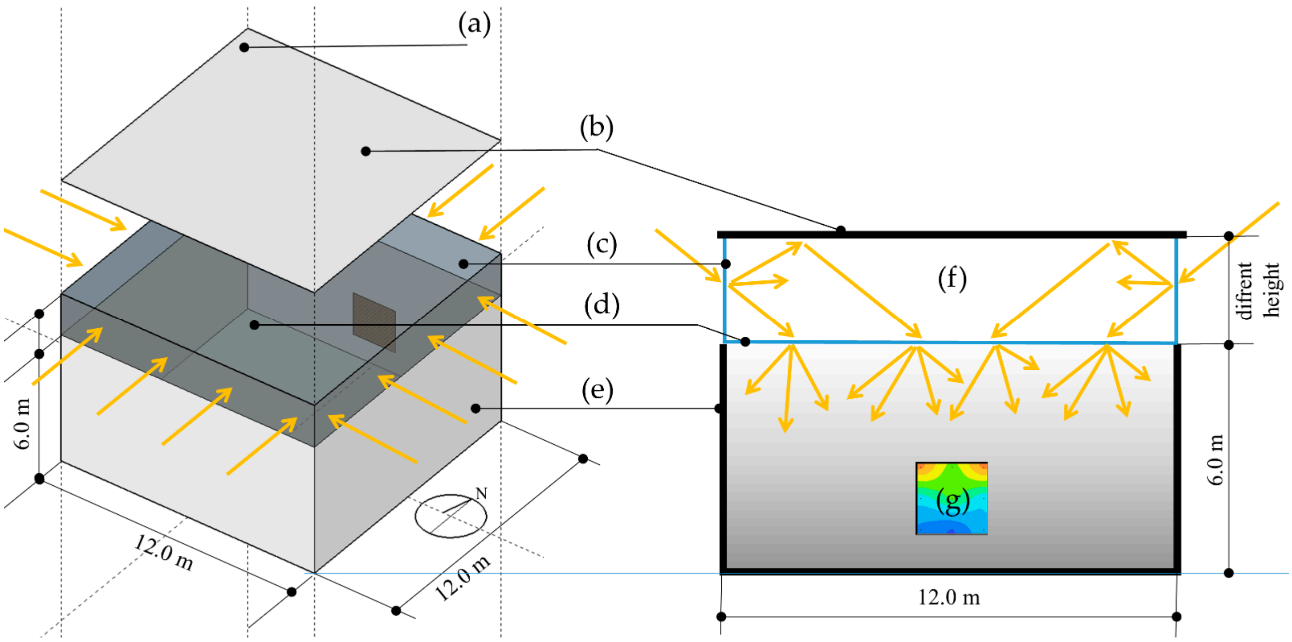


Figure 1. The geometry of the test room: on the right an exploded axonometric showing the plenum, and on the left the schematic section showing the location of translucent surfaces in the test room (marked in blue). Description: (a) roof daylight sensor; (b) solid roof; (c) translucent façade glazing; (d) translucent ceiling; (e) test room; (f) daylight distribution plenum; (g) evaluated artwork.

To date, there are three completed museum buildings (at least those three are known to the author) that feature this new type of exhibition illumination scenario: the Kirchner Museum in Davos (arch. Annette Gigon and Mike Guyer, 1982), the Kunsthaus Bregenz (arch. Peter Zumtor, 1997) [15,16], and the Nadir Afonso Contemporary Art Museum in Chaves (arch. Álvaro Siza Vieira, 2015). In the first case, the exhibition rooms are stacked one on the other, while in the Davos building, the rooms are arranged on one level, similarly, as in the case of the building in Chaves. In all the presented buildings, the daylight is scattered at least twice before it is admitted into the exhibition room.

Architects and exhibition designers address a twofold problem: they need to consider the artworks' preservation requirements and the visual comfort of the visitors. All existing buildings featured above have different dimensions of the exhibition hall and different proportions (depth/height) of the plenum space that illuminates the exhibitions. This paper suggests a procedure (computer simulation) to evaluate the annual luminous exposure K lx·h/year coming from daylight in the modeled test room with three different sizes of illuminating plenum size. The main aim of the presented paper is to verify if it is possible to limit the annual luminous exposure (K lx·h/year) below the thresholds defined by various conservatory institutions, bodies, or individual researchers by modifying the proportions of the plenum and by the use of additional automatic shading louvers. More precisely, the objectives of this study are (i) to determine the level of H_v (annual luminous exposure) from daylight using the adopted test room and real weather data, (ii) to specify the technical solution to adequately regulate the level of daylight, and (iii) to determine what type of artwork can be displayed in the proposed test room. It also appears to be a significant challenge to design a potential shading system and its triggering parameters to adequately limit the amount of daylight in the room for the protection of precious artworks.

2. State of the Research

2.1. Lighting in Museum and Exhibition Spaces

Lighting is the most important aspect of the exhibition space. It is currently the subject of many research projects, procedures, and design works, including the most renewed architectural offices in the world. In the view of climate change and raising awareness of the issues of sustainability, the design of museum buildings has become a discipline balancing the issues of conservation (e.g., as established by the Illuminating Engineering Society of North America [17], ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property) [18], and ICOM (International Council of Museums), viewer's comfort and sustainability.

Many reports have been prepared from the perspective of the evaluation of the museum's environmental conditions. Early in 1999, Avrami et al. presented a model for evaluating museum environmental management needs [19] as a result of the studies by the National Institute for Conservation at the Getty Conservation Institute. The model had the form of a survey, with questions regarding the different aspects of the use of museum space, inducing the extended chapter on daylight. Later, Corgnati et al. developed a method of evaluation of microclimatic quality in exhibition spaces, and stated that "lighting aspects are of primary importance in the analysis of the indoor environmental quality" [20]. In 2015, Onuwe et al. [21] presented a review of different museum designs discussing the importance of the provision of daylight in opposition to the established practice of the use of artificial light to avoid glare and discomfort. Selected reviews have also addressed issues of daylight in the context of energy efficiency. In 2016, a report by Lucchi featured an analysis of 50 museum buildings (including the above-cited Kunsthaus Bregenz and Museum Boijmans) from the perspective of environmental and energy quality. The presented simplified assessment method stated that "light parameters are the most important in affecting the environmental quality" [3]. Multidisciplinary risk-based analysis for supporting the decision-making process on conservation, energy efficiency, and human comfort in museum buildings was also provided by Lucchi [22]. The cited paper used the SOBANE strategy (screening, observation, analysis, expertize) to propose a new method of assessing energy and environmental quality in the museum. The most recently published report by McGhie addressed the issues of international climate change policies and how they relate to museums' activities [23].

In the field of lighting, specifically for museum buildings, many studies are undertaken that indicate the importance of this issue in the design of exhibition spaces. Improvement of light quality and lowering energy consumption are studied by many researchers. In 2013, Pedro et al. stressed the importance of the fact that the lighting system should provide excellent visual performance while reducing the exposure to the exhibition [24]. Xu et al. elaborated on the combination of task lighting and general lighting (including daylight) by analyzing the visual comfort using the Delphi method [25]. Garside et al. prepared questionnaires and performed interviews with English museum experts to determine the best lighting system in the museum [26]. The review produced by Sharif-Askari and Abu-Hijleh delivered results on the solutions used to improve the parameters of existing museum buildings and discuss different indoor environment quality (IEQ) requirements in museums [27]. Al-Sallal et al. evaluated the effectiveness of daylight and potential risk on artifacts, reporting the DGP and annual exposure for artifacts [28]. One of the most recent research studies, published in 2020 by Hassanizadeh and Noorzai [29], discusses the lighting efficiency in the museum, and after performing their simulations, a drop in energy consumption by 80% was reported in the case of the use of artificial light.

Interesting lighting studies featuring the museum buildings in Italy were undertaken by Leccese et al. Their report, published in 2011, discussed the lighting in the New Diocesan Museum in Piombino [30], while their report published in 2018 featured a light analysis in the National Museum of San Matteo in Pisa (Italy) [31]. In 2016 a study by Mayorga Pinilla et al. reported an advanced daylight evaluation on the cloister of Santa Maria El Paular in Spain [32] and suggested a method using the assessment of Global Risk Factor for understanding the daylight action. In the most recent study, Luengo analyzed the issues of sustainable illumination of painting collections and reported that lighting in museum buildings should be "the result of scientific studies, both general and specific for each piece" [33].

2.2. Daylight Simulation

Daylight should be used in museums with caution, therefore many simulation efforts are undertaken to analyze the issue before daylight scenarios are implemented in reality. In 2011, Kim and Chung [34] performed a Radiance analysis of daylight in a museum room that was equipped with different types of toplights (toplights being understood as a different form of glazing that is located in the upper part of the museum room: skylights, monitor shaped, and saw-tooth roofs). The results showed that computer simulation models could accurately represent the lighting environment under clear sky conditions. An important analysis of lighting conditions in heritage buildings was conducted in 2019 by the team of Saraiva et al. [35], which used the metric of *annual cumulative exposure* to assess the potential damage for endangered bookshelves in the library simultaneously seeking the proposal of preventive actions. Most recent studies address the issues of the provision of daylight through skylights. Marzouk et al. analyzed the parametric configuration of skylights in heritage buildings, using useful daylight illumination (UDI) as the main metric regarding the estimation of the use of the skylights [36]. Another paper by the same team delivers the results addressing the use of light-redirecting elements to equalize the level of light in the museum exhibition room in the Omar Tosson Heritage Palace in Egypt [37]. In 2020, Huang and Zhu [38] conducted an optimization of daylighting patterns for the sculpture exhibition hall. The latter study was particularly interesting from the perspective of the presented research as the optimization result is achieved by a combination of flat skylights and high side windows (reminding of the clerestory windows used in the exhibition room model). Huang and Zhu argued that the suggested solution "can improve the daylighting quality" and "yield a suitable light environment " [38]. In another paper, Huang et al. [39] had analyzed daylighting patterns in the calligraphy gallery in the Museums for Chinese Calligraphy, taking into account the position of the display cases and reflection bouncing off the glazing. As a consequence, fatigue syndrome is reduced and, therefore, can contribute to the improvement of the viewer's visual comfort. Both studies used daylight factor (DF), to evaluate the suggested solutions. The DF metric is problematic as it can be used only under overcast sky conditions, therefore, the possibility of reflecting the momentary sky conditions is none. Therefore, following the reports presented by Mavromatidis et al., DF is "not sufficient to consider the dynamic lighting and energy performance of window configurations due to the varying sun position" [40]. This opinion is supported by Bogdanov and Smirnov [41], who observed the need for revising standards for exhibition lighting, including the new lighting measures adopted, such as the annual luminous exposure H_v.

The most recent reports addressing the simulation of the value of H_v (annual luminous exposure in the exhibition rooms) have been provided by two teams. While Leccese et al. used climate-based daylight simulation to assess lighting conditions of space and artworks in historical buildings [2], e.g., in the Cetacean Gallery in Monumental Charterhouse of Calci, Fathy et al. evaluated the simulation tools that address the daylighting standards in museum rooms at the design phase. The first team recently reported on the possibility to assess museums' daylighting adequacy without an annual measurement campaign [2], which constituted a significant step forward because it simplifies the data collection phase. The latter team initially developed a simulation procedure with the conclusion that current daylighting metrics can be adapted for the preservation of exhibits [6] and subsequently published a paper [5] stating that the façade design is the key to maintain preservation standards. The latter team also suggested "pixelating façades into small openings instead of using one large window" [5] for the provision of uniformed daylight. Both teams used the annual luminous exposure H_v to evaluate the illumination conditions in the exhibition room, which was obtained by computer simulations in different types of software.

2.3. Shading Elements

The problem of shading elements has been investigated from many different perspectives, however, only a few of them are considering exhibition spaces. The general approach is towards the minimization of heat gain and the reduction of illuminance. Most authors use UDI (Useful Daylight Illuminance) and DGP (Daylight Glare Probability) in the evaluation of the shading systems. Palmero-Marrero and Oliveira [42], Gratia and De Herde [43], and Manzan [44] have studied the shading elements and their influence on building energy requirements. In general, various types of blinds and louvers are used in different configurations (e.g., by Atzeri et al. [45], Zheng et al. [46]). From the perspective of the current study, vertical and horizontal shading devices were analyzed by Alzoubi and Al-Zoubi [47], but only for south exposed façades in a dry climate. Holophane model was used to estimate the average illuminance level on the workplane compared to the surface of artwork as in the current study. Despite these differences, the results of Alzoubi and Al-Zoubi are very relevant to the current study because the authors determined that it is the horizontal louvers that are most effective in regulating illuminance level in the interior and for the illumination uniformity.

2.4. Museum Illumination Standards

The review of annual luminous exposure limits for different types of museum artifacts by different authors and standards is presented in Table 1. Not every standard and every author provides all the required levels. The basis for the evaluation conducted in the paper is a standard CIE 157:2004, Control of Damage to Museum Objects by Optical Radiation [48]. This standard provides the following material classification of museum artefacts: irresponsive, low responsivity, medium responsivity, and high responsivity. Other standards follow similar distinctions. For the further evaluation in the paper, the level of H_v = 600 ÷ 650 K lx·h/year was adopted based on the [48,49] with the assumption that the maximum level of illumination at the surface of artwork should not exceed 150 lx for moderately sensitive-artworks, based on [50]. It has to be remembered that in some cases, the maximum illuminance at the surface of an artwork is based on the assumption, that the artworks will be exposed to light for a defined period, e.g., 8 h per day for 250 days per year, as in the case of CCI. In fact, those assumptions might be difficult to accept in commonly used opening times of museum and galleries that tend to attract visitors even seven days a week.

Table 1. The review of annual luminous exposure limits for different types of museum artifacts by different authors and standards.

Ref No.	Author or Standard	Year	Artwork Type	Maximum Illumination [lx]	H_v [K lx·h/year]
[18]	ICCROM	1975	painting	150	
			paper	50–150	
[51]	Thomson, G.	1986	moderately sensitive	50–200	650
			sensitive material	50	200
[52]	IES Recommended Practice for Museums	1996	moderately susceptible materials	-	480
[53]	Fontoynont (ed.)	1998	oil paintings	-	DF 0.5–2% *
[48]	CIE 157:2004	2004	irresponsive	no-limit	no-limit
			low responsibility	200	600
			medium responsivity	50	150
			high responsivity	50	15

Table 1. *Cont.*

Ref No.	Author or Standard	Year	Artwork Type	Maximum Illumination [lx]	H_v [K lx·h/year]
[49]	Cuttle, C.	2007	non-responsive	no-limit	no-limit
			slightly responsive	-	600
			moderately responsive	-	150
			highly responsive	-	15
[54]	GB/T 23863-2009	2009	highest light sensitivity	50	50
[50]	Texas Historical Commission	2013	sensitive collections	50	-
			less sensitive collections	150	-
			least sensitive collections	300	-
[55]	CIBSE LG08	2015	irresponsive	n/a	n/a
			low responsivity	200	600
			medium responsivity	50	150
			high responsivity	50	15
[56]	Canadian Conservation Institute (CCI)	2018	moderately sensitive	-	1000 **
			high sensitivity	-	100 **

* Only the values of DF were provided. ** These values are based on 8 h per day and 250 days per year, at the same illumination level.

It must be made clear here that most recent scientific research seeks to rely on the calculated value of H_v rather than on a predefined level, formulated generally for different types of artwork according to CIE 157:2004. Dang et al. developed a method in which the H_v value can be calculated individually for specific artworks depending on what pigments were used in the painting (organic and inorganic). This method used a so-called "damage model", which was developed based on the different colour curves [57].

3. The current Empirical Research

The presented text aims to develop a new procedure for the assessment of annual luminous exposure based on Radiance calculated values of illumination at the surface of an artwork. Previously unexplored factors influence the innovativeness of the presented approach, which include:

- the new typology of museum rooms that are illuminated by clerestories and the translucent ceiling is evaluated. This typology of exhibition room was used in museum buildings, as cited above, but no analytical simulation study of this type is known to the author. Another factor influencing the innovativeness of the presented approach is the fact that the main strategy adopted was the "light avoidance" strategy, where penetration of daylight was gradually limited;
- a computer-aided procedure to assess the daylight in museums is presented based on annual luminous exposure from daylight. The procedure uses the simulation performed by the Radiance engine—which is not new—but is used not to access the lighting quality at the horizontal work plane, but at the surface of vertically hung artwork;
- procedure uses weather-based data representing climate and daylighting conditions;
- the conclusions are based on software that has been recently validated by other researchers [58,59].

3.1. Simulation Software

The annual luminous exposure, H_v, in kilo lux-hours per year (K lx·h/year) was obtained by calculating and adding the values of illumination for every hour in the year in the so-called "annual simulation campaign" using the 3D model of the test room (see Figure 1) and Radiance-based software DeLuminæ (DL-Light, ver. 11.0.9). The Radiance is a daylight simulating software core of established prestige that was previously validated by other researchers. The 3D model is featuring translucent surfaces and Venetian-style louvers. Reinhart and Walkenhorst prove that Radiance based simulation methods "are able to efficiently and accurately model complicated daylighting elements such as (. . .) Venetian blind system" [58], while Reinhart and Andersen have demonstrated that translucent materials "can be modeled in Radiance with an even higher accuracy than was demonstrated in earlier (. . .)" [59]. The methodology was also based on the previous works by Hoyo-Meléndez et al. [60] and Saraiva et al. [35].

3.2. Measures Adopted in the Current Study

The evaluation was based on four parameters: (i) the annual luminous exposure H_v and, (ii) the number of hours in the simulated year for which the illumination exceeded 150 lx at the surface of the artwork—marked as t_{150}, (iii) the maximal illumination value in the year E_{max}, and (iv) the mean daylight uniformity U_{mean}.

H_v was calculated based on the Formula (1):

$$H_v = \sum_{i=1}^{8760} E_i \cdot \Delta t_i \quad (1)$$

where E_i is illuminance at the surface of an artwork, and t_i is exposure duration in hours. The i variable numerates the hours in the year (i = 1, ..., 8760). For each hour of the year, the value of E_i was simulated. For the suggested illuminating scenario, it was necessary to calculate 525,600 illuminance values (10 grid points per 8760 h for all below analyzed cases). The values of t_{150} and E_{max} were determined based on the results of the previous simulation using standard spreadsheet software.

The value of mean uniformity U_{mean} was calculated as an average value of the values of daylight uniformity for an artwork U_s for daylight hours for four days in the year: two days of the equinox, the Summer, and the Winter solstice. U_s was calculated based on Formula (2):

$$U_s(i) = \frac{E_{min}\,(i)}{\overline{E}\,(i)} \quad (2)$$

where E_{min} is the minimal value of illuminance, and $\overline{E}$ is an average value of illuminance at the surface of an artwork calculated for 9 sensors at a specified hour in the year i (U_s is calculated at one-hour intervals). If U_s equals 1, it means that the artwork is illuminated evenly, the lower the value of U_s (as the fraction of unity), the lower the uniformity of illumination at the surface of an artwork. The value of U_{mean} simply averages the values of U_s for daylight hours in 4 days of the year, showing the potential influence of all seasons of the year.

3.3. Simulation Setup FOR Annual Luminous Exposure

The case study museum room that was analyzed in the current study was a 12.0 × 12.0 m exhibition room with a height of 6.0 m (144 m^2, 864 m^3). Two axes of symmetry were aligned with the directions of the compass (N–S, W–E). The room was illuminated by the translucent dropped ceiling made of glass with the parameters given in Table 2 according to the geometry given in Figure 1. Annual luminous exposure was measured at the surface of a 2.0 × 2.0 m artwork that was hung centrally on a north wall 1 m above the floor level.

Table 2. Geometries' characteristics per material.

	Vertical Surfaces of the Test Room	Floor	Dropped Ceiling	Window Glazing	Louvers
Material	White paint	Dark gray concrete	Translucent glass	Translucent glass	Gray metal
Reflectance	0.82	0.23	0.34 [1]	0.34 [1]	0.39
Transmittance	0	0	0.59 [1]	0.59 [1]	0

[1] parameter of a double layer of 4 mm Pilkington Optifloat™ Opal.

3.4. Analysis Assumptions for Calculations of Daylight

Annual luminous exposure from daylight was calculated for Wroclaw, a city in South-West Poland (51 deg. N lat.) with the use of the real weather data obtained from the Institute of Meteorology and Water Management, National Research Institute. H_v values were calculated on a grid of approximately 0.9 × 0.9 m at the surface of artwork by nine virtual sensors (measuring points). The highest record at the surface of an artwork—the worst-case scenario—was taken into account in the evaluation that is presented below, see Figure 2.

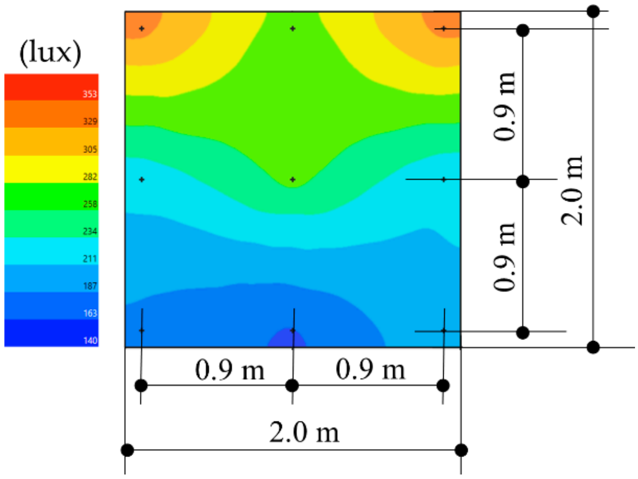


Figure 2. The dimension of the artwork and location of measuring sensors. The values given in the figure are for the illustration only.

Simultaneously, a single virtual sensor recording horizontal illuminance values (lx) was placed at the roof of the test room to evaluate the real sky illuminance for the defined simulation setup for the given weather data.

3.5. Sequence of Simulation

The simulation process comprised three consecutive phases. First, the optimal proportions of the plenum's height and depth were determined based on H_v calculated for an artwork. Three values were simulated for 4, 2, and 1 m height (Variants 1–3). Second, the system of four external 25 cm wide fixed shading louvres was simulated for a 1 m height plenum (Variant 4). Third, to further reduce the H_v, the same system of louvers was virtually mechanized and automated, with the assumption that it was activated when certain illumination values were detected by the sensor on the roof (Variants 5–6). The geometrical assumption was made that the louvers limited the illumination by rotating around an axis at a 60-degree angle (see Figure 3).

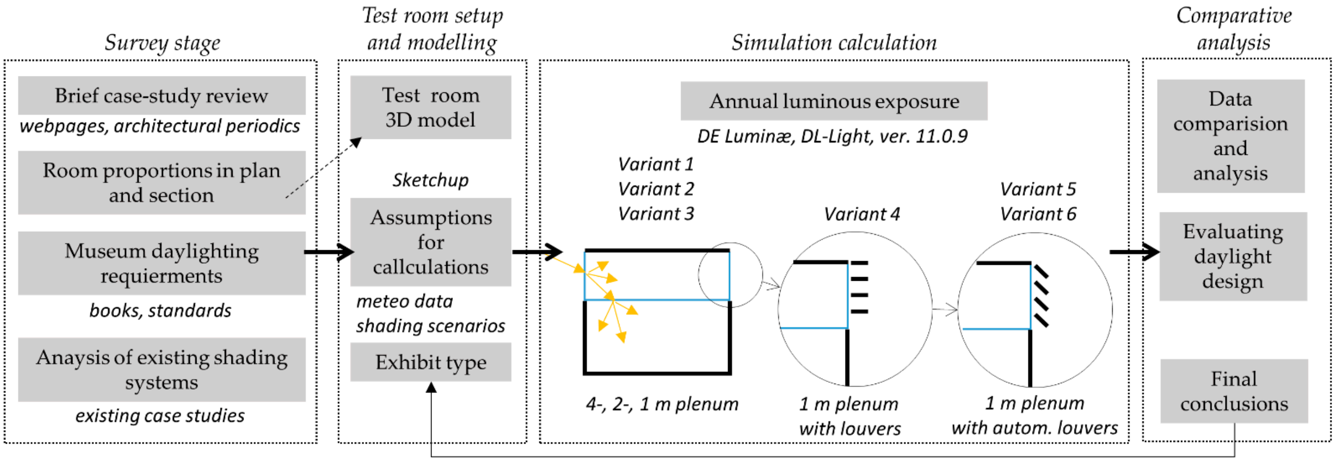


Figure 3. The schematic diagram of the adopted methodology and sequence of simulation.

4. Results

The results of three consecutive phases of the simulation are presented in the following sections, in Figures 4–6 and Table 3.

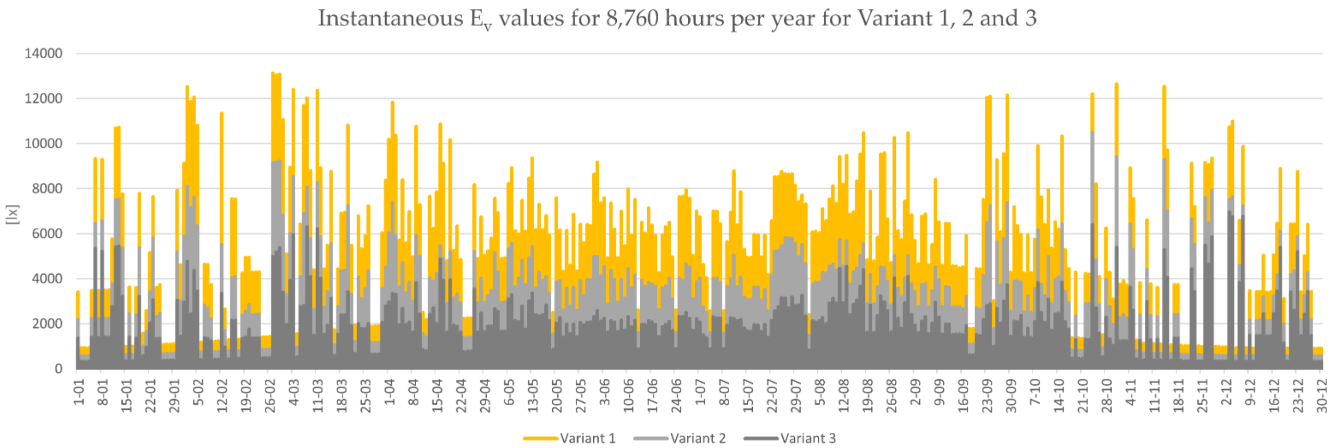


Figure 4. Instantaneous E_v values for 8760 h per year for Variant 1, 2, and 3. Please note, the graph is not showing exactly all 8760 values of E_v, but was scaled to fit the page. Exact values are given in the data file in Supplementary Materials.

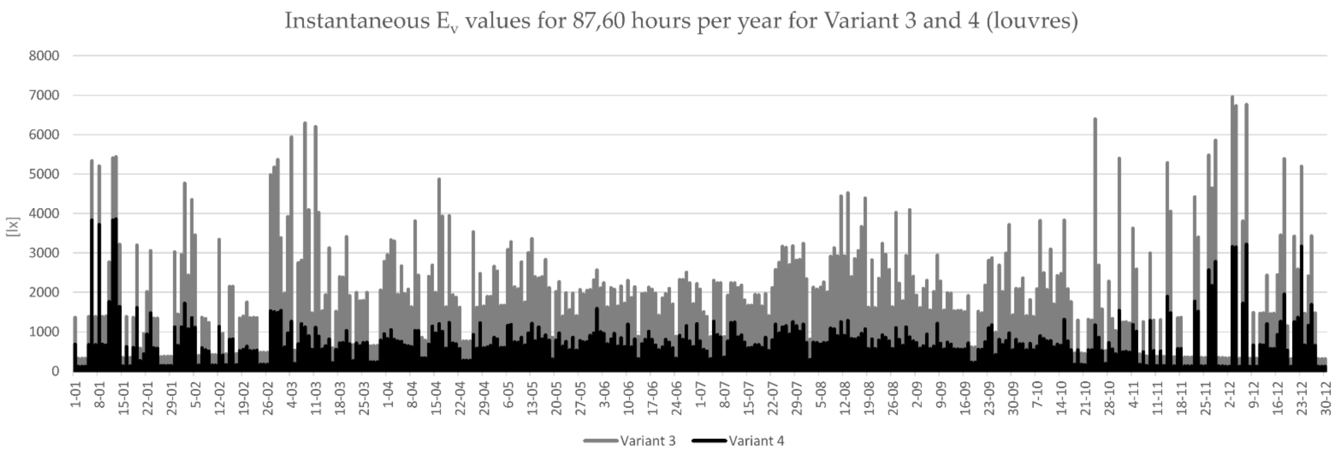


Figure 5. Instantaneous E_v values for 8760 h per year for Variant 3 and 4. Please mind, the graph is not showing exactly all 8760 values of E_v, but was scaled to fit the page. Exact values are given in the data file in Supplementary Materials.

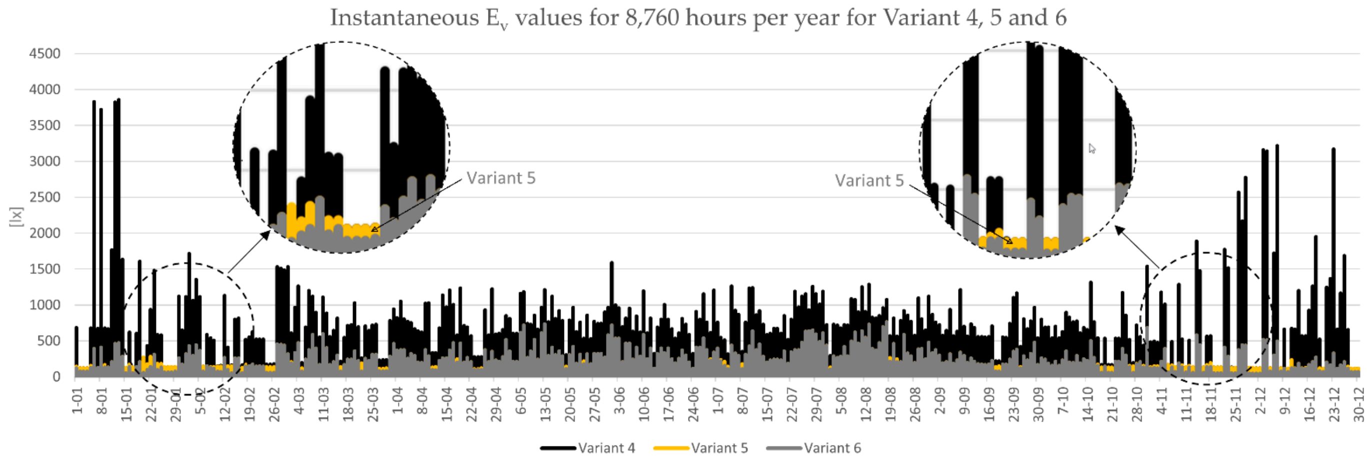
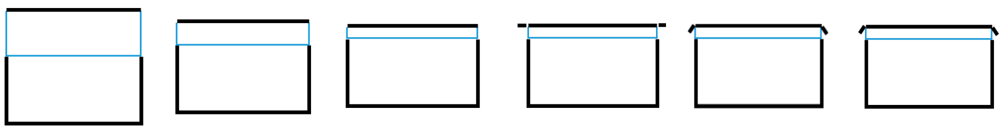


Figure 6. Instantaneous E_v values for 8760 h per year for Variant 4, 5, and 6. For visibility, Variant 5 is shown in yellow for better contrast. Please mind, the graph is not showing exactly all 8760 values of E_v, but was scaled to fit the page. Exact values are given in the data file in Supplementary Materials.

Table 3. The results of the computer simulation of all analyzed variants.

Analyzed Variant	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6
short description	4 m plenum	2 m plenum	1 m plenum	1 m plenum static louvers	1 m plenum automatic louvers	1 m plenum automatic louvers
schematic section						
E_v triggering value (lx)	n.a.	n.a.	n.a.	n.a.	10,000	5000
the area of façade glazing (m^2)	192	96	48	48	48	48
H_v (K lx·h/year)	14,643	8885	4976	1839	663	604
E_{max} (lx)	13,590	10,481	8085	3857	911	911
t_{150} (h)	4190	4097	3903	3154	1859	1703
U_{mean}	0.90	0.91	0.92	0.85	0.87	0.87
σ	2479	1500	859	327	104	97

4.1. First Phase of the Simulation

The results of the first phase of the simulation are given in Figure 4 and Table 3. The introduction of 2 and 4 m height plenum (Variant 1 and Variant 2) produced the values of H_v in the range of 14.6M–8.9M lx·h/year (standard dev. σ = 2479 and, respectively, σ = 1500). These values far exceed the permissible annual luminous exposure levels H_v provided by the standards cited the state of the research for virtually any type of artwork (except those non-responsive). Furthermore, the results show high variability over time. The highest instantaneous exposure values of E_v are recorded for the dates close to the equinox (Spring and Autumn). This could be explained by the lower angle of the incidence of the rays of the Sun striking the vertical surface of the illuminating window and the relatively long duration of daylight (12 h). In addition, relatively high values of E_v were recorded for the winter days, which was a result of the increased albedo of the terrain covered by the snow. The results of E_{max} (respectively, 13,590 lx and 10,481 lx) and the values of t_{150} were also very high, above any acceptable levels.

For the 1 m height of the plenum (Variant 3), the value of H_v = 4.97M lx·h/year (standard dev. σ = 859) was calculated. This value exceeds the permissible annual exposure, but it is almost 63% smaller than values for 4 m height plenum. Therefore in the next phase, steps have been undertaken to verify whether it is possible to further reduce the H_v for this variant of plenum size.

The U_{mean} is very high at the range of 0.90–0.92 for Variants 1–3, which means that the artwork is almost evenly illuminated.

4.2. Second Phase of the Simulation

In the second phase of simulations, horizontal static louvers were designed to further reduce the H_v level in the exhibition room. Four 25 cm louvers were installed at the level of the window, as illustrated in Figure 3. The results of the second phase of the simulation are given in Figure 5 and Table 3. In Variant 4, the introduction of horizontal louvers allowed the radical reduction of H_v to the level of 1.83M lx·h/year (standard dev. σ = 327), which was still too much, but is an almost threefold improvement in comparison to the Variants 1 and 2 without the louvers. Also, other parameters were significantly lower. The number of hours with the illumination above 150 lx was still high and equals 3154 out of a total of 4311 h of daylight illumination per year, however, this value is a 20% improvement in the comparison to 1 m plenum variant (Variant 3) without the louvers.

The U_{mean} was 8% lower than in the previous Variant 3, and at the level of 0.85, also provided very good illumination conditions.

4.3. Third Phase of the Simulation

In the third phase of the simulation, automatic louvers were introduced. The geometry of the louvers was the same as in the previous variant, but the louvers rotated at the angle of 60 degrees towards the surface of the window, limiting the penetration of daylight. Louvers were automatically closed when the level of illumination detected by the sensor located at the roof of the room exceeded a certain value. Those triggering values tested were E_v = 10.000 (Variant 5) and 5.000 lx (Variant 6).

The results of the third phase of simulation are given in Figure 6 and Table 3. The introduction of louvers, which are mechanized at the threshold of 10.000 lx, allowed for the reduction of H_v to the level of 663K lx·h/year (standard dev. σ = 104), while the threshold of 5.000 lx allowed for even further reduction of H_v to the level of 604K lx·h/year (standard dev. σ = 97). This represented a striking improvement of 88% in comparison with the version without any louvers. Furthermore, an interesting tendency was observed. The change in the triggering values produced the results that were mainly visible in the winter months (clearly visible in Figure 6, shown in yellow for contrast), when the instantaneous E_v values were particularly high, which can be explained by the low angle of incidence of solar radiation and the high albedo of the terrain (due to the snowfall in Wroclaw). During the summer months, the change in the triggering threshold brought relatively small changes.

The values of t_{150} are also significantly reduced respectively to the level of 1856 and 1746 h. The maximum level of 911 lx was recorded at the level of artwork for both triggering values, which exceeds the values of 150 lx postulated by some standards and researchers, but lasts only for 1 h in the entire year.

In Variant 5 and 6, the U_{mean} is even higher than in the previous Variant, but still 6% lower than in the case of Variant 3, assuring even illumination of artwork.

5. Discussion

The gathered data show that the H_v values for all louver-uncovered variants are very high, and lower results are obtained when the ratio of plenum height to exposure room width is like 1:12. H_v values are likely to decrease as this ratio decreases, although this was not examined in the paper. Still, it is certainly possible to set a ratio at which the values of E_v would be too small to allow for comfortable observation of artworks.

Concerning the daylight performance of the test room in the six simulated variants, weather-based calculation showed that, regardless of the plenum height (4 m, 2 m, or 1 m), the H_v is largely exceeded for the first three simulated Variants 1–3 equalling 14, 6 M, 8.8 M and 4.9 M lx·h/year respectively and the illuminance level 150 lx was surpassed for approximately 97, 95 and 90% of daylight time, respectively. These values are much over the level adopted in the present study. The test room is simply overlit for most of the time regarding the conservation requirements. Simulations also showed that H_v is almost exactly proportional to the area of glazing, meaning the lower the area of the glazing, the more H_v is reduced. The values of E_{max} reaching 13,950 lx, 10,481 lx and 8085 lx, respectively, can influence the artwork and might cause visual discomfort problems to the visitors.

In consequence, sensor-controlled automatic shading louvers were suggested to tackle the high illuminance levels. This significantly lowered the H_v to an acceptable level of 663K lx·h/year for the Variant 5 (with the triggering value of 10.000 lx) and 604K lx·h/year for Variant 6 (with the triggering value of 5.000 lx). The improvement between Variant 5 and Variant 6, i.e., the reduction in H_v, is only 9% which is the result of the fact that the variation of illumination detected by the roof sensor between 5.000 and 10.000 lx is present for a relatively short period of 689 h, which means 7.68% of the year.

The translucent glazing undoubtedly affects the quality of light inside: the light is diffused and uniformity is greater with the translucent glazing than when the transparent glass is used (as patches of direct sunlight are excluded). Nevertheless, the amount of light is not sufficiently reduced. The uniformity U_{mean} of the illumination of the artwork is at a high level in all analyzed Variants (0.85–0.92). Therefore, it is justified to state that the translucent dropped ceiling, as an illumination tool, performs very well, assuring an even distribution of daylight in the exhibition space.

The results show that in the exhibition room, the display of medium-sensitive artworks can be considered, with the assumption that H_v will not exceed 650K lx·h/year. Usually, museum facilities operate through 6 out of 7 days of a week (from Tuesday to Sunday), with the assumption that the louvers are fully shut on Monday, the annual H_v from daylight can be further reduced to and 513K lx·h/year, respectively. It must be taken into account that the calculated H_v values relate to the illumination from daylight only, and under conditions of insufficient visibility (after dusk for winter days, when E_v is lower than 150 lx), artificial illumination should be provided, which will increase the total H_v. To further reduce the H_v, it is also advisable to shut the louvers in the summer months for the entire day except during museum opening hours.

However, it should be made clear that although the H_v values from daylight for Variant 6 are met, the E_{max} values temporarily far exceed the adopted conservation standards of 150 lx for medium-sensitive artifacts. In Variant 6, E_{max} is 911 lx, which is almost six times higher than the acceptable level of 150 lx. However, it should be stressed that conservation standards that address instantaneous E_{max} are frequently based on fixed exposition scenarios, e.g., 8 h per day and 250 days per year, at a constant illumination level.

Addressing the hypothesis formulated in this paper, it can be said that it is possible to assess the level of H_v from daylight using the adopted test room and real weather data. It is also justified to state that in the simulated room, it will be possible to safely display works of art only for the moderately-sensitive category. For other types of artwork, further steps should be taken to reduce the amount of daylight in the interior.

5.1. Visual Comfort in the Proposed Solution

Excessive and/or insufficient light causes visual fatigue which is caused by the difference in luminance between the artwork and its background. The mechanism of this phenomenon is explained by the adaptation of eye muscles, which are forced to make a constant adjustment. Therefore, certain rules apply regarding the difference in lighting level in exhibition spaces. The preferable condition, as raised by Preto and Gomes [61], is lighting introduced by the skylight, a high ceiling height, and the absence of shadows, with the exclusion of glare and shadows. Given the above-raised requirements, the solution presented in the paper has the potential to be positively evaluated, with the detailed points raised below:

In Variants 4, 5, and 6, the uniformity of daylight, respectively, is 0.85–0.87, which means that the distribution of daylight is even, and the proposed suspended ceiling spreads the light effectively. The influence of shadows (and potential high difference in luminance values in the observer's field of view) is also excluded. Shadow is produced when light—coming from a particular direction—is interacting with the opaque object. In the analyzed Variants 1–6, no direct sunlight inside the exhibition room is present, which results in the absence of strong shadows and high luminance differences.

One of the most important issues regarding visual comfort is the value of standard deviation σ, which determines the level of illumination differences that take place in the exhibition room. This analysis has some interesting insights. In Variants 1–3 the deviation is very high and reaches almost 2.500 lx. This shows that even the use of a light scattering system is not able to attenuate large differences in daylight illumination that is recorded outside. Only the introduction of louvers visibly reduced standard deviation σ to values in a range of 300–100 for Variants 4–6, which clearly shows the high potential of this shading method in exhibition design.

At a psychological level, no glare and a pleasant environment should be provided in the exhibition room. Wienold [62] provides a simplified DGPs formula, which could be used when no direct sunlight is present. Using the highest values of vertical illumination in Variant 6, the calculated level of the DGPs equals 0.24 (or 24%). As stated by Bodard and Cauwerts [63] and Wienold [62], a DGP lower than 35% is an "imperceptible" glare, which proves that it is assessed as a variant where the glare is absent, mainly because of the use of the automated louver mechanism to limit the penetration of daylight.

5.2. Energy Efficiency in the Proposed Solution

Energy efficiency is not the main subject of the presented study, however, some conclusions might be drawn. The presented simulation shows that in the most optimized Variant 6, the exhibition room does not require artificial lighting for 1215 h of the year, which is 30.2% of the operating time (the value of illumination on the surface of the artwork is more than 150 lx). Achieving the daylight autonomy of 50% (estimated as "normal" value) is usually a challenge in exhibition rooms, considering the fact that the general adopted strategy is "daylight avoidance" rather than a daylight gain. When it is assumed, that the exhibition room is used for 10 h a day (10:00–20:00) for 365 days of the year (7 days of the week), the artificial light is required for 2435 h. A rough estimation shows that the use of daylight allows saving 5.9 kWh annually for each analyzed artwork of 4 m^2. surface in the comparison with a variant that is entirely artificially illuminated. This estimation is based on the assumption that for artificial illumination LED lamps of 90 lumen/W efficacy are used. If we assume that 20 works are exhibited in the room (5 on each wall), the saving will be approximately 118 kWh of energy per year.

6. Conclusions

The presented study has demonstrated the importance of analyzing new methods of museum space illumination from above, especially in the context of the implication of artwork preservation. This study proposes a novel procedure to assess daylight performance in rooms illuminated by the translucent dropped ceiling based on annual luminous exposure of an artwork that takes into account the maximum levels of H_v resulting from conservation needs for an artwork. The procedure uses weather-based (representing climate conditions) simulations to evaluate the illuminance level at the surface of artwork for 8760 h in the year in the specified location in the city of Wroclaw, Poland. The use of the weather data assures the most accurate results, and the procedure is open to use the most recent data from weather files as soon as they become available. Similar behaviors are expected in galleries with similar window sizes and floor areas, provided that the location is taken into account.

The Radiance software, previously validated by other studies, was used to make all simulations. This method offered detailed information about changes in natural lighting exposure throughout the entire year.

The findings of this study support the assumption that translucent dropped ceilings can be effectively used for safe daylight illumination of exhibition spaces for moderately-sensitive artworks, provided that appropriate devices limiting the access of daylight are used. The advantage of these solutions is that they provide correct color rendering and maintain a relatively uniform illumination level in the interior at the surface of an artwork. Because the exhibition room geometry, location, weather-file, and the orientation of the exhibition space can be changed based on the client's needs, it is justified to state that the presented procedure of calculating H_v might be used by architects and exhibition planners in the design of any exhibition space to initially evaluate if the annual luminous exposure levels are not exceeded for the specified types of artworks.

The results also show that while meeting the requirements for the display of fragile works of art, a very high level of visual comfort for visitors is also achieved. This is demonstrated above all by the results of the standard deviation calculation σ, which in the optimised Variants 5 and 6 does not exceed 100 lx. Low standard deviation, in comparison to other Variants, indicates that the values of E_v tend to be close to the mean, which proves that constant light conditions for observing works of art can be maintained while ensuring adequate color reproduction in the exhibition room.

A further study should examine how H_v values can be changed by opening the vertical glazing only to certain directions, e.g., north. The choice of other types of glazing should also be examined, preferably in conjunction with the possibility of varying the orientation of the building. Interesting studies have also appeared [64], which analyzed the geometry of the ceiling in the exhibition room, and the geometry of the façade fins/louvers [65]. In planned future research, it seems necessary to consider the aspect of roof and ceiling shape and its influence on daylight distribution.

Supplementary Materials: The supplementary materials are available online at https://www.mdpi.com/article/10.3390/buildings11050193/s1. The simulation data presented in this study are openly available in https://drive.google.com/file/d/1RqeDfD6SVwpLLlfrhCKNCS1OK7guenO8/view?usp=sharing.

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