Daylighting simulation of a heritage building by comparing matrix methods and solar models

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Abstract

Lighting simulation is a useful instrument in predicting lighting conditions in buildings. Modelers can use several matrix methods according to the buildings' characteristics and the objectives of the analysis. However, it is unknown which methods are the most appropriate for lighting analysis of heritage buildings. The Joanina Library located in the University of Coimbra – a World Heritage building – was used to compare different matrix methods (2PH, 3PH, and 5PH) under several solar models (BRL, DISC, Perez, and Reindl) using Radiance-based simulations. On-site measurements (indoor and outdoor) were used to calculate each method's accuracy under different solar models. The combination of the 2PH method with the DISC solar model presented the highest accuracy with an average $\mathrm{MBE_r}$ and $\mathrm{RMSE_r}$ of 2.8 % and 43.6 %, respectively. Therefore, the 2PH method was the best choice for the case study, even though the 3PH method may also be considered, especially for parametric studies of improving measures.

Keywords:
Lighting modeling, Historic buildings, Climate-based methods, Indoor illuminance, Natural lighting

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Nomenclature

R^2	Coefficient of Determination
CDF	Cumulative Distribution Function, %
DC	Daylight Coefficients Matrix
D	Daylight Matrix
DHI	Diffuse Horizontal Irradiance, W/m^2
DNI	Direct Normal Irradiance, W/m^2
E_a	Extraterrestrial Irradiance, W/m^2
GHI	Global Horizontal Irradiance, W/m^2
T_{out}	Outdoor Temperature, °C
RE	Relative Error, %
RE_{Cum}	Relative Error of the cumulative daily exposure , %
RH	Relative Humidity, %
MBE_r	Relative Mean Bias Error, %
$RMSE_r$	Relative Root-Mean-Square Error, %
V	View Matrix
θ_z	Zenith Angle, rad

Acronyms

2PH	2-Phase method
3PH	3-Phase method
4PH	4-Phase method
5PH	5-Phase method
6PH	6-Phase method
DISC	Direct Insolation Simulation Code
LFP	Lower Floor Plan
UFP	Upper Floor Plan

1. Introduction

The quality of an indoor environment comprehends a variety of parameters, one of which is lighting. Indoor lighting influences human comfort in several ways, including visually, thermally, and psychologically [1]. In the face of health [2] and energy performance [3] effects, daylighting has been studied in the past years [4], particularly on how to estimate light distribution in buildings [5].

Building designers are able to create scaled physical models to predict indoor daylight. However, these are costly and time-consuming to build and depend on how accurate the sky is for testing [6]. An alternative approach is to use computer-based lighting simulation, a particularly useful instrument for building designers and researchers.

The use of lighting simulation in heritage buildings is residual in this research field (full detail of the systematic literature review is described in Subsection 2.3). While the majority of the scientific studies focus on office spaces [7], lighting simulation has been used to evaluate the conditions of indoor lighting in heritages buildings [8, 9], assess the quality of the indoor environment [10], and study possible retrofitting measures to improve both exhibiting environment and the conservation of collections [11, 12]. Due to the small number of studies in heritage buildings, the question arises as to how to find the best simulation approach to predict indoor lighting cost-effectively.

Among the available lighting prediction software, Radiance is the most used and powerful engine [1] adding versatility and more detail, especially for analyses of extended periods. The remaining tools offer point-in-time simulations, which are just useful to acquire general information. Therefore, for annual evaluations, Radiance allows more comprehensive assessments with higher accuracy [12]. This aspect is even more important for heritage buildings as conservation guidelines [13, 14] recommend the thresholds for cumulative annual exposures. Therefore, this need to simulate indoor lighting over an entire year has led to climate-based methods, which replicate the sky and sun's dynamic changes over time [15]. These methods have been improving in terms of simulation performance and accuracy [16], and their application depends on the building context (dynamic skies, scenes, and shading) and the objective of the study [1]. Opting for one method or another will depend on the context of the buildings [16]. A summary of the available matrix methods is presented in Subsection 2.2.

Therefore, there are relevant issues regarding lighting simulation to be discussed in heritage buildings mainly due to the employed software and the specified timeframe. Even though Radiance does not have an easy interface for designers, it allows running climate-based simulations that are crucial for the annual analysis of lighting in this type of building.

Another relevant aspect is raised whenever annual analyses are required. Climate-based simulations require a weather input to compute predictions [17]. When studying ways to improve solutions, studies use available statistical datasets from International Weather for Energy Calculations (IWEC) or national regulations, however, for validation purposes, custom weather files allow an adequate evaluation of a model's accuracy. Outdoor daylight measurements are important to produce accurate predictions of the lighting distribution inside a building [18], for example, using sun trackers, pyranometers, and pyrheliometers [19]. However, significant problems have emerged concerning the costs of accurate instruments to monitor the Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) [20]. As it is costly to make such measurements, most weather stations only measure the Global Horizontal Irradiance (GHI), leaving DNI and DHI to be determined using solar models [21]. There are numerous solar models to carry out such determinations. For example, Abreu et al. [22] compared 121 models to compute DHI, while Gueymard and Ruiz-Arias [19] used 24 to estimate DNI. Outdoor irradiances were compared using the prediction of solar models, but their impact on the indoor lighting simulation and its validation is yet to be thoroughly studied. In fact, very few studies discuss the influence of using different solar models in lighting prediction [23], meaning that opting to use different solar models to compute DNI and DHI as inputs of several matrix methods may bring considerable differences in predictions. This motivates the present research to find the best approaches to predict indoor lighting and how they affect the validation process in heritage buildings. The combination with the highest accuracy should be the most suited for carrying out lighting simulations. Therefore, the study's objective focuses on determining a suitable simulation method by comparing different matrix methods using several solar models in Radiance, taking a heritage building as the study case. Predictions of different simulation configurations are compared with on-site measurements with low-cost monitoring devices. The output of this research proposes a methodology of modeling and simulating indoor lighting to support engineers and designers.

2. Methodology

A methodology was devised to determine the most suitable simulation method in three stages (Fig. 1). The goal is to compare different combinations of matrix methods and solar models. The Joanina Library was chosen for the case study. It is one of the most visited buildings of the University of Coimbra, with richly decorated indoor spaces housing rare and valuable books [24]. In the first stage, the building survey and the measurement of the outdoor and indoor conditions are carried out. In the intermediate stage, the modeling and simulation for the library's indoor lighting distribution are carried out. The 2-Phase method (2PH), 3-Phase method (3PH), and 5-Phase method (5PH) were selected due to their suitability/applicability building under study, for the measured weather based on different solar models (BRL, DISC, Perez, and Reindl). In the last stage, the results are compared using different statistical indicators to understand which matrix methods and solar models best meet the simulation for heritage buildings. Each stage is described in detail in the following sections.

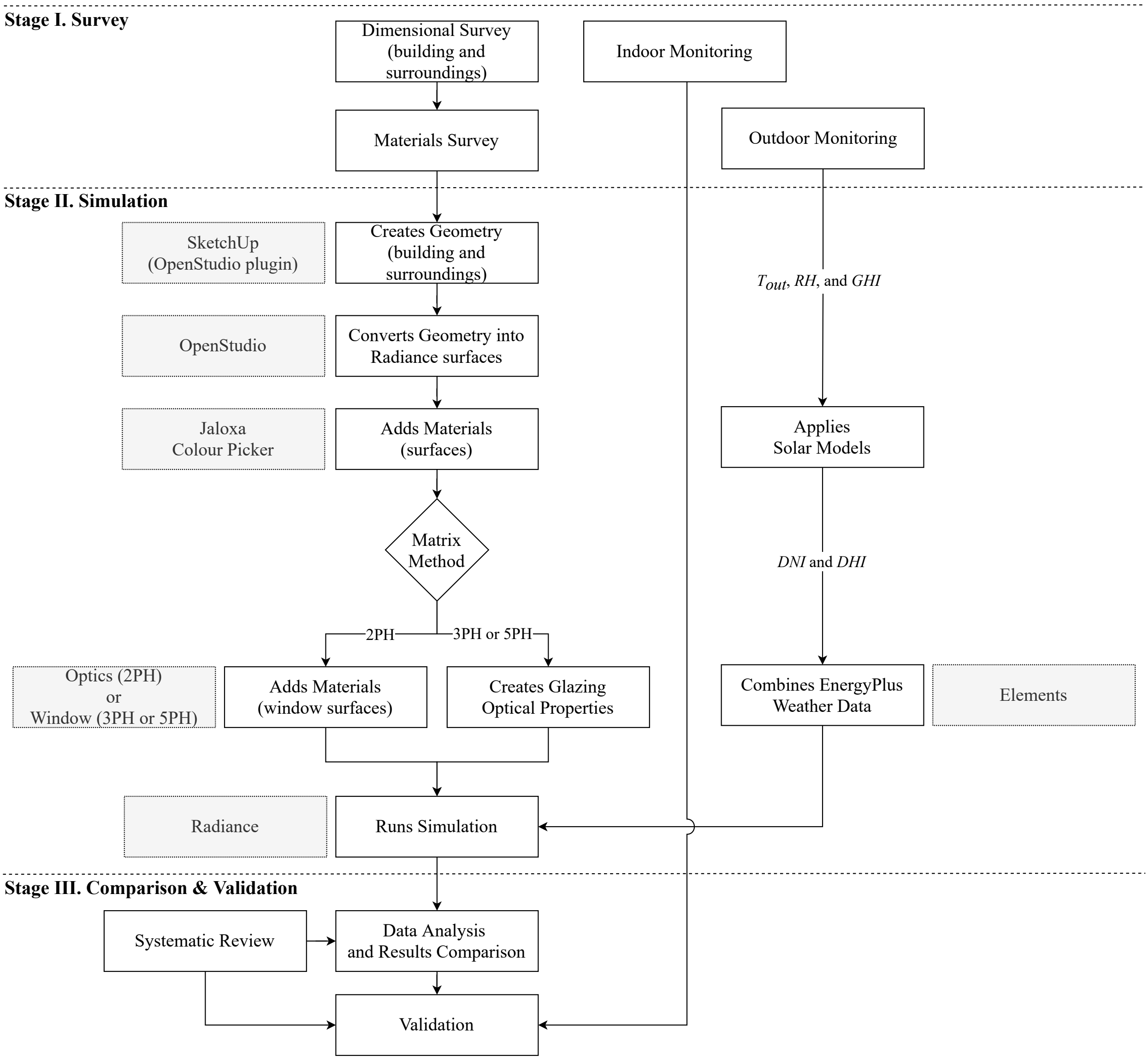

Figure 1: The three stages of the study: I. survey, II. simulation, and III. analysis. Grey boxes indicate the software used in each step of the simulation stage workflow.

2.1. Survey

The subject of the case study is a World Heritage library from the 18^{th} century, a building found in the courtyard of the University of Coimbra. It is located in the very heights of the historic center (95 m altitude) with the adjacent buildings at the same level (Fig. 2a, and Fig. 2b). The surrounding buildings, found at a lower altitude, were not surveyed, as the reflected diffuse radiation was considered neglectable. The building's main façade is south-oriented, with a 12° rotation to the east. The library's first floor (Fig. 2c and Fig. 2d) is 33.6 m in length, 12.0 m in width, and 11.5 m in height, organized in three open and contiguous rooms (Space 1, Space 2, and Space 3). A balcony creates second-floor level within each space: Lower Floor Plan (LFP) and Upper Floor Plan (UFP).

In terms of glazed openings to the exterior, the library has nineteen windows (south and north oriented). The blue markings on Fig. 3 indicate the windows that contribute to daylighting. The library's glazing consists of 4 mm single-pane glass with a radiant beam transmittance of 91 % and 0.05 m thick metal frames. Windows have 0.3 m reveals and are partially shaded by thick red opaque curtains (Fig. 2d). Finally, the southern windows on the UFP have internal diffuser shades with unknown optical properties.

The monitoring comprised measurements of the outdoor and indoor environment. The outdoor conditions (GHI, Outdoor Temperature (T_{out}), Relative Humidity (RH)) were monitored hourly with the Vantage Pro 2 weather station from Davis Instruments, which is located near the building site (100 m). The Onset HOBO Pendant Temperature/Light 64K data loggers (model UA-002-64) were used to monitor and register the indoor conditions in a 5-min time step, which were later converted to average hourly values.

From the sun path analysis inside the library, the bookshelves facing west and east on the southern side of the library's UFP were determined to be the most exposed to sunlight during the wintertime. Moreover, as Spaces 2 and 3 on the LFP have office with small side doors, which are permanently closed, the only light contribution on this level comes from the southern windows in Space 1. The sensors were placed in bookshelves at a height ranging between 1.60 m and 1.75 m above the floor or above the balcony floor (marked in red in Fig. 3), similarly to what was done in other approaches [25, 26]. Sensors were distributed as follows: (i) one sensor in Space 1 on LFP ($\mathrm{S1_N}$) – the only space where the windows of the LFP are open and receive direct light under the

(a) View of the south façade.

(b) View of the east façade and university courtyard.

(c) View of the main corridor.

(d) View of the balcony in Space 2 facing the southern wall.

Figure 2: Views of the Joanina Library surroundings and interior.

balcony; (ii) one sensor in Space 2 in the UFP ($S2_{\mathrm{N}}$) – zone without direct light; and (iii) two sensors in Space 2 and Space 3 – the most exposed bookshelves ($S2_{\mathrm{W}}$ and $S3_{\mathrm{W}}$) and direct incident light due to a small gap between the opaque drapes and diffuse curtains.

A systematic review of the most used statistical indicators in heritage building studies was carried out in Stage I – such literature review allowed to identify methods for the evaluation of the simulation results. Scopus database was consulted with the following string to search: "(TITLE((heritage OR historic OR museum OR architect OR historical) AND (light OR lighting OR

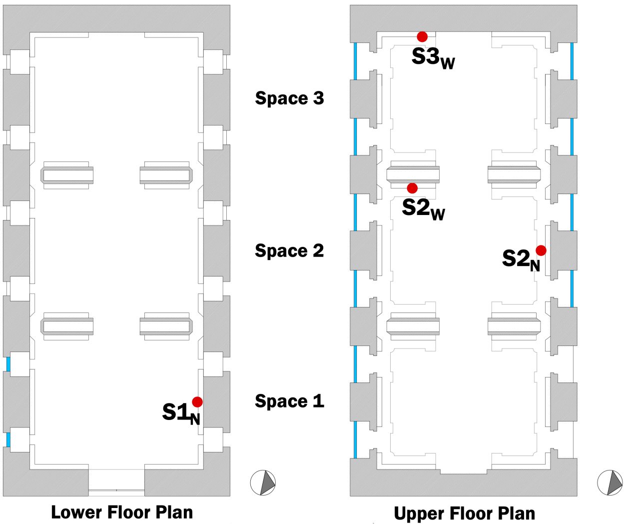

Figure 3: Library's layout (major length of 34 m). Blue rectangles represent windows that contribute with light, and red markers depict the position of the lux meters.

daylight OR daylighting) AND NOT (photo OR realistic OR virtual OR archaeological OR artificial OR led OR shed OR neuro)) AND (ABS(simulation OR natural OR radiance OR conservation OR matrix OR retrofitting))", from which 123 studies were found regarding the lighting simulation of heritage buildings. From those studies, 27 were selected when searching for the word "valid*" covering words such as "validation", "validated" and/or "validating", to certify simulation models given the statistical indicators. From the 27 studies, which were carefully examined, 14 were selected as only these contributed to the validation of the simulation – the results are presented in a summary table in Subsection 3.1.

2.2. Simulation

Fig. 1 depicts the workflow used for each combination of matrix method and solar models. With the information gathered during the building survey stage on the geometry, materials, and outdoor monitoring, the procedure starts and creates the building's geometry and surroundings using SketchUp with the OpenStudio plugin. Then, the model geometry is converted from OpenStudio format into Radiance objects.

In the next step, the approximate color, specularity, and roughness is assigned for each surface material using Jacob's auxiliary tool [27]. Due to the lack of photometric equipment, it was not possible to measure the diffuse reflectance of each surface individually following the approach proposed by Al-Sallal et al. [11]. Instead, the diffuse reflectance of surfaces was chosen from values found in the literature [1, 28, 29]. Relatively to the reflectance coefficients, outdoor surfaces have 0.60, façades, and roofs, 0.03, and indoor surfaces, floors, ceilings, and walls, 0.03, of 0.42, 0.60, and 0.63, respectively. The reflectance of materials of the interior is 0.35, 0.07, 0.04, and 0.67 for golden materials, wood, carpet, and stone, respectively. The internal diffusers were modeled as parallel surfaces to the glazing [30] with a plain weave and white color material [31]. These surfaces had a diffusion coefficient of 0.75 and a specular transmittance of 0.04. Internal diffusers were considered as a medium gloss material with 0.10 of roughness. Radiance allows modeling this type of material by declaring surfaces as “trans” or “BRTDfunc” material types. Both lead to similar results.

When carrying out Radiance-based simulation, the following methods were employed:

- 2PH method was used for an annual daylight simulation in a static scene [32]. It is dependent on the outdoor environment (sun and sky contributions), the geometry of the building and its surroundings, and the optical properties (color, transmittance, and reflectance) [18]. Due to its simplicity, other light sources are not decomposed, which introduces errors when interpolating predictions. However, the parametrization of the glazing geometry and its optical properties requires detailed sketching and technical information. Also, although requiring less computational effort for single runs, the 2PH simulation performance may be affected when performing several runs since it always requires the repeated computation of the Daylighting Coefficients (DC). The definition of windows’ surfaces for the 2PH used “optics2glazedb”, which converts the output of Optics 6 to a Radiance material;

- 3PH method splits the optical path of lighting rays into several phases that are processed by operation between matrices (view V, transmission T, daylight D, and sky S) [33]. The phase splitting allows the independent computation of matrices to improve the performance of several simulation runs. Moreover, the definition of complex fenestration systems was eased by the computation of the T matrix. Nevertheless, the 3PH does not account for changes and/or complex external shading in the lighting prediction algorithms [34]. Therefore, the 4-Phase method (4PH) method with façade matrix was developed as an additional phase in the light ray path [35]. This matrix represented the façade component to include the contribution of dynamic and complex external shading;

- 5PH method combines the 3PH with the developments of the Direct Daylight Simulation (DDS) Treguenza and Waters [32] to calculate the contribution of direct sunlight [36, 37] more accurately. The approach replaces the flux transfer from the sun in the 3PH with a more precise one (further details are found in ref. Geisler-Moroder et al. [38]). The same approach was replicated for the 4PH to develop the 6-Phase method (6PH) [39]. For 3PH and 5PH, Window 7.7 was used to create the Transmission Matrix (T) regarding the glazing optical properties.

The remaining methods available, 4PH and 6PH, are more useful for dynamic and complex façades. Therefore, these two matrix methods were not considered in this study.

Apart from the building modeling, the outdoor conditions are also an essential input to carry out the simulation. From an economic perspective, it is less expensive to only measure the *GHI* and then decompose it into *DNI* and *DHI* using solar models. Abyad [21] tested the performance of the BRL, DISC, Perez, and Reindl models when predicting both *DNI* and *GHI*. The Perez model [40] adds correction coefficients to the Maxwell model [40], known as Direct Insolation Simulation Code (DISC), which calculates the *DNI* from the measured *GHI*. In contrast, the BRL [41] and Reindl [42] models determine *DHI* from *GHI*. While the DISC and Perez are two of the most used models [1], Dervishi and Mahdavi [43] still recommend the Reindl model. The comparison of the solar models dictates/suggests that performance depends on the location. [21]. Torres et al. [44] conclude that the Perez and BRL models are more accurate than the others for the Iberian Peninsula. As the present case study is located in Portugal, the BRL model was also found to be the most adequate for the Portuguese weather [45]. The application of solar models was used to combine four different weather data corresponding to each solar model: BRL, DISC, Perez, and Reindl, to decompose *GHI* into the two light components (*DNI* and *DHI*) according to Table 1 and Eq. 1. Measurements of the outdoor conditions (*GHI*, T_{out}, and *RH*) were obtained during the building survey stage to serve as inputs for the solar models.

$$GHI = DNI \cdot cos\theta_{\mathrm{z}} + DHI \tag{1}$$

GHI – Global Horizontal Irradiance, W/m^2; *DNI* – Direct Normal Irradiance, W/m^2; θ_{z} – Zenith Angle, rad; *DHI* – Direct Horizontal Irradiance, W/m^2.

Lastly, simulation was run with high-level parameters (Table 2) to reduce the non-deterministic

Table 1: Inputs required for each solar model.

Solar Model	Inputs	Source	Output
BRL [41]	*GHI*	Measured	*DHI*
	Extraterrestrial Irradiance (E_a)	EnergyPlus	
	Zenith Angle (θ_z)	Estimated	
	Hour Angle	Estimated	
DISC [40]	*GHI*	Measured	*DNI*
	E_a	EnergyPlus	
	θ_z	Estimated	
	Air Mass	Tomasi and Petkov [46]	
Perez [47]	*GHI*	Measured	*DNI*
	E_a	EnergyPlus	
	DNI_{DISC}	Estimated	
	θ_z	Estimated	
	Dew Point Temperature	Measured	
Reindl [42]	*GHI*	Measured	*DHI*
	E_a	EnergyPlus	
	T_{out}	Measured	
	RH	Measured	
	θ_z	Estimated	

character of Radiance predictions and achieve a convergence of the results [48]. Simulation parameters were iteratively increased until they reached a convergence coefficient lower than 7 %. Sky matrices were created for each solar model (BRL, DISC, Perez, and Reindl) by using 2305 sky patches (parameter MF:4) to reduce the uncertainty associated with the sky discretization [49], especially for the 2PH [34].

Table 2: Radiance parameters used in simulations.

Matrix Method	**2PH**	**3PH**		**5PH**		
Parameter	***DC***	***D***	***V***	$\boldsymbol{D}_{\mathbf{d}}$	$\boldsymbol{V}_{\mathbf{d}}$	$\mathbf{C}_{\mathbf{ds}}$
Ambient bounces (-ab)	20	20	20	0	1	1
Ambient divisions (-ad)	262 144	131 072	262 144	131 072	262 144	262 144
Limit weight (-lm)	3.81e-06	7.62e-06	3.81e-06	-	3.81e-06	3.81e-06

2.3. Comparison and Validation

The final task included the estimation of the statistical indicators, the comparison of all the simulation configurations (matrix method and solar model), and the validation of the best configuration. Given the indoor measurements and predictions, the most relevant statistical indicators found in the literature were estimated. The performance of each simulation configuration was done by comparing such statistical indicators for the four sensors. The most appropriate configuration revealed the best performance of all the statistical indicators. Afterward, the best configuration and their performance indicators were compared with thresholds obtained in the systematic review of the literature.

3. Results

The presentation of the results follows the structure adopted in Section 2.

3.1. Survey

The building survey was carried out with on-site visits to evaluate the spatial distribution of the indoor light and the influence of surroundings on its availability. At the same time, the survey of types of materials was done. Detailed photographs were captured to support the 3D modeling of the building and surroundings.

The monitoring campaign (outdoor and indoor) started on December 27th, 2019, and April 11th, 2020. After April 11th, 2020, the library was closed due to the COVID-19 pandemic, and, therefore, the opaque drapes covered the windows on the south side, blocking any entrance of light rays. Thus, the monitoring data was limited to 106 days, which was considered sufficient for this study mainly for two reasons. In the first place, the winter season covers all types of weather (overcast, mixed, and clear), providing a broader coverage of the different types of skies than, for example, summer, which has mainly clear and sunny days. Outdoor measurements display a uniform frequency of sky patterns: 41 days with clear sky, 35 with mixed, and 30 with overcast. The second reason is related to the lower position of the sun. For this specific case study, the gap between the occlusion systems led to sun rays entering the library as direct incident light on bookshelves, increasing the rate of deterioration of the collections. However, direct exposures produced larger errors in lighting simulation for this case study, which has proven to be the most demanding scenario from a conservation perspective.

The GHI, T_{out}, RH had average values ranging between 195.1 W/m^2 and 310.6 W/m^2, 10.8 °C and 14.7 °C, 71 % and 81 %, respectively – the full characterization of these variables is presented in Figure S2 and Table S2 in the Supplementary Material.

From the literature review, it was found that the most commonly used indicators in lighting simulation for all types of buildings are the Relative Mean Bias Error (MBE_r) and the Relative Root-Mean-Square Error ($RMSE_r$) [50, 51, 38, 52, 53] (Table S1 of the Supplementary Material). MBE_r captures the model's performance in general terms, while $RMSE_r$ provides more information about the major differences in model performance. However, both also present some problems as they depend on the predicted/measured units. The Coefficient of Determination (R^2), also used in certain studies [54, 55], describes how well predictions match measurements. Nevertheless, the goal must focus on studies related to lighting simulation in heritage buildings. From the literature survey, it was observed that the analysis process regarding statistics is not very deep nor is it detailed in the practical application of lighting simulations in the field of cultural heritage. In fact, The majority of studies in cultural heritage have only analyzed the Relative Error (RE) (Table 3)), which is insufficient to understand how good the accuracy is. For low illuminance levels, high RE values may not properly capture relevant deviations. Apart from RE, other indicators were used in only a few studies, Relative Error of the cumulative daily exposure (RE_{Cum}), and the Cumulative Distribution Function (CDF) of RE. RE_{Cum}, for instance, is important in conservation since the cumulative effect of light on collections is the major cause of degradation [14]. Therefore, to evaluate the lighting model for the case study, there were combined indicators found in heritage buildings complemented with others found in studies of lighting simulation. These indicators are the MBE_r, $RMSE_r$, R^2, RE, CDF of daily RE, and the RE_{Cum}. The full description of these indicators is presented in Section 4 of the Supplementary Material.

The validation thresholds found in the literature review were required to critically analyze the results obtained by simulation predictions. The validation criteria presented in each study varied substantially. However, it was observed that the process generally was not very deep in the practical application of lighting simulations, especially in studies on cultural heritage – see Table 3. The lack of more information regarding such thresholds required the inclusion of other indicators found in studies of lighting simulation – see Table S1 in the Supplementary Material.

Table 3: The accuracy of lighting studies compared to on-site measurements for museum and heritage buildings.

Museum & heritage buildings Reference	**Software**	**Validation Criteria**	**Statistical Indicators**	**Validation Achieved**	**Weather**	**Period**
Ng et al. [56]	Radiance	Indoor illuminance	RE	≤ ±18 %	CIE overcast sky	One day (9h00 to 16h00)
Bacci et al. [57]	I2-based model PCA-based model Colour change based model	Cumulative exposure	RE_{Cum}	≤ ±60 %	-	-
Del Hoyo-Meléndez et al. [9]	Superlite 2.0	Indoor illuminance	RE	≤ ±25 %	Web databases; Different sky conditions	Specific times of the year
Kim and Chung [58]	Radiance	Indoor illuminance of a scaled model	RE	≤ ±52 %	CIE sky conditions	Point-in-time 12h00 in five days
Ciampi et al. [59]	DIALux	Indoor illuminance	RE	≤ ±61.6 %	Clear, intermediate and overcast skies	Several days
Mayorga Pinilla et al. [10]	DIALux	Monthly cumulative exposure	$RMSE_r$	≤ ±6 %	Measurements of clear, covered and cloudy skies	7th and 21st of each month (Jan to Jun 2012)
Balocco et al. [60]	DIALux	Indoor illuminance	RE	≤ ±37.8 %	Winter sky	Point-in-time
Al-Sallal et al. [11]	DIVA-for-Rhino (Radiance)	Indoor illuminance	RE	≤ ±4 %	Clear sky conditions	Point-in-time – 10th June and August – Noon
Nocera et al. [61]	Radiance	Indoor illuminance	RE	≤ 7 %	Measurements of GHI	12h30 14th May
Almodovar-Melendo et al. [8]	DianaX	Indoor illuminance	R^2	≥ 0.92	Partly cloudy sky	Noon 21st December
Balocco and Volante [26]	DIALux	Indoor illuminance	RE Mean Standard Deviation Mean Chi-Square Error	≤ 10 % ≤ 39.61 % ≤ 39.74 %	- - -	Short period (working hours) - -
Eldaidamony et al. [62]	DIVA-for-Rhino	Outdoor and Indoor illuminance	RE	≤ 4 %	Clear sky	Noon 10th June and August
Leccese et al. [12]	Radiance	Indoor illuminance (horizontal and vertical)	Mean RE	≤ ±40 %	CIE overcast sky; CIE clear sky; Climate-based skies; TMY weather data	Point-in-time (6th December 10h25 – 12h25)
Mahmoud et al. [63]	Honeybee+ and Ladybug OR Daylight facto	Daylight factor	RE	≤ 1.47 %	Overcast sky	10h23 – 12h25 6th December

CIE 171:2006 [64] suggests ranges of error for test cases: RE ±5 % as desirable, ±20 % threshold achievable, and a maximum of ±40 %. Other than CIE 171:2006 [64], no other standard suggests minimum requirements for validating a model, especially for real case studies. Therefore, the minimum acceptance thresholds were retrieved from the literature of both tables, being:

- MBE_r lower than 20 %;
- $RMSE_r$ lower than 35 %;
- R^2 higher than 0.70;
- RE lower than 61.6 % or CDF with a coverage of 75 % with RE lower than 20 %.
- RE_{Cum} lower than 60 %.

3.2. Simulation

Every combination of simulation method and solar model was carried out for the different measuring points. This combination totalized 480 simulations (ten runs, four measuring points, three methods, four solar models) for the case study model (Fig. 4 depicts the geometry of the building and surroundings). An hourly timestep was considered in order to analyze the accuracy of the matrix methods. In this way, simulation results and on-site measurements were averaged to hourly values commonly adopted in other studies [11, 12]. The simulation period started on December 27th, 2019, and ended on April 11th, 2020, with daily cycles from 7 am to 6 pm, totalizing 106 days.

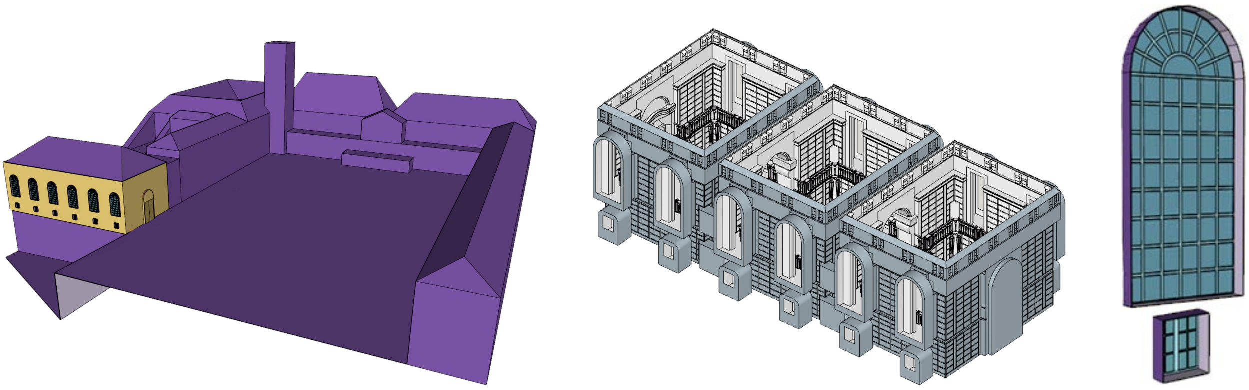
(a) (b) (c)

Figure 4: Model geometry of the surroundings (a), indoor spaces (b), and windows (c).

3.3. Comparison and Validation

Daily time series were produced for the indoor illuminance behavior during the total period of the study were produced. Even though most of the predictions were fairly accurate, as depicted in Figures S3 and S4 in the Supplementary Material, there were some mismatches for specific events. Fig. 5 illustrates one of these, demonstrating that it was more difficult to predict direct lighting as it only occurred whenever the light was entering through the small gap between the occlusion devices. Results indicate that, for $\mathrm{S1_N}$, the model did not predict direct lighting while, for the $\mathrm{S3_W}$ sensor, it was predicted when it was not measured. Whenever such considerable mismatches occurred, differences between illuminances severely penalized the error analysis, as discussed below. Nevertheless, the simulation was able to correctly predict direct light incidence in certain moments.

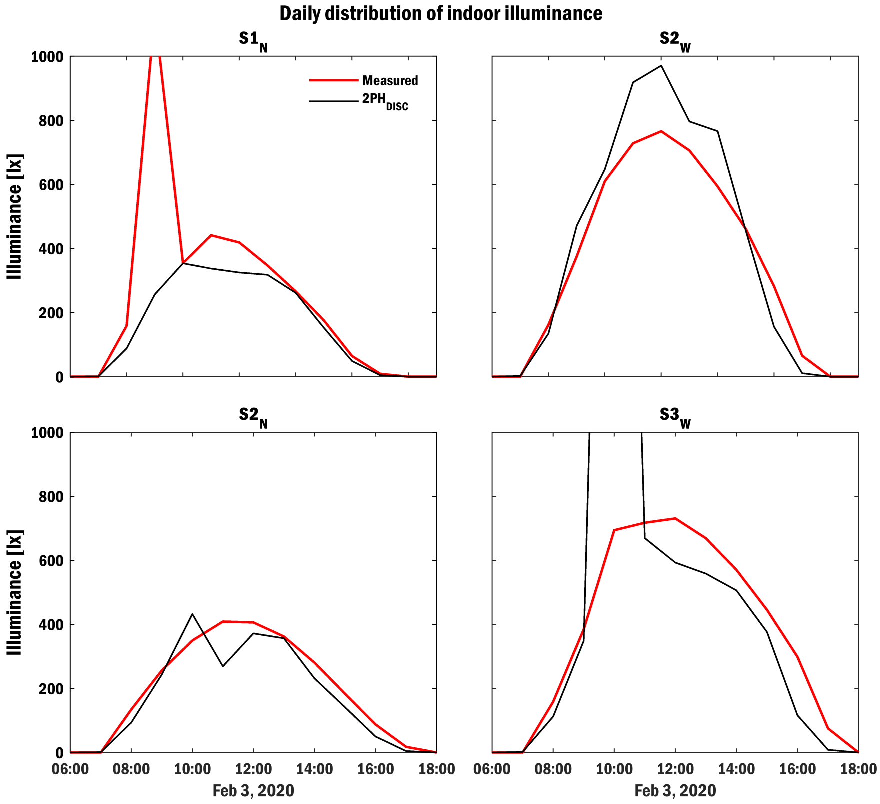

Figure 5: Comparison of illuminance values for predictions for the best configuration (2PH and DISC) with measurements on 3$^{\mathrm{rd}}$ February, 2020.

Most of the MBE_r values show that the simulation model underpredicts the lighting values, varying between $-35.4\,\%$ to $11.9\,\%$ (Table S3 in the Supplementary Material). As for matrix methods, 2PH predictions have lower values indicating better performance than the remaining when results are converted to positive values. It is also evident that 2PH produces higher illuminances as it has larger MBE_r values. When comparing solar models, DISC produces lower absolute MBE_r values in most sensors, indicating that this solar model provides a lower average error. Results also indicate that higher MBE_r values are mainly achieved for the DISC model since it contributes to higher solar radiation. Therefore, for an underpredictive model, it is expected that DISC will compensate with higher predictions performing better than the remaining. Another relevant aspect is related to the MBE_r values of the 3PH and 5PH methods being the same for $\mathrm{S2_N}$ because there is no direct light at this sensor, which is the major update of the 5PH.

The drawback of only analyzing MBE_r is that positive errors compensate the negative ones, making it evident that it is essential to include other indicators, such as $RMSE_r$, in the performance evaluation of the model. When analyzing $RMSE_r$ values, the negative values are eliminated by squaring differences, ultimately resulting in a bigger averaged error. This indicator is contrary to the MBE_r, which calculates the average error using the actual values of the differences (positive or negative). Therefore, $RMSE_r$ allows to understand which methods and solar models have larger differences between measurements and predictions. The $RMSE_r$ values range between 23.2 % to 312.7 % (Table S4 in the Supplementary Material). Such a broad range of values depends on the positions of each sensor. The sensors $\mathrm{S2_W}$ and $\mathrm{S3_W}$ are exposed to a greater amount of light as they are closer to windows, thus have a higher $RMSE_r$ than $\mathrm{S1_N}$ and $\mathrm{S2_N}$. This result means that there is a greater difficulty in predicting illuminance accurately in places with more light. However, the definition of a reference value is still challenging since it depends on each situation – in this case, different sensors have different results. The model should be evaluated as a whole and not as singular points.

Concerning the comparison of the matrix methods, 2PH outperforms other methods for $\mathrm{S2_W}$, $\mathrm{S2_N}$, and $\mathrm{S3_W}$, while 3PH has lower values for $\mathrm{S1_N}$. For the solar models, the $RMSE_r$ values of the DISC model are usually lower than in the rest (except for $\mathrm{S3_W}$).

There is a plausible explanation for having higher $RMSE_r$ values. Since the exposure to direct solar radiation is limited to short periods (only some minutes on specific days due to the 30 cm gap between occlusion devices), a mismatch will likely happen when the geometry does not have precise dimensions or tilt angles (the library is not perfectly aligned with the north). These events happened only on February 3^{rd}, 2020 for $\mathrm{S1_N}$, on February 15^{th}, 18^{th}, and 19^{th}, 2020 for $\mathrm{S2_W}$, and on February 5th, 6th, 7th, and 11th, 2020, for S3$_{\mathrm{W}}$. Some of them mismatched the predictions – leading to significant errors, especially for S3$_{\mathrm{W}}$, which presented more events of direct radiation. In turn, if the model only had diffuse radiation, results would not have differed from those in S2$_{\mathrm{N}}$. This idea is corroborated by having higher $RMSE_r$ values for the 5PH method than others on every shelf. As mentioned before, the 5PH method is more precise in terms of spatial light distribution. However, in this case, this advantage turns into a disadvantage when the geometry survey is not carried out with a high degree of precision, thus jeopardizing the accuracy and performance of illuminance predictions. Therefore, the method should only be considered when more resources and advanced technologies are available.

For each simulation, the coefficients of determination, R^2 vary from 0.26 to 0.93 (Table S5 in the Supplementary Material). This statistical parameter indicates good suitability for all solar models and matrix methods (majorly above 0.75), excluding 5PH in S3$_{\mathrm{W}}$. The mismatch between predictions and measurements in S3$_{\mathrm{W}}$ is again confirmed by having such low R^2 values for 5PH. If both predictions and measurements are plotted, a perfect model would have an R^2 equal to 1, which corresponds to the solid red line in Fig. 6 (the figure depicts 2PH and DISC results). Differences are much bigger for lower illuminances in relative terms, meaning that errors and uncertainty are higher during sunrise and sunset. It is clear that for all sensors, most predictions are higher than measurements.

Another important fact is that there is a mismatch between the measured direct radiation with the predictions in points that are temporarily facing direct sun rays, thus emphasizing that the model may have some problems related to the geometry of the surfaces and/or their optical properties. There is a higher accuracy in predicting light for locations without direct light incidence (S1$_{\mathrm{N}}$ and S2$_{\mathrm{N}}$), representing most of the bookshelves in the historic library. Thus, indicating promising validation results in diffuse environments.

The DISC model has a higher mean value than the others but within a similar range of values. There is no apparent advantage in using one solar model over others when comparing R^2.

CDF corresponds to the percentage of points within a range of *RE*. As shown in Fig. 7, almost 75 % of the points have 50 % less *RE* regardless of the simulation method or solar model. For 45 % of the points, *RE* is less than 25 % revealing that predictions produce accurate results for all measuring points. However, some differences in the evolution of the curve are noticed depending

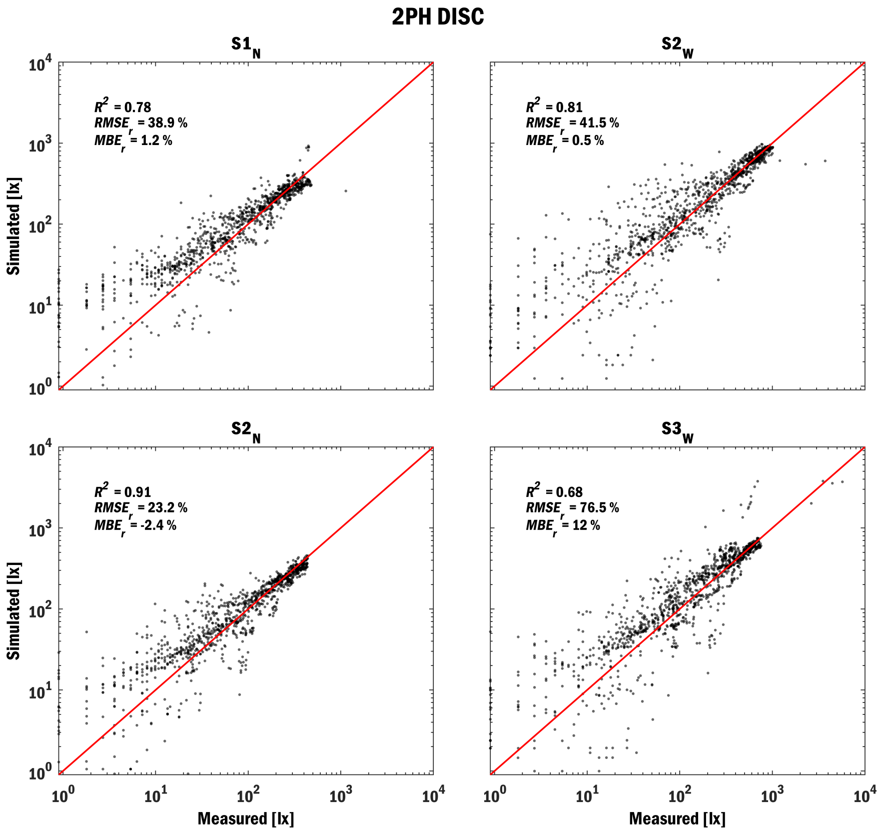

Figure 6: Representation of the illuminance simulated and measured and respective R^2 indicator for the building model using 2PH and DISC solar model.

on the measurement point. The 2PH is outperformed by 3PH for S1N and S2N and by 5PH for $\mathrm{S2_W}$ and $\mathrm{S3_N}$ when RE is above 30 %. Overall, 3PH and 5PH have higher point coverage when considering errors up to 95 %. It is worth noting that the 3PH and 5PH methods are colinear for the measuring point $\mathrm{S2_N}$ since it does not receive any direct light. Relative to solar models, DISC has higher coverage of lower RE for almost all matrix methods.

Finally, the model's performance may be analyzed using a lighting metric applied in conservation – the cumulative exposure for a certain period. It is recognized that cumulative metrics tend to average differences over the analysis period. For this reason, this metric should not be used alone to evaluate the performance of models. For this study, the monitoring period corresponded to one-third of the year since it started in December and finished in April (106 days). The errors of the final cumulative values are analyzed for the four measuring points.

Considering the daily accumulated exposure, the model underpredicts most of the measured illuminances, as shown in Fig. 8 (RE_{Cum} in Table S6 in the Supplementary Material). However,

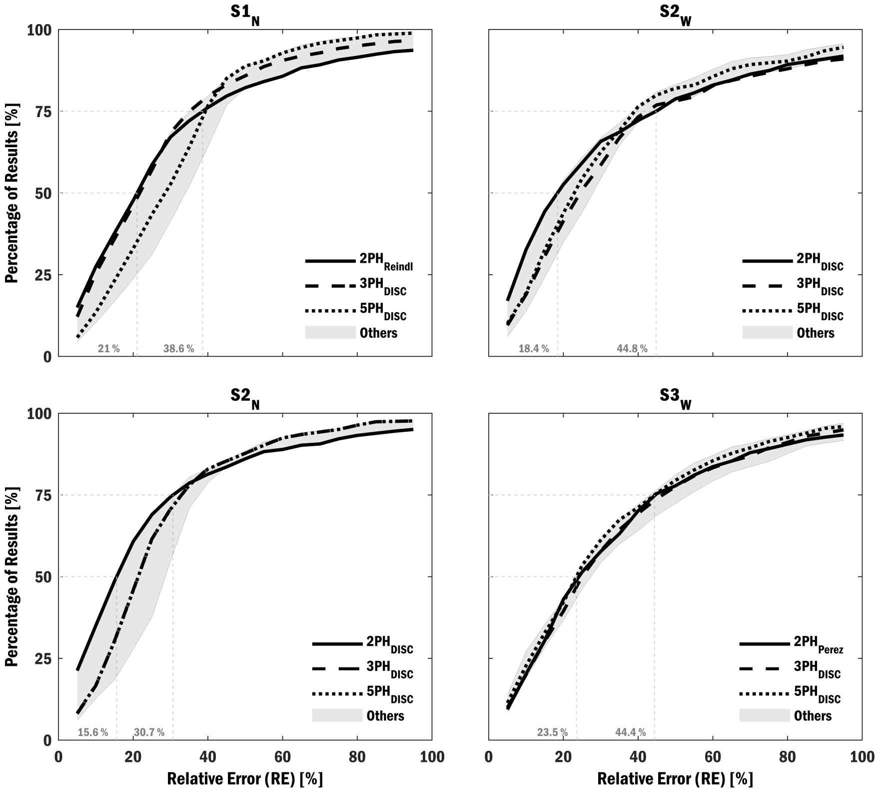

Figure 7: Cumulative Distribution Function of the Relative Error for the total measuring points.

values at the measuring points with more incident light facing west ($\mathrm{S2_W}$ and $\mathrm{S3_W}$) are often overpredicted when carrying out a 2PH simulation. For this reason, solar models with lower solar contribution seem more suitable for this simulation method – BRL for $\mathrm{S1_N}$, Reindl for $\mathrm{S2_W}$, and Perez for $\mathrm{S3_W}$. The REs of the cumulative illuminance (RE_{Cum}) over the monitoring period differ from bookshelf to bookshelf but achieve reasonable low errors between $-33.1\,\%$ and $13.3\,\%$.

After averaging results for the whole model, 2PH has the best performance for MBE_r, $RMSE_r$, RE, and R^2, as shown in Table 4. For the same input conditions, higher illuminance values for the 2PH model have an advantage for conservation purposes since the model is safer for the design process. 5PH is the method that most underpredicts, which may be considered risky for conservation goals. These conclusions cannot be extended to the remaining solar models.

4. Discussion

Every threshold presented in Subsection 3.1 was compared to the statistics of predictions. MBE_r, R^2, and RE_{Cum} were within the defined validation range. However, for $RMSE_r$ and CDF,

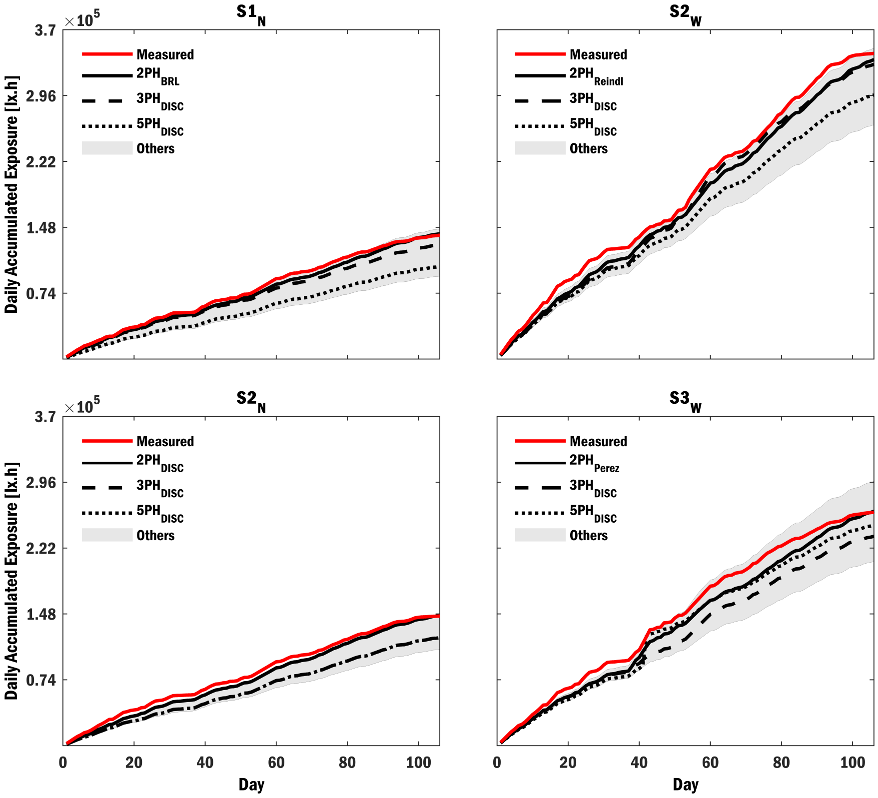

Figure 8: Cumulative comparison between measurements and predictions.

Table 4: Average values for each statistical indicator for the whole model.

	MBE_r (%) (min)			$RMSE_r$ (%) (min)			R^2 (-) (max)			REcum (%) (min)		
	2PH	**3PH**	**5PH**	**2PH**	**3PH**	**5PH**	**2PH**	**3PH**	**5PH**	**2PH**	**3PH**	**5PH**
BRL	-2.80	-16.49	-22.11	44.60	53.35	91.11	0.79	0.74	0.72	0.28	-13.97	-19.97
DISC	2.82	-11.45	-16.90	45.03	51.77	108.24	0.80	0.75	0.72	5.17	-9.55	-15.29
Perez	-7.55	-21.33	-26.09	43.63	54.02	105.06	0.81	0.77	0.71	-5.32	-19.53	-24.55
Reindl	-1.59	-15.44	-20.99	43.91	52.80	95.45	0.80	0.75	0.72	1.19	-13.16	-19.03
Best	**2PH & DISC**			**2PH & BRL**			**2PH & Perez**			**2PH & DISC**		

the results exceeded the set values. $RMSE_r$ was 43 %, exceeding the value of 35 %, and CDF was 75 % for RE up to 45 %, exceeding the RE of 20 %. Nonetheless, it is important to highlight the fact that the validation process is a challenging process when using climate-based simulation of a real case, i.e., without a controlled environment where the input variables are predetermined and controlled. It also depends on the timeframe of the study. Most studies validate models only for a specific time (point-in-time), during a specific short period for predefined weather conditions. Therefore, these validation thresholds found in the literature may be difficult to achieve for the present case study considering a continuous monitoring and dynamic simulation of the lighting conditions.

Notwithstanding, these results indicate that a cost-effective lighting model is still useful, especially considering the compliance of MBE_r, R^2, and RE_{Cum}. It may be important to consider less strict parameters considering the variables involved, their inaccuracies (skies, matrix methods, materials, and geometry), timeframe, and the limitations of the present work.

This procedure has some limitations. For instance, there might be some errors associated with the solar models (BRL, DISC, Perez, and Reindl) when converting the GHI into DNI and DHI; the optical properties of all interior and exterior surfaces were not measured; the geometric inaccuracies (dimensional, angular, and simplifications of surfaces) during the sketching process; and the weather station is located 100 m away from the building. Moreover, the non-uniformity of the color of the bookshelves, due to previous fading or damaged varnish from solar exposures, induces an error in the definition of surface materials that may slightly influence results. Although these limitations could be overcome in future developments, such improvements will require more expensive equipment and longer periods for the calibration of the model.

The recommendation for further applications of Radiance in heritage buildings should depend on its application. It is important to replicate simulations several times and use their averaged values, especially when simulation parameters are not significantly high. When choosing the matrix method, 2PH should be primarily used for its simplicity and performance in studies regarding lighting distribution where diffuse radiation is the primary light source, such as in museums or heritage buildings. Although simpler, 2PH is challenging to parameterize and specify complex glazing or façades geometries and/or optical properties. Instead, the 3PH method facilitates the modeling of complex glazing by including a transmission matrix generated from Window 7.7. The study of conservation conditions should employ the 3PH when the building does not contemplate complex geometries and fenestration systems. Moreover, parametric studies require many simulations, where 3PH could speed up the process by dividing calculations into several phases. In contrast, when direct radiation is a major source of light and the focus is on glare analysis, 5PH is a more appropriate method. It must be considered that this method requires much more precise equipment to measure the surfaces' dimensions and optical properties. However, this low-cost analysis demonstrated that results did not differ excessively to justify the use of the 5PH. Relatively to the solar models, DISC has the highest fraction of DNI and indoor illuminances, which agrees well with this lighting model that tends to underpredict. Contrarily, the Perez model produces the lowest *DNI* and indoor illuminances, which are essential in analyzing the lighting conditions that collections are exposed to. Therefore, the use of at least two models to compare results is recommended.

Despite results being for a heritage library, the adopted methodology can be replicated in other historic buildings, thus generalizing the findings. For other types of buildings, further research is recommended. Any building with a complex façade, detailed overhang shadings with complex geometry and materials, or façades that dynamically change over time, would require other matrix methods, for instance, the 4PH or 6PH models.

5. Conclusion

Approaches to carry out daylighting simulation in heritage buildings are most of the times skipped and not well documented in most studies. The need to clarify what are the most appropriate simulation methods in this type of buildings motivated the development of the present work. This study compared matrix methods and solar models to determine the most accurate combination when validating a lighting model of a heritage library. The building's natural lighting was simulated using the 2PH, 3PH, and 5PH methods and the BRL, DISC, Perez, and Reindl solar models to decompose *GHI*. The purpose was to determine a cost-effective lighting simulation, which could be applicable to other case studies.

Relatively to matrix methods, the results indicate that the 2PH method presented the best values, while 3PH could be an alternative in parametric analysis. The 5PH method did not significantly improve accuracy because the method requires precise tools to measure optical properties of materials and solar contributions (*DNI* and *DHI*), which are expensive and not easily accessible to designers and engineers.

The comparison between the solar models indicates that at least two should be used, even when the results are not meaningfully different. From all the tested solar models, DISC performed the best due to the higher prediction of the *DNI*. The best combination was 2PH-DISC, which presented average MBE_r and $RMSE_r$ of 2.8 % and 43.6 %, respectively. By comparing with the thresholds found in literature, the validation of the model was achieved, even though the optical properties of surface materials and dimensional simplification of the building geometry were deduced. Therefore, a cost-effective monitoring campaign may be used for validating lighting simulation of heritage buildings if using a good combination of matrix methods and solar models. The methodology proposed in the present study may be replicated in similar case studies, which will allow reaching a standardized simulation procedure and establish validation thresholds for lighting simulation in heritage buildings.

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References

[1] M. Ayoub, 100 Years of daylighting : A chronological review of daylight prediction and calculation methods, Solar Energy 194 (2019) 360–390. doi:`10.1016/j.solener.2019.10.072`.

[2] I. Turan, A. Chegut, D. Fink, C. Reinhart, The value of daylight in office spaces, Building and Environment 168 (2020) 106503. doi:`10.1016/j.buildenv.2019.106503`.

[3] R. M. Reffat, R. M. Ahmad, Determination of optimal energy-efficient integrated daylighting systems into building windows, Solar Energy 209 (2020) 258–277. doi:`10.1016/j.solener.2020.08.086`.

[4] P. B. Purup, S. Petersen, Research framework for development of building performance simulation tools for early design stages, Automation in Construction 109 (2020). doi:`10.1016/j.autcon.2019.102966`.

[5] M. Ayoub, A review on light transport algorithms and simulation tools to model daylighting inside buildings, Solar Energy 198 (2020) 623–642. doi:`10.1016/j.solener.2020.02.018`.

[6] N. Lechner, Heating, Cooling, Lighting, Sustainable Desing Methods for Architects, 4th edt ed., Wiley, Hoboken, New Jersey, 2015.

[7] M. Ayoub, A review on machine learning algorithms to predict daylighting inside buildings, Solar Energy 202 (2020) 249–275. doi:`10.1016/j.solener.2020.03.104`.

[8] J. M. Almodovar-Melendo, J. M. Cabeza-Lainez, I. Rodriguez-Cunill, Lighting features in historical buildings: Scientific analysis of the Church of Saint Louis of the Frenchmen in Sevilla, Sustainability (Switzerland) 10 (2018). doi:`10.3390/su10093352`.

[9] J. M. Del Hoyo-Meléndez, M. F. Mecklenburg, M. T. Doménech-Carbó, An evaluation of daylight distribution as an initial preventive conservation measure at two Smithsonian Institution Museums, Washington DC, USA, Journal of Cultural Heritage 12 (2011) 54–64. doi:`10.1016/j.culher.2010.05.003`.

[10] S. Mayorga Pinilla, D. Vázquez Moliní, A. Álvarez Fernández-Balbuena, G. Hernández Raboso, J. A. Herráez, M. Azcutia, Á. García Botella, Advanced daylighting evaluation applied to cultural heritage buildings and museums: Application to the cloister of Santa Maria El Paular, Renewable Energy 85 (2016) 1362–1370. doi:`10.1016/j.renene.2015.07.011`.

[11] K. A. Al-Sallal, A. R. AbouElhamd, M. B. Dalmouk, UAE heritage buildings converted into museums: Evaluation of daylighting effectiveness and potential risks on artifacts and visual comfort, Energy and Buildings (2018) 333–359. doi:`10.1016/j.enbuild.2018.06.067`.

[12] F. Leccese, G. Salvadori, G. Tambellini, Z. T. Kazanasmaz, Application of climate-based daylight simulation to assess lighting conditions of space and artworks in historical buildings: the case study of cetacean gallery of the Monumental Charterhouse of Calci, Journal of Cultural Heritage (2020). doi:`10.1016/j.culher.2020.06.010`.

[13] IESNA, The Lighting Handbook - 10th Edition, 2011.

[14] CEN, CEN/TS 16163:2014 Conservation of Cultural Heritage – Guidelines and procedures for choosing appropriate lighting for indoor exhibitions (2014) 1–24.

[15] P. Tregenza, J. Mardaljevic, Daylighting buildings: Standards and the needs of the designer, Lighting Research and Technology 50 (2018) 63–79. doi:`10.1177/1477153517740611`.

[16] S. Subramaniam, Parametric modeling strategies for efficient annual analysis of daylight in buildings, 2018. URL: `https://www.researchgate.net/publication/325248582_Parametric_modeling_strategies_for_efficient_annual_analysis_of_daylight_in_buildings`.

[17] M. Ayoub, Self-organizing profiles to characterize representative temporal settings for daylight simulations, Solar Energy 214 (2021) 248–267. doi:`10.1016/j.solener.2020.11.051`.

[18] D. H. Li, A review of daylight illuminance determinations and energy implications, Applied Energy 87 (2010) 2109–2118. doi:`10.1016/j.apenergy.2010.03.004`.

[19] C. A. Gueymard, J. A. Ruiz-Arias, Validation of direct normal irradiance predictions under arid conditions: A review of radiative models and their turbidity-dependent performance, Renewable and Sustainable Energy Reviews 45 (2015) 379–396. doi:`10.1016/j.rser.2015.01.065`.

[20] WenminQin, L. Wang, C. A. Gueymard, M. Bilal, A. Lin, J. Wei, M. Zhang, X. Yang, Constructing a gridded direct normal irradiance dataset in China during 1981–2014, Renewable and Sustainable Energy Reviews 131 (2020) 110004. doi:`10.1016/j.rser.2020.110004`.

[21] E. Abyad, Modeled Estimates of Solar Direct Normal Irradiance and Diffuse Horizontal Irradiance in Different Terrestrial Locations, Ph.D. thesis, University of Ottawa, 2017.

[22] E. F. Abreu, P. Canhoto, M. J. Costa, Prediction of diffuse horizontal irradiance using a new climate zone model, Renewable and Sustainable Energy Reviews 110 (2019) 28–42. doi:`10.1016/j.rser.2019.04.055`.

[23] D. S. Lee, J. H. Jo, Application of simple sky and building models for the evaluation of solar irradiance distribution at indoor locations in buildings, Building and Environment (2021) 107840. URL: `https://doi.org/10.1016/j.buildenv.2021.107840`. doi:`10.1016/j.buildenv.2021.107840`.

[24] L. D. Pereira, A. R. Gaspar, J. J. Costa, Assessment of the indoor environmental conditions of a baroque library in Portugal, Energy Procedia 133 (2017) 257–267. doi:`10.1016/j.egypro.2017.09.385`.

[25] N. Ahmad, S. Sh Ahmad, A. Talib, Luminous exposures and light-fastness survey in daylit historical museum galleries under tropical sky conditions, Advanced Materials Research 488-489 (2012) 1547–1552. doi:`10.4028/www.scientific.net/AMR.488-489.1547`.

[26] C. Balocco, G. Volante, A method for sustainable lighting, preventive conservation, energy design and technology-Lighting a historical church converted into a university library, Sustainability (Switzerland) 11 (2019) 1–17. doi:`10.3390/su11113145`.

[27] A. Jacobs, JALOXA: RADIANCE colour picker, 2013. URL: `https://www.jaloxa.eu/resources/radiance/colour{_}picker/`.

[28] E. Brembilla, C. J. Hopfe, J. Mardaljevic, Influence of input reflectance values on climate- based daylight metrics using sensitivity analysis, Journal of Building Performance Simulation (2018). doi:`10.1080/19401493.2017.1364786`.

[29] CEN, EN 12464-1 - Light and lighting — Lighting of work places, Technical Report, European Standard, 2011.

[30] A. Tzempelikos, A review of optical properties of shading devices, Advances in Building Energy Research 2 (2008) 211–239. doi:`10.3763/aber.2008.0207`.

[31] N. Kotey, J. L. Wright, M. Collins, Determining off-normal solar optical properties of drapery fabrics, ASHRAE Transactions 115 PART 2 (2009) 3–17. URL: `https://uwaterloo.ca/solar-thermal-research-laboratory/sites/ca.solar-thermal-research-laboratory/files/uploads/files/ash_fabricprops_bw400.pdf`.

[32] P. R. Treguenza, I. M. Waters, Daylight coefficients, Lighting Research & Technology (1983) 65–71. doi:`10.1177/096032718301500201`.

[33] M. Saxena, G. Ward, T. Perry, L. Heschong, R. Higa, Dynamic Radiance - Predicting Annual Daylighting with Variable Fenestration Optics using BSDFS, In: 4th national conference of IBPSA-USA, 11– 13 August 2010 New York City, New York. (2010) 402–409. URL: `http://www.ibpsa.us/pub/simbuild2010/papers/SB10-DOC-TS08A-01-Saxena.pdf`.

[34] E. Brembilla, J. Mardaljevic, Climate-Based Daylight Modelling for compliance verification: Benchmarking multiple state-of-the-art methods, Building and Environment 158 (2019) 151–164. doi:`10.1016/j.buildenv.2019.04.051`.

[35] G. J. Ward, Out of plane shading, 14th International Radiance Workshop (2015). URL: `https://www.radiance-online.org/community/workshops/2015-philadelphia/presentations/day1/OutOfPlaneShading.pdf`.

[36] J. Mardaljevic, Daylight simulation: validation, sky models and daylight coefficients (2000). URL: `https://repository.lboro.ac.uk/articles/thesis/`.

[37] G. Ward, R. Mistrick, E. S. Lee, A. McNeil, J. Jonsson, Simulating the daylight performance of complex fenestration systems using bidirectional scattering distribution functions within radiance, LEUKOS - Journal of Illuminating Engineering Society of North America 7 (2011) 241–261. doi:`10.1080/15502724.2011.10732150`.

[38] D. Geisler-Moroder, E. S. Lee, G. J. Ward, Validation of the Five-Phase Method for Simulating Complex Fenestration Systems with Radiance against Field Measurements (2017) 1808–1816. URL: `https://eta.lbl.gov/publications/validation-five-phase-method`.

[39] E. S. Lee, D. Geisler-Moroder, G. Ward, Modeling the direct sun component in buildings using matrix algebraic approaches: Methods and validation, Solar Energy 160 (2018) 380–395. doi:`10.1016/j.solener.2017.12.029`.

[40] E. L. Maxwell, A Quasi-Physical Model for Converting Hourly Global Horizontal to Direct Normal lnsolation, Technical Report, Report SERI/TR-215-3087, Solar Energy Institute, Golden, CO, 1987. URL: `https://www.nrel.gov/docs/legosti/old/3087.pdf`.

[41] J. Boland, B. Ridley, B. Brown, Models of diffuse solar radiation, Renewable Energy 33 (2008) 575–584. doi:`10.1016/j.renene.2007.04.012`.

[42] D. T. Reindl, W. A. Beckman, D. J. A, Diffuse fraction correlations, Solar Energy 47 (1990) 311–312. doi:`10.1016/0038-092X(91)90123-E`.

[43] S. Dervishi, A. Mahdavi, Computing diffuse fraction of global horizontal solar radiation: A model comparison, Solar Energy 86 (2012) 1796–1802. doi:`10.1016/j.solener.2012.03.008`.

[44] J. Torres, M. De Blas, A. García, A. de Francisco, Comparative study of various models in estimating hourly diffuse solar irradiance, Renewable Energy 35 (2010) 1325–1332. doi:`10.1016/j.renene.2009.11.025`.

[45] C. Magarreiro, M. C. Brito, P. M. Soares, Assessment of diffuse radiation models for cloudy atmospheric conditions in the Azores region, Solar Energy 108 (2014) 538–547. doi:`10.1016/j.solener.2014.08.003`.

[46] C. Tomasi, P. B. H., Calculations of relative optical air masses for various aerosol types and minor gases in Arctic and Antarctic atmospheres, Journal of Geophysical Research: Atmospheres 119 (2014) 1363–1385. doi:`10.1002/2013JD020600`.

[47] R. Perez, P. Ineichen, R. Seals, J. Michalsky, R. Stewart, Modeling daylight availability and irradiance components from direct and global irradiance, Solar Energy 44 (1990) 271–289. doi:`10.1016/0038-092X(90)90055-H`.

[48] F. Kharvari, An empirical validation of daylighting tools: Assessing radiance parameters and simulation settings in Ladybug and Honeybee against field measurements, Solar Energy 207 (2020) 1021–1036. doi:`10.1016/j.solener.2020.07.054`.

[49] L. Santos, A. Leitão, L. Caldas, A comparison of two light-redirecting fenestration systems using a modified modeling technique for Radiance 3-phase method simulations, Solar Energy 161 (2018) 47–63. doi:`10.1016/j.solener.2017.12.020`.

[50] A. McNeil, E. S. Lee, A validation of the Radiance three-phase simulation method for modelling annual daylight performance of optically complex fenestration systems, Journal of Building Performance Simulation 6 (2012) 24–37. doi:`10.1080/19401493.2012.671852`.

[51] C. F. Reinhart, O. Walkenhorst, Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds, Energy and Buildings 33 (2001) 683–697. doi:`10.1016/S0378-7788(01)00058-5`.

[52] J. Mardaljevic, Validation of a lighting simulation program under real sky conditions, Lighting Research and

Technology 27 (1995) 181–188. doi:https://doi.org/10.1177/14771535950270040701.

[53] J. Osborne, Building a comprehensive dataset for the validation of daylight simulation software, using complex “real architecture”, 2012. URL: http://hdl.handle.net/10063/3054. doi:10063/3054.

[54] J. van Duijnhoven, M. P. Aarts, H. S. Kort, A. L. Rosemann, External validations of a non-obtrusive practical method to measure personal lighting conditions in offices, Building and Environment 134 (2018) 74–86. doi:10.1016/j.buildenv.2018.02.033.

[55] N. S. Shafavi, M. Tahsildoost, Z. S. Zomorodian, Investigation of illuminance-based metrics in predicting occupants' visual comfort (case study: Architecture design studios), Solar Energy 197 (2020) 111–125. doi:10.1016/j.solener.2019.12.051.

[56] E. Y. Y. Ng, L. K. Poh, W. Wei, T. Nagakura, Advanced lighting simulation in architectural design in the tropics, Automation in Construction 10 (2001) 365–379. doi:10.1016/S0926-5805(00)00053-4.

[57] M. Bacci, C. Cucci, A. A. Mencaglia, A. G. Mignani, S. Porcinai, Calibration and use of photosensitive materials for light monitoring in museums: Blue Wool Standard 1 as a case study, Studies in Conservation 49 (2004) 85–98. doi:10.1179/sic.2004.49.2.85.

[58] C. S. Kim, S. J. Chung, Daylighting simulation as an architectural design process in museums installed with toplights, Building and Environment 46 (2011) 210–222. doi:10.1016/j.buildenv.2010.07.015.

[59] G. Ciampi, A. Rosato, M. Scorpio, S. Sibilio, Daylighting contribution for energy saving in a historical building, Energy Procedia 78 (2015) 1257–1262. doi:10.1016/j.egypro.2015.11.270.

[60] C. Balocco, D. Paganini, E. Marmonti, Assessment of the luminous climate inside Historical, IEEE Xplore (2016) 1–6.

[61] F. Nocera, A. L. Faro, V. Costanzo, C. Raciti, Daylight performance of classrooms in a mediterranean school heritage building, Sustainability (Switzerland) 10 (2018). doi:10.3390/su10103705.

[62] M. Eldaidamony, A. A. Shetawy, Y. Serag, A. Elshater, Adapting Geographies of Gentrification in Egypt: Lesson Learned from Fatimid Cairo and Heliopolis, 2019. doi:10.1007/978-3-030-10871-7_5.

[63] A. H. Mahmoud, M. M. Elsharkawy, M. M. Marzouk, Experimental investigation of daylight performance in an adapted egyptian heritage building, Journal of Engineering and Applied Science 67 (2020) 1193–1212.

[64] CIE:171, Technical report - Test cases to assess the accuracy of lighting computer programs, Technical Report, ISSN: 978 3 901906 47 3, Vienna, Austria, 2006. URL: https://cie.co.at/publications/test-cases-assess-accuracy-lighting-computer-programs.