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EXPERIMENTAL INVESTIGATION OF DAYLIGHT PERFORMANCE IN AN ADAPTED EGYPTIAN HERITAGE BUILDING

A. H. MAHMOUD[1], M. M. ElSHARKAWY[2] AND M. M. MARZOUK[3]

ABSTRACT

Skylights are widely utilized in buildings to improve daylighting conditions for deep spaces. However, the majority of skylights in historical spaces are not efficiently designed to adapt to public reuse and they uncover challenges in satisfying daylight requirements of potential visitors. This paper investigates a case of an old historical palace located in Cairo, Egypt, originally designed as a residence. The reuse purpose is a public museum where daylight plays an important experiential dimension, which makes it more challenging to adjust to the new daylighting conditions. In this study, adequacy of daylight is tested and verified with a developed comprehensive simulation model based on Daysim, for investigating the daily illuminance levels for fixed points on a 5×5 m grid. Comparative analysis is performed between simulation results and actual palace lux readings taken on the same created grid for the different skylight affected floor levels. Finally, the most significant skylight influential factors on the daylight performance are discussed for further skylight redesign with optimum performance.

KEYWORDS: Daylight analysis, Experimental measurements, Skylight, Daily simulation, Arid climate

1. INTRODUCTION

Adaptive reuse of historical buildings is by all means critical. Since the originally intended design function is altered, retrofitting must consider adaptation with minimum design interventions to maintain the originality of the building. It is important to enhance efficient daylighting into these spaces, for the economic consequence of heritage values salvage, material hub rescue, utility costs savings, and the environmental benefit of relying on a sustainable source of energy. The positive physiological impact of utilizing daylight on occupants remains most significant for being able to reflect the heritage beauty in a pleasant, healthy, and tranquillizing

[1] Professor, Department of Architecture, Faculty of Engineering, Cairo University, Giza, Egypt.
[2] Ph.D. Candidate, Department of Architecture, Faculty of Engineering, Cairo University, Giza, Egypt, maryam.sharkawy@hotamil.com
[3] Professor, Structural Engineering Department, Faculty of Engineering, Cairo University, Giza, Egypt.

setting. However, few publications addressed the significance of daylight in adapted museum spaces, and mostly focused on energy reduction [1-3]; neglecting the fact that occupant's visual comfort is as fundamental as thermal comfort in all building spaces [4].

Although successful heritage reuse and adapted museums have been widely adopted in many European countries, few addressed enhanced reuse in tough hot arid climatic conditions. Daylighting design in desert climate is challenging for the high possibility of non-uniform solar distribution and discomfort arising from daylight intensity. Thus, daylight availability has negative consequences on visual comfort if not efficiently integrated into design. A historical palace located in Cairo, Egypt is examined for adaptive reuse. The palace could be used as a museum for artifacts, and thus daylight design is more challenging [5, 6]. A daylighting simulation study focuses on the crumbled skylight of the palace, in which the skylight rebuild should fit the new purpose and provide appropriate daylighting conditions for visitors.

Diva and Grasshopper software packages are utilized to validate simulation and experimental readings through a comparative analysis between both lux measurements for the affected skylight floor zones, which contributes to evaluate the lux calibration values to be generalized to similar palaces in arid climates. The methodology was previously adopted in studies that focused on new buildings and small ones [7, 8], but few handled validation studies on deteriorated large historical spaces; which is the focus of the study. The second part of the paper investigates the efficient daylight influential factors for the palace skylight redesign. The impact of well-designed skylights in terms of daylight adequacy and visual comfort has been highlighted in multiple studies [3, 4, 6]. Figure 1 depicts different identified skylight shapes, which are utilized in buildings [9].

It is worth noting that adapted museum design daylight aspects create an additional challenge to minimize lux exposure values [5]. As such, this study provides a comprehensive daylight analysis and guidance for adapted reuse of similar adapted museum cases located in arid climatic conditions with skylight openings. The study is essential especially in the case of an old historical space in which anticipation of daylight performance may vary according to improper fitting and material translation in the simulation software.

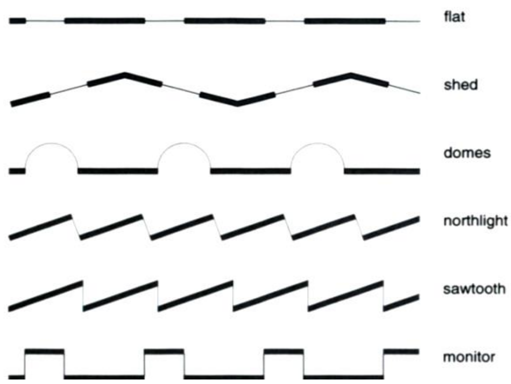


Fig. 1. Different skylight shapes [9].

The historical challenge dimension extends to the fact that meeting daylight limits is critical to preservation purposes [23] and that historical interior beauty should be reflected with charming daylight. Annual simulation uses a different daylight model and requires time to calculate the varying input values along the varied annual sky conditions. However, it requires abstraction of data but still they are able to reflect real conditions in most cases [10, 11].

2. LITERATURE REVIEW

Retrofitting of heritage buildings is a common goal when ongoing refurbishment for efficient reuse. Retrofits were widely investigated by researchers that solely target energy reductions [12-14]. Historical retrofitting as a process involves gathering related nonphysical information such as intended reuse purpose, electricity consumption, and occupation density before proceeding with any retrofit intervention that was highlighted as being preliminary [15]. Also, heritage buildings recommended for retrofitting should have minimum façade interventions to minimize the impact on the physical appearance and to save the originality of the building [14, 15]. Dealing with heritage in Egypt has been challenging in terms of preservation, restoration and enhancement. However, the significant role of technology has enhanced the efficiency of reutilization of heritage buildings [1]. Environmental performance in buildings has been recently assessed using reliable simulation methods with the aid of technological advances, software, tools, and accurate BIM models creation. This resulted in prompt growth of the digitalization assessing methods. The daylighting and solar gain in residential spaces was investigated to perform an efficient optimization strategy to assess the influence of different design factors on performance in order to reach the most effective combination of design parameters in terms of maximum utilization of efficient daylighting and minimum solar gain potential [16]. An energy assessment technique was adopted to explore design variables in an attempt to validate experimental measurements with simulated ones, emphasizing the higher accuracy of daily simulation on annual simulation. The differences between simulations results retrieved from different simulation software were presented and it was suggested to consider social behavioral differences between occupants in the spaces and to identify the parameters that contributed to reforming the performance gap [17].

In a retrofit study, the significance of artifacts protection is indicated to provide visual comfort at recommended illuminance levels. The daylight performance of a flat ceiling and a pitched roof ceiling model of a historical museum were compared and it was found that better illuminance distribution was obtained for the pitched roof [3]. The effect of different skylight design parameters on building performance was studied using a parametric method to provide 100 different design solutions and assess those in Useful Daylight Illuminance (UDI) and Energy Use Intensity (EUI) [18]. It has been recommended that the effective skylight to floor ratio (SFR) should range between 4-10% and energy reductions were varied according to building type, glazing type, climate, and light control method [19]. In a regular office ceiling, a skylight opening with 7% skylight to floor ratio (SFR) was added with a slated light well, to examine and simulate the proposed design to enhance daylighting [20]. Glazing sizing in atrium spaces were discussed, indicating that the most difficult sized are those with rectangular shapes. The relationship between daylight performance and the visual comfort in building space was revealed to aid decision makers [21].

Experimental and simulation studies have been widely compared to evaluate the accuracy of the utilized simulation software. Simulation methods to assess daylighting in spaces usually provide higher illuminance values than from experimental measurements [22]. The Kriging method was used to provide effective daylight prediction that saves annual simulation time. They compared different daylight simulation engines to the prediction method in different sky cover conditions of the year [10]. Different daylight dynamic and static metrics were criticized and evaluated in assessing human perceived daylight in classroom spaces where it was found that Spatial Daylight Autonomy (sDA) and Annual Solar Exposure (ASE) are more indicative [22]. Previous research indicated the significance of adjusted skylight in increasing daylight adequacy in spaces, but those mostly lack information on enhancing reused skylights in adapted conditions and daylight analysis has never been thoroughly analyzed.

3. RESEARCH FRAMEWORK

This study is conducted to investigate the daylight performance in an arid climate of the skylight of an Egyptian heritage palace. The methodology adopted is depicted in Fig. 2. First, a validation model is generated to compare the daily simulation component to the experimental component in a systematic procedure, where the analysis of general daylight trends and daylight unruly issues is formulated to provide guidance for similar cases.

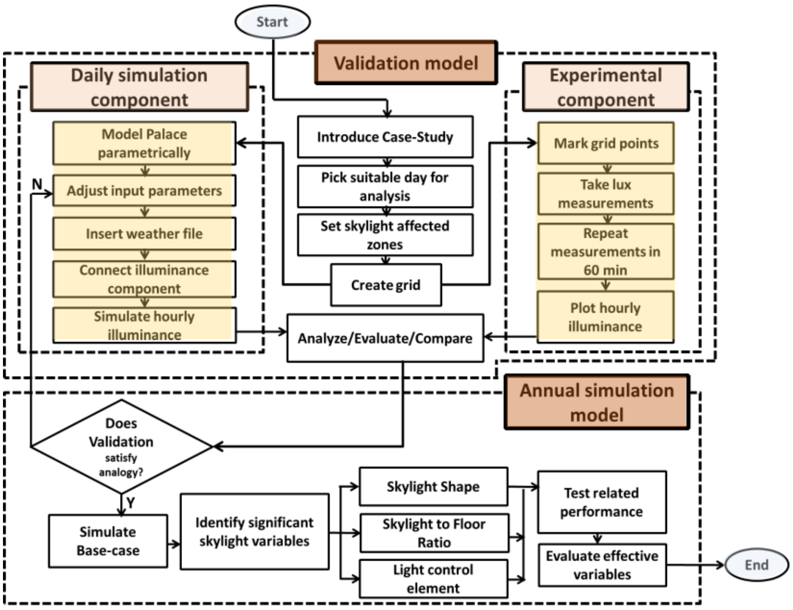


Fig. 2. Methodology flowchart.

The annual simulation model is then created to perform base case daylight analysis, identify significant skylight variables, and evaluate skylight influential parameters. Those are considered finding keys to assist in any further configuration of the noted skylight optimally in such climatic conditions.

4. CASE STUDY: TOSSON PALACE

An Egyptian adapted palace located in Shubra, Cairo, Egypt is investigated for possible reuse. It was built in the 19th century for Prince Omar Tosson. The palace front façade and entrance are shown in Fig. 3a. The palace incorporates a huge broken skylight covering the main staircase and affecting the daylight of adjacent halls as shown in Fig. 3b. The palace structure is currently unoccupied and has been abandoned for years. The palace interior encompasses a huge main hall with arched marble columns and a baffled wooden ceiling as shown in Fig. 3c. The floor plans are shown in Fig. 3d in which the skylight area utilized for analysis in this study is highlighted.

4.1 Simulation Settings

The palace main hall is parametrically modeled using Grasshopper plugin for the Rhinoceros software and simulated with radiance via Diva-for-Rhino using Cairo, Egypt climate data. The palace parameters are summarized in Table 1 while the radiance settings used in the simulation are given in Table 2, adopted from [23].

Table 1. Palace model parameters.

Building size, m	13H×38W×88L
Floor numbers	2
Internal surfaces materials and reflectance [9]	
Walls medium colored internal-walls	50%
Ceiling off-white colored ceiling	80%
Floor generic floor	20%

Table 2. Radiance simulation settings [23].

Ambient bounce	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution
6	1000	20	0.1	300

a. Palace Entrance

b. Skylight and stair case

c. Ground Main hall

d. Ground and first floor plans

Fig. 3. Tosson palace description.

4.2 Daylight Climatic Conditions

Connection with the nearest weather station of Cairo, Egypt, allows accurate simulation for the palace existing conditions. Figure 4 illustrates the direct radiation, diffused radiation, and sky cover condition for the selected location during the different months of the year. The hours of total darkness are shaded in black and the hours of day light are shaded in light grey. Direct radiation extensively occurs in clear sky conditions in which there are few blocking components for the sunrays. As a result, there is high availability of unpleasant direct daylighting that usually cause glare inside spaces. That gives a broad image of the positive and negative aspects of the available daylight conditions. The sun path is analyzed for the palace on the 21st of December, Fig. 5a and on the 21st of June, Fig. 5b at 9:00 am and at 4:00 pm, respectively to reveal the summer and winter sun angles.

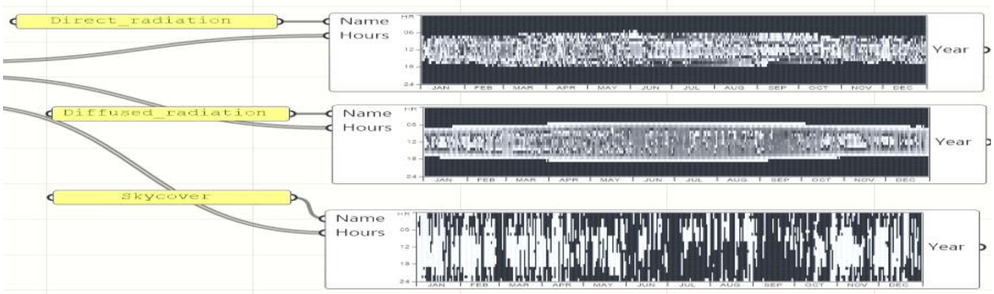
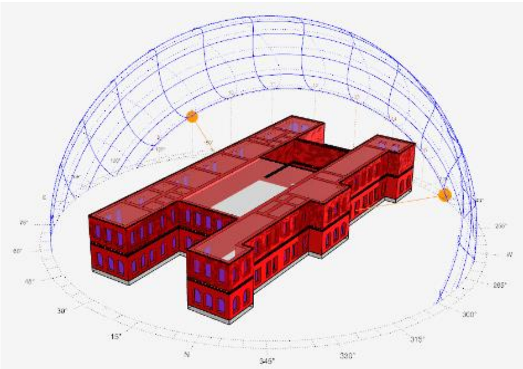


Fig. 4. Direct and diffused sunlight radiation schedule in Cairo, Egypt.


a. winter sun angles

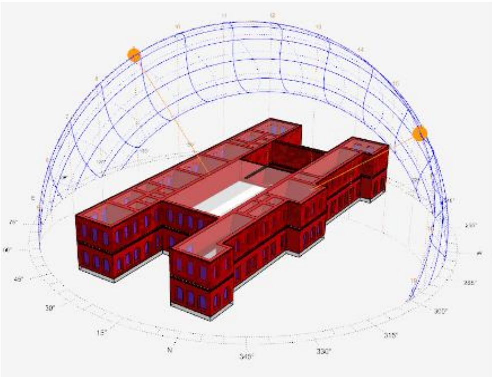

b. summer sun angles

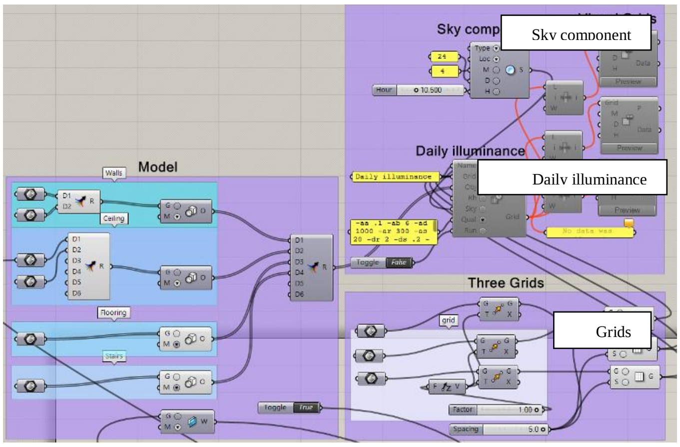
Fig. 5. Sun path diagram for the palace.

5. EXPERIMENTAL STUDY PROCEDURE

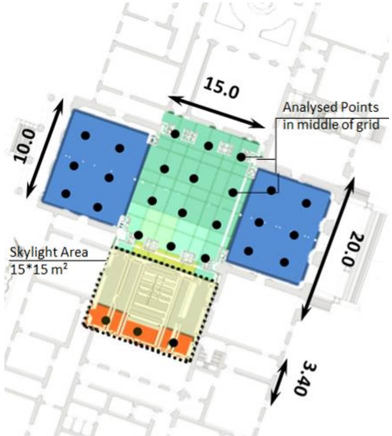
This study compares the daily lux measurements with the simulated measurements to validate the effectiveness of the software in providing accurate daylight readings for such conditions to be used as calibration values. It is significant to avoid taking measurements on days of unexpected weather conditions. Also, summer months are avoided where high lux readings might overpass the lux-meter limits (50,000 lux) and provide misleading results. Real conditions are illustrated in the software to ensure similar material conditions.

5.1 Daily Simulation

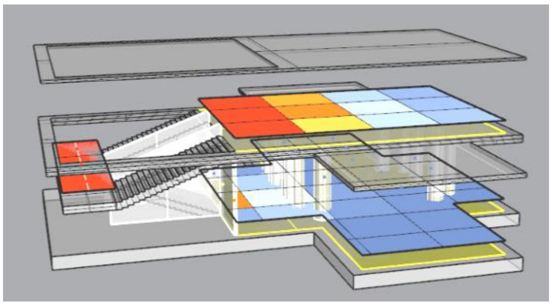
The simulation is performed on the clear sunny sky cover on 24/04/2019, Cairo, Egypt. A grasshopper script is adjusted according to the exact field measurements conditions, to reflect the same physical conditions (sky conditions, and time of the day). Materials' reflectivity are adjusted manually in the software to account for the old flooring and other surfaces indicated in Table 1, which is an attempt to translate material effectively using visual match with material data [9]. As shown in Fig. 6a, the script is previously connected with the model for daily illuminance simulation. Illuminance output is visualized on the three grids connected to the three floor levels and based on the average dimensions of 10×15×20 m a grid module 5×5m is shown in Fig. 6b and Fig. 6c. From the color tones represented on the analyzed floor grids in Fig. 6d, it is seen that grid points located near the skylight have higher lux values (Red), and points further away from the light source decrease gradually in illumination (Blue). Skylight affected floor zones are addressed in three separate distinct areas for daylight analysis that covered the ground, first, and intermediate floors, which included 28, 11, and 3 points respectively.



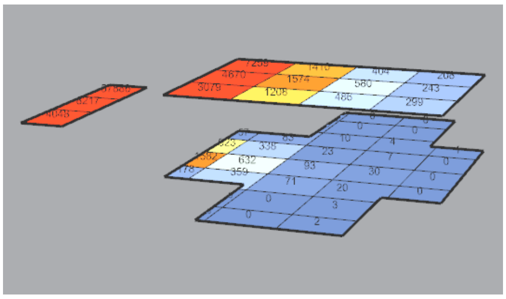
a. Grasshopper script



b. Main hall floor dimensions



c. Affected stairs, hall, and floor levels



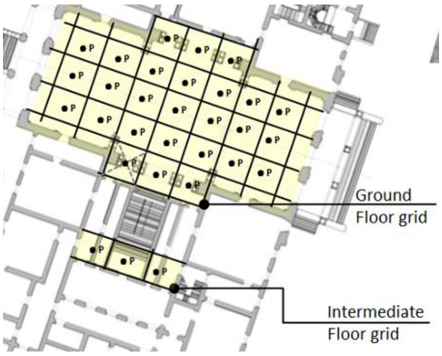
d. Grid and lux points

Fig. 6. Simulation model

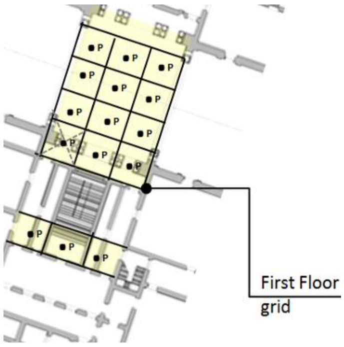
5.2 Measurement Procedure

The illuminance measurements are taken on the same selected day for the simulation, namely 24/04/2019. A 5×5 m grid is first created on the three floor levels as shown in Fig. 7b and 7c (similar to that grid created by the parametric model) in a maximum area of 15×30 m^2. Increasing the grid or points will cause time lag. The grid center points are marked with a colored tape on the floor and numbered. A high stool 1:00 m high is moved on each floor mark, carrying the lux meter device (LX-105 Lutron) shown in Fig. 7a. This meter provides instant lux readings at each identified location position. The illuminance measured in lux is to be recorded at intervals of 60 minutes between 8:30 to 14:30 during the day at the same marked points. After taking lux readings for all the marked points in the three floors, another reading round follows in the following hour and so on.

a. Lux meter device



b. ground and intermediate grids

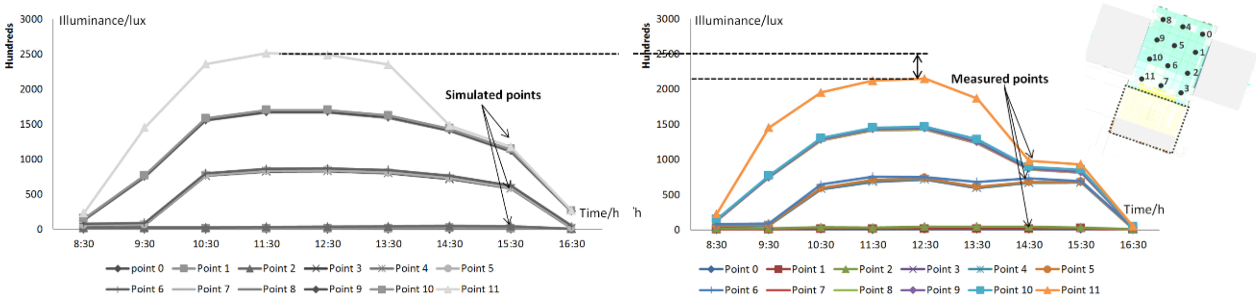


c. first floor grid

Fig. 7. Experimental tools.

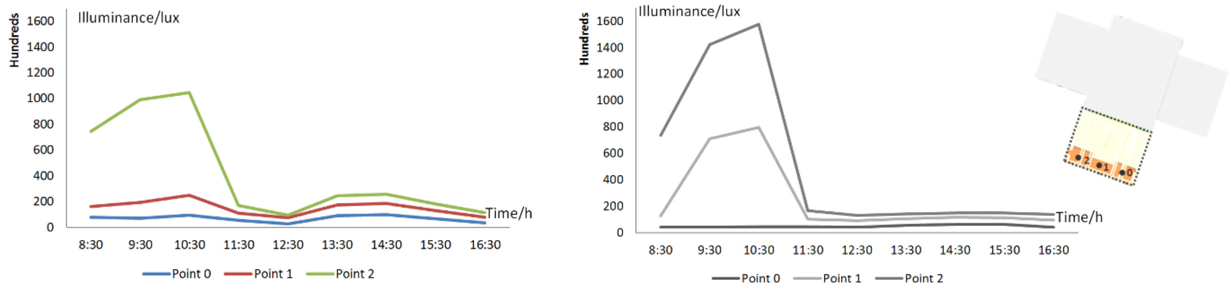
6. EXPERIMENTAL AND SIMULATION RESULTS

In the validation study, a comparative analysis is performed between the simulated and measured data for the illumination values of the affected points. In each floor, marked points are given numbers to identify their location within the plan as indicated in the plan key provided in Figs. 8-10 respectively. The first-floor plan simulated and measured readings are compared. Figure 9a shows the simulated values and Fig. 9b shows the measured values for the 12 points that are assessed every hour during a single day. The overall trend of each single assessed point during the day, i.e. from 8:30 to 16:30 is shown below in Fig. 8a and Fig. 8b. Each curve represents the lux journey of a single point during the day, showing the peak hours at 11:30 and 12:30. The simulated ground floor results in Fig. 8a are very close to the measured ground Floor results shown in Fig. 8b. The highest simulated point at 12:30 pm was higher than the measured point with 400 lux. Also, the measured results show steeper curves at lower lux levels in the afternoon at 14:30 and at 15:30 pm than the simulated results. Simulated results of the intermediate floor plan analysis of lux points is graphically represented in Fig. 9a and the measured readings are shown in Fig. 9b. Both are relatively similar in trend shape. The assessed 3 lux points are low at the early morning, peak at 10:30 and drop within an hour at 11:30 then fluctuates. Also, the largest difference in Fig. 9a and 9b appears in the simulated value of (point 2) with 500 lux higher than the measured values, but the measured values appear higher at lower diffused daylight levels shown at 13:30 and 14:30 by almost a 100 lux variation.



a. Simulated Results b. Measured results

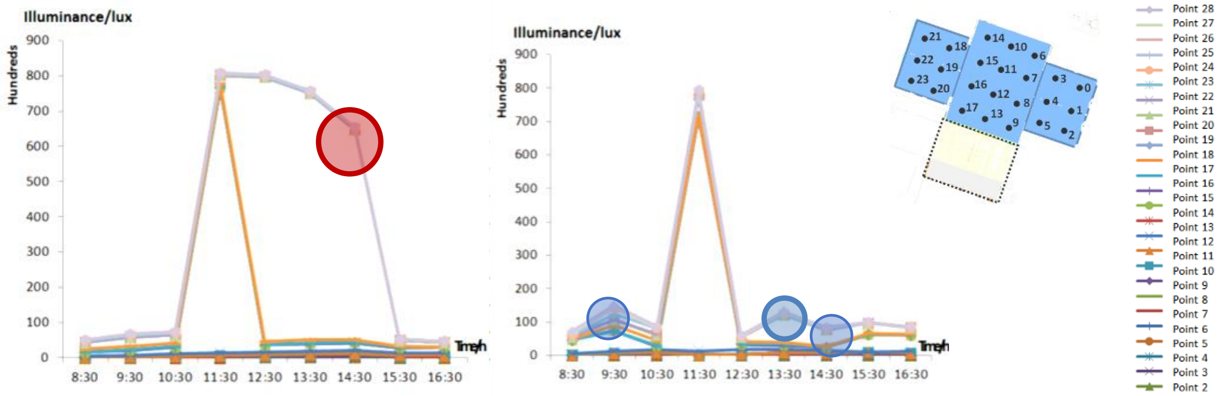
Fig. 8. First floor assessed results in lux on 24/04/2019.



a. Simulated Results b. Measured results

Fig. 9. Intermediate floor assessed results in lux on 24/04/2019.

The ground floor plan simulated results are shown in Fig. 10a. It is seen that the peak lux occurs at 11:30 a.m. in all points. However, there are slight differences in the overall shape between the simulated and the measured results as shown in Fig. 10a and Fig. 10b, respectively. The series of several points shows an error or a substantial difference in the afternoon readings between the simulated and measured lux values. A different trend in some simulated points highlighted in red reflects the success of the simulated afternoon sun angle from the skylight in reaching deeper points.

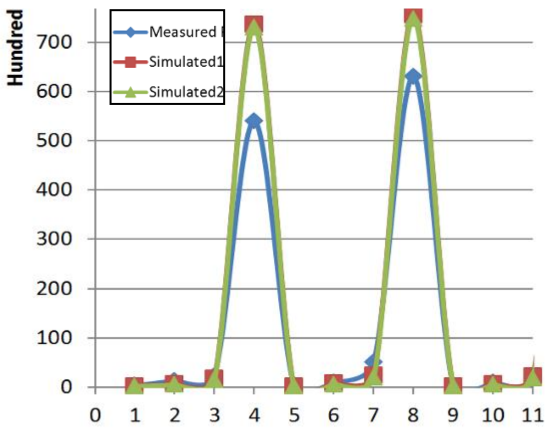


a. Simulated Results b. Measured results

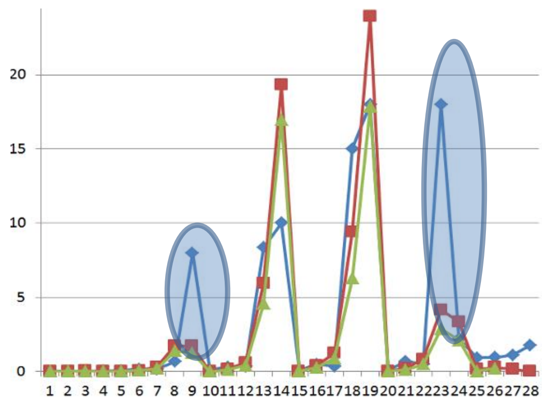
Fig. 10. Ground floor assessed results in Lux on 24/04/2019.

When the sun succeeds in going deeper in the low sun angles of afternoon i.e., at 13:30, 14:30 and 15:30 in the simulation results, there is a smooth decrease in the lux values which reflect the gradual decrease of the sun angle. In the measured points however, diffused daylight was blocked due unknown reason. Figure 10a and Fig. 10b show high differences in the ground floor simulated and measured values at accordingly it is recommended to rely mainly on the other floor grids in further simulations and ignore the ground floor simulations as they are not indicative for the current case and are invalid. Also, some light managed to escape from non-tightly external windows and doors which resulted in higher lux fluctuation readings in both the early morning and afternoon with average 60 lux difference at early low sun angle at 9:30 a.m. and average 30 lux difference during afternoon hours.

Comprehensively, these lux values give an overall comparison and progress image of the daylighting in the palace, but a single hour is selected to provide closer image on the daylight performance. The assessed lux points on 24/04/2019 at 10:30 a.m. are taken as a sample of the evaluated floors in the study is provided in first and ground floors in Figs. 11a and 11b, respectively. In Figure 11a, the measured and simulated values of the tested points are highlighted in blue and red curves respectively. The two lux peaks represent the points located near the skylight affected area on the first floor (i.e. the area closest to the skylight), in which high differences in values reach 26.6% and 16.5%. Apparently, the simulated values are closely similar to the measured values in all points that depend on the amount of diffused daylight from the skylight. The simulated points show relatively higher values i.e. average 10 lux than the measured ones in most assessed points and the difference gap increase with the increase of direct daylight on the assessed points with an average of 150 lux. Only two peak points appear on the represented first floor, which give an idea of the limited number of points highly affected with the skylight daylight. The ground floor tested points are shown in Fig. 11b that reveals the lux level of each point in that specific hour where obvious differences between the simulated and measured points appear only at points closest to the skylight. Those points (14 and 18) vary with maximum lux difference 49% and 24.7% respectively. The peak points reach maximum illuminance with an average 24 (hundred lux). On the other hand, there are two lower peak illuminance values at 8 and 17 (hundred lux) shown in points 9 and 23, respectively. There is a substantial increase in values of the measured points over the simulated ones and this indicates a possible error or a different interfering factor. However, in an attempt to enhance material reflectance translation into software values in Fig. 11, *Simulation 2* is performed with lower wall reflectance (35%) and ceiling reflectance (70%). The results indicate that points of *Simulation 2* are slightly lower compared to *Simulation 1* by almost 15% in most assessed points of the ground floor which makes them of improved match with measured values except in points exposed to direct sunlight. For more accurate material translation, multiple reflectivity measurements are to be taken in a further study to estimate the exact surface reflectance values.



a. First floor points



b. Ground floor points

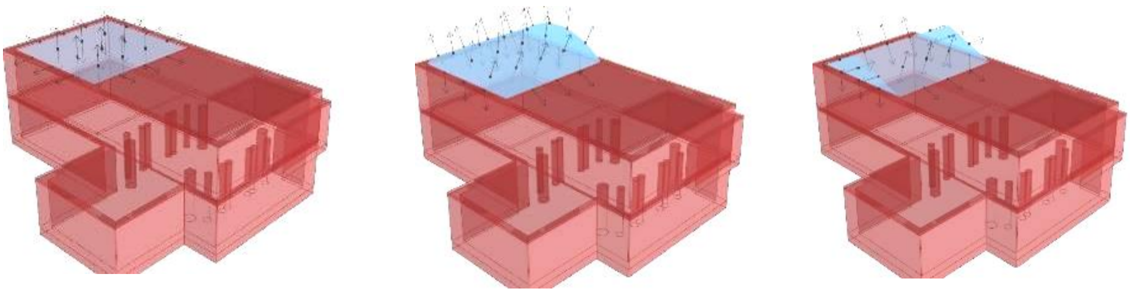
Fig. 11. Simulated and measured values at 10:30 am

7. ANNUAL DAYLIGHT ANALYSIS RESULTS

Annual daylight performance is analyzed for the palace to explore the possible capabilities of the current design and avoid the unpleasant daylight effect on occupants and building overall performance. Recent daylight evaluating metrics are utilized in the study such as sDA, ASE and UDI. Daylight glare probability (DGP) describes the vertical illuminance and is measured through a simplified daylight glare probability index that range daylight quality. Influencing factors on enhancing daylight performance of the skylight are explored. Those include the skylight form, skylight to floor ratio, and shading elements.

7.1 Influence of Skylight Form

Comparison for three main skylight shapes (Flat, Vault, and Pyramid) is applied in terms of daylighting as shown in Fig. 12. The effect of the three different proposed shapes on performance is shown in Fig. 13. The performance is measured and assessed in percentages of sDA, ASE, and UDI. It is seen that there are only slight differences in performance. This is because the effect of changing the skylight shape is not substantial and requires additional intervention. Neither the daylight quality (ASE) nor the daylight quantity (sDA) is improved. Even the UDI indicates the same time percentage of useful daylight in the year.



a. Base case b. Vault c. Pyramid

Fig. 12. Different proposed skylight shapes.

7.2 Influence of Skylight to Floor Ratio

Comparing two skylight to floor ratios as shown in Fig. 14. The first, is the base case with 100% skylight to floor ratio (SFR), with skylight area is all covered in (translucent surface/Glazing material). While the second, consists of an SFR of 30% glazed and 70% opaque roofing.

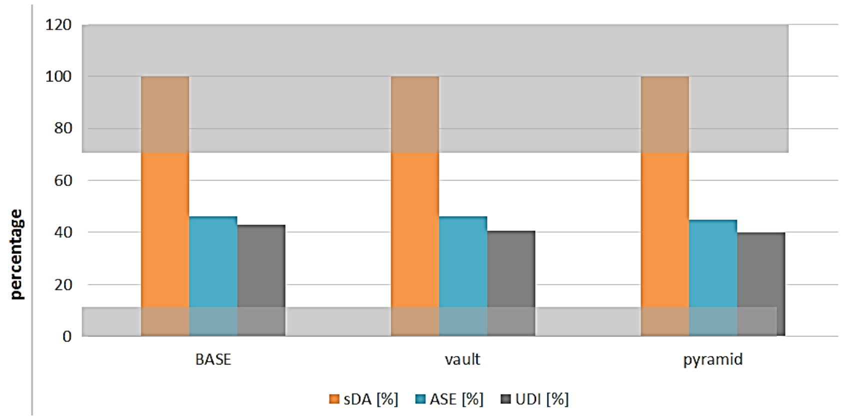


Fig. 13. Effect of three skylight shapes on performance.

There is a significant influence of SFR on sDA, and ASE % as shown below in Fig. 14, where a positive influence is attained on the daylight quality as a result of reduction of glare indicated by the ASE reduced percentages, that illustrates the significance of slicing and reducing the glazing area of the skylight in enhancing the daylight performance.

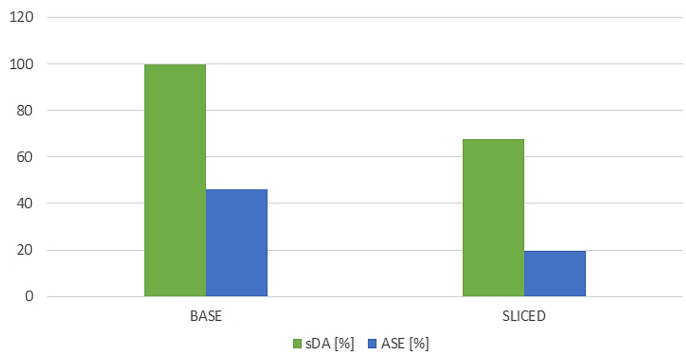
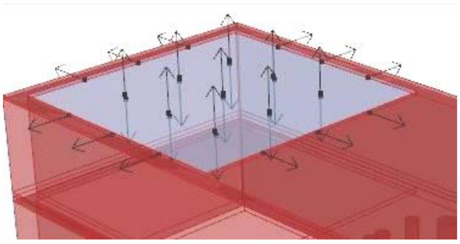


Fig. 14. Base case versus sliced case of simulated main hall.

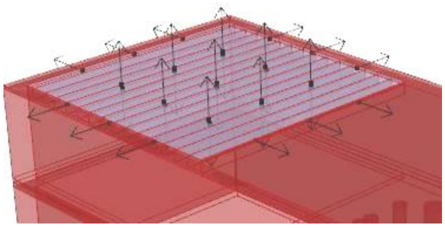
7.3 Influence of Skylight Additional Shading Elements

Additional shading elements to the current skylight is used to enhance palace overall daylight performance and block direct daylight in an attempt to enhance visual comfort. A series of 23 shading element spaced at 600 mm, with a depth 600m, thickness 20 mm and 1500 mm long are situated across the skylight area as shown in Fig. 15. The negative issue in the current daylight performance is high percentages of ASE values that indicate possibility of high glare occurrence in the simulated space.

To emphasize and illustrate the daylight problem indicated, annual glare analysis is provided to identify the glare level and time of occurrence during the months of the year. The glare view inside the skylight coverage area is visualized for the annual glare as shown in Fig. 16a and Fig. 16b, respectively using the glare probability index. It is seen that the glare level before the usage of shading elements is considered intolerable with a DGP greater than 0.45 in most months of the year shown in Fig. 16b. After the usage of the shading elements the DGP is considered acceptable ranging between 0.35 and 0.40 in most months of the year with higher concentrations in May and June.



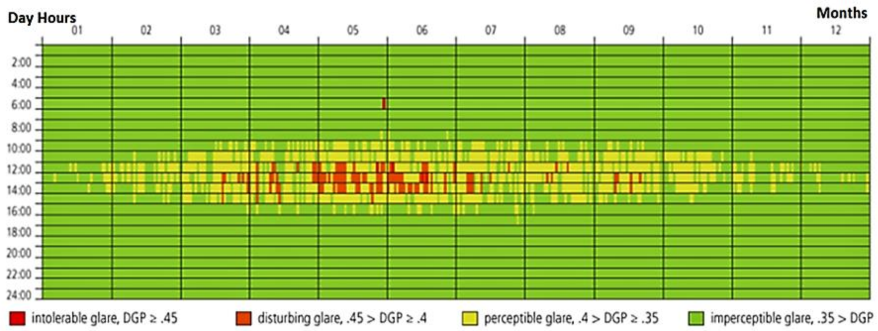
a. Without shading elements



b. With shading elements

Fig. 15. Different skylight configurations.

a. The palace current case



b. With additional shading elements

Fig. 16. Annual glare view angle and image for the skylight opening.

The annual glare graph reveals the significance of the shading elements in controlling and minimizing glare. However, this only solves the glare issue and would probably participate in lowering the adequacy of daylight in several year months, thus optimization is required to resolve the conflicting metrics.

8. DISCUSSION

This research focuses on enhancing daylight performance inside a heritage adapted museum space in hot climatic conditions. A validation analysis utilizing simulation and experimental daily lux measurements is performed to provide an overview of the daylight performance. It was found that simulation readings are relatively higher than measured readings. However, the ground floor measurement readings were surprisingly higher than the simulated values at points of direct daylight, which omitted the ground floor grid validity for performing further simulation studies. Error markup has been justified for four main reasons; the first is related to inaccurate translation of internal finishes within the model. The second reason is concerned with the presence of unfitted external windows and other façade openings, which acted as an additional daylight source in addition to the assessed skylight. The third reason is due to self-shadowing from the experimenter holding the device. Finally, the fourth reason is due to time lag in taking the measurements.

In the current case, non-uniform distribution of daylight resulted from direct solar radiation prevent the adapted reuse to satisfy the international illumination standards. The maximum illuminance level values [23] of 200 lux suitable for various types of exhibits is not satisfactory for Tosson palace as an adapted museum. The palace daylight availability is insufficient to achieve occupants' visual comfort where low daylight distribution with high intensity occur in the area covered with the skylight. Furthermore, the adopted strategy will aid in ensuring that the redesign will satisfy recommended daylight performance.

9. CONCLUSION

This research focuses on daylight analysis of skylights located in arid climates. The daylight validation procedure provides calibration values for typical cases. Subsequently, the procedure was enriched to explore possible daylight enhancements for skylight redesign parameters. The daylight experimental results revealed that simulation values are relatively higher than the measured values except for points of direct daylight. In addition, the explored skylight parameters covered different shapes, SFRs, and control elements that revealed that, skylight performance could be enhanced utilizing the influential parameters effectively. Furthermore, the strategy aids in ensuring that the redesign will satisfy recommended daylight exhibition levels, visual comfort, and enhanced daylight distribution. This research can be expanded in the future to consider sensitivity analysis for different daylight grid modules. It is recommended to accurately translate materials using spectrophotometer measurements.

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DECLARATION OF CONFLICT OF INTERESTS

The authors have declared no conflict of interests.

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تجارب دراسة تأثير اداء ضوء النهار في المباني التراثية معادة الاستخدام

يقدم البحث دراسة حالة لقصر عمر طوسون بالقاهرة وتفترض أنه سوف يتم إعادة استخدامه كمتحف مما يؤدى لصعوبة ضبط ظروف ضوء النهار وفقًا لمعايير التصميم الجديدة حيث تم تطوير نموذج محاكاة باستخدام برنامج Daysim للتحقق من مستويات الإضاءة اليومية للنقاط الثابتة على شبكة ذات أبعاد ٥ x٥ م واجراء دراسة مقارنة بين نتائج المحاكاة والقراءات الفعلية التي تم رصدها بالقصر و تحليل لأهم العوامل المؤثرة في قوة وجودة الضوء بالمباني المعاد استخدامها لتحديد الأداء الأمثل عند إعادة تصميم الفتحات العلوية.