



Optimizing daylight utilization of flat skylights in heritage buildings

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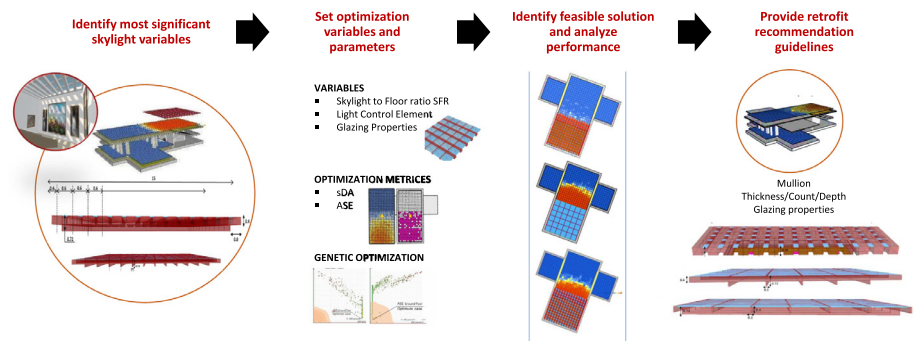
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HIGHLIGHTS

- Enhancing energy and daylight through different skylight configurations in heritage buildings.
- Assessing performance using Spatial Daylight Autonomy and Annual solar exposure.
- Optimization of skylight glazing technologies and skylight size genetic algorithms optimization.
- Exploring the flat skylight parameters that affect performance in hot climate zones.

GRAPHICAL ABSTRACT



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ABSTRACT

Introduction: Adapted reuse in old historical buildings has been a real challenge since the state of deterioration is usually found severe, and suggested retrofitting is applied with high delicacy to preserve the building originality. Additionally, on altering the potential users' activity, special considerations are required to fulfill the new needs. Daylight in historical buildings has a special significance in conceiving the massive artistic content within the interior spaces, in providing visual comfort for users, and affecting the total energy performance.

Objectives: The main goal is to meet the new daylight requirements in heritage building spaces, and to rely on relaxing daylight instead of artificial light sources during the day.

Methods: The research is implemented in Tosson Palace, a historical palace in Egypt, where a top-lit space's daylight performance is assessed using *Rhino + Grasshopper's Diva* package, then the skylight is parametrically configured to optimize daylighting conditions using *Radiance*, and *Daysim* engines in high intensity solar climate. Optimization of skylight glazing technologies and skylight size is conducted by changing optimization parameters including the number the two perpendicular mullions grid, and mullions' depth, which also acts as a shading element. These parameters are genetically optimized using a multi-objective *octopus* plugin and the optimized configuration is evaluated using LEED v4.1 in Spatial Daylight Autonomy (sDA), and Annual Sun Exposure (ASE) criteria that show both the daylight adequacy, and the comfortable daylight exposure percentages in the skylight covered space.

Results: The outcomes offer guidance for heritage adapted reuse in hot climatic conditions with minimum design interventions to meet the original design and provide potential users' comfort conditions.

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Furthermore, enhancement of both visual, and thermal conditions through the skylight configurations is to be studied.

Conclusion: The selected optimum case succeeded in compromising the assessing metrics such that ASE was reduced by 38% from the base-case, avoiding unpleasant direct daylight, and providing protection for interior artifacts from sunlight and achieving a moderate uniform daylight distribution on both affected floors levels.

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Introduction

Heritage is considered an extremely valuable asset, which makes it our duty to preserve for future generations. Old, neglected heritage structures might further expose the heritage to deterioration [1]. Thus, adaptive reuse of heritage is considered beneficial for the health of the structures [2] However, adapting to the new occupancy criteria is challenging, function switch, and the climatic fluctuation gave the material decay status while causing minimal change to maintain the originality of the historical structure. With the target of enhancing potential occupancy positive experience, aiming at providing day lit spaces that promote visual comfort without the compromise of identity loss is essential [3].

Large skylights provide a huge daylight inlet to the interior spaces, and proper opening design can enhance both visual, and thermal comfort as indicated by Eltaweel and Su [4], who proved that skylights can reduce solar gain by 30%, and energy consumption by 35% along with daylight adequacy in spaces located in hot climatic conditions such as New-Cairo, Egypt. Several researchers [5–7] emphasized the significance of the different design factors on enhancing daylight into spaces. Others explored skylights and top-lit openings' effect on daylight [8]. Acosta et al. [9] embraced the positive influence of optimized skylights on attaining high visual comfort and enhancing solar distribution into space. Critically in hot climatic zones where direct sunlight is dominant through the year and visual satisfaction is difficult [10–13]. Consequently, daylight optimization is adopted for a heritage space through parametric skylight configuration for the skylight glazing technology, Skylight to Floor Ratio (SFR), and internal light control element depth. This is achieved utilizing *Diva + Grasshopper* simulation software which is widely validated in research, and multi-objective genetic optimization plugin named *Octopus* to provide an optimum solution within Spatial Daylight Autonomy (sDA), and Annual Sunlight Exposure (ASE) attempting to increase sDA percentage as an indication for daylight adequacy and decrease ASE percentage as an indication for glare avoidance within LEED v4.1 criterion.

Heritage reuse has been widely studied in previous research, yet studies focused on green retrofitting, and energy usage [14], rather than focusing on occupancy comfort-oriented strategies. Indeed, the potential occupancy visual comfort will reassure the successful reuse of the heritage structure. Also, genetic algorithm optimization is recently used with new buildings, and rarely used with reused buildings design [15,16]. Optimizing the building skylight openings has not been intensively studied, as much as optimizing other building variables such as form, side-lit openings, building façade, and others, thus, this research area needs more exploration. Further investigation is required to find ways to improve daylight adequacy while attaining visual comfort using different configurations of a skylight. An Egyptian historical palace is studied for possible adapted reuse, situated in Cairo, Egypt, and previously occupied by Prince Omar Tosson. The palace is proposed for hosting museum visitors for its considerable artistic interior spaces; therefore, special daylight considerations are to be appraised that fit into the artifact preservation standards [17]. It

is still difficult to attain those daylight standards and provide day-lit comfortable user experience [18–20].

Environmental analysis of historical buildings has been emphasized globally to adopt on performing retrofit measures. This urged the usage of different building simulation software that is consistent with BIM. With the aid of such software, heritage originality has been easier to maintain with the fewest interventions to the original design while increasing the building performance [21–22]. Yu and Su [7] illustrated the daylight availability assessing methods in buildings, and the possible energy savings associated. They identified, and validated the main techniques utilized by researchers to conduct efficiency in buildings such as building simulation, field measurements, calibrated equations, and estimations based on external factors. Ahmad et al. [14] emphasized the significance of preserving the exhibit's artistic elements with attention to the illuminance exposure critical limits. They analyzed the possible roof interventions to a historical museum retrofit strategy as well. Differentiating the performance of the flat roof to the pitched roof in terms of daylighting, they measured the performance on 1.0 m level plane, identified for exhibition items level, in specific days of the year in which the results indicated the effectiveness of the pitched roof over the flat ceiling in enhancing daylight distribution, but the negative issue was that illuminance values were higher than the recommended limits, and a compromise decision was taken to use the flat roof instead to be able to preserve artistic items properly. Onuwe et al. [23] examined multiple museums in design to debate about daylight's importance in providing visual comfort and relaxing conditions for occupants and the fact that many museums depend on artificial lighting rather than daylighting to easier be able to control interior light levels. Pointing out the difficulty in turning old structures into museums, and the significance in averting direct sunlight penetration into museum spaces using upper windows or light shelves.

Zhang and Huang [24] optimized daylight conditions, thermal comfort, and energy consumption of an educational unit for the WWR, and glazing criteria. They utilized both *Daysim* and *Energy-Plus* engines to arrive at optimum compromised designs that illustrate the impact of each design variable on performance. Xue et al. [25] optimized thermal and daylight performance for a typical unit's different orientation and WWRs with the addition of a shading element referring to a base-case without the usage of shading elements. They deduced, and optimized WWR suitable for each orientation. Comparing the energy-saving, and the DF of each design combination. They concluded that combined shading elements are essential to reduce energy consumption in buildings. Oh et al. [26] optimized energy consumption, glare index, and comfortable illuminance to assess the performance of an electrochromic glazing technology in different locations. The study's results revealed the effectiveness of that glazing technology in Saudi Arabia for being able to reduce annual energy consumption by 19% while maintaining efficient solar radiation providence in space. Yu and Leng [27] optimized the design of a glazed skylight to achieve both the lowest energy consumption and highest daylight performance using three approaches that relied on integrating shades, inner blinds, and exterior blinds systems to the glazed skylight. They used

statistical analysis tools such as the analysis of variance (ANOVA), and regression method to uncover the optimal solutions. They realized that the exterior blinds' system with small sized slates, provides the highest performance for both objectives. Kheiri et al. [28] reviewed different optimization techniques applied to the building design variables in terms of energy conservation. Also, they emphasized the applicability of the genetic algorithms in performing building optimization problems through the widely used *Rhino + Grasshopper* which is considered 47% of current software users but mostly performed optimization on office, and educational spaces which highlights the research significance. Optimization approaches are recently utilized in multiple new building types but rarely used in adopted reuse structures. Reused heritage structure is considered a sensitive matter of analysis, and decision making is guarded with extensive considerations, and limits.

Fang and Cho [5] performed a parametric analysis for a retail skylight to analyze 100 design alternatives through their effect on energy consumption and efficient daylight distribution in space. They recommended maintaining a 3% Skylight to Floor Ratio (SFR), keeping the skylight area away from the roof edges as much as possible, avoiding high building depth, and ensuring low curb height. Also, suggested clearstory windows in northern, and southern facades with higher percentages than that of the eastern, and western facades. They finally used a sensitivity analysis to evaluate the percentage of influence of each skylight design variable, and provided that skylight size, and dimensions affect both daylight, and energy consumption. Erlendsson [29] identified the different factors affecting skylight performance which included sensors, shading, and light well, and insulation. They recommended the use of skylight to floor ratio within 4–10% which is identical to maintain low energy consumption with efficient daylight. However, energy savings vary with climatic variation, glazing technology, building type, and light control utilization. Cochran et al. [30] simulated multiple skylight designs for a commercial layout to evaluate their relative effect on energy consumption. Possible energy consumption reduction was achievable with a range of 0.8% to 14%, while light energy reduction was achievable with an average of 30%. Such results indicate the effect of shading elements on further reducing energy consumption by 2%. The authors also recommended utilizing a dynamic shading device to effectively utilize skylights with energy savings. Marzouk et al. [31] optimized tilted skylight configuration with additional light redirecting elements to enhance daylight performance inside interior spaces. They utilized sDA and ASE metrics to assess the quality of daylight in the attached halls to the skylight. The study ensured the applicability of multi-objective optimization approach in improving interior conditions. Also, Marzouk et al. [32] investigated the optimum skylight tilt angle and orientation with respect to thermal and visual efficiency utilizing the multi objective genetic approach, which prompts the use of the tested method in improving the performance of interior spaces. Dynamic openings were successfully adopted and applied in skylights [32,33]. Lee et al. [34] highlighted the significance of diffused reflection of lightshelves to interior spaces. They analyzed different design cases of lightshelves in varied seasons to assess the most suitable lightshelves' designs to achieve daylight performance.

Many similar approaches for enhancing daylight performance inside building spaces located in hot climates have been studied [11,12,13,31,32,35,36]. These studies are different in their utilized simulation method. El-Abd et al. [11] utilized genetic algorithms optimization in assessing skylight performance to reach improved daylight spaces by 12% and reduce glare by 5%. Also, Mazouk et al. [31] who identified the influence of light control elements on skylight performance, where improved daylight reached 56% and reduced glare reached 38%. In another study, the optimum skylight shape and apex orientation is highlighted with respect to daylight

enhanced performance [32]. In addition to, Kirimtat et al. [35] who optimized the the amorphous side openings' shading elements in office building spaces to maintain daylight availability above 50% with respect to energy savings. Other studies followed the brute force simulation method. For example, Eiz et al. [12] in assessing skylights for educational spaces that suggested East-West oriented skylight with 90° tilt angle provides optimum daylight exposure inside space and must be combined with additional glare reduction techniques. Also, another study led by Talip et al. [13] assessed the daylight performance in different openings' ratio for both courtyards and atriums, highlighting the significance of shading devices to reach improved daylight results. Lou et al. [36] suggested that a skylight ratio of 9% is preferable in air-conditioned spaces to maximize the use of daylight while reducing cooling loads. However, they are all slightly different in their objective metrics that may cover dynamic daylight metrics solely such as (UDI, sDA, ASE, etc.) or combined with energy assessment metrics such as kWh. [11,12,32]. But, they mostly encounter new building cases with either side or top lit openings that are not restricted to design. The challenge of old restricted designed skylights in historical buildings has been rarely tackled [14]. The main goal is to meet the new daylight requirements in the space, and to rely on daylight instead of artificial light sources during the day which is achieved through optimization of skylight glazing technologies, skylight size, determined by the number of the two perpendicular mullions grid, and mullions' depth, which also acts as a shading element, and are set as the two optimization parameters. These parameters are genetically optimized using a multi-objective octopus plugin in which the optimized configuration is evaluated using LEED v4.1 in Spatial Daylight Autonomy (sDA), and Annual Sun Exposure (ASE) criteria that reflect both the daylight adequacy, and the comfortable daylight exposure percentages in the skylight covered space. This study provides a novel approach in minimizing skylight design interventions in heritage spaces located in a hot climate, using a multi-objective genetic optimization method. The skylight mullion configuration is often implemented without the interest of its effect on daylight performance and is newly utilized in daylight performance enhancement.

Research methodology

In this study, an optimization model is created for a historical skylight configuration to arrive at optimum design configurations through four main stages (see Fig. 1): (1) identify most significant skylight variables, (2) set optimization variables and parameters, (3) identify feasible solutions and analyze performance, and (4) provide retrofit recommendation guidelines. Optimization parameters are selected relying on previous studies that emphasize their significance in enhancing daylight performance in top-lit spaces. Measuring the performance is to be done using Spatial Daylight Autonomy (sDA), and annual sun exposure ASE on both the ground, and first floor created grids on (+1:00 m) level, providing a total of four objectives through the study.

The Palace, which was previously introduced, and classified by Marzouk et al. [37], is located in Shubra, Cairo. The Historical Skylight to be analysed is situated on a second-floor level of +13 m inside Tossou Historical palace, in which the skylight covers the main staircase of the palace as shown in Fig. 2. Daylight performance inside the adjacent halls is directly affected by the skylight configurations that are investigated. The skylight total area is 225 square meters. while the affected hall size varies in each floor level where on the Ground floor, the affected area is 436 square meter, and the first-floor hall area is 336 square meter. Windows are kept closed in the simulation to rely only on the daylight from the

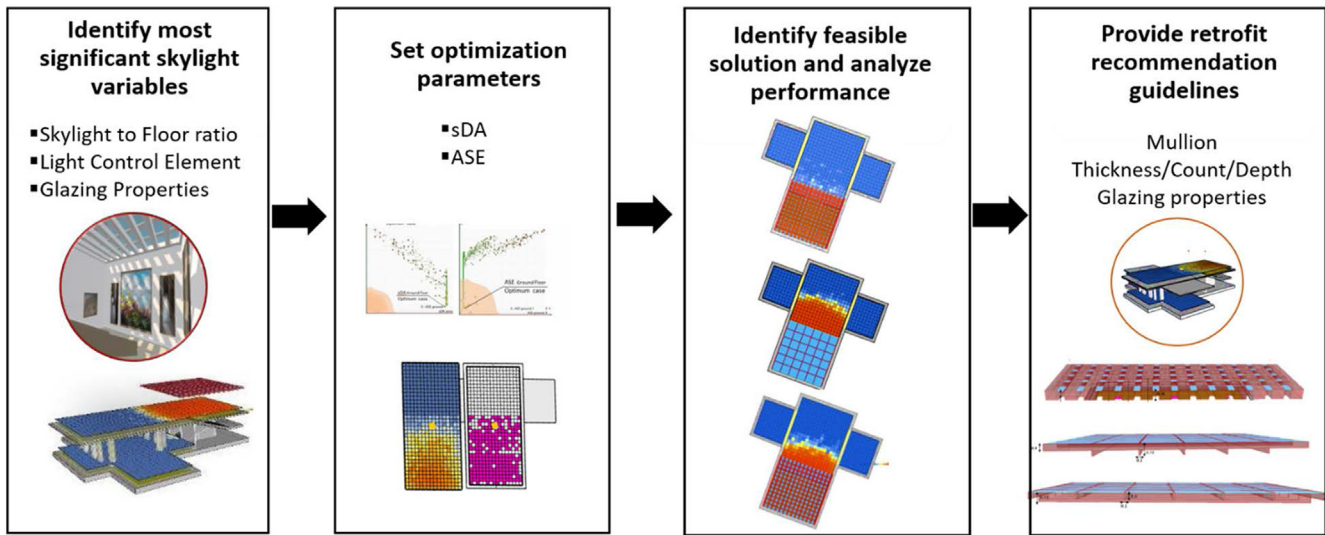


Fig. 1. Flowchart of adopted Research Methodology.

skylight source. The skylight shape is kept as flat as the original design to minimize design interventions.

Simulation and optimization

The Palace building, and the skylight opening are parametrically modelled with *Grasshopper + Rhinoceros* software as shown in Fig. 3 and simulated with *Radiance* through *Diva-for-Rhino* that used Cairo, Egypt climatic data. *Diva* Software is widely validated by many researchers [6,38,39]. The palace model is shown in Fig. 4a, and the daylight performance is obtained from *Diva* Software on a reference plane, +1.0 m for the main hall of the palace. In which the analysis points are distributed on a grid of 1.0*1.0 m as shown in Fig. 4b. The Optimization, and *Radiance* simulation settings are shown in Table 1, additionally, the table includes the internal material reflectivity affecting the palace daylight simulation.

A sun path diagram is performed for the palace to evaluate the sun angles affecting the skylight configuration. The software uses Cairo, Egypt climatic data to give an overview of the daylight inletting angle, and direction into the palace through the skylight as shown in Fig. 5. The daylight performance in the palace is assessed through the sDA, and ASE metrics; where an increase in the sDA percentage indicates an improvement in the illuminance levels, and the distribution of daylight. On the contrary to sDA, a decrease in the ASE percentage indicates the enhancement of visual comfort through the reduction of discomfort glare. LEED v4.1 provides the acceptable bench limits for maintaining suitable daylight adequacy in buildings indicating the sDA percentages to be greater than 75%, and the ASE percentages to be lower than 10% [41].

The attempt to optimize both conflicting objectives to enhance daylight into space without the loss of occupant visual comfort was carried out using multi-objective optimization to providing optimum compromised solutions. The Pareto-frontier shows the optimum compromised values for the different identified objectives in the case study to satisfy the multi-objective approach, which provides an optimum solution as a compromise of the measuring objectives, selecting the closest points to the Pareto-frontier origin as highlighted in red points as shown in Fig. 6. Where solution points that favour one objective rather than the other, would be located far from the origin but rather rafted towards the extreme end, close enough to one single objective as highlighted in grey for the x-axis or the y-axis as shown in Fig. 6. Where the objectives in our case are indicated by maximizing the sDA_{ground}, and

sDA_{first} which are the Spatial Daylight Autonomy for the ground and first floor grid, respectively, and minimizing the ASE_{ground} and ASE_{first} which are the Annual solar exposure for the ground, and first floor grid, respectively.

Considering a solution set for multi-objective optimization, a whole set of points that lies within the Pareto-frontier are called optimum solutions instead of selecting a single optimum solution point to propose varied options for stakeholders, and architects [42]. The skylight configuration for the base-case is assumed to be fully flat, single glazing with no visible mullions, where the current state is analysed on the created ground floor and first floor grids. sDA and ASE percentages are shown in Table 2, which are found to be below acceptable levels according to LEED v4.1. Also, shown in Fig. 7 are the visual representations for the base-case floor grids and the first-floor plan visuals for the ASE in Fig. 7a, and the Illuminance in Fig. 7b of the current skylight.

The proposed skylight shape is flat shaped to reflect the original design without substantial form interventions i.e., with minimum design interventions to maintain the originality of the historical palace. However, the investigated methodology allows a change in the skylight to floor ratio as the mullion thickness, and spacing change accordingly. Also, additional skylight shading elements' effect on daylight performance are evaluated via alteration of different mullion depths.

Glazing technologies

Glazing technologies are listed in the script below, each with their relative visible transmittance percentage ranging from high daylight transmittance at 88% to low daylight transmittance at 30%.

```
Glazing_SinglePanel_88
Glazing_Double pane_Clear_80
Glazing_Electrochromic_Clear_60
EC_Tinted_30
```

Mullion configuration

Vertical, and horizontal mullion configurations within the skylight vary independently in the following:

Mullion Spacing: changes by 0.2 m, ranging from 0.6 to 1.6 as maximum mullion spacing;



Fig. 2. Tossou Palace main staircase and above skylight (source:authors, 2019).

Thickness: increments by 0.1 m, ranging from 0.1 to 0.8 as a maximum mullion thickness;

Depth: increases by 0.04 m, ranging from 0.04 as a minimum and increases to 0.8 as a maximum mullion perpendicular depth.

As shown below in Table 3, the tackled parameters that are within minimum design modifications requirement by the Egyptian heritage authority and would participate in improving the daylight current performance inside the palace. The change in the mullions thickness, and count will result in a change in the skylight to floor ratio. The change in the mullion depth will result in creating a skylight light control element. Both the vertical mullions, and the horizontal mullions participate in blocking direct sunlight.

Results and discussion

The retrofit of a historical building is characterized by two main important aspects compared to the new building. The first aspect is

related to the retrofitting operation itself as the original material asset should be maintained in the case of the historical building. Whereas the second aspect is concerned with the historical building which should be maintained in a manner that keeps the originality of the asset with minimum change to the original structure. As such, the optimization study should adhere to the original form of the skylight as much as possible, even though a total change of the skylight form might result in more appealing optimum performance results.

The pareto-frontier points are the outcome of the genetic optimization process that shows the feasible solutions of the multi-objective optimization problem [42,43]. There were not indicative Pareto-frontier points formed by the population points through the optimization process where the red points indicate the Pareto front points (see Fig. 8). Those points cannot be accepted as optimum as they favor one objective over the other, resulting in unfavorable lighting conditions indoors. A straight line is formed from the population points which illustrated a strong inverse relationship within the analyzed objectives [43]. The shown line is formed from

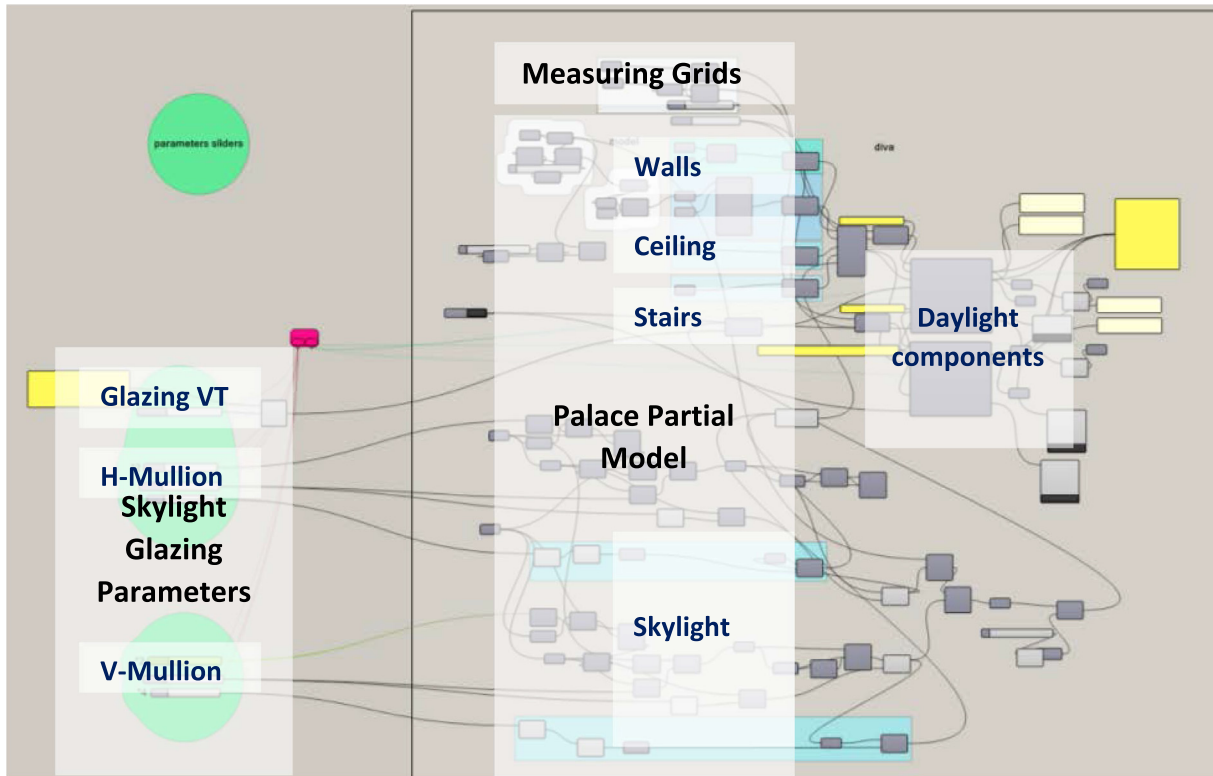


Fig. 3. Grasshopper script for skylight daylight analysis.

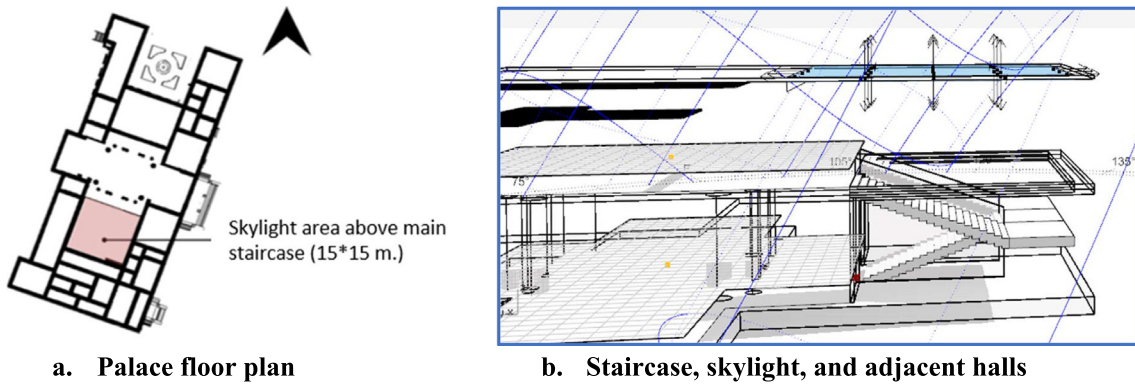


Fig. 4. Palace model description.

Table 1
Simulation and Optimization Parameters.

Optimization Settings	Elitism: 0.5 Mutation rate: 0.1 Crossover rate: 0.6 Population size: 100 Maximum no. of Generation: 100
Radiance Settings [40]	Ambient bounces: 6 Ambient division: 1000 Ambient sampling: 20 Ambient accuracy: 0.1 Ambient resolution: 300
Internal finishes reflectivity	Walls: 50% Floor: 20% Ceiling: 80%

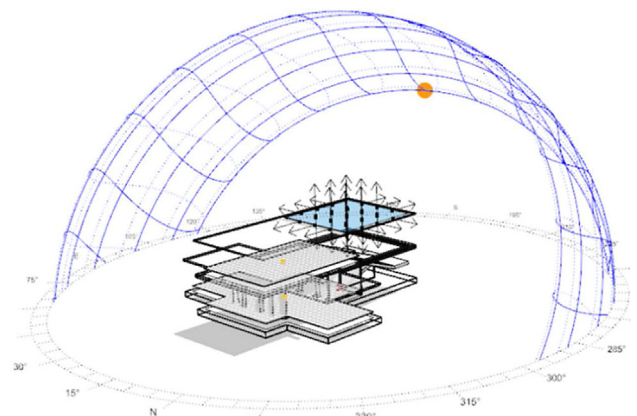


Fig. 5. Sun path diagram for the analyzed main hall of the palace.

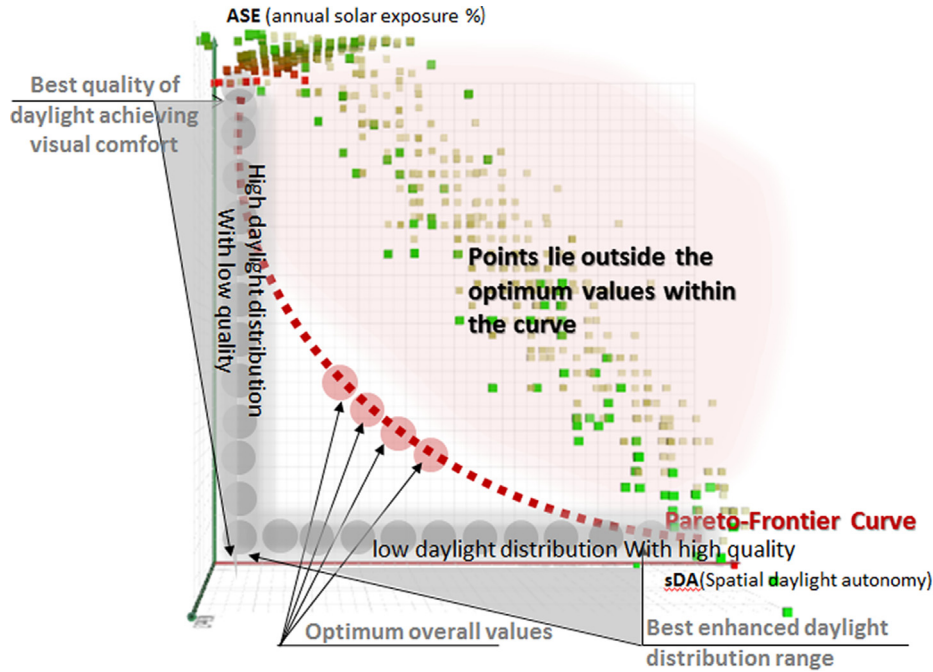


Fig. 6. Pareto-Frontier curve of the analyzed parameters.

Table 2
Base Case sDA and ASE levels.

Grid Floor Level	sDA(%)	ASE(%)
Ground	82	73
First	9.1	8.1

100 populations after 90 generations. The optimized solutions of skylight configurations concerning different objectives are shown in Fig. 8; as expected ASE, and sDA values show high conflict and a compromised solution is often difficult to attain [44].

In this study, the sDA and ASE are inversely proportional, especially for the first-floor results, as a straight line of multiple population points is formed as shown in Fig. 8a. Only optimum values of sDA, and ASE are shown on the graph, and no compromised values are present in the colored area where the Pareto frontier should have been formed. That inverse relationship is not as clear as on the ground floor results due to the weak effect of daylight in the lower floor area which is shown in Fig. 8b. However, comparing both floors' ASE percentages, some optimum points lie in the graph center to reveal the possibility of attaining a low ASE percentage effective for avoiding direct daylight on both floors. In the sDA percentages of both floors, the best values that achieve high

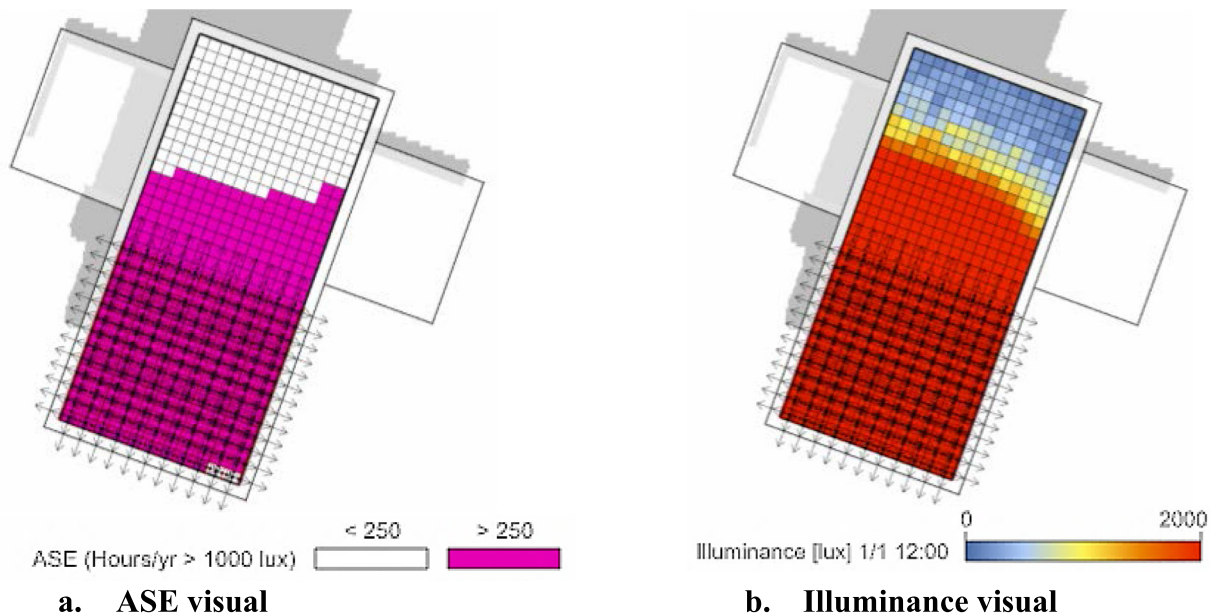


Fig. 7. Daylight performance visualization for the Base Case.

Table 3
Skylight variables.

Skylight Glazing type					
GLAZING	Single panel	Double panel	Electrochromic	tinted	No of Cases
Visible transmittance	88	80	60	30	4
Skylight Mullion configuration					
MULLION		Interval (meter)	Min value (meter)	Max value (meter)	No of Cases
Vertical	V. Spacing	0.2	0.6	1.6	6
	V. thickness	0.1	0.1	0.8	8
	V. Depth	0.04	0.04	0.8	20
Horizontal	H. Spacing	0.2	0.6	1.6	6
	H. thickness	0.1	0.1	0.8	8
	H. Depth	0.04	0.04	0.8	20
Total Sets	4 *6*8*20 *6*8*20				

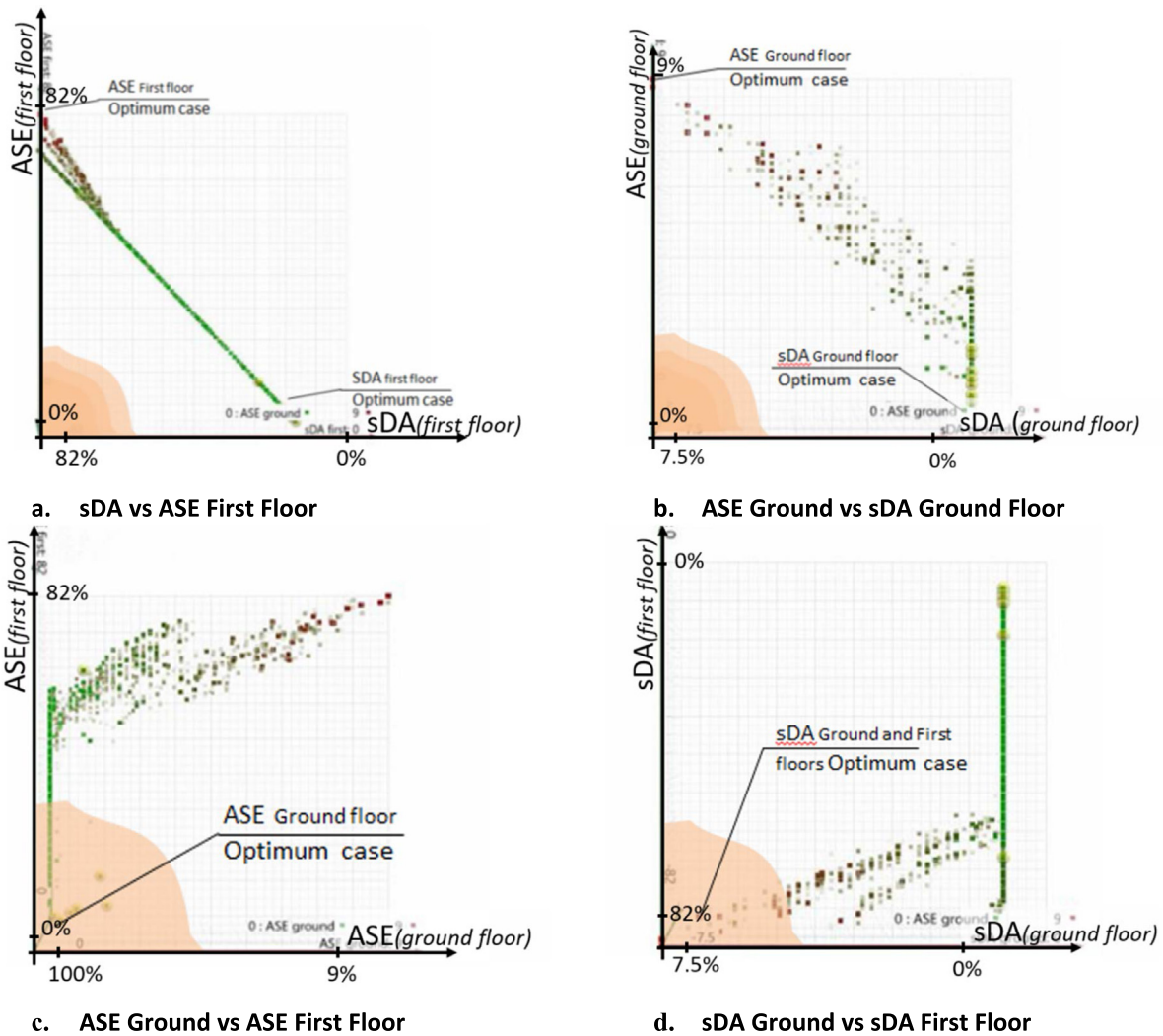


Fig. 8. 2D preview for the optimization results.

daylight efficiency could be provided through the graph shown in Fig. 8d.

The results of the analysis reveal the following:

- **The enhanced ASE** results are solely shown in Case 4, which comes along with a combination of tinted glazing, deep mullion (0.76 m, and 0.68 m), high thickness (0.8 m), and medium

spacing of 1.2-meter. These combinations of parameters are effective in decreasing the high intensity of daylight entering the interior space, thus improves visual comfort as shown in Fig. 11.

- **The enhanced sDA** results solely shown in Case 3, are described with Electrochromic clear glazing, and wide mullion spacing of 3.0-meter, mullion thickness 0.1 m, and depth of horizontal

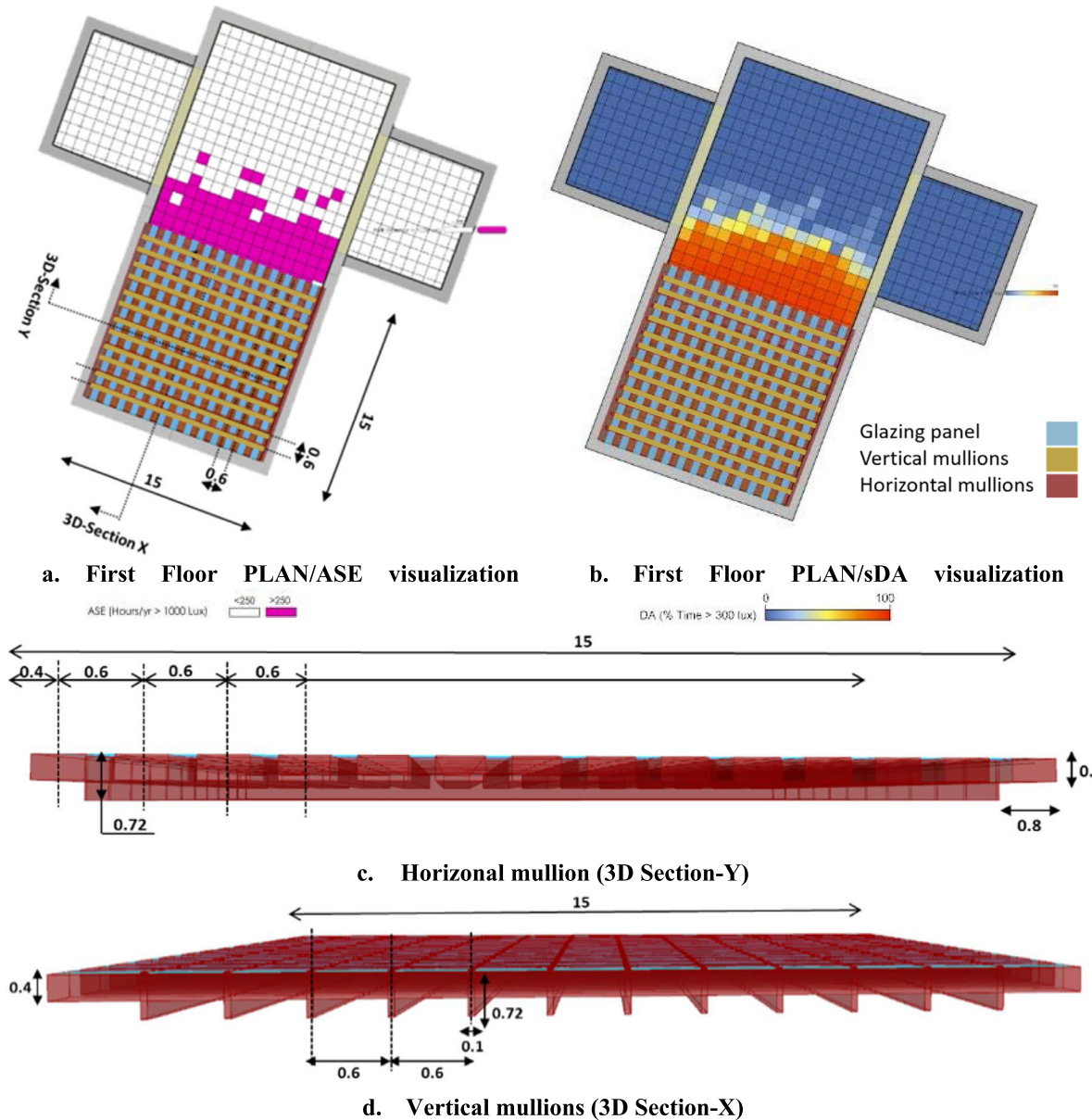


Fig. 9. Optimum compromised solution (Case 1).

mullion are 0.4 m, and vertical mullion 0.04 m. The visualization of the compromised results shown in Case 1 and Case 2 are comprehensively illustrated in Figs. 9 and 10, respectively.

- **The mullion effect on the results:** vertical, and horizontal mullions both participate in enhancing daylight conditions, but the vertical mullions are found with a stronger impact on the daylight performance as these are located perpendicularly to the daylight source direction.
- **Mullion Thickness** variation is effective in achieving compromised solutions as shown in Case 1, and 2. In Case 1, the horizontal thickness is maximized to 0.8 m, and the vertical thickness is minimized to 0.1 m. While in Case 2, the availability of higher glazing efficiency i.e., change of glazing from single pane to double pane cover the need for maximized horizontal thickness [26], and would require both vertical, and horizontal mullions to be of 0.1 m thick. Maximum mullion thickness

(0.8 m) is effective to provide solely visual comfort as in Case 4, and minimum thickness (0.1 m) is effective to provide solely adequate daylight as in Case 3.

- **Mullion Count** varies along with the change in the spacing between mullions in the study. Maximizing mullion spacing results in lower mullion count. Maximum spacing between both vertical, and horizontal mullion that reach 3.0 m in Case 3 provided the optimum results for sDA is shown in Fig. 10, but too much direct daylight is allowed into space. While the minimum spacing of 0.6 m in Case 1 surprisingly participates in providing successful compromised results between visual comfort, and daylight adequacy in space. In an attempt to avoid unpleasant direct daylight shown in Case 4, the mullion spacing is 1.2 m (medium spacing). In which the highest mullion count is provided to maximize visual comfort in spaces as illustrated in Fig. 11.

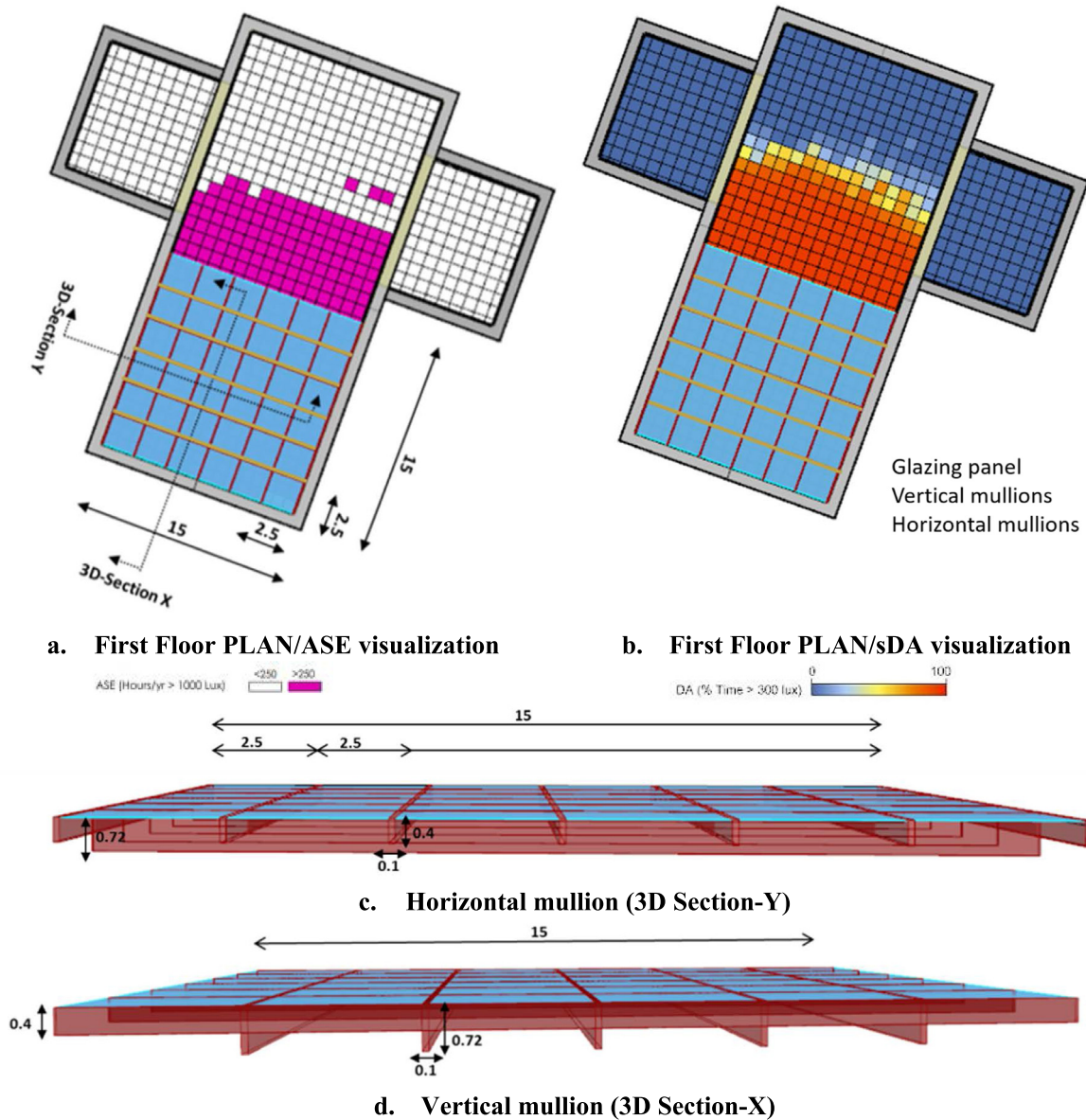


Fig. 10. Optimum compromised solution (Case 2).

- Mullion Depth** affects the provision of daylight into space. The vertical mullion increase in depth successfully contributes to appealing results (low ASE, and high sDA values). However, an increase in depth means blocking more daylight into space. The horizontal mullion increase in depth is more efficient in blocking direct sunlight as it is perpendicularly located in the direction of sunlight summer, and winter angles. Thus, in Case 1, where a compromised solution is achieved, the vertical mullion depth is higher than the horizontal mullion with 0.32 m, and in total 0.72 m while in Case 3, where only the effective daylight distribution is achieved without the provision of visual comfort represented in high sDA values, vertical mullion depth is minimized to 0.04 m, resulting in higher concentrates of daylight space. The attempt to achieve visual comfort by solely maximizing both vertical, and horizontal mullion depths is provided in Case 4 in which the vertical mullion reached 0.76 m, and the horizontal one reached 0.68 m, which is shown in Table 4.

- The glazing properties** affect both the sDA, and ASE values on the palace grids. The clear single, and double glazing are the only properties achieving compromised results that achieve both criteria of visual comfort, and daylight adequacy as illustrated in Figs. 9 and 10 respectively. On the other hand, in case of achieving visual comfort solely, Electrochromic tinted glazing VT 30% is utilized as in Case 4. In the case of high daylight adequacy with high sDA percentages, Electrochromic clear 60%. Single glazing panel optimum solution is considered the most efficient in providing a compromise between occupants' visual comfort, and daylight provision into space. Illustrated in Fig. 9, the configuration required dimensions, and data to be provided to stakeholders to assign upon construction.

However, utilizing the genetic optimization did not provide an optimum single solution rather than a range of solutions to choose from upon user preferences [43]. Also, performing the analysis on a

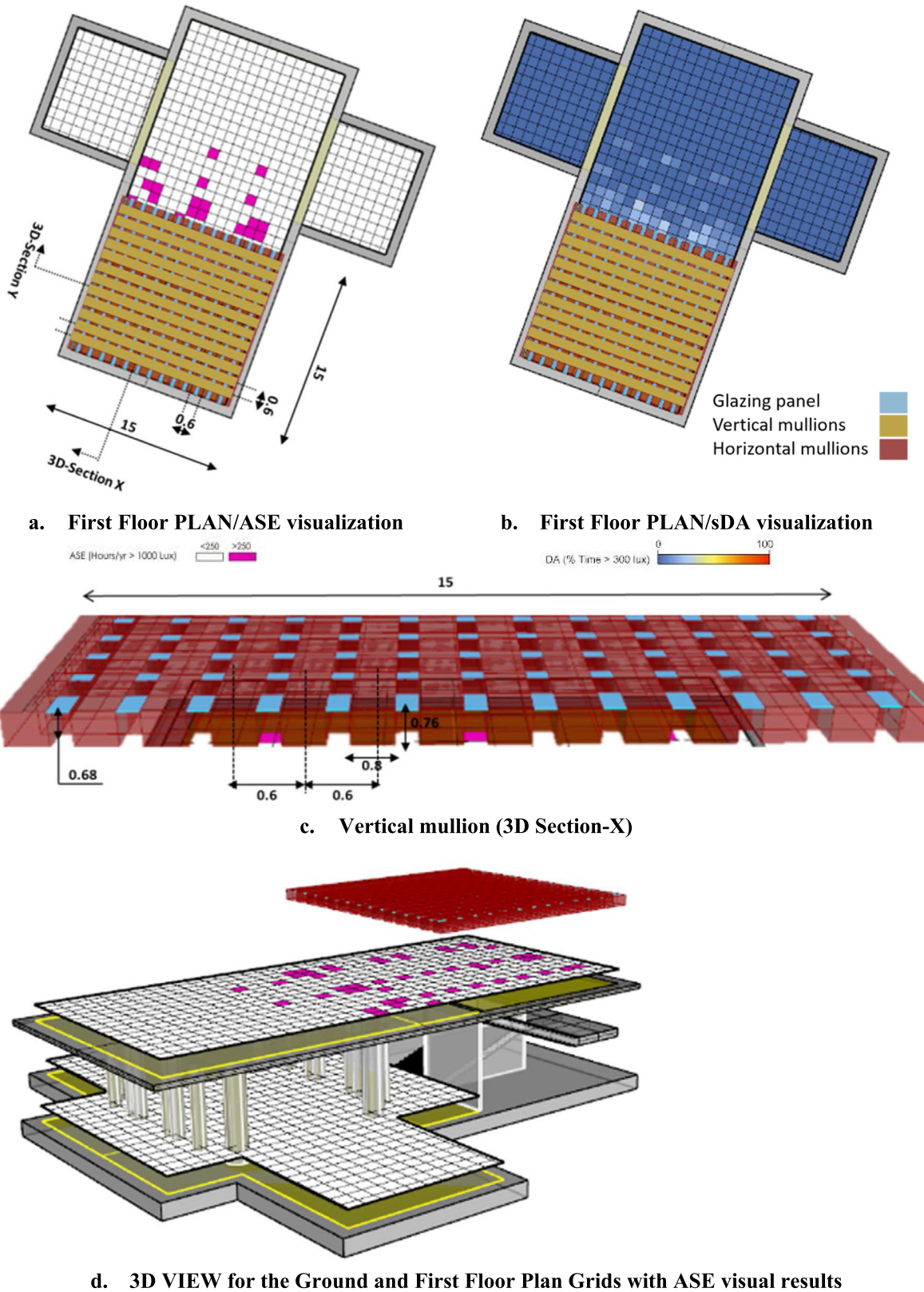


Fig. 11. Optimum visual comfort solution (Case 4).

single historical palace could be generalized only to similar building types in similar climatic conditions. The skylight mullion optimization study could be also applied to any building type located in similar climatic conditions, but the fact that the model is not

restricted to change, it is recommended to use the same model configurations, but with a defined tilt angle [32].

Suggestions to explore different skylights in different climatic conditions, and different sky-covers would be beneficial in further

Table 4
Optimized sDA, and ASE levels.

Case	Mullion parameters				Glazing	Objectives		Visual representation <small>DA (% Time > 300 lux) 0 100</small> <small>ASE (Hours/yr > 1000 Lux) <250 >250</small>
	M-D	M-T	M-P	M-S		G-T	sDA %	
1	H.	0.8	0.4	0.6	Single panel_88	0.0	1.0	
	V.	0.1	0.72	0.6		52.2	45.4	
2	H.	0.1	0.4	2.6	Double panel_clear_80	5.3	7.0	
	V.	0.1	0.72	2.6		71.3	66.9	
3	H	0.1	0.4	3.0	Electro chromic clear_clear_60	2.9	7.5	
	V	0.1	0.04	3.0		80	69.1	
4	H	0.8	0.68	0.6	EC Tinted_30	0	0	
	V	0.8	0.76	0.6		0	9.2	

Note:
M-D is Mullion Direction (meter), M-T is Mullion Thickness (meter), M-P is Mullion Depth (meter), M-S is Mullion Spacing from center point (meter), H. is Horizontal mullion, V. is Vertical mullion, and G-T is Glazing Technology.

Note: M–D is Mullion Direction (meter), M–T is Mullion Thickness (meter), M–P is Mullion Depth (meter), M–S is Mullion Spacing from center point (meter), H. is Horizontal mullion, V. is Vertical mullion, and G-T is Glazing Technology.

study. The study is also limited to daylight provision inside spaces, and that could be further enhanced with artificial light to provide the required illuminance levels.

Conclusion

Keeping the originality of the flat skylight while attempting to optimize its daylight performance is significant to the heritage value. However, flat skylights are not highly effective in providing optimum sDA and ASE inside building spaces in which enhancing daylight in flat skylight adjacent spaces require additional integration of shading system. The vertical and horizontal skylight mullion optimized parameters were able to improve the interior daylight conditions to a great extent, most significantly, the mullion depth which acted as efficient shading elements, vertically with average of 0.4 m and horizontally with an average of 0.72 m. Both the mullion thickness and mullion spacing were responsible for modifying the Skylight to Floor Ratio (SFR). Thus, a mullion thickness of 0.8 m combined with a mullion spacing with 0.6 m achieved the compromised optimum daylight conditions in terms of both metrics such as 52.2% sDA and 45.4% ASE for the first floor. The glazing technology mainly participated in improving the sDA conditions solely. However, the study effectively improved the ASE values by 38% from the base-case but crashed at improving the

sDA values. This is translated into the avoidance of unpleasant direct daylight, providence of protection for interior artifacts from sunlight and achieving a moderate uniform daylight distribution on both affected floors levels. This research can be extended in the future to incorporate the inclusion of a dynamic daylight control system to ensure high daylight uniformity in addition to the protection of interior artifacts as well as encountering both visual, and energy demand for the skylight configuration in heritage spaces.

Compliance with Ethics Requirements

All Institutional and National Guidelines for the care and use of animals (fisheries) were followed.

CRediT authorship contribution statement

Mohamed Marzouk: Conceptualization, Methodology, Supervision, Writing - review & editing, Funding acquisition. **Maryam ElSharkawy:** Visualization, Investigation, Validation, Writing - original draft. **Ayman Mahmoud:** Conceptualization, Methodology, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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