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Daylight Enhancement Strategies Through Roof for Heritage Buildings

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Abstract

Enhancing daylighting in heritage buildings is a complex challenge that requires a delicate balance between preserving architectural integrity and improving visual comfort. This paper investigates enhancing daylight in heritage buildings, balancing preservation and visual comfort. It focuses on a 1905 heritage building undergoing reconstruction, addressing insufficient daylight on the ground floor and glare on the first floor. The study investigated novel design solutions by using simulation and optimization approaches. A multi-objective optimization algorithm, called JDEMO Algorithm (a multi-objective self-adaptive differential evolution algorithm), was utilized to obtain Pareto optimal results, and integrated with performative simulations using ClimateStudio (CS) plug-in for Grasshopper. Strategies include altering skylight glazing materials, surface materials, and using Tubular Daylight Guidance Systems (TDGS). Results show TDGS with larger diameters improve Useful Daylight Illuminance (UDI) and reduce Spatial Disturbing Glare (sDG). Material selection impacts daylight distribution, emphasizing the importance of skylight glazing materials. While specific to one case, this research has wider implications for heritage preservation and daylighting. By innovating sustainable design, it contributes to preserving heritage buildings while enhancing visual comfort.

1. Introduction

Overcoming insufficient daylight in heritage buildings presents a unique challenge due to the need of balance modern solutions with the preservation of their architectural integrity. Since heritage buildings generally have specific design elements, materials, and construction techniques that reflect their built era and must be protected, the challenge lies not just in increasing daylight use but also in ensuring that any changes do not jeopardize the historical, cultural, and aesthetic significance of heritage buildings. Recognizing the importance of maintaining the exterior appearance of these buildings, alternative approaches have been explored to address the daylight deficiency while minimizing any visual impact [1]. Among the various options available, skylight and tubular systems that are integrated on the roof, offer efficient solutions that seamlessly integrate into existing buildings to increase daylight penetration and reduce glare while preserving the building's exterior appearance and cultural value. The significance of this study is its potential to provide an optimization approach by adapting tubular systems to enhance daylight use in heritage buildings that face strict preservation guidelines (where no alterations are made to materials, facades, or dimensions) and are constrained by their existing architectural features.

Tubular systems, also known as light tubes, solar tubes, or sun pipes, are architectural devices designed to transport natural light from the exterior of a building into interior spaces. They consist of highly reflective tubes that capture sunlight and direct it to desired areas within the building. One significant advantage of light tubes is their efficiency in delivering daylight to spaces with limited access to windows through channeling natural light over the whole hemisphere [2]. Skylights, another effective daylighting solution, can also be implemented on the roof to increase daylight penetration while minimizing glare in heritage buildings [3]. Skylights are essentially windows placed on the roof, allowing natural light to enter the building from above. They can be strategically positioned to capture sunlight and direct it to areas that lack sufficient daylight, such as the ground floor or interior spaces. Skylights provide an efficient means of introducing

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daylight into a building while minimizing the need for alterations to the building's façade. By carefully selecting the size, shape, visible transmittance (VT) of glazing (given in percentages, representing the quantity of visible light that penetrates through glass), placement, inclination angle and moving apex of skylights, the desired level of daylight penetration can be achieved without compromising the building's exterior appearance or cultural value [4-8].

Both light tubes and skylights offer efficient daylighting solutions that address the challenges of insufficient daylight penetration and glare while preserving the exterior appearance and cultural value of heritage buildings [9]. By utilizing the roof as a platform for implementing these solutions, natural light can be harnessed effectively and distributed to the desired areas within the building. The seamless integration of light tubes and skylights ensures that the exterior façade remains intact, safeguarding the building's historical significance and architectural character. Ultimately, the efficiency of these approaches lies in their ability to enhance the daylighting conditions of heritage buildings while respecting and preserving their unique cultural heritage and they are commonly preferred for reconstruction of heritage buildings [10].

Within this study, a heritage building that will be reconstructed and suffers from conflicting visual problems is investigated. The building originally has four skylights, which fail to achieve visual comfort for both floors. The first floor suffers from glare, while the ground floor lacks sufficient daylight penetration. The main objective of the current study is to increase visual comfort and daylight availability for both floors through the roof. Design proposals that include the integration of Tubular Daylight Guidance Systems (TDGS) and changing the skylight glazing material were generated by using the optimization method to increase daylight availability and illuminance distribution while reducing glare for both floors. Despite the concern over the building's cultural value deterioration, the proposal does not change any of the building's structural components, retaining the building's original facade design. The development of innovative daylighting methods and approaches for heritage buildings may benefit from the suggested TDGS integration and glazing alteration strategy.

2. Background

2.1. Daylight enhancement in heritage buildings

Due to their representation of past eras and ability to provide perspectives into them, heritage buildings require unique conservation measures. Any intervention must be sensitive to the historic character and materials of the building while also complying with applicable building codes and regulations. Most importantly, keeping their cultural worth through preserving and bringing their assets into line with the future in the greatest form possible while preventing deterioration is critical [11].

Reuse and retrofitting of heritage buildings have been widely studied in the literature yet rather less studies focused on daylight improvement and visual comfort strategies [8]. There are few studies in the literature focusing on optimizing daylighting in heritage buildings while simultaneously aiming to preserve their historical significance [5,6,8,12,13]. Furthermore, no optimization study utilizing Tubular Daylight Guidance Systems (TDGS) specifically targeting daylight optimization in heritage buildings has been identified in the literature, thus highlighting the uniqueness of this study.

Improving daylight availability in a heritage building can be achieved through several modifications that can be done on the façade and roof without compromising its original facade appearance. One can be listed as window upgrades which require replacing existing single glazed windows with double or reflective glazed windows. This change can improve daylight usage by reducing heat loss and solar gain, however, it might limit daylight penetration to the interior due to the reduced visible transmittance (VT) values [1,14]. Another modification can be listed as installing light shelves that reflect light deeper into the building to improve daylight distribution [15]. Before installing a light shelf, careful consideration of load-bearing capability of buildings, climatic conditions, orientation, and design suitability are necessary. Besides existing windows' placement and size are crucial because the light shelf should be positioned in a way that it doesn't block daylight penetration. In addition to those heritage buildings can be rediscovered and enhanced with the use of innovative building design techniques [16].

2.2. Tubular daylight guidance systems (tdgs) and skylights

Using tubular systems guidance systems (TDGS), which direct daylight to the target areas and reduce the need for artificial lighting while preventing glare and excessive heat gains, is another common solution when the rooms have no or insufficient outward windows [17,18]. The term TDGS has been referred to by a variety of names in the literature, including light pipe, light tube, light guide, sun pipe, solar pipe, daylight pipe, tubular skylight, tubular daylighting device, sun scoop, and hollow light [19,20,21,22]. However, for the sake of simplicity, the TDGS abbreviation is used in this study. Despite the various names, they are all made up of three main parts: collector, tube, and diffuser, and can be positioned in various directions (horizontal and vertical) (Fig. 1).

As long as the circumstances allow, the use of TDGS reduces lighting systems operating hours and the related energy consumption while preserving the façade of heritage buildings. Numerous studies focused on the efficacy and energy saving potentials of TDGS through various methods such as measurement [23,24], survey [25], evaluations [26], algorithms [27] and

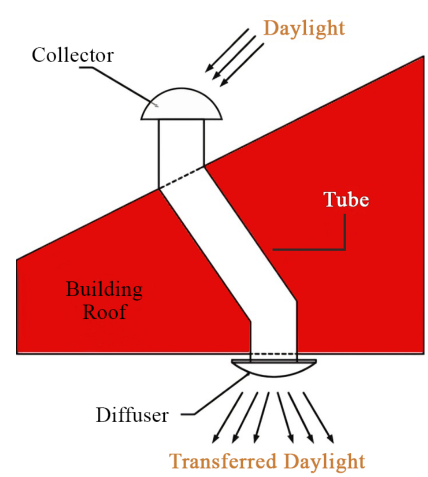


Fig. 1. Tubular Daylight Guidance System components (Source: Authors).

simulations [28-32]. The efficacy of TDGS is highly influenced by the properties of its components such as tube reflectivity [33,34], position, geometry, bend angle [17,33], pipe length [17,28]. In addition to that, environmental and operational factors such as dominant sky type [15,33,34], interior reflectance colors [17,37], climatic conditions [17,38,39], dust accumulation and dew condensing [38] can reduce the performance of TDGS.

Previous research suggests that, to maximize efficacy, the TDGS should have some or all the following properties: being short and straight, having low aspect ratios [24,28], having higher light reflectance on the inner surface of light guides, and having a

Table 1. Case studies about daylighting buildings through TDGS.

Reference	Year	Case Location	Climate Condition	Method	Function	Daylighting Intervention	Lighting Energy Saving	Remarks
Elsiana et al. [32]	2022	Surabaya, Indonesia	Intermediate sky	Simulation (IES-VE software)	Office East	Horizontal Light Pipe and shading systems	-	• Illuminance level in the deep area increased to 135%, decreased by 55% near the side window • With shadings uniformity improved up to 800% • Blinds and light shelves reduced the glare • Using light pipes, shelves and blinds made more uniform distribution in overall
Alatawneh et al. [9]	2021	Hebron, Palestine	Clear sky	Simulation (DIALux), measurement	Classroom	Light pipe Changing interior colors	-	• The installation of light pipe resulted in the largest increase in daylight availability (70%).
Heng [29]	2021	Penang, Malaysia	Overcast sky	Simulation (IES-VE software)	High-rise office South	Skylight shading device and horizontal light pipe	-	• Illuminance level improved up to 91.54% were observed in the front area of the room • The combined use provides uniform daylight distribution.
Obradovic et al. [25]	2021	Sandvika, Norway	Whole year	Survey	Office South-east	Horizontal light pipe	-	• Users found places with TDGS to be more appealing, interesting, and thrilling.
Baglivo et al. [28]	2019	Lecce, Italy	CIE overcast sky global	Simulation (DAYSIM software)	Plant area room	Comparing 0.3 m length-9 pipes	Up to 72%	• Illuminance levels decrease when tube length increases. • Glare risk decreases when tube length increases. • Summer is the best performing period.
Vasilakopoulou et al. [27]	2016	Seven cities in Europe	Dec,Jun,Sept Overcast	Calculation	Residence	-	18-56%	• Highest energy savings were observed in September • Energy savings altered according to the city significantly.
Darula et al. [31]	2013	Bratislava, Slovakia	Overcast and clear sky	Simulation (Holigilm)	No info	-	-	• The diameter, length and inner reflectance of a TDGS are the key factors in performance. • The overcast sky is the most unfavourable sky for TDGS
Darula et al. [39]	2010	Tropic of Capricorn, Australia	June Dec	Simulation (Holigilm	Room	-	-	• TDGSs are more efficient in high solar altitudes and long sunshine durations.
Maňková et al. [30]	2009	Bratislava, Slovakia	Overcast sky	Simulation (Radiance)	Room	tube placement and quantity change	-	• The diameter of the tube and efficiency are logarithmically proportional. • As tube length increases, efficacy decreases exponentially. • As reflectivity of tube increases, efficacy increases linearly.
Carter [23]	2008	UK	Nov-March 2006	Measurement and survey	15 office buildings	-	-	• The payback period of TDGS is long (over 20 years).
Oakley et al. [24]	2000	Leicestershire, UK	July overcast-clear	Measurement	3 rooms (Office, workshop, residential)	Aspect ratio Tube diameters	Up to 100%	• Straight, short, low aspect ratio and wider light pipes are more efficient.

Table 2. Research on glazing type effectiveness.

Reference	Year	Case Location	Climate/Sky Condition	Method	Function	Daylighting Intervention	Lighting Energy Saving	Remarks
Shirzadnia et al. [5]	2023	Iran	Humid subtropical climate	Optimization	Factory	Skylight	-	• VT of skylight should be higher than VT of windows • Skylight to floor ratio should be 12-13%.
Fazlee and Fadzil [7]	2020	Malaysia	Overcast and clear sky	Simulation, measurement	Classroom	Top and side lit skylights	-	• Regarding the distribution of uniform illumination, side lit skylights outperformed top lit skylights in tropical climates
Marzouk et al. [6]	2020	Egypt	Clear sky	Simulation, optimization	Palace	Daylight redirecting system attached to the skylight	-	• the light redirecting system enhances the daylight in the halls closer to the first floor but its effect diminished in the ground floor.
Cabeza-Lainez et al. [46]	2019	Denmark	All sky conditions	Simulation, measurement	School building	different sky conditions were tested for the proposal	-	• with controlled beam radiation, energy use was reduced due to the diminished glazed apertures
Bodart and Herde [49]	2002	Belgium	Overcast sky	Simulation	Office building	Glazing transmission value and façade configurations	up to 80%	• High visible transmittance value decreases lighting energy consumption; however, the effect is not linear and beyond a certain value artificial lighting energy consumption does not reduce.

larger diameter [32]. On Table 1, a summary of some of the intriguing study findings on the effectiveness and energy savings of TDGS is provided. To be more specific, Baglivo et al. [28] used simulation to assess the efficiency of different tube lengths, and it was discovered that as tube length increased, illuminance levels declined dramatically, implying that a low aspect ratio delivers higher illuminance levels. Another example of this can be seen in Darula et al. [33] where increasing the tube length from 1 to 2 meters (while maintaining the same reflectance and diameter) results in a 3% reduction in efficiency. Despite the lower efficiency, increased tube length reduces glare and the risk of overheating [28]. This conclusion is also consistent with the findings of the investigations conducted by Maňková et al. [30] and Oakley et al. [24].

In addition to length, the tube's efficacy is also impacted by bending related to light loss. The conclusions of several studies have been found to contradict one another. Tsang et al. [36] reported that bending the tube reduced transmittance due to an increase in reflections, but Robertson et al. [41] discovered that bending the bottom half of the pipe increased light transmission by 7%. It is critical to emphasize that none of the aforementioned factors influence the findings on their own. The internal reflectivity of the tube and the diameter of the diffuser are other important considerations. The way that tubes reflect light will most likely alter depending on the inner surface material. This is exemplified in a simulation study where increasing the light reflectance (ρ) of the inner surface of light guides from 0.90 to 0.98 provided an increase of about 27% for light efficiency [33].

The study of Maňková et al. [30] mentioned that an increase in the diameter results in logarithmic increase, e.g., tube diameter of 20cm has 80.4% daylight transmission coefficient while 80 cm has 87.5% in Bratislava, which has a moderately continental climate under a CIE overcast sky. Similarly, to increase tube diameter from 0.2 m to 0.3 m increased lighting efficiency [34]. Incident light angle is another substantial factor that has an impact on light output [42], and effects illumination and light distribution [43,44]. The study of Ng. et al. [44] supports the idea with an experimental study conducted in Malaysia, which has a tropical climate, using light pipe with bending angles of 0°, 30° and 45° and shows that straight light pipe (0° angle) has the highest efficiency [44]. Besides, the study of Mahawan and Tgongtha [34] conducted in a testing room demonstrates that the increase of incidence angle from 0 to 80 improved lighting efficiency. A laboratory model placed in a dark environment with a light source directed at two different angles of 45 ° (inclined) and 90 ° (vertical) to the ground authenticates previous studies, and demonstrates that at 90°, the interior is more illuminated. Utilizing light tubes at vertical angles not only improved light distribution but also increased intensity by up to 17.5% [43,45].

There are some significant problems associated with the use of TDGS. The first is where and how to place them. Collectors' efficiency significantly increases under predominantly clear skies therefore climatic conditions should be considered [22]. Besides, TDGS pass through the construction elements, thus providing structural support and fire protection for existing buildings is necessary.

The choice of glazing material for a skylight plays a crucial role visual comfort, thermal comfort, and energy consumption [46], and mitigating glare issues in buildings. Daylight usually penetrates indoors in three forms: direct sunlight, diffused skylight, and reflected light (from the ground, nearby surfaces, or skylight) [4]. Glazing materials, configuration (such as single-double-triple pane) and being tinted can significantly impact the first two of them, which affect both the visual comfort and heat gains/losses of the building. For example, using clear glass (whose typical visible transmittance value can be considered around 90%) allows a high level of visible transmission and leads to a high UDI, indicating good daylight penetration. However, due to the excessive direct sunlight penetration, it potentially causes glare problems.

There are three key parameters to assess glazing materials' performance: visible transmittance (VT), heat transfer coefficient (U) and solar heat gain coefficient (SHGC) [47]. Within this study, thermal comfort and energy considerations were excluded thus glazing types were assessed only on VT values.

Another important point is that although glazing with high visible transmittance results in reduced lighting energy consumption, there is not a linear relationship between them [48, 49]. The relation of glazing and daylight availability is a rather complex relation and numerous studies examined this issue as given on Table 2.

3. Research Methodology

3.1. Case study, use and indoor conditions

Within this research, a heritage passage building known as ''The Historical Akin Passage'' on Havra Street / Izmir (38°25'11.4"N 27°08'11.3"E) (Fig. 1) was evaluated. The building was constructed in 1905 and was originally used as a winery, molasses factory, and biscuit factory. The two-story masonry passage, which covers 535 m2, was converted to reinforced concrete in 1968. Despite the desire to preserve the original building's character, its architectural significance and cultural heritage became endangered due to severe damage and deterioration. Following careful evaluations and consultations with heritage experts, it was determined that the existing building was not suitable for restoration, and it was decided to proceed with reconstruction to recreate the original structure. Before reconstruction, detailed documentation and research (through historical records, photographs and drawings) were done to ensure accurate reconstruction. The reconstruction of the passage was completed by TARKEM (Historical Kemeralti Construction Investment Trade Inc.) in the first half of 2024 [50] as shown in Fig. 2.

The Historical Akin Passage, an adaptive reuse concept, is envisioned as a restaurant with a 100-person capacity on the first floor, which measures 7.93 meters in width, 26.04 meters in depth, 3.35 meters in height, and 130 m^2 in calculated area, while the ground floor, which measures 7.93 meters in width, 34.35 meters in depth, 3.75 meters in height, and 195.5 m^2 in calculated area, will be designated as a location for the display and sale of specialties from Izmir cuisine [50]. Effective daylighting is essential for these commercial areas to give the right vision for food and guarantee that product colors can be appropriately seen in sales, exposition, and production workplaces [51].

The building faces two significant daylight-related challenges, each posing its own set of problems. Firstly, the ground floor suffers from inadequate daylight penetration, primarily due to its close proximity to neighboring buildings and the absence of windows on this level. Daylight on the ground floor is primarily derived from gallery areas within the passage, which transmit light

Fig. 2. Photographs from the Current State of the historical akin passage. (left) interior view from the first floor [50] (right) exterior view (source: authors).

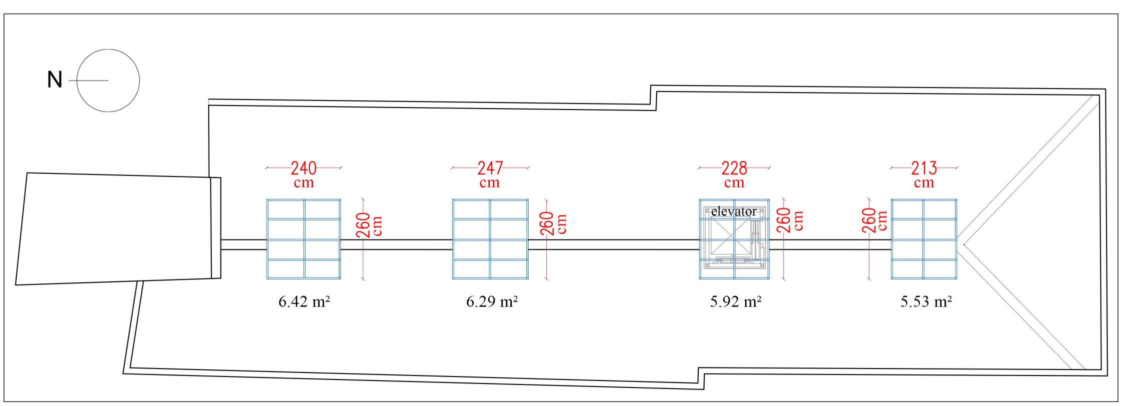


Fig. 3. Skylight measurements of historical akin passage.

from skylights and lateral windows situated on the first floor. However, even on the first floor, daylight access is limited by the nearby buildings. The primary source of daylight for the first floor is provided by four rectangular skylights on the roof, with areas measuring 6.42 m^2, 6.29 m^2, 5.92 m^2, and 5.53 m^2, as illustrated in Fig. 3. Notably, the 5.92 m^2 skylight corresponds to the glass elevator, which may somewhat diminish light distribution to the surrounding floors. In summary, the first-floor benefits from daylight through skylights and side windows, but the absence of shading elements poses the risk of excessive light penetration. Conversely, the ground floor faces a shortage of daylight, while the first floor may experience glare issues. Addressing these conflicting situations collectively is essential to optimize and resolve the identified issues.

To address the conflicting visual issues of glare and insufficient daylight on both floors, a multifaceted approach is essential. This approach involves reducing solar exposure on the first floor while augmenting daylight penetration on the ground floor. Achieving this requires optimization through the manipulation of various design variables to explore alternative techniques and identify the most effective design solution.

In preserving the building's original architectural design and cultural significance, proposed solutions focused utilizing the building's roof. The proposed alterations to the roof involve the implementation of Tubular Daylight Guidance Systems (TDGS) and modifying the glazing of existing skylights. TDGS is intended to channel natural light into the ground floor, while adjusting the skylight glazing aims to mitigate glare issues on the first floor.

3.2. The 3D model and simulation

To determine the effectiveness of the proposal, the original building was simulated by using Rhinoceros and a three-dimensional (3D) model of the two-story building was developed (Figs. 4 and 5). Cadmapper.com, which provides CAD (Computer-aided design) data for every location on Earth, was utilized to create the passage's surroundings and take account of surrounding buildings' shading effects. Because of the project location, the climate conditions corresponding to the Clear Sky with Sun (CIE Clear Sky), along with Izmir-Guzelyali weather data (172200), were considered to create the model and perform simulations.

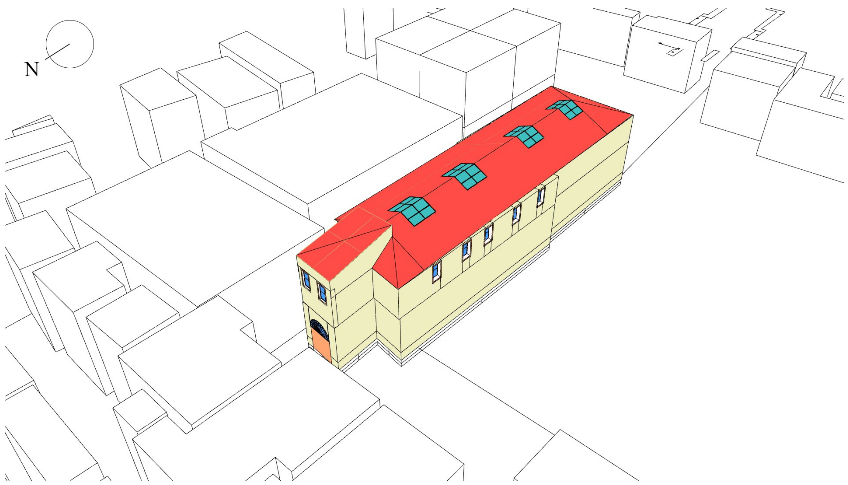


Fig. 4. 3D modelled view of the historical akin passage with its surrounding.

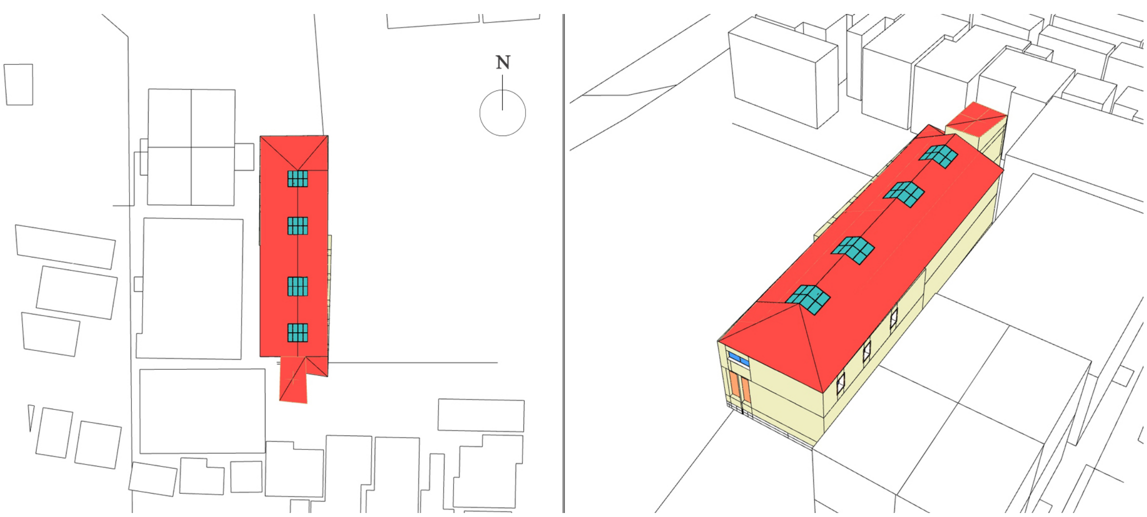


Fig. 5. Site modeling and 3d model of the historical akin passage (left) top view, (right) perspective view

Table 3. Reflectance and Transmittance levels of the stabilized surface materials.

Stabilized Surfaces	Reflectance (R) and Visible Transmittance (VT) Levels
Building Ground	**R:** 28.9%
Metal	**R:** 13.2%
Ceramic Ground	**R:** 39.1%
Ceiling Wooden Beam	**R:** 52.0%
Ceiling Diffuser	**R:** 52.0%
Building Ceiling (Exterior)	**R:** 13.8%
Interior Wall	**R:** 58.2%
Window Frame	**R:** 71.8%
Windowsill	**R:** 84.36%
Wooden Door	**R:** 45.4%
Ground Floor Ceiling	**R:** 70.0%
Window Glass	**VT:** 77.4%
Top of the Elevator	**VT:** 80.6%
Elevator Glass	**VT:** 77.4%

Table 4. Reflectance and Transmittance levels of the controllable variables (for surface materials).

Surfaces	Material Alternatives	Reflectance (R) and Visible Transmittance (VT) Levels
Skylight	Kalwall 70mm Air CrystalWhite	**VT:** 30%
	Atlantica_Solarban 67 (3) Double_Argon	**VT:** 40.2%
	Solarban 90 (2) Double_Argon	**VT:** 50.3%
	Solarban 60 (2) on Slexia_Clear_Double_Krypton	**VT:** 60.4%
	Clear_Solarban 60 (3) Argon	**VT:** 69.6%
	Starphire_Sungate 400 (3) on Starphire_Double	**VT:** 80.5%
GF. and FF.	Laminate Wood Floor	**R:** 10.1%
	Wooden Parquet Floor	**R:** 19.8%
	Wood Floor 2	**R:** 29.3%
	Wood Laminate Floor	**R:** 38.7%
	Light Wood Floor	**R:** 52%
GF.'s Wall and FF.'s Wall	Beige Painted Door Frame	**R:** 58.2%
	Beige Painted Wall	**R:** 68.1%
	White Painted Room Walls	**R:** 81.2%
	White Painted Concrete Wall	**R:** 89.1%
GF Ceiling	Ceiling LM83	**R:** 70%
	Plastic Ceiling Vent E14 548	**R:** 80.6%
	White Painted Ceiling	**R:** 89.4%

GF: Ground Floor, FF: First Floor

After the modeling phase was completed, modeled surfaces in Rhinoceros were defined in Grasshopper. ClimateStudio (CS) was used to assess the environmental performance of the case study. CS assesses daylight availability, annual sunlight exposure, and glare probability using a variety of static and dynamic metrics. Among the known daylight metrics, Useful Daylight Illuminance (UDI) and Spatial Disturbing Glare (sDG) are evaluated in this study.

Following the definition of the surfaces to the templates defined automatically by CS, materials were defined for the solid surfaces based on the reflectivity values contained in ClimateStudio, and for glass surfaces based on the transmittance values. Table 3 shows the reflectance and transmittance values of stabilized materials. On the template, new codes were written to allow for the definition of more than one material option on some surfaces for optimization. Table 4 shows the reflectance and transmittance values of these changeable materials.

Table 5 displays the SolaTube brand Tubular Daylight Guidance Systems (TDGSs) selected from CS's own list for optimization, and Fig. 6 shows the created script for TDGS in Grasshopper software. In selecting these three distinct options, attention was paid to using the same lens (OptiView Wide Diffuser Lens) and choosing the smallest, medium, and largest diameters suitable for the Historical Akin Passage (250 mm, 350 mm, and 550 mm). These TDGS models are denoted by abbreviations representing their attributes, such as DS for Daylighting System, DA for Acrylic Dome, C for Closed Ceiling, and L5 for OptiView Wide Diffuser Lens. To minimize disruption to circulation within the model, these TDGSs have been strategically installed on the sides of the metal columns that extend from the roof to the ground floor ceiling. A total of 19 TDGSs were strategically positioned on the ground floor ceiling near the external walls, maximizing their number while ensuring a minimum distance of 2.5 meters between each TDGS. This placement considered circulation areas as well as potential seating and table arrangements on the first floor.

3.3. Optimization algorithm

Architectural design problems are characterized by complexity because most of the problems have non-linear objectives such as including Radiance method in Daylighting calculations/simulations. In this study, a Multi-Objective Evolutionary Algorithm is utilized to address the complex problem of heritage building reconstruction considering two different daylight metrics, which are UDI and sDG (Table 6). Useful Daylight Illuminance (UDI) is a common dynamic daylight metric that measures the percentage of working hours when daylight levels fall within specific ranges. It categorizes daylight into four bins: failing (UDI_f) for less than 100 lux, supplemental (UDI_s) for between 100 and 300 lux, autonomous (UDI_a) for between 300 and 3000 lux, and excessive (UDI_e) for more than 3000 lux [52]. The UDI metric considers daylight levels between 300 lux and 3000 lux as optimal [53], and achieving this range for at least 50% of occupied hours is often targeted [54]. Spatial Disturbing Glare (sDG), a novel glare metric that can be calculated on CS with DGP results, is the least prevalent of the given dynamic metrics. The sDG metric refers to the percentage (%) of total views that have a Disturbing or Intolerable Glare (DGP) greater than 38% for at least 5% of the occupied hours [52]. These two-objective functions subject to several constraints are formulized computationally in a parametric CAD environment (Grasshopper Software-GH) by using CS Workflow Templates (ClimateStudio Software). Within the CS Workflow Templates, the Daylight Availability Template was used to obtain UDI and the Annual Glare Template was used to obtain sDG metric results.

To tackle this problem, JDEMO Algorithm (a multi-objective self-adaptive differential evolution algorithm) is proposed, which presented satisfactory design results in various studies in the field

Table 5. Selected types of TDGS from SolaTube brand.

No	Image	Type of TDGS	Diameter Size	VT. annual	Diffuser Size	Light Coverage Area	Potential Tube Length
P1		Solatube_160DS-DA-L5	250 mm	0.51	225.1 mm	14-19 m^2	6 m
P2		Solatube_300DS-C-DA-L5	350 mm	0.61	609.600 mm	No info.	9 m
P3		Solatube_330DS-C-DA-L5	530 mm	0.34	609.600 mm	No info.	15 m

DS: Daylighting System, DA: Acrylic Dome, C: Closed Ceiling, L5: OptiView Wide Diffuser Lens

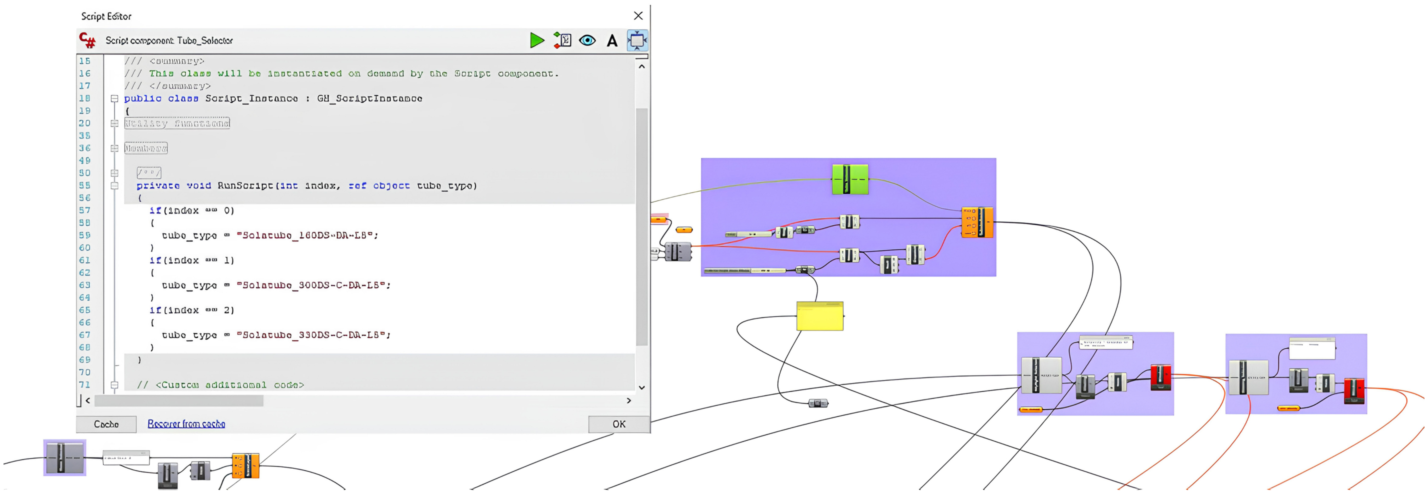


Fig. 6. The Script Created for TDGS in Grasshopper (Source: Authors).

Table 6. Evaluated daylight metrics in the study.

Daylight Metric	Acceptable Range
Useful Daylight Illuminance (UDI)	300 lux ≤ UDI ≤ 3000 lux [52] at least 50% of occupied hours [54]
Spatial Disturbing Glare (sDG)	DGP > 38%, ≥ 5% of occupied hours, DGP > 38%, ≤ 5% of occupied hours [52]

of Architecture [53]. The algorithm details are explained as follows. JDEMO is modified version of some heuristics algorithms, which are based on population to present a search space and have the feature of converging over generations. JDEMO is used in the form of C# scripts generated in Grasshopper environment as part of Optimus tool [62].

A Basic Differential Evolution (DE) is an evolutionary algorithm developed by Storn and Price [54]. In DE algorithms with each individual *Iij* with *j=1, ..., D* dimensions, a random target population (I) with size $N=|I|$ is uniformly produced within the boundaries of each decision variable (design parameter). To generate mutant population, three individuals are selected from the target population. The difference vector of two individuals is multiplied by the mutation scale factor MC and added to a third individual to generate mutant population (V) as follows:

$$V_{ij}^{t+1} = I_{r_1 j}^{t} + MC * \left(I_{r_2 j}^{t} - I_{r_3 j}^{t}\right) \quad \forall i = 1,..,|I|;\ \forall j = 1,..,D \tag{1}$$

Then, a trial population is created from target and mutant populations by using a binomial crossover operator (CO) as follows:

$$Q_{ij}^{t+1} = \begin{cases} V_{ij}^{t+1} & if\ r_{ij} \le CO\ or\ j = D_j \\ I_{ij}^{t} & otherwise \end{cases} \quad \forall i = 1,..,|I|;\ \forall j = 1,..,D \tag{2}$$

where r_{ij} is a uniform random number in [0, 1] and D_j is a random integer in [1, D], which ensures that at least one dimension is generated from the mutant population.

In this paper, a multi-objective DE algorithm, which was inspired from DEMO [57,58] is implemented to address the heritage building design/renovation problem. The only difference

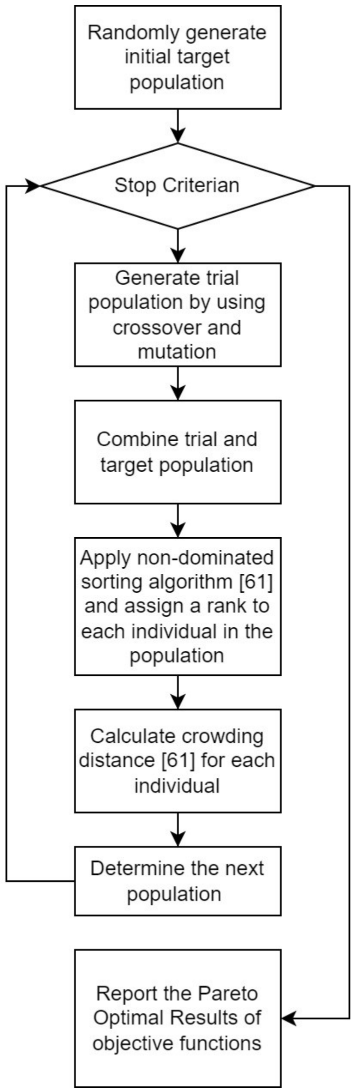


Fig. 7. Overview of the JDEMO algorithm flowchart.

between JDEMO and DEMO is to employ the self-adaptive parameter updating of the jDE algorithm [59,60]. As is well-known, DE algorithms have two factors, which are crossover rate, *CO* and mutation scale factor, *MC*. These two factors significantly affect the performance of DE algorithms. In the jDE algorithm, these two factors are updated at each generation instead of taking them as constant. Initially, these parameters are assigned to $CO_i=0.5$ and $MC_i=0.9$ for each individual in the population. Though, with a small probability, these two factors are restructured at each generation (t) as follows:

$$MC_i^{t+1} = \begin{cases} MC_l + r_1.MC_u & if\ r_2 < p_1 \\ MC_i^t & otherwise \end{cases} \tag{3}$$

$$CO_i^{t+1} = \begin{cases} r_3 & if\ r_4 < p_2 \\ CO_i^t & otherwise \end{cases} \tag{4}$$

where $r_j \in \{1,2,3,4\}$ are uniform random numbers in the range [0,1]. p_1 and p_2 denote the probabilities to adjust the MC_i and CO_i operators. They are taken as $p_1=p_2=0.1$ and $MC_l=0.1$ and $MC_u=0.9$.

Referring to the very powerful and well-known algorithm called NSGA-II in the literature [61], its unique features of non-dominated sorting algorithm and crowding distance as well as constrained-dominate rule are employed in JDEMO for solving the multi-objective problem with Pareto-optimal results. The NSGA-II includes SBX crossover and PM mutation operators while creating an offspring population. However, the JDEMO algorithm uses the DE mutation and crossover factors while creating the offspring population. The flowchart of the jDEMO algorithm is shown in Fig. 7. In this figure, target and trial population refers to design parameters while objective functions refer to sDG and UDI values, which are obtained from simulation software (Climate Studio).

4. Findings

This study developed an optimization model for a heritage building reconstruction design task by utilizing computational optimization techniques. Significant improvements were achieved, resulting in efficient designs that minimize sDG for the First Floor and maximize UDI for the Ground Floor.

Regarding the design/decision variables of the optimization model, Fig. 8 shows the interval plot of the decision variables after the 50th generation, along with the 95% CI (Confidence Interval) for the mean. The results indicate convergence for several decision factors, including tube type (Solatube_330DS-C-DA-L5, 530 mm), ceiling material (89.4% reflectance), GF wall material (89.1% reflectance), GF ground surface material (52% reflectance), and FF ground surface material (10.1% reflectance). Divergence was noted for skylight glazing and FF wall material, with skylight glazing material significantly impacting optimized results. An increase in UDI demands more receiving light, higher reflectance, and higher transmittance, whereas a decrease in sDG demands a decrease in light exposure and lower reflectance and transmittance levels. Given the conflicting objectives of UDI and sDG, skylight glazing material plays a crucial role in optimal outcomes, as expected.

Figure 9 shows 11 different Pareto-optimal results, with red circles highlighting the most favorable three results based on the highest UDI (No.1), mid-range of UDI and sDG (No.2), and the lowest sDG (No.3). Table 7 shows the base case and the three selected optimal results. Optimal results were achieved with the use of largest tube diameter (P3= 530 mm). The base case has a UDI of 10% and an sDG of 31%, which were significantly improved through optimization.

- No.1 achieves a 300% increase in UDI and a 25.8% decrease in sDG.
- No.2 achieves a 270% increase in UDI and a 48.38% decrease in sDG.
- No.3 achieves a 220% increase in UDI and a 67.74% decrease in sDG.

The optimized daylighting solutions from this study significantly enhance energy efficiency and occupant comfort in heritage building restorations while preserving their architectural integrity. These findings can inform new guidelines and standards for daylighting in heritage buildings, influencing policy-making and best practices in architectural preservation. The integration of computational optimization techniques demonstrates a cutting-edge approach to achieving sustainable design goals in heritage conservation.

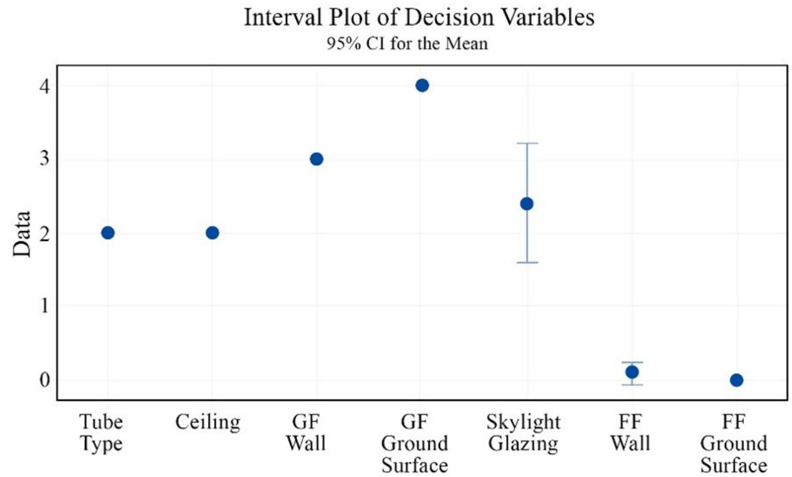


Fig. 8. Interval plot of decision variables in 50th generation.

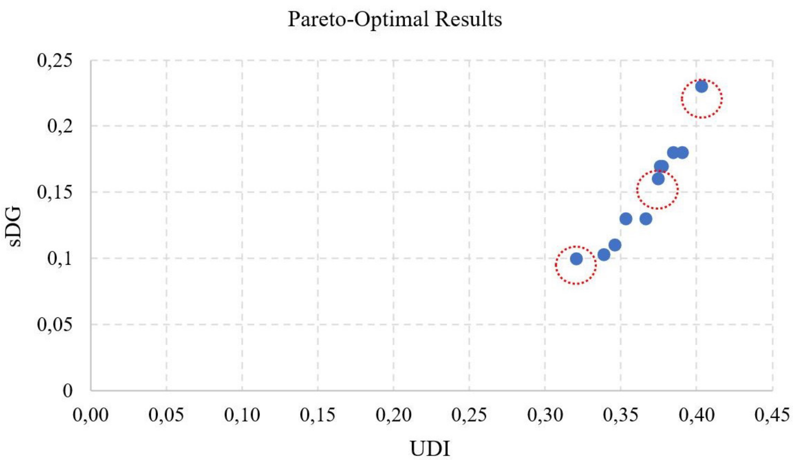
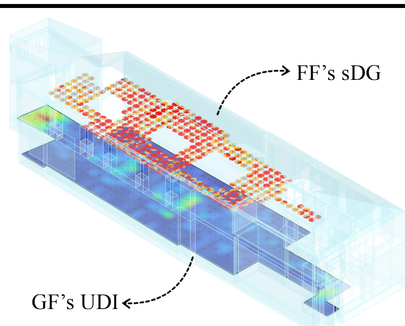
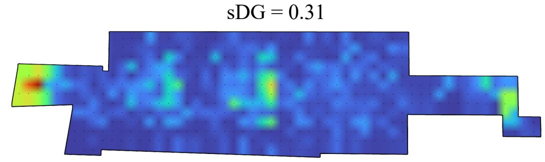
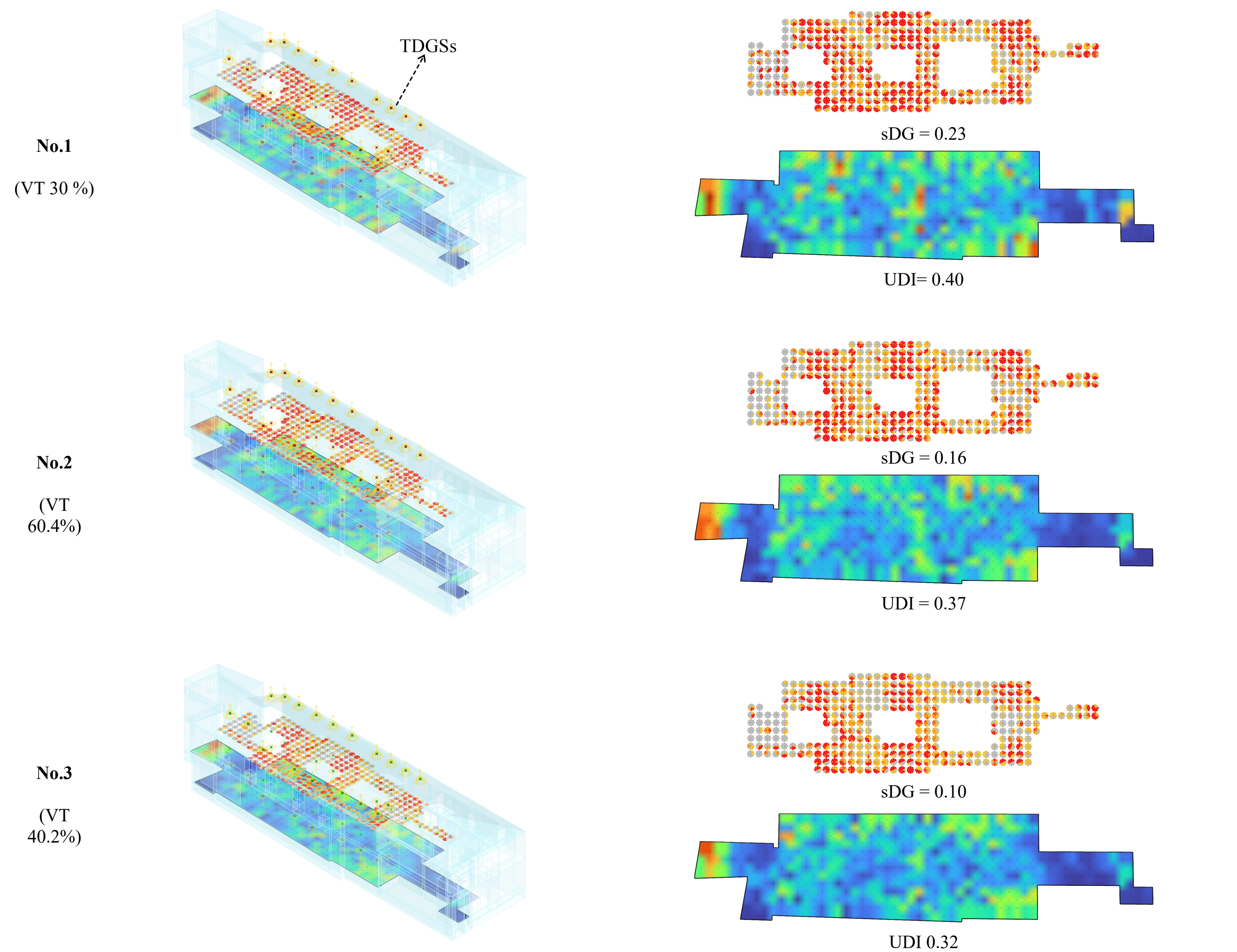


Fig. 9. Pareto-optimal results of UDI and sDG.

Table 7. Optimal Results with Visualization.

No	3D View of Results	FF's sDG & GF's UDI Results
Base Case (VT 77.4%)		 sDG = 0.31  UDI = 0.10



5. Conclusions

Improving the daylight availability and uniformity of a heritage building without jeopardizing the original architecture and cultural significance of the building necessitates careful evaluation and calculation of the impact of each modification. Aside from building and regulatory constraints, several alternatives may be required, particularly when two conflicting visual problems (glare and insufficient daylight) are present. Once the design parameters have been established, simulation and optimization techniques frequently make the process easier and reduce the time needed to produce an effective proposal. The study's goal is to improve daylight availability and uniformity of the Historical Akin Passage through the roof utilizing TDGS and skylight glazing alteration. To achieve the targeted daylight levels, CAD and GH tools, and CS plug-in are employed.

This study highlights the potential of TDGS and the choice of skylights and surface materials to improve daylight availability and distribution, particularly in the context of historically significant buildings that are not subject to major alterations. Results revealed that with the use of P3 having a 530 mm diameter (see Table 6), a 300% increase in the UDI and a 67.74% decrease in the sDG can be achieved. The study's findings indicate that TDGSs with the largest diameter consistently yielded the best results. The VT of the skylight has a considerable influence on deciding the course of the objectives, which necessitates opposing interferences. Furthermore, surface materials with high reflectivity were predominantly effective for the ground level, where a high UDI (Useful Daylight Illuminance) was desired. Conversely, materials with lower reflectivity and skylight glazing with lower VT on the first level were effective in reducing the sDG (Spatial Disturbing Glare). These findings underscore the need for different material selections depending on the building's floor function and specific lighting goals.

Because of the building's historical significance, changes to window sizes and the addition of new window openings were prohibited. Additionally, the study was restricted to using SolaTube brand TDGSs, and modifications to several tube properties, including diameter size, VT annual, and diffuser size, were not possible. Nonetheless, the analyzed TDGSs sufficiently demonstrate that TDGS characteristics influence the enhancement of daylight efficiency.

This research offers insights into improving daylight conditions in heritage buildings and contributes to the field of conserving buildings by investigating several alterations to the roof and building interiors. TDGSs can be a preferable choice for optimizing daylight utilization and directing it to specific areas within the building, particularly in heritage buildings where visual comfort is essential. Achieving effective daylight distribution involves selecting interior surface materials with high reflectivity and skylight glass types with high transmittance. It's crucial to balance daylight intake in spaces with large glass surfaces to avoid visual discomfort. The optimization method can be seen as remedy for resolving conflicting objectives, such as maximizing daylight efficiency while minimizing visual discomfort.

While this study focused on TDGSs in a specific scenario, its results may be applicable to other installations and offer guidance on maximizing daylight utilization in heritage buildings. Further research in this area may lead to innovative solutions, such as reflectors, adaptive shading systems, and dynamic glazing that may optimize daylighting conditions without compromising the building's historical identity or architectural appearance. The effects of TDGS placement, assessing potential wear and degradation of materials over time as well as glass and surface material choices, on lighting energy use may also all be studied in the future. By addressing these areas, subsequent research can build on the current findings and provide more robust guidelines for the application of TDGS and other sustainable technologies in the preservation and enhancement of daylight conditions in heritage buildings.

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Contributions

Nurefşan Sönmez: Methodology, Investigation, Visualization, Formal analysis, Writing - Review & Editing. Arzu Cılasun Kunduracı: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing. Cemre Çubukçuoğlu: Methodology, Data Curation, Investigation, Software, Writing - Review & Editing.

Declaration of competing interest

The authors declare no conflict of interest.

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