

Article

Sustainable Daylighting Retrofit of a Heritage Hotel Under Façade Preservation Constraints: A Climate-Based Simulation Study in Biskra, Algeria

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Abstract

Improving daylight performance in heritage hotels is essential for enhancing comfort, quality, and energy efficiency, especially in hot-desert climates where solar availability must be balanced with glare and overheating risks. However, façade preservation requirements limit conventional daylighting interventions, creating a need for climate-responsive and conservation-compatible solutions. This study investigates daylight optimization strategies for the Transatlantique Hotel in Biskra, Algeria, using Climate-Based Daylight Modelling (CBDM). The methodology combines three-dimensional modelling, in situ material characterization, and Radiance-based simulations with ClimateStudio version 2.3. Daylight performance was assessed using Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), Useful Daylight Illuminance (UDI), and Daylight Factor (DF). Tested scenarios included improved glazing transmittance, increased surface reflectance, and tubular daylighting devices (TDDs). Results show that the existing configuration provides insufficient daylight in guest rooms, with average illuminance in poorly performing rooms ranging from 140 to 310 lux. Material-based optimization increased Room 210's sDA from 3.9% to 62.3%, representing an approximately +1497% relative improvement, while UDI reached 58.6%. TDDs produced the strongest improvement: Room 110 sDA increased from 11.8% to 82.4% (+598%), while ASE decreased from 10.6% to 0.0%; Room 310 sDA increased from 31.2% to 100% (+221%), while ASE decreased from 16.9% to 0.0%. The novelty lies in integrating material-based and TDD strategies under strict façade-preservation constraints in a hot-desert heritage hotel.

Keywords: daylighting; climate-based daylight modelling; sustainable retrofit; façade preservation; tubular daylighting devices; visual comfort; hot-desert climate; heritage buildings

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1. Introduction

Natural daylight is a fundamental component of architectural design, playing a crucial role in enhancing visual comfort, occupant well-being [1,2], and reducing dependence

on artificial lighting [3]. In regions with high solar availability, such as hot desert climates, effective daylighting strategies can significantly lower energy consumption while improving indoor environmental quality [4,5]. Advances in climate-based daylight modelling (CBDM) have further enabled accurate assessment of daylight performance under real climatic conditions, using dynamic metrics such as Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE), and Useful Daylight Illuminance (UDI) to evaluate daylight availability, glare risk, and visual comfort [6].

However, optimizing daylight performance in historic buildings remains a major challenge due to strict heritage preservation constraints [7]. In protected structures, façade modifications, including changes to window size, position, or architectural expression, are often prohibited, limiting the application of conventional daylighting strategies [8]. This constraint is particularly critical in heritage hotels, where indoor environmental quality directly influences guest comfort, spatial perception, and overall hospitality experience, while also affecting operational energy use [9]. Recent studies on tourist accommodation confirm that indoor environmental quality is an important factor in guest satisfaction. For example, Zhang et al. analyzed more than 543,000 online guest reviews from 1397 hotels and serviced apartments and found that indoor environmental quality dimensions, including lighting and visual conditions, influenced accommodation ratings and guest dissatisfaction patterns [10]. Similarly, research on green hotels has shown that indoor lighting significantly affects guests' comfort and satisfaction, confirming the importance of the luminous environment in hospitality buildings [11]. In the Algerian context, although hotel-specific daylight satisfaction surveys remain limited, post-occupancy research in public buildings has shown that more than 60% of users were dissatisfied with the natural-light environment in a university library in Oum El Bouaghi, indicating that daylight quality is a relevant concern in Algerian indoor environments [12]. As a result, there is a pressing need to develop alternative, conservation-compatible solutions capable of improving daylight conditions without compromising architectural identity. This makes daylight optimization in heritage buildings not only a visual comfort issue but also a sustainable retrofit challenge that must balance environmental performance, user comfort, and cultural heritage preservation [13,14].

The Transatlantique Hotel in Biskra, Algeria, exemplifies this challenge [8]. Located in a hot desert climate characterized by intense solar radiation [15,16]. The building offers high daylighting potential [17] but simultaneously suffers from insufficient and unbalanced daylight distribution in its interior spaces, particularly in rooms [16]. This inadequacy not only affects visual comfort and user satisfaction [18] but also increases reliance on artificial lighting, contradicting contemporary sustainability objectives [19]. At the same time, the historical value of the building imposes strict limitations on façade interventions [20], making it an ideal case to explore innovative and non-invasive daylight optimization strategies [21]. Therefore, the building provides a relevant case study for testing daylighting strategies that improve indoor environmental quality while respecting façade preservation constraints.

Although previous studies have addressed daylight performance in heritage buildings [22], adaptive reuse, and CBDM, much of this research remains focused on either new buildings, isolated daylighting strategies, or façade-based interventions that are often incompatible with protected heritage façades [23,24]. In addition, studies on historic hotels in hot-desert climates remain limited, particularly where daylight improvement must be achieved without modifying window geometry or external architectural expression. This creates a clear research gap concerning the combined evaluation of conservation-compatible strategies, such as glazing improvement, surface reflectance enhancement, and TDD integration, under real climatic conditions [25,26]. Therefore, this study hypothesizes that significant improvements in daylight autonomy and visual comfort can be achieved

through non-invasive, façade-preserving strategies. By testing this hypothesis in the Transatlantique Hotel in Biskra, the study positions CBDM as a decision-support method for sustainable daylight retrofit in heritage hospitality buildings. This study tests this hypothesis in the Transatlantique Hotel using a comprehensive simulation-based approach [27]. By combining climate-based daylight modelling with multiple passive strategies, including glazing enhancement, interior surface reflectance improvement, and the integration of tubular daylighting devices, this research evaluates their individual and combined effectiveness under real climatic conditions [28]. The objective is to demonstrate that significant improvements in daylight availability and visual comfort can be achieved without façade alteration [24], thereby contributing to the development of sustainable, conservation-compatible retrofit strategies for heritage buildings in high solar radiation contexts [29].

2. Literature Review

2.1. Daylighting in Heritage Buildings

Daylighting in heritage buildings presents unique challenges due to the need to preserve architectural integrity while improving environmental performance [29]. Unlike contemporary buildings, where façade modifications can be freely implemented to optimize daylight access [30,31], historic structures are often subject to strict conservation regulations that limit or prohibit alterations to external elements such as window size, geometry, and façade composition [8]. These constraints significantly restrict the application of conventional daylighting strategies, including the enlargement of openings or the introduction of new fenestration systems [32]. Consequently, daylighting solutions for heritage buildings must be evaluated not only according to lighting performance but also according to their compatibility with conservation requirements.

Previous studies have highlighted that inadequate daylight conditions are a common issue in historic buildings, particularly in deep-plan spaces or buildings designed before modern lighting standards were established [8]. Researchers have explored various non-invasive strategies to address these limitations, focusing primarily on interior interventions such as increasing surface reflectance, optimizing interior layouts [33], and improving glazing performance without altering the external appearance [34]. These approaches aim to enhance daylight distribution while maintaining compliance with heritage preservation requirements.

However, the effectiveness of such strategies is highly dependent on building geometry, orientation, and climatic context [35]. In hot climates, the challenge is further compounded by the need to balance daylight availability with visual and thermal comfort, as excessive solar radiation can lead to glare and overheating [36]. As a result, daylight optimization in heritage buildings requires a careful integration of passive strategies that respect conservation constraints while improving indoor environmental quality [7].

2.2. Sustainable Retrofit and Conservation-Compatible Interventions

Sustainable retrofit in heritage buildings requires a balance between environmental performance, occupant comfort, and the preservation of architectural authenticity [37,38]. Unlike conventional retrofit approaches, interventions in historic buildings must respect conservation principles such as minimum intervention, reversibility, material compatibility, and the protection of significant architectural features [39]. For this reason, daylighting strategies in heritage contexts should avoid altering façade composition, window geometry, and external architectural expression whenever these elements contribute to cultural value [8].

Within this framework, non-invasive or low-impact interventions, such as improving interior surface reflectance, optimizing glazing properties [40], and introducing daylight redirection systems where structurally and visually acceptable, can contribute to better indoor environmental quality while maintaining heritage integrity [41]. These strategies are particularly relevant in hot-desert climates, where high solar availability creates opportunities for daylight use but also increases the risk of glare and overheating. Therefore, sustainable daylight retrofit in heritage buildings should be understood as an integrated design problem that combines energy efficiency, visual comfort, climate responsiveness, and cultural heritage preservation [14,30].

2.3. Climate-Based Daylight Modeling (CBDM)

CBDM has become a widely adopted approach for evaluating daylight performance in buildings under realistic environmental conditions. Unlike traditional static methods, CBDM uses hourly climate data to simulate daylight availability throughout the year, providing a more comprehensive understanding of indoor lighting conditions [42]. Tools based on the Radiance simulation engine are commonly used due to their high accuracy in modelling light behavior and material interactions [43].

Several dynamic daylight metrics have been developed to assess different aspects of daylight performance. sDA measures the percentage of floor area that receives a minimum illuminance level (typically 300 lux) for at least 50% of occupied hours, providing an indication of daylight sufficiency. ASE evaluates the percentage of space exposed to excessive direct sunlight (above 1000 lux for more than 250 h per year), serving as an indicator of potential glare and visual discomfort. UDI assesses the proportion of time when illuminance levels fall within a desirable range (commonly 100–3000 lux), reflecting the usability of daylight in occupied spaces [44].

These metrics are widely adopted in international standards and green building certification systems, such as LEED, to evaluate daylight performance [45]. CBDM has been applied extensively in the analysis of both new and existing buildings, enabling the comparison of different design strategies and their impact on visual comfort and energy performance [46]. However, its application in heritage buildings remains relatively limited, particularly in studies that integrate multiple daylight optimization strategies within constrained architectural contexts [47].

2.4. Tubular Daylighting Devices (TDD)

TDDs, also known as light pipes or sun tunnels, are innovative systems designed to capture daylight at the roof level and transport it into interior spaces through highly reflective tubes [48]. These systems are particularly effective in deep-plan buildings or spaces with limited façade exposure, where conventional daylighting strategies are insufficient [49]. TDDs typically consist of a rooftop collector, a reflective tube, and a diffuser that distributes light evenly within the interior space [48].

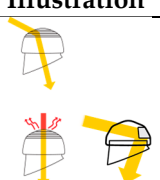
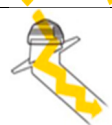
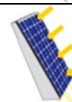
Previous research has demonstrated that TDDs can significantly improve daylight availability and distribution, reducing reliance on artificial lighting and enhancing visual comfort. Studies have shown that TDDs are capable of delivering diffuse daylight with minimal glare, making them suitable for climates with high solar radiation. Additionally, their relatively compact design allows for integration into existing buildings with limited structural intervention, which is advantageous in retrofit scenarios [50].

Among contemporary TDD solutions, Solatube daylighting systems represent an advanced application of this technology. These high-tech tubular skylights are designed to efficiently deliver natural light into interior spaces of varying sizes and are available in multiple configurations, including models with integrated night-lighting and impact-resistant features. Unlike conventional skylights, Solatube systems employ advanced opti-

cal components to actively capture, transfer, and distribute daylight while minimizing heat gain and losses [51]. The rooftop dome integrates Raybender 3000 Technology and a LightTracker reflector to optimize sunlight collection under varying solar angles, while Spectralight Infinity tubing, with up to 99.7% reflectivity, enables efficient light transmission over long distances. In addition, an integrated photovoltaic module powers a built-in NightLight for nighttime illumination, and customizable diffusers enhance indoor visual comfort. In this study, a specific Solatube model is selected based on its performance suitability for the investigated context [52] (Table 1).

However, several limitations have also been identified. The performance of TDD systems depends on factors such as tube length, diameter, reflectivity, and sky conditions. Their effectiveness may decrease in spaces located far from the roof or in buildings with complex structural configurations. Furthermore, the application of TDDs in heritage buildings remains underexplored, particularly in cases where architectural constraints or conservation regulations limit roof interventions. As a result, further research is needed to evaluate their performance in real-world heritage contexts and in combination with other passive strategies [51].

Table 1. Main components and daylighting roles of a TDD [52].

Stage	Component	Main Function	Relevance to Daylight Performance	Illustration
1. Capture	Rooftop collector	Captures and redirects daylight	Increases daylight collection under different solar angles	
2. Transfer	Reflective tube	Transmits daylight from roof to interior	Reduces light loss during transmission	
3. Generate	Solar Electric Module	Converts solar energy	Powers integrated night lighting system	
4. Deliver	Interior diffuser	Distributes daylight into the room	Improves uniformity and reduces direct glare	

The reviewed literature indicates that daylight retrofit in heritage buildings cannot be treated as a purely lighting problem (Table 2). In arid climates, high solar availability increases daylight potential but also raises glare and overheating risks; therefore, strategies that improve sDA may also increase ASE or thermal discomfort if solar exposure is not controlled. Previous studies on glazing, surface reflectance, and shading often assess these measures separately, limiting understanding of their combined suitability for protected buildings. TDDs offer a promising roof-based solution for deep or poorly lit spaces because they introduce zenithal daylight without altering protected façades. However, their application in heritage buildings remains insufficiently explored, especially regarding conservation compatibility and daylight/thermal trade-offs in hot-desert climates. This study addresses this gap by comparing material-based and TDD-based strategies through CBDM in a façade-preserved heritage hotel.

Table 2. Summary of literature gaps and relevance to the present study.

Research Theme	Main Focus in Previous Studies	Limitation Identified	Relevance to This Study
Daylighting in heritage buildings	Improving daylight while respecting conservation constraints	Many strategies are limited by façade preservation requirements	This study tests non-façade-altering strategies
CBDM	Annual daylight evaluation using sDA, ASE, UDI, and DF	Fewer applications in heritage buildings under strict conservation constraints	This study applies CBDM to a heritage hotel
Material-based optimization	Glazing and reflectance improvement	Often tested as isolated strategies	This study compares individual and combined strategies
TDD	Daylight delivery to deep-plan spaces	Limited research on heritage buildings and hot desert climates	This study evaluates TDDs in a heritage hotel in Biskra
Sustainable retrofit	Improving building performance while preserving heritage value	Need for integrated visual comfort, energy, climate, and conservation approaches	This study frames daylight optimization as sustainable retrofit

3. Case Study

3.1. Climate and Historical Context

The study focuses on the Transatlantique Hotel. It is a historic building dating back to the colonial period, constructed between 1907 and 1912 (Figure 1). The design is attributed to architect Jacques Guiauchain, while the construction was carried out by the Rodari brothers' company. The hotel is part of a network of Transatlantique establishments developed across Algeria (Figure 2a), reflecting a significant architectural and cultural heritage [53].



Figure 1. Transatlantique Hotel in Biskra Across Different Historical Periods. Source: [53,54].

Regarding heritage protection, the Transatlantique Hotel is treated in this study as a heritage building of architectural and historical value, based on its colonial-period origin, preserved façade composition, distinctive openings, and archival documentation from the Cultural Affairs Directorate of Biskra [54,55]. However, no publicly accessible national

register confirming its formal listing/classification was identified; therefore, the study adopts a precautionary conservation approach. Algeria's Law No. 98-04 of 15 June 1998 on the protection of cultural heritage defines national cultural heritage and establishes general rules for its protection, safeguarding, enhancement, inventory, and classification [55]. Accordingly, interventions affecting culturally significant external features, including window dimensions, façade geometry, external materials, and architectural expression, were excluded from the daylighting scenarios. The tested strategies were therefore limited to interior material improvements, glazing-performance assumptions that preserve external appearance, and roof-based TDDs where compatible with conservation constraints.

The Transatlantique Hotel is located in the city of Biskra, in southeastern Algeria (34.79° N, 5.74° E). The region is characterized by a hot desert climate (BWh) according to the Köppen classification and is classified as ASHRAE climate zone 2 (hot) (Figure 2b). Biskra experiences very high solar radiation levels, estimated at approximately 2017 kWh/m² annually, along with long, hot summers where temperatures can exceed 40 °C, and mild winters [15].

These climatic conditions provide significant daylight availability throughout the year, making the location particularly suitable for investigating daylight-driven design strategies. However, the high intensity of solar radiation also introduces challenges related to glare and overheating, requiring careful control of daylight penetration to ensure visual and thermal comfort. Therefore, Biskra represents a relevant context for evaluating daylight optimization strategies that aim to balance daylight availability and occupant comfort.

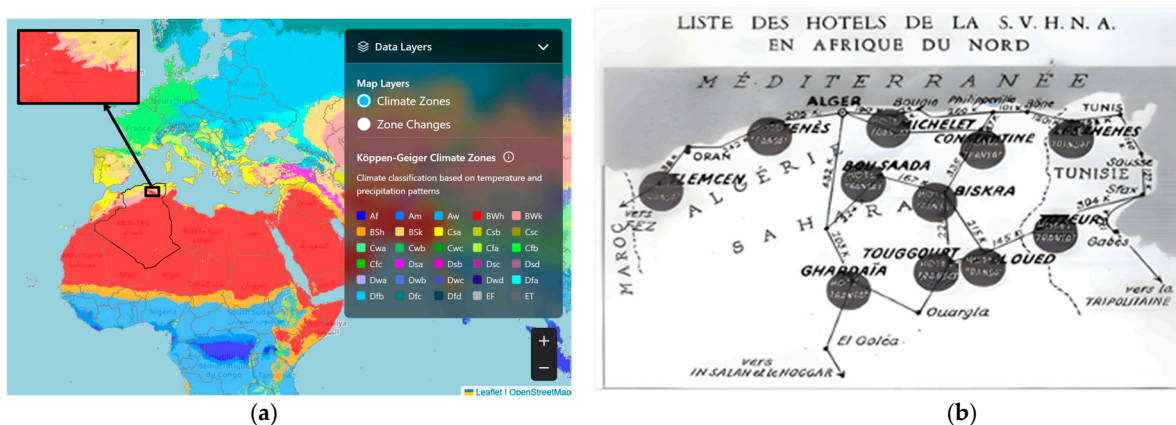


Figure 2. (a) The Transatlantic Hotel Chain in Algeria. Source: [56]. (b) The Köppen classification of the city of Biskra, Algeria. Source: [15].

3.2. Architectural Description of the Building

The hotel is organized as a T-shaped structure composed of a ground floor and two upper levels, originally accommodating approximately eighty guest rooms. The building is arranged around an interior courtyard featuring vegetation (Figure 3a), which contributes to natural ventilation and daylight access in some areas.

The ground floor includes the main lobby, reception areas, dining spaces, and several guest rooms connected through corridors. The upper floors consist primarily of guest rooms organized along longitudinal corridors, with access to balconies and openings (Table 3) oriented towards the exterior or courtyard (Figure 3b).

The spatial configuration of the building, characterized by corridor-based layouts and varying room orientations, results in heterogeneous daylight conditions. In particular, rooms located on lower floors or deeper within the building experience limited day-

light penetration, while others may be exposed to excessive direct sunlight. This variability makes the building suitable for analyzing different daylight performance scenarios under varying spatial and environmental conditions [53,54].

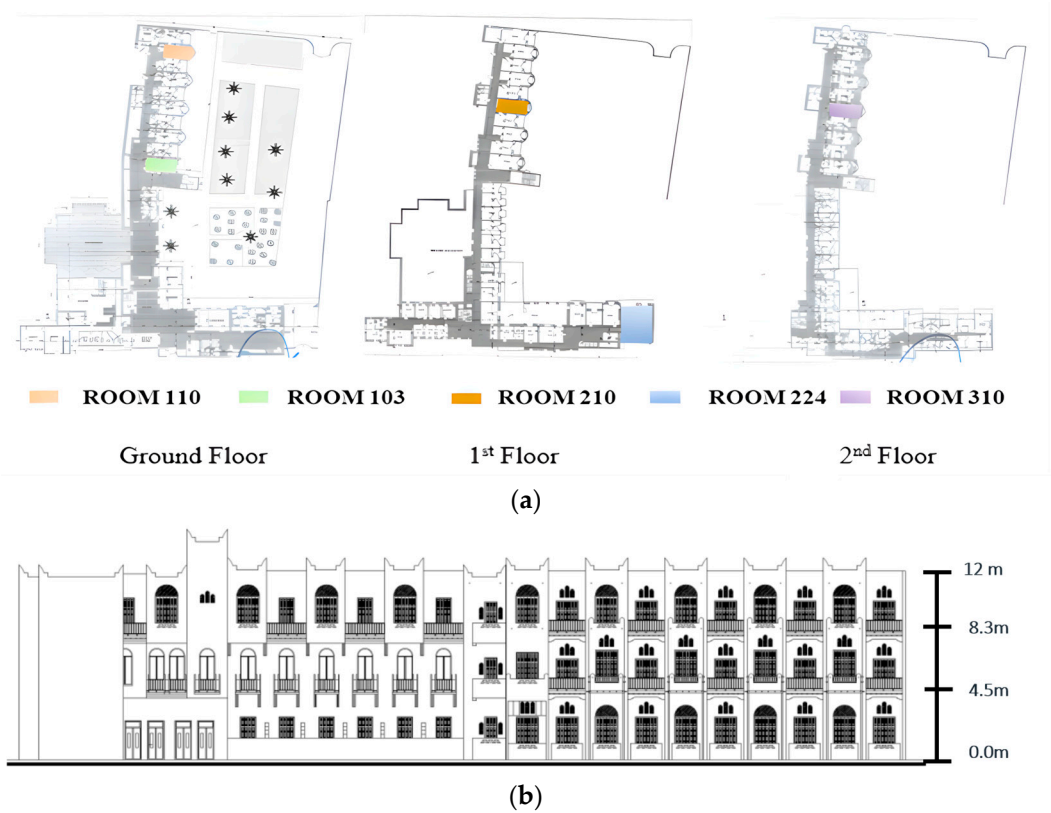
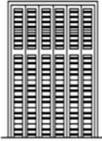
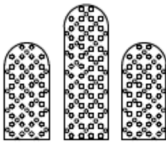


Figure 3. (a) Architectural Plans Supplied by the Cultural Affairs Directorate, Biskra. (b) Main Elevation of the Transatlantique Hotel. Source: [54].

Table 3. Typology of openings of the Hôtel Transatlantique. Source: [54].

Type of the Window	Description
 2.2m 1.6m	Rectangular French window with wooden louvered shutters
 1.7m 1.2m	Rectangular French window with wooden louvered shutters and a semicircular transom adorned with geometric motifs.
 0.4 × 0.25m 0.6 × 0.4m 0.4 × 0.25m	Triplet of Slender Semicircular Arched Openings Enclosed by Geometric Claustras

In this study, the heritage-sensitive elements are considered to include the external façade composition, rhythm and proportions of openings, window geometry, wooden louvered shutters, arched transoms, decorative motifs, and claustra elements. Therefore, interventions that modify window dimensions, façade geometry, external materials, or architectural expression were excluded from the tested scenarios. Acceptable interventions were limited to reversible or low-impact strategies, including interior surface reflectance improvement, glazing-performance enhancement where the exterior appearance is preserved, and roof-based TDDs only where technically and visually compatible. Although TDDs avoid direct façade alteration, they still require roof-level intervention; therefore, their application must be assessed in terms of roof visibility, structural feasibility, reversibility, waterproofing, maintenance access, and approval by heritage authorities.

3.3. Selection of Studied Spaces

The daylight analysis focuses on five guest rooms: Rooms 103, 110, 210, 224, and 310 (Figure 3a). These rooms were selected because they were accessible during the field survey, while several other rooms were under restoration and could not be reliably documented or measured. Despite this limitation, the selected rooms represent different floor levels, orientations, depths, window conditions, and daylight exposure situations within the hotel. They therefore provide a representative sample for evaluating daylight behavior under façade-preservation constraints. This selection allows the study to compare daylight performance across different spatial conditions, including variations in solar exposure, depth of daylight penetration, and vertical position within the building. By analyzing representative spaces rather than the entire building, the study ensures a focused and detailed assessment of daylight behavior while maintaining computational efficiency (Tables 4 and 5, Figure 4).

Table 4. Physical and daylight-relevant characteristics of the selected guest rooms.

Room	Floor	Orientation	Area (m ²)	Height (m)	Depth (m)	Window Type	Window Dimensions (m)	WWR	Reason for Selection
103	Ground Floor	South	29.8	4.5	7.57	Rectangular French window	2.2 × 1.6 m	19.87%	Low-level room with limited daylight
110	Ground Floor	South	31.8	4.5	7.57	Rectangular French window	2.2 × 1.6 m	18.62%	Deep room suitable for TDD testing
210	1st Floor	South	28.8	3.8	7.57	Rectangular French window	2.2 × 1.6 m	24.35%	Favorable geometry/exposure
224	1st Floor	East	88	3.8	8	Rectangular French window + Triplet of Slender Semicircular Arched Openings Enclosed by Geometric Claustras	2.2 × 1.6 m + Small openings: 0.4 × 0.25 m, 0.6 × 0.4 m, 0.4 × 0.25 m	9.47%	Tests effect of reflectance improvement
310	2nd Floor	South	31.3	3.7	8.62	Rectangular window	1.7 × 1.2	15.18%	Upper-floor room suitable for TDD scenario

WWR was calculated as the ratio between the total window area and the corresponding external wall area of each room.

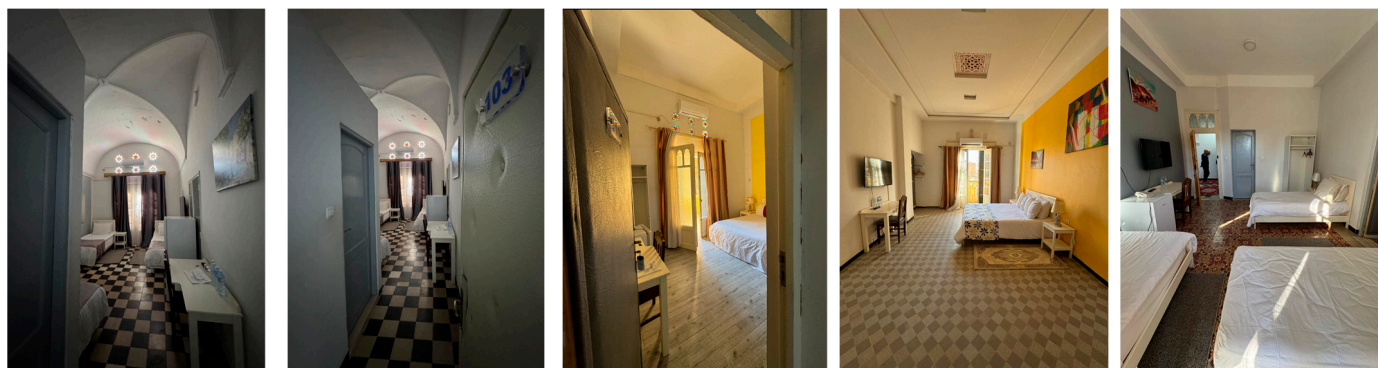


Figure 4. Views of Transatlantique Hotel Rooms, Biskra, Algeria.

Table 5 . Summary of surface reflectance measurement procedure.

Parameter	Description
Instrument	Testo 545 lux meter
Reference surface	Grey card with known reflectance of 18%
Measurements per surface	Three repeated measurements were taken for each surface type, and the average value was used
Measurement time	Daytime field measurements, conducted during stable daylight conditions
Sky condition	Clear to partly clear sky conditions, with no rapid change in daylight during measurement
Sensor distance	Kept constant during all measurements, approximately 20–30 cm from the tested surface
Sensor angle	Kept constant and perpendicular to the tested surface as much as possible
Uncertainty estimate	Mean value $\pm$ standard deviation of repeated measurements

4. Methodology

4.1. Research Framework

The study is conducted under strict heritage preservation constraints, which prohibit any modification to the building façade, including changes to window dimensions, geometry, or external appearance. Consequently, daylight optimization strategies are limited to non-invasive interventions that do not affect the architectural identity of the building.

These constraints restrict the range of possible solutions to interior material adjustments, such as increasing surface reflectance and improvements in glazing performance, as well as the integration of roof-based daylighting systems where feasible. In spaces without access to the roof, only façade-independent strategies can be applied.

This study adopts a quantitative, simulation-based approach to evaluate and optimize daylight performance in selected rooms of a historic hotel under façade preservation constraints. The research methodology (Figure 5) is structured as a sequence of interconnected steps, including data collection, digital modelling, simulation, and performance evaluation.

The overall workflow consists of:

- In situ data collection and material characterization,
- Development of a three-dimensional digital model,
- Definition of optical material properties,
- CBDM, analysis, and comparison of performance metrics across different scenarios.

This structured approach enables a systematic assessment of daylight performance and the evaluation of alternative retrofit strategies within realistic environmental conditions.

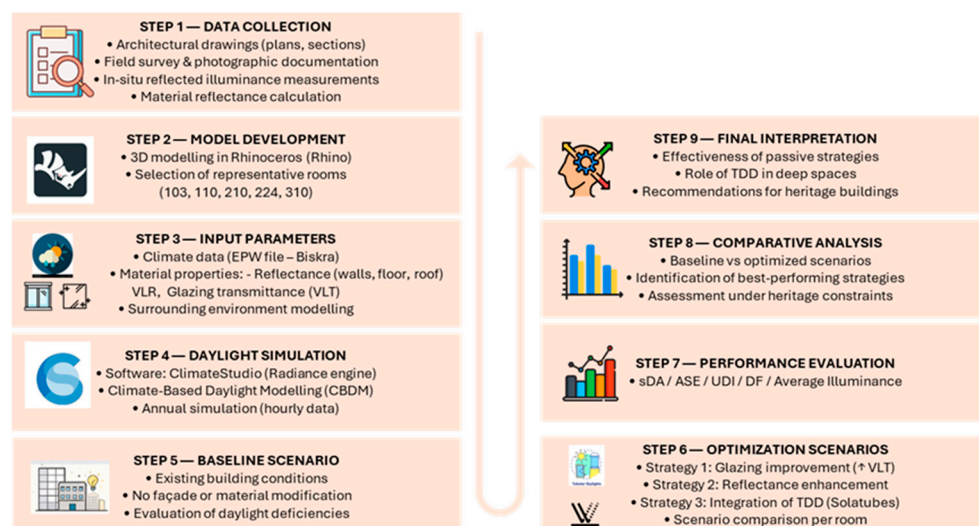


Figure 5. Methodological Framework Applied to the Case Study Building in Biskra.

4.2. Data Collection and Material Characterization

Field measurements were conducted to obtain accurate information on the physical and optical properties of interior surfaces. Architectural drawings and building documentation were provided by the Cultural Affairs Directorate, while on-site observations were used to verify geometric and material conditions.

To determine approximate surface reflectance values, in situ reflected illuminance measurements were carried out using a Testo 545 lux meter (Figure 6). The reflectance of each surface was estimated by comparing the reflected illuminance measured from the tested surface with that measured from a reference grey card of known reflectance, using the following Equation (1):

$$R_{test} = R_{ref} \times \frac{E_{test}}{E_{ref}} \quad (1)$$

- R_{test} : Estimated reflectance of the tested surface
- E_{test} : Reflected illuminance measured from the tested surface
- E_{ref} : reflected illuminance measured from the reference grey card
- R_{ref} : known reflectance of the reference grey card

During measurements, the reference card and tested surfaces were positioned under identical lighting conditions. The sensor position, measurement distance, and angle were kept as constant as possible to reduce measurement variability. The obtained reflectance values were subsequently used to define material properties within the simulation model.

For each material type, at least three reflected-illuminance measurements were taken at different points on the same surface, and the average value was used in the simulation model. Measurements were conducted during the daytime under stable sky conditions to reduce rapid variations in incident daylight. The reference grey card had a known reflectance value of 18%. During all measurements, the lux meter position, distance from the surface, and angle of measurement were kept as constant as possible. Reflectance was calculated by comparing the reflected illuminance from the tested surface with that from the reference card. Measurement uncertainty was estimated using the variation between repeated measurements, expressed as standard deviation or percentage variation. Surfaces showing high variation were remeasured to reduce uncertainty.



Figure 6. In situ surface reflectance measurement setup using a Testo 545 lux meter and a reference grey card.

4.3. Digital Modelling and Simulation Setup

A three-dimensional digital model of the selected rooms was developed using Rhinoceros 3D (Figure 7), accurately representing the geometry, openings, and spatial configuration of the building. The model was then imported into ClimateStudio, which utilizes the Radiance engine to perform physically based daylight simulations.

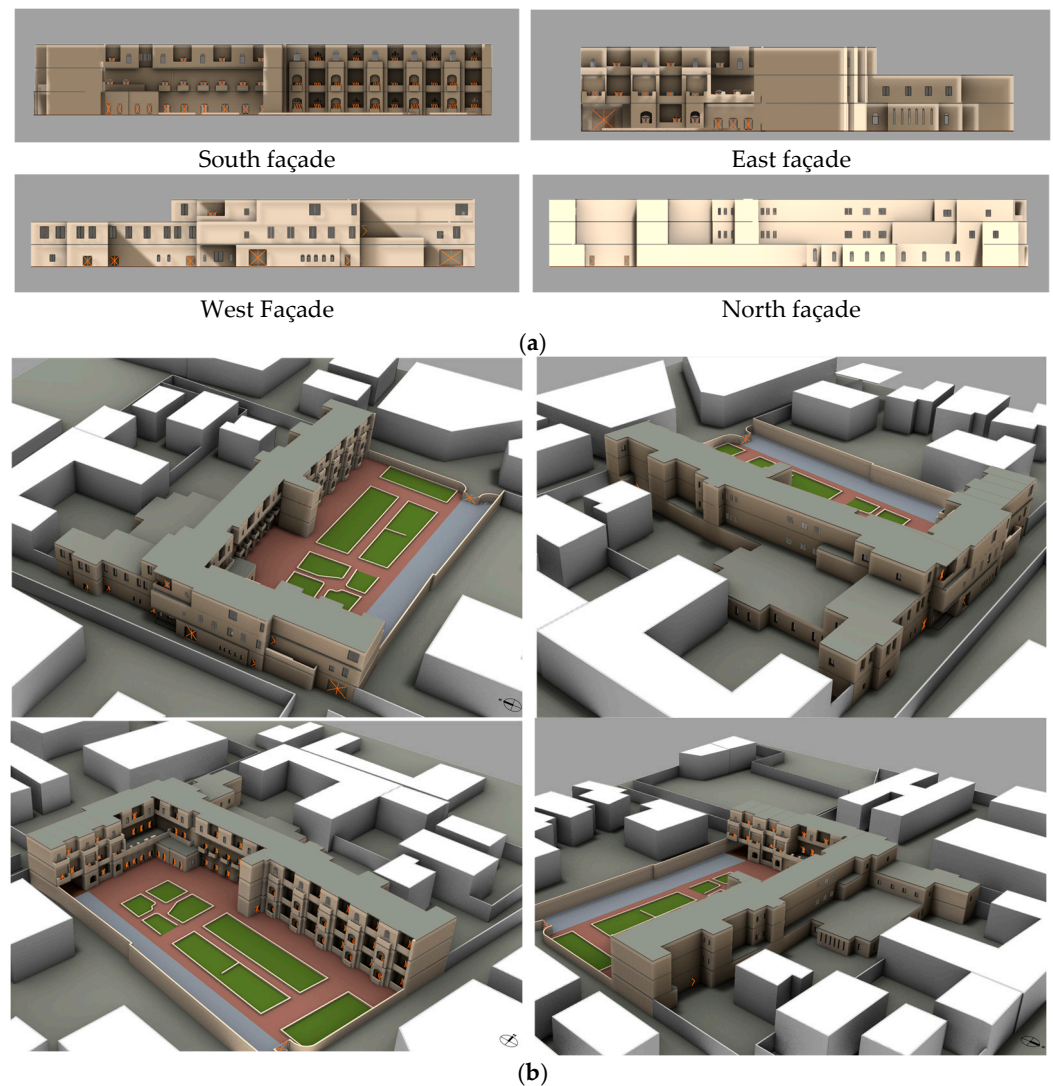


Figure 7. (a) Digital modeling of the four façades of the Hotel Transatlantique in Biskra using Rhinoceros (Rhino). (b) A three-dimensional digital model of Transatlantique Hotel developed by Rhinoceros 3D.

CBDM was employed using an EnergyPlus Weather (EPW) file for Biskra, providing hourly climate data that represents real sky and sun conditions throughout the year. This

approach allows for a realistic evaluation of daylight availability and distribution over time.

The simulation parameters were defined as follows:

- Sensor grid resolution: 0.5 m.
- Sensor height: 0.8 m above floor level.
- Daylight assessment period: 08:00–18:00, used to evaluate annual daylight availability during daytime hours.
- Sky model: Climate-based (annual simulation using EPW data).
- Simulation engine: Radiance (via ClimateStudio).

It should be noted that the 08:00–18:00 period is not intended to represent the complete occupancy profile of a hotel guest room, since hotel rooms may be occupied during evening and night hours. Instead, this period is used as a daytime daylight-assessment schedule, consistent with the objective of evaluating natural daylight availability and visual comfort. Night-time occupancy is therefore excluded because it is not relevant to daylight performance and would mainly involve artificial lighting. Material optical properties were assigned based on measured reflectance values and glazing characteristics, including (VLT) and (VLR). This ensured that the simulation model closely represents the building's actual physical conditions.

The main Radiance/ClimateStudio parameters used in the simulations are reported to improve reproducibility. The simulations were performed using the quality preset in ClimateStudio. The critical Radiance parameters included ambient bounces (-ab), ambient divisions (-ad), ambient super-samples (-as), ambient resolution (-ar), and ambient accuracy (-aa), as summarized in Table 6.

Table 6. Climate-Based Daylight Simulation Parameters and Settings Used in ClimateStudio

Parameter	Value Used
Simulation engine	Radiance via ClimateStudio
Simulation type	Annual climate-based daylight simulation
Quality preset	Default ClimateStudio annual daylight simulation settings
Ambient bounces	Default value controlled by ClimateStudio; not manually modified
Ambient divisions	Default value controlled by ClimateStudio; not manually modified
Ambient super-samples	Default value controlled by ClimateStudio; not manually modified
Ambient resolution	Default value controlled by ClimateStudio; not manually modified
Ambient accuracy	Default value controlled by ClimateStudio; not manually modified
Weather file	Biskra EPW weather file
Sky model	Climate-based annual sky model
Sensor grid resolution	0.5 m
Sensor height	0.8 m above floor level
Daylight assessment period	08:00–18:00
Daylight metrics	sDA, ASE, UDI, DF, and average illuminance

The Radiance parameters were not manually overridden; therefore, the simulations were carried out using the default ClimateStudio annual daylight simulation settings.

4.4. Daylight Performance Metrics

Daylight performance was evaluated using widely recognized climate-based metrics that assess both daylight availability and visual comfort:

- sDA300/50%: Percentage of floor area receiving at least 300 lux for 50% of occupied hours, indicating daylight sufficiency.

- ASE1,000,250: Percentage of floor area receiving illuminance above 1000 lux for more than 250 h per year, used to assess potential glare and overexposure.
- UDI100–3000 lux: Percentage of time during which illuminance falls within a useful and comfortable range, reflecting daylight usability.
- DF: Ratio of indoor to outdoor illuminance under overcast sky conditions, used as a complementary static metric.

These metrics are commonly adopted in international standards and certification systems, enabling a comprehensive evaluation of daylight quantity, distribution, and quality.

4.5. Scenario Definition

To assess the effectiveness of daylight optimization strategies, multiple simulation scenarios were developed for each selected room. These include:

- Initial Scenario (Baseline): Represents the existing building condition, with original material properties, glazing systems, and no modifications.
- Optimized Scenarios: Introduce progressive improvements through:
 - a. Enhancement of VLT.
 - b. Increase in interior and exterior surface reflectance.
 - c. Integration of TDDs, where roof access is available.

The scenarios were designed to evaluate the impact of each strategy, as well as their combined effect on daylight performance. The selected VLT and reflectance values were defined according to three criteria: existing measured or observed conditions, feasibility of retrofit implementation, and compatibility with façade-preservation constraints. Baseline values represent the current material and glazing properties documented during fieldwork. Optimized VLT values represent feasible improvements in glazing performance that do not require changes to window size, position, or external architectural expression. Similarly, optimized reflectance values represent reversible interior surface improvements, such as lighter finishes for walls, ceilings, and floors, intended to increase daylight distribution without modifying protected external elements. Therefore, the selected values were not arbitrary maximum values but practical retrofit assumptions compatible with conservation requirements.

TDDs were selected only for rooms where roof access and spatial configuration made the intervention technically feasible. Their number and placement were determined according to room depth, location of poorly lit zones, roof accessibility, and the need to improve daylight uniformity without altering the façade. Rooms without roof access were excluded from TDD scenarios. This selection also considered known TDD performance factors, including tube length, diameter, internal reflectivity, sky condition, and the relationship between the roof collector and the interior diffuser.

4.6. Model Validation and Assumptions

To improve the reliability of the simulation results, the model was calibrated using in situ reflectance estimates derived from reflected illuminance measurements. While direct validation of simulated illuminance values was limited, the use of measured material properties and accurate geometric modelling enhances the credibility of the results.

Several assumptions were adopted in the simulation process. All surfaces were considered Lambertian reflectors, and the surrounding environment was simplified with uniform reflectance values. These assumptions are commonly used in daylight simulation studies and allow for a balance between model accuracy and computational efficiency.

5. Results

To improve interpretation, the results are discussed according to three daylight-performance dimensions. First, daylight sufficiency is evaluated using sDA, average illuminance, and DF, which indicate whether the rooms receive enough daylight for visual tasks. Second, daylight usability and distribution are assessed using UDI and spatial daylight maps, which show whether daylight levels remain within a useful range and how evenly daylight is distributed across the room. Third, potential overexposure and glare risk are evaluated using ASE, which identifies areas receiving excessive direct sunlight. However, ASE is used here only as an indicator of possible overexposure; it does not represent a complete glare assessment. A full glare analysis would require luminance-based indicators, such as Daylight Glare Probability (DGP), which were outside the scope of this study.

5.1. Baseline Daylight Performance

The baseline simulations reveal generally weak daylight performance in most analyzed rooms, confirming the limitations imposed by the existing spatial configuration and façade-preservation constraints.

Daylight sufficiency. Rooms 103, 110, 210, and 224 show low daylight sufficiency, with sDA values below the recommended threshold and average illuminance ranging from approximately 140 to 310 lux. These values indicate that most spaces do not receive enough daylight for typical visual tasks and would require frequent use of artificial lighting. DF values below 1% in most rooms further confirm weak daylight penetration under diffuse sky conditions. Room 310 performs better, with a higher average illuminance of approximately 616 lux and sDA around 31.2%, but it still does not fully achieve satisfactory daylight autonomy.

Daylight usability and distribution. UDI values remain low in Rooms 103, 110, 210, and 224, showing that only limited areas receive daylight within a useful and comfortable range. The spatial daylight maps indicate that daylight is mainly concentrated near the openings, while deeper zones remain underlit. This confirms that the main problem is not only insufficient daylight quantity but also uneven daylight distribution.

Potential overexposure and glare risk. ASE values are generally low in the poorly lit rooms, suggesting limited direct sunlight exposure. However, this low ASE mainly results from insufficient daylight access rather than effective glare control. Room 310 shows a higher ASE value of approximately 16.9%, indicating potential overexposure and glare risk. Therefore, the baseline condition combines insufficient daylight in most rooms with localized overexposure risk in the better-lit upper-floor room. It should be noted that ASE is used in this study as an indicator of potential direct-sunlight exposure and overexposure risk. It should not be interpreted as a complete glare assessment, since no luminance-based glare metric, such as Daylight Glare Probability (DGP), was calculated.

Room 103 exhibits poor daylight performance, with sDA values below recommended thresholds. Daylight penetration is limited to areas near the façade, while the deeper zones remain underlit. UDI values confirm that only a small portion of the space achieves acceptable daylight levels. DF values below 1% further indicate weak diffuse daylight availability. ASE values remain low, suggesting negligible glare risk (Figure 8).

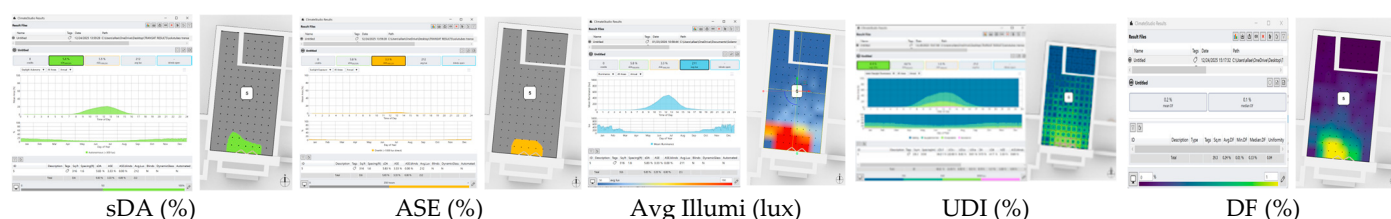


Figure 8. Baseline Scenario Daylighting Performance Analysis of Room 103.

Similar to Room 103, Room 110 shows insufficient daylight availability. The spatial distribution of daylight is uneven, with strong reliance on artificial lighting in deeper zones. UDI and DF values remain low, reinforcing the limited effectiveness of natural lighting. ASE values indicate minimal glare, primarily due to low daylight penetration (Figure 9).

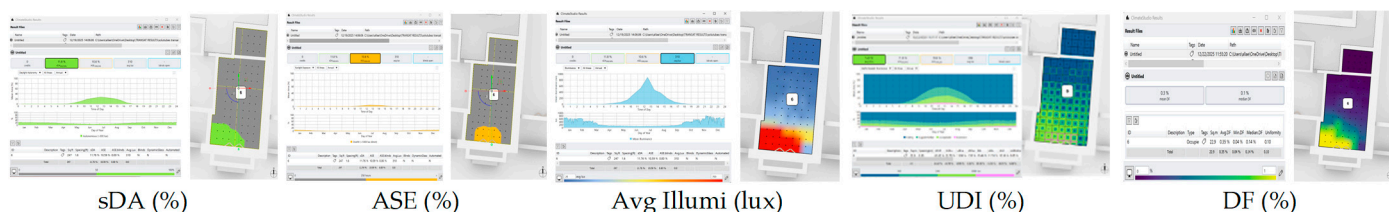


Figure 9. Baseline Scenario Daylighting Performance Analysis of Room 110.

Room 210 presents one of the weakest daylight performances among the analyzed spaces. Daylight is highly concentrated near openings, with rapid decay toward the interior. DF values below 1% confirm poor daylight penetration. Both sDA and UDI remain low, indicating inadequate daylight autonomy. ASE values are minimal (Figure 10).

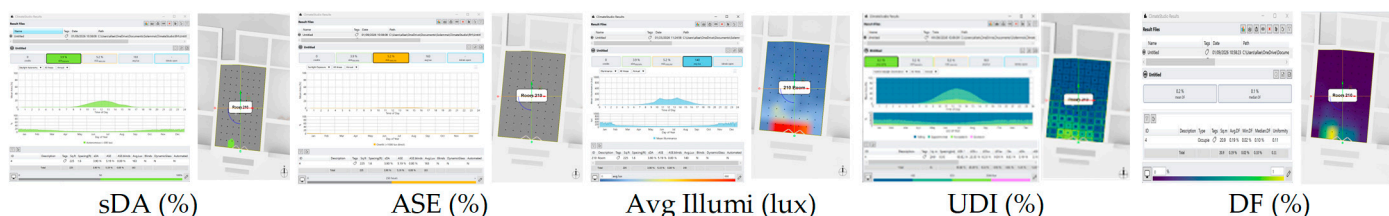


Figure 10. Baseline Scenario Daylighting Performance Analysis of Room 210.

Room 224 shows slightly more distributed daylight compared to other rooms; however, overall performance remains below acceptable thresholds. UDI values suggest that only localized areas benefit from adequate daylight. DF values remain low, and ASE is minimal, indicating low glare but insufficient daylight availability (Figure 11).

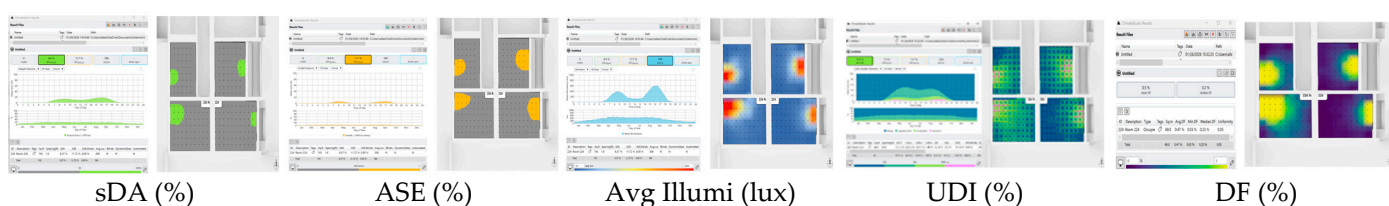


Figure 11. Baseline Scenario Daylighting Performance Analysis of Room 224.

Room 310 represents an exception within the baseline scenario. It achieves higher daylight levels, with average illuminance exceeding 600 lux and improved daylight distribution. However, this increased daylight access leads to higher ASE values, indicating potential glare issues, particularly near the façade. While daylight availability is improved, visual comfort may be compromised without proper shading strategies (Figure 12).

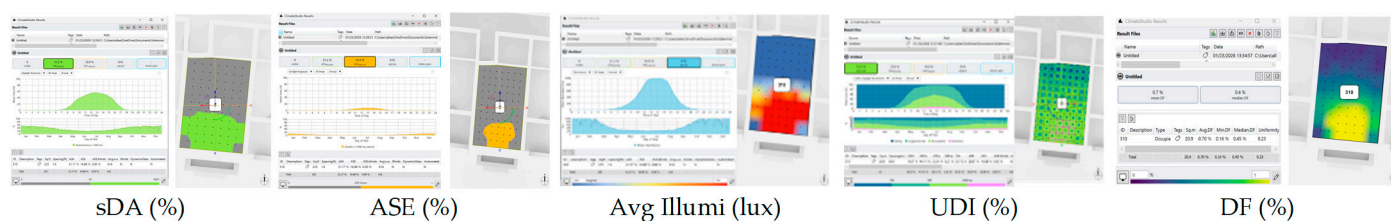


Figure 12. Baseline Scenario Daylighting Performance Analysis of Room 310.

5.2. Impact of Glazing and Reflectance Optimization

The introduction of improved glazing properties and increased surface reflectance resulted in a consistent enhancement of daylight performance across all analyzed rooms. Increasing VLT and internal reflectance values significantly improved daylight penetration and redistribution within the spaces.

Across rooms without access to roof-based interventions (Rooms 103, 210, and 224), these strategies led to substantial increases in sDA and UDI. In particular, Room 210 achieved high daylight performance (sDA $\approx$ 62.3%, UDI $\approx$ 58.6%) using façade-based optimization alone, indicating that favorable geometry and orientation can enable effective daylighting without additional systems (Figure 13).

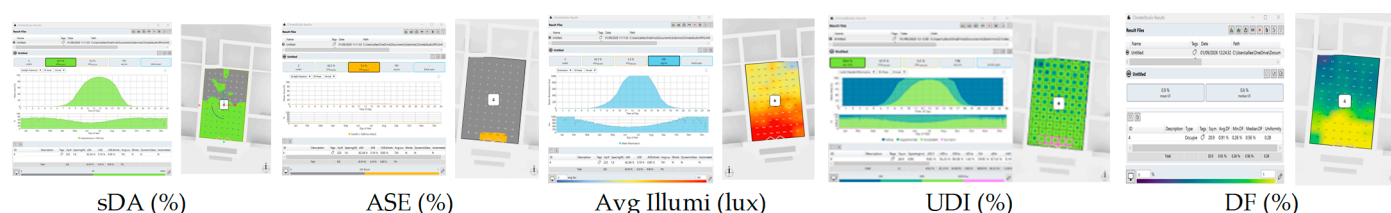


Figure 13. Daylighting Performance of Room 210 under the Glazing and Reflectance Optimization Scenario.

In contrast, Room 224 demonstrated that glazing optimization alone produces limited improvement, while the combination of glazing and reflectance enhancement leads to a significant increase in daylight availability (sDA $\approx$ 46.4%) and usability (UDI $\approx$ 45.4%) (Figure 14).

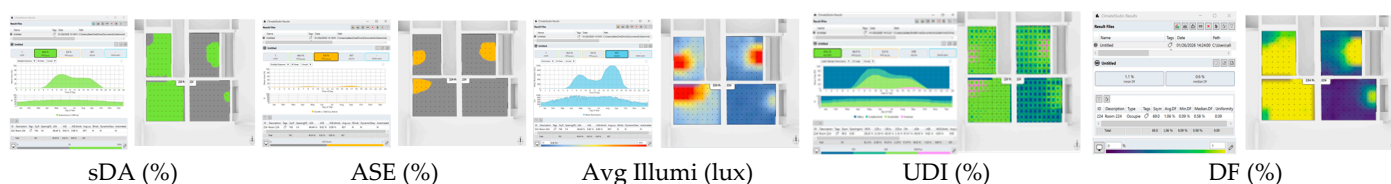


Figure 14. Daylighting Performance of Room 224 under the Glazing and Reflectance Optimization Scenario.

Similarly, Room 103 showed progressive improvement across scenarios, ultimately reaching acceptable daylight performance (sDA $\approx$ 56.7%) with controlled ASE levels (Figure 15).

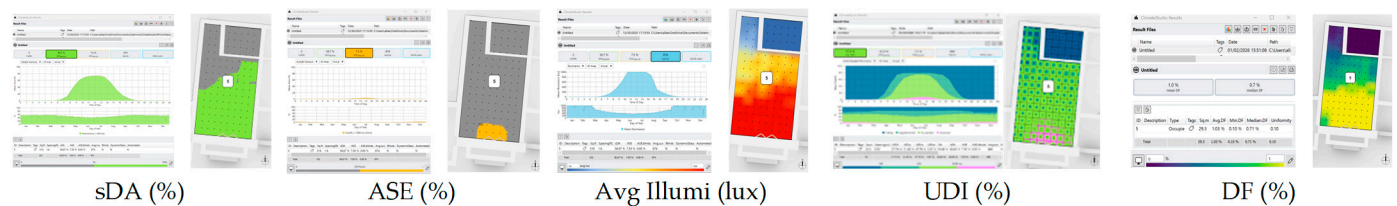


Figure 15. Daylighting Performance of Room 103 under the Glazing and Reflectance Optimization Scenario.

Overall, these results confirm that material-based strategies play a critical role in enhancing daylight distribution, particularly in spaces where façade modifications are not possible.

5.3. Effect of Tubular Daylighting Devices (TDDs)

The integration of TDDs produced the most significant improvements in daylight performance, particularly in deeper or more constrained spaces. In Room 110, the addition of TDD systems increased sDA from 42.4% (glazing optimization only) to 82.4%, while simultaneously reducing ASE from 10.0% to 0.0%, indicating the elimination of glare risk (Figure 16).



Figure 16. Daylighting Performance of Room 110 with TDDs.

A similar trend was observed in Room 310, where the combination of glazing optimization, enhanced reflectance, and TDD integration resulted in optimal daylight performance. The space achieved full sDA = 100% while maintaining zero ASE = 0.0%, along with a high UDI value ($\approx 75.8\%$), indicating a well-balanced and highly effective daylight environment (Figure 17).

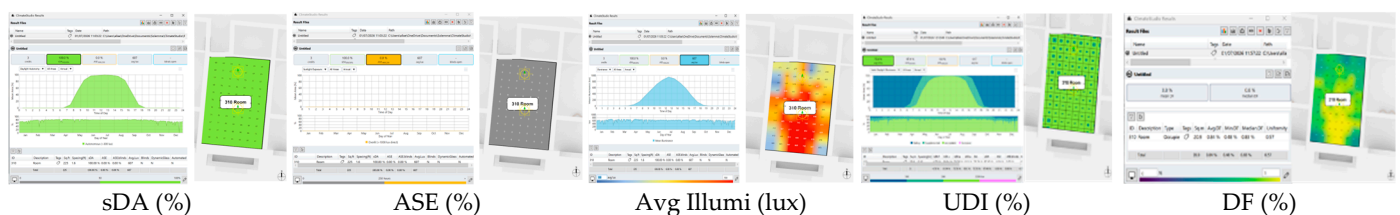


Figure 17. Daylighting Performance of Room 310 with TDDs.

These results demonstrate that TDD systems are highly effective in redistributing daylight deeper into interior spaces, providing diffuse illumination that enhances daylight availability without increasing visual discomfort.

5.4. Comparative Performance Analysis

A comparative analysis of all scenarios highlights clear trends in the effectiveness of the different strategies. Across all rooms, increasing glazing transmittance and internal surface reflectance consistently improved sDA and UDI, while maintaining ASE within acceptable limits.

However, the effectiveness of these strategies varies depending on spatial conditions. In rooms with favorable geometry and exposure, such as Room 210, façade-based optimization alone is sufficient to achieve high performance. In contrast, deeper or more constrained spaces require additional interventions to reach acceptable daylight levels.

The integration of TDD systems emerges as the most effective strategy for achieving high-performance daylighting, particularly when combined with optimized material properties. These systems significantly enhance daylight distribution while controlling glare, making them especially suitable for buildings located in high solar radiation climates.

Overall, the results indicate that a multi-strategy approach, combining glazing optimization, reflectance enhancement, and, where feasible, TDD integration, is essential for achieving balanced daylight performance in heritage buildings under façade preservation constraints (Table 7).

Table 7. Simulation Input Parameters and Daylighting Intervention Scenarios (VLT, VLR, and TDD) by Room.

Room	Scenario	French Window (VLT/VLR)	Window (VLT/VLR)	Exterior Wall (VLR)	Interior Wall (VLR)	Floor (VLR)	TDD
103	Baseline	42%/5%	53%/6%	64%	7.8%	49%	No
	Scen 1	88%/8%	53%/6%	64%	42%	49%	No
	Scen 2	91%/8%	53%/6%	75%	68%	62%	No
110	Baseline	42%/5%	53%/6%	64%	7.8%	49%	No
	Scen 1	58%/15%	66%/6%	84%	42%	49%	No
	Scen 2	66%/6%	66%/6%	84%	42%	49%	No
	Scen 3	58%/15%	66%/6%	84%	42%	49%	Yes (3TDDs)
210	Baseline	42%/5%	53%/6%	64%	7.8%	49%	No
	Scen 1	88%/8%	88%/8%	71%	87%	78%	No
224	Baseline	42%/5%	53%/6%	64%	8%	49%	No
	Scen 1	58%/15%	67%/7%	64%	8%	49%	No
	Scen 2	58%/15%	67%/7%	70%	89%	67%	No
310	Baseline	42%/5%	53%/6%	64%	7.8%	49%	No
	Scen 1	88%/8%	88%/8%	71%	87%	78%	Yes (2TDDs)

Because the results are based on deterministic simulation outputs rather than repeated experimental samples, inferential statistical tests were not applied. Instead, descriptive statistical indicators were used to support scenario comparison. Baseline and optimized scenarios were compared using absolute change, percentage-point change, and relative percentage improvement (Equations (2) and (3)). In addition, mean, minimum, maximum, and standard deviation values were calculated across the five studied rooms to describe the variability of daylight performance between spaces (Equations (4) and (5)).

$$\text{Percentage-point change} = \text{Optimized value} - \text{Baseline value} \quad (2)$$

$$\text{Relative improvement (\%)} = [(\text{Optimized value} - \text{Baseline value}) / \text{Baseline value}] \times 100 \quad (3)$$

$$\text{Mean} = \sum x / n \quad (4)$$

$$\text{Standard deviation} = \sqrt{[\sum (x - \text{mean})^2 / (n - 1)]} \quad (5)$$

6. Discussion

6.1. Interpretation of Daylight Optimization Results

The results of this study demonstrate that significant improvements in daylight performance can be achieved in heritage buildings without modifying the façade, provided that appropriate passive strategies are carefully combined. The findings highlight the critical role of material properties, glazing performance, and, where feasible, the integration of TDDs in enhancing daylight availability and distribution. This confirms that daylight optimization in heritage buildings should be understood as a sustainable retrofit strategy that combines visual comfort, reduced dependence on artificial lighting, and cultural heritage preservation.

Across all analyzed rooms, increasing glazing transmittance and internal surface reflectance consistently improved sDA and UDI, confirming the importance of both daylight admission and internal light redistribution. In particular, surface reflectance plays a decisive role in redistributing daylight deeper into the room, especially where geometry limits direct daylight access. This is evident in Room 224, where glazing optimization alone produced limited improvement, while the addition of high-reflectance surfaces resulted in a substantial increase in daylight performance.

The comparison between façade-based strategies and combined approaches further reveals that glazing optimization alone may not be sufficient in deeper or more constrained spaces. In Room 110, increasing glazing transmittance improved daylight availability but led to higher ASE, indicating a potential glare risk. In contrast, the integration of TDD systems significantly enhanced daylight distribution while reducing ASE to negligible levels. This indicates that TDDs do not simply increase illuminance; they modify the spatial distribution of daylight by introducing diffuse zenithal light, which can reduce contrast between window-adjacent and deeper zones.

The results obtained for Room 310 further reinforce this observation. The combination of high-performance glazing, enhanced surface reflectance, and TDD integration produced optimal daylight conditions, achieving full sDA = 100% while maintaining zero ASE = 0%. This demonstrates that the synergy between façade-based and roof-based daylighting strategies can overcome the limitations imposed by building depth and orientation. However, this result should be interpreted in relation to room geometry, roof accessibility, and the assumed TDD configuration, meaning that similar performance cannot be generalized to all heritage rooms without case-specific evaluation.

These findings are consistent with previous studies showing that glazing improvement and high-reflectance interior surfaces can improve daylight availability in existing and heritage buildings without major architectural intervention [36,42]. However, the present results also show that material-based strategies remain limited when room depth, window position, and protected façade geometry restrict daylight penetration. The stronger performance of TDDs agrees with studies describing tubular daylighting systems as effective solutions for deep-plan spaces and rooms with limited façade exposure [28,50–52]. Unlike many previous studies that examine glazing, reflectance, or TDDs separately, this study compares these strategies within the same heritage hotel and under the same hot-desert climatic conditions.

6.2. Implications for Heritage Conservation

From a heritage conservation perspective, the proposed strategies are significant because they avoid direct alteration of the protected façade. In historic hotels, façades often carry architectural, symbolic, and urban value; therefore, interventions that change window size, rhythm, ornamentation, or external appearance may compromise heritage authenticity. The strategies evaluated in this study are conservation-compatible because

they focus on interior material properties, glazing performance, and roof-based daylight delivery where feasible, rather than modifying the façade composition.

Nevertheless, the integration of TDDs should be assessed carefully in relation to roof visibility, structural compatibility, reversibility, and approval by heritage authorities. While TDDs can be considered minimally invasive compared with façade modification, their installation still requires physical intervention at the roof level. Therefore, their application should follow conservation principles such as minimum intervention, reversibility, and compatibility with the historic fabric.

6.3. Sustainability and Energy Implications

The results also have implications for sustainable building retrofit in hot desert climates. Improving daylight availability may reduce dependence on artificial lighting during daytime use; however, this study did not quantify electric lighting-energy savings, cooling-load effects, or thermal comfort impacts. Therefore, energy and thermal implications are discussed as potential outcomes that require further integrated daylight, thermal, and energy simulation. At the same time, daylight strategies in high solar radiation contexts must avoid increasing glare and overheating. The findings show that increasing daylight availability does not necessarily increase visual discomfort when daylight is re-distributed through reflective surfaces or delivered as diffuse zenithal light through TDDs.

In addition to operational performance, the study supports the adaptive reuse of heritage buildings by improving indoor environmental quality while preserving embodied cultural value. This is particularly relevant for heritage hotels, where user comfort, cultural identity, and tourism value are closely connected. Therefore, the proposed approach contributes to sustainability not only through potential energy savings but also through cultural continuity and the extended service life of existing buildings.

6.4. Practical Recommendations for Retrofit Design

From a practical perspective, the results suggest a step-by-step retrofit approach. Interior surface reflectance improvement should be considered first because it is reversible, relatively low-cost, easy to maintain, and does not affect the protected façade. Glazing enhancement may also be useful, but only when the replacement or treatment preserves the external appearance, window proportions, and heritage character. TDDs should be considered for deep or poorly lit rooms where façade-based strategies are insufficient and where roof access is technically possible. However, their use requires careful evaluation of roof visibility, structural feasibility, waterproofing, reversibility, maintenance access, installation cost, and approval by heritage authorities. Therefore, daylight retrofit decisions should not be based only on performance metrics but also on conservation regulations, technical feasibility, long-term maintenance, and implementation cost (Tables 8–11).

Table 8. Baseline Daylighting Performance Evaluation of Selected Hotel Rooms in Biskra.

Room	sDA (%)	Avg Illuminance (lux)	UDI	DF (%)	ASE (%)	Performance
103	5.8% < 40%	211 lux	8.9% Low	0.2% < 1%	3.3% < 10%	Poor
110	11.8% < 40%	310 lux	14% Low	0.3% < 1%	10.6% > 10%	Poor
210	3.9% < 40%	140 lux	8.3% Low	0.2% < 1%	5.2% < 10%	Poor
224	8.4% < 40%	306 lux	10.2% Low	0.5% < 1%	11.7% > 10%	Poor
310	31.2% < 40%	616 lux	32.5% Medium	0.7% > 1%	16.9% > 10%	Mixed (daylight + glare risk)

Table 9. Comparative Daylighting Performance Analysis of Rooms Under Different Design Strategies.

Room	Scenarios	Strategy Applied	sDA (%)	ASE (%)	UDI (%)	Avg. Illuminance (lux)	Performance Assessment	Key Finding
Room 103	2	Glazing + Reflectance	56.7%	7.5%	47.8%	874	Acceptable/LEED-compliant	Progressive material optimization can achieve balanced daylight without TDD
Room 110	3	Glazing → Reflectance → +TDD	82.4%	0.0%	64.1%	622	Very High Performance	TDD integration significantly enhances daylight in deep spaces
Room 210	1	Glazing + Reflectance	62.3%	5.2%	58.6%	741	High Performance	Favorable geometry allows façade-only strategy to perform effectively
Room 224	2	Glazing → +Reflectance	46.4%	9.6%	45.4%	657	Moderate Performance	Reflectance is critical; glazing alone is insufficient
Room 310	1	Glazing + Reflectance + TDD	100%	0.0%	75.8%	607	Optimal Performance	Combined façade + zenithal daylighting achieves fully daylit space

Table 10. Descriptive statistical comparison of optimized scenarios across the five rooms.

Metric	Mean	Standard Deviation	Minimum	Maximum
sDA (%)	69.6	21.5	46.4	100.0
UDI (%)	58.3	12.4	45.4	75.8
ASE (%)	4.5	4.4	0.0	9.6
Average illuminance (lux)	700.2	110.2	607	874

Table 11. Decision matrix for daylight retrofit strategies under façade-preservation constraints.

Strategy	Daylight Improvement	Glare/AS E Risk	Thermal Risk	Conservation Compatibility	Reversibility	Execution Complexity	Relative Cost	Main Recommendation
Interior surface reflectance improvement	Medium	Low	Low	High	High	Low	Low	Recommended as a first-level intervention because it is low-impact, reversible, and does not alter the façade
Glazing-performance enhancement	Medium to high	Medium	Medium	Medium to high	Medium	Medium	Medium	Suitable only if window proportions, external appearance, and heritage character are preserved
TDD integration	High in deep rooms	Low to medium	Medium	Medium	Medium	High	High	Recommended for deep or poorly lit rooms with roof access, after checking roof visibility, structure, waterproofing, and heritage approval

Combined strategy	High	Low to medium	Medium	Medium to high	Medium	Medium to high	Medium to high	Recommended when a single intervention is insufficient to achieve balanced daylight performance
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7. Conclusions

This study demonstrates that daylight retrofit in heritage hotels should be approached as an integrated conservation and environmental design problem rather than only as a lighting-performance issue. In buildings where façade modification is restricted, daylight improvement depends on strategies that respect architectural identity while responding to room geometry, climatic conditions, and visual-comfort requirements. The findings show that façade-independent interventions, such as improved glazing performance and increased interior surface reflectance, can enhance daylight availability while preserving the external architectural expression of heritage buildings. However, these strategies are more effective in rooms with favorable geometry and exposure. For deeper or poorly lit spaces, roof-based daylighting systems such as tubular daylighting devices can provide an additional source of diffuse daylight and improve daylight distribution without altering the protected façade composition. The broader contribution of this study is the development of a conservation-compatible daylight retrofit framework for heritage buildings in hot-desert climates. Rather than proposing a universal solution, the framework provides a decision-support approach for selecting daylighting strategies according to the physical, climatic, and conservation conditions of each building. This approach can support architects, conservation specialists, and building managers in identifying interventions that improve indoor environmental quality while maintaining cultural value. Nevertheless, this study has some limitations. First, it is based on a single case study and selected representative rooms; therefore, the results cannot be directly generalized to all heritage hotels, building typologies, or climatic contexts. Second, the study focuses mainly on daylight availability and visual-comfort indicators, including sDA, ASE, UDI, average illuminance, and DF. Full thermal simulation, cooling-load analysis, and quantified electric lighting-energy savings were outside the scope of this work. This limitation is particularly important in hot-desert climates, where daylight improvement may influence solar heat gains and cooling demand. In addition, although the simulation model was developed using verified geometry and measured surface reflectance values, long-term experimental validation using indoor illuminance measurements was limited. Future studies should therefore include extended field measurements under different sky conditions and seasons to strengthen model validation. Furthermore, the feasibility of tubular daylighting devices was assessed mainly from a daylighting perspective. Structural compatibility, roof visibility, reversibility, waterproofing, cost, maintenance access, and approval by heritage authorities should be investigated before real implementation.

Future research should extend the proposed framework by integrating daylight simulation with thermal comfort assessment, cooling-load analysis, electric lighting-energy savings, cost analysis, occupant satisfaction, and conservation decision-making. The framework should also be tested in other heritage building typologies and climatic contexts to evaluate its broader applicability.

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Abbreviation

The following abbreviations are used in this manuscript:

ASE	Annual Sunlight Exposure
CBDM	Climate-Based Daylight Modelling
DF	Daylight Factor
EPW	EnergyPlus Weather file
LEED	Leadership in Energy and Environmental Design
sDA	Spatial Daylight Autonomy
TDD	Tubular Daylighting Device
UDI	Useful Daylight Illuminance
VLR	Visible Light Reflectance
VLT	Visible Light Transmittance
R test	Estimated reflectance of the tested surface
E test	Reflected illuminance measured from the tested surface
E ref	Reflected illuminance measured from the reference grey card
R ref	known reflectance of the reference grey card

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