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# Evidence-Driven Multi-Objective Optimisation for Evaluating Built Heritage Renovation in Mediterranean Dry–Hot Climates

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## ABSTRACT

Historic palaces in hot, dry climates must improve energy performance and indoor environmental quality without compromising their cultural, architectural, and material authenticity. Conventional renovation measures, such as extensive insulation, façade modification, or mechanical upgrades, risk damaging historic fabric and eroding heritage value, particularly given heterogeneous and deteriorated materials. Existing approaches rarely integrate energy and comfort standards, deterioration risks, or heritage preservation, and decisions often rely on qualitative judgement rather than performance-based evidence. This study asks how a performance-driven workflow can support the optimisation of renovated heritage buildings in hot, dry climates, especially in South Mediterranean countries such as Egypt, in terms of energy, daylight, and thermal comfort while respecting conservation constraints. Saffron Palace in Cairo, designed by Anton Laščak and now an educational museum, serves as the case study. The methodology combines architectural documentation, hygrothermal and daylight monitoring, and material deterioration assessment with a parametric BIM model linked to calibrated energy and daylight simulations. Passive and envelope strategies are evaluated through multi-objective optimisation. Expected outcomes include renovation strategies that enhance efficiency and indoor quality while retaining cultural identity, a decision-support guideline for policymakers and stakeholders, and consideration of climate-change resilience and risk.

## KEYWORDS:

Conservation guidelines, Built Heritage renovation, Energy efficiency, optimisation, Indoor environmental quality

## 1. INTRODUCTION

Climate change accelerates the frequency and severity of extreme weather events worldwide that impact the historic structures located in hot-dry climates. The 2025 Alliance for Research on Cultural Heritage (ARCHE) Strategic Research and Innovation Agenda (SRIA)[1] underscores that built heritage must be understood not as a statistic artifact, but as a dynamic component of a complex socio-ecological system essential to the green transition. In arid and semi-arid regions as in the southern Mediterranean, heritage renovation faces dual pressure. Climate change is

intensifying thermal stress on historic buildings, as projections for hot-arid residential typologies show cooling loads and overheating risk rising sharply, with one study finding the overheating burden in traditional (vernacular) buildings increasing by roughly 68–90% by late century relative to present conditions[2]. Historic buildings are especially exposed because they rely on passive strategies — thermal mass, natural ventilation, courtyard shading — whose performance under future climate scenarios remains poorly quantified, and because they typically operate without mechanical cooling, making indoor thermal stress a growing health and comfort concern in addition to the threat climate change poses to the materials themselves[3] .

Historical palaces represent a critical component in the globally built heritage representing cultural identity and embodies historical continuity, requiring constant restoration and maintenance[4]. With accelerating climate change, regions characterized by dry hot climates, as in North Africa, face challenges in historic buildings and collections to update their response effectively to harsh environmental conditions [5] . Unlike new buildings, it cannot iterate dynamically multiple strategies such as mass shading and façade devices. These approaches would ruin the identity of a listed building and weaken its historical value, derived from its heritage design and aesthetic feeling interiorly and exteriorly.

However, these climate pressures exposed the limitations of existing heritage structures. Saffron Palace underwent multiple renovations to restore its aesthetic paintings and decorative details. Rising temperatures and changing occupancy patterns significantly increased cooling loads, posing serious risks to the building's energy performance, comfort and sustainability. Consequently, the renovation of heritage buildings in hot dry climates has become a complex, multi-dimensional challenge to balance energy performance, IEQ (indoor environmental quality), and the conservation of cultural values.

Conventional retrofit methods often prioritize single-objective improvements, such as reducing energy consumption or enhancing thermal comfort, without addressing the trade-offs across other sustainability criteria. In heritage contexts, renovations must adopt holistic approaches that respect all criteria of building functionality, performance and architectural authenticity. Recent studies[6] emphasizes that heritage renovation requires integrated frameworks capable of balancing multiple objectives simultaneously, including daylighting, thermal comfort and energy efficiency. Despite these advances, there remains a significant gap in evidence-driven and quantitatively validated methodologies that support decision-making across these competing domains, particularly in hot–arid environments.

By integrating simulation tools with analysis of field measurements, multi-objective Optimisation enables simultaneous exploration of design solutions across various horizons to achieve optimum

output for sustainable renovation. Combining empirical on-site data with simulation models supports more robust and context-sensitive decision-making processes in heritage renovation projects. This research presents a case study of Saffron Palace as an evidence-driven framework for evaluating built heritage renovations in dry–hot climates. The study investigates how environmental performance can be enhanced within conservation constraints. By approaching an optimum solution, the research demonstrates that multi-objective optimisation can guide future case studies to improve heritage building sustainability while preserving heritage values. The following sections provide a background breakdown on Saffron palace, outlining its architectural significance, changing functions and renovations across different periods. The existing situation is analysed in detail alongside on-site measurements to highlight possible comfort deficits, and design shortcomings. A proposed renovation derived from multi-objective optimisation is then examined and compared with current conditions demonstrating how the intervention respects the heritage character, while improving environment comfort within the building. Subsequently, the preferred renovation option is reviewed to clarify how this approach can inform future evaluations. Ultimately, this study helps bridge the gap between heritage conservation and performance-driven renovation in dry hot climates, offering a structured methodology that supports decision-making for the sustainable renovation of historic buildings in similar climatic contexts.

Historic buildings in dry hot climates increasingly face the dual challenge of preserving cultural and architectural authenticity while meeting contemporary environmental performance requirements. In regions such as the Southern Mediterranean and the Middle East, heritage palaces and institutional buildings are exposed to severe climatic stresses including high solar radiation, elevated cooling demands, thermal fluctuations, dust accumulation, and deteriorating environmental conditions associated with climate change. These pressures have intensified the need for environmentally responsive renovation approaches capable of improving indoor environmental quality and operational efficiency without compromising heritage significance.

Many previous studies have focused on the refurbishment of heritage buildings from a sustainable perspective, highlighting the significance of this topic. One study proposes an optimisation model that predicts future climate, aiming to achieve simultaneous improvements to historical buildings during renovation across four dimensions: energy, environment, thermal comfort and economy [7]. Another study presented a methodology using multi-objective optimisation simulation to reduce energy use and improve comfort without compromising any architectural heritage value or preservation conditions, with quantitative analysis based on European Standards[1]. In addition, another scientific work validates protective energy-saving retrofitting measures for a typical rammed earth heritage building, based on multi-objective optimisation and building information modelling (BIM)[8].

Conventional renovation strategies applied to existing buildings, such as Saffron Palace (Figure 1) ,frequently prioritise prescriptive energy-efficiency measures, including façade insulation, replacement of openings, mechanical cooling upgrades, and envelope modifications[9]. While such approaches may improve operational performance in contemporary buildings, their direct application to heritage structures remains problematic. Historic buildings possess unique material characteristics, construction techniques, and spatial configurations that are often incompatible with invasive interventions. Excessive insulation, inappropriate replacement materials, or alterations to historic façades may result in irreversible loss of heritage fabric, moisture-related deterioration, altered hygrothermal behaviour, and reduced architectural authenticity[10]. Consequently, heritage renovation requires a conservation-sensitive approach that balances environmental performance objectives with architectural preservation principles[11].

Recent research has shown growing interest in the use of building performance simulation tools in heritage context[12]. Studies on addressing energy modelling, daylight simulation, thermal comfort assessment, and passive environmental strategies have demonstrated that digital performance analysis can support more informed retrofit decision-making processes for historic buildings[13]. However, most existing studies remain limited either by focusing exclusively on energy reduction targets or by applying generalised retrofit methodologies derived from contemporary building standards without sufficient consideration of conservation constraints, historic material behaviour, or cultural value assessment[10].

Another limitation identified in current heritage renovation practice is the predominance of



*Figure 1: photograph of Saffron palace, northern elevation, Qasr al Zaafran book, El Damaty (2020).*

qualitative and experience-based decision-making processes. Renovation interventions are frequently determined through visual inspection or conservation-oriented judgement alone, with limited integration of measurable environmental performance criteria[14]. This issue becomes increasingly critical in heritage buildings where thermal comfort, daylight quality, energy consumption, and material conservation must be considered simultaneously under strict intervention constraints. Furthermore, the lack of integrated digital workflows capable of evaluating multiple renovation scenarios reduces the possibility of identifying optimised and conservation-compatible solutions.

In response to these challenges, recent scholarships have increasingly emphasised the importance of performance-driven, simulation-based renovation methodologies. Building Information Modelling (BIM), parametric modeling, dynamic energy simulation, and multi-objective optimisation techniques have emerged as valuable tools for evaluating renovation alternatives and supporting evidence-based conservation decisions. Such approaches enable the simultaneous assessment of thermal comfort, daylight availability, energy performance, and environmental responsiveness while considering conservation regulations and architectural sensitivity[15].

## 2. METHODS

The methodology adopts an integrated approach that combines architectural documentation with quantitative performance-based analysis. The Saffron Palace architectural documentation consists of reviewing architectural background, renovations and adaptive reuse. The quantitative phase consists of three stages. First, indoor environmental monitoring is conducted on-site over one year, focusing on temperature and relative humidity to understand the building's operational conditions, advantages and deficits. This is coupled with an analysis of the results and the palace's current condition. Simultaneously, stage two assesses thermal and visual comfort within various heritage constraints, through full simulation of the current conditions, followed by deep analysis. Stage three includes generation of multiple iterations by multi-objective optimisation, critically examined to identify possible enhancements to the palace's indoor environmental quality and its current deficits. The optimisation workflow is implemented to study performance criteria such as energy efficiency, thermal comfort, and daylight quality, represented by sDA, ASE and thermal load.

### 2.1. CASE STUDY: SAFFRON PALACE, HISTORY AND BACKGROUND

The preceding sections established the theoretical and methodological framework underpinning the present investigation. Building on this foundation, the current section contextualises the selected case study through a historical and architectural review of the Saffron Palace, which constitutes the principal subject of the environmental simulation and hypothetical architectural intervention scenarios examined in this research. The historical account presented here is drawn primarily from the authoritative monograph "Qasr al-Zaafran, The fragrance of history and future foresight" by Mamdouh Mohamed El Damaty (2020)[16].

The historical emergence of the Saffron Palace is intrinsically linked to the nineteenth century urban expansion of the Abbassiya district, located on Cairo's northeastern periphery. The origins of this urban transformation date to 1809, when Muhammad Ali Pasha established a royal estate at al-Hassah, then situated at the desert edge beyond Cairo's consolidated urban fabric. In 1847, the estate was transferred to Abbas Pasha I, who subsequently initiated a systematic urban development strategy for the surrounding district. In January 1851, Abbas Pasha officially designated the quarter as Abbassiya and directed its planned urbanization by allocating land parcels to members of the ruling elite and aristocracy for the construction of palatial residences (El Damaty, 2020).

Under the successive patronage of Abbas I, Said Pasha, and Khedive Ismail, *Abbassiya* evolved into one of Cairo's most prestigious residential districts during the second half of the nineteenth

century. The concentration of royal palaces and aristocratic estates established the district as a prominent architectural and socio-political enclave characterised by large, landscaped compounds, monumental residences, and formal urban planning principles that reflected Khedival modernization policies.

The first Saffron Palace was commissioned in 1869 by Khedive Ismail as a residence for his mother, Khushyar Hanim, within the expanding royal precinct of al-Abbasiyya. Historical accounts describe the palace as an elite royal establishment associated with ceremonial functions, extensive domestic infrastructure, and landscaped surroundings. The old Saffron Palace was demolished and reconstructed in the early 1900s as shown in Figure 2 and Figure 3.

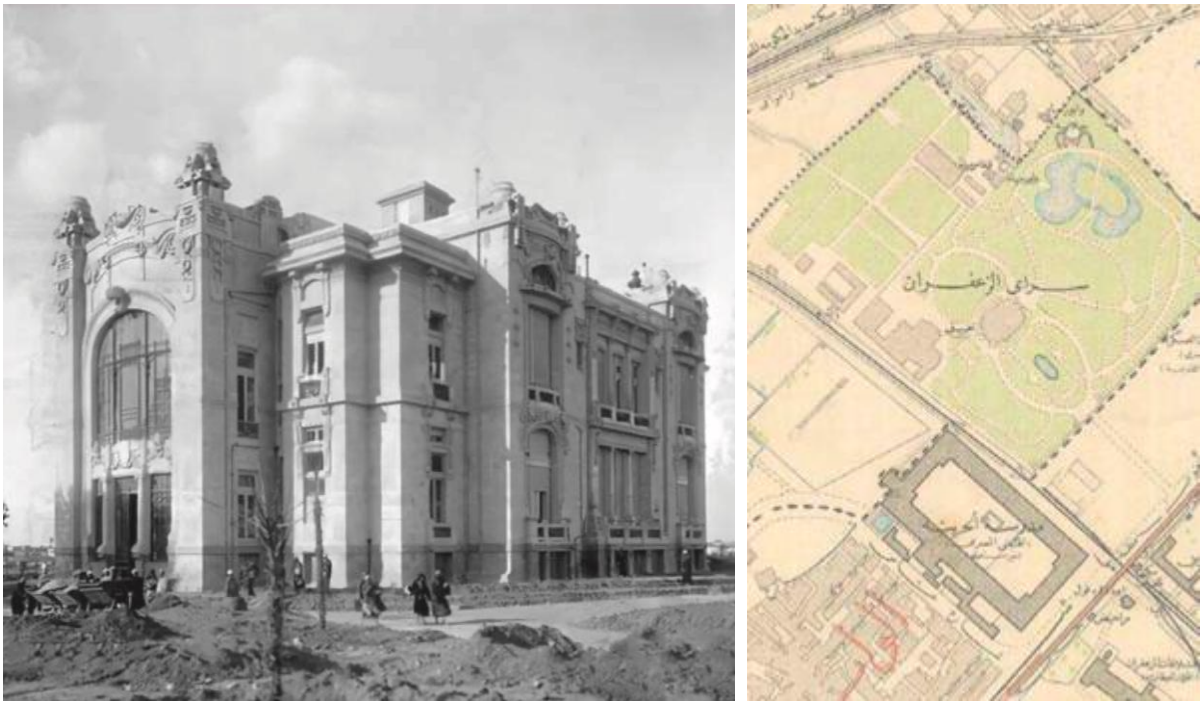


*Figure 2: Left, photograph of Saffron palace construction 1902, Southern and Eastern elevations, Qasr al Zaafran book, El-Damaty (2020).*

*Figure 3:Right, Urban map, 1915, illustrating Saffron palace location along different military facilities, Qasr al Zaafran book, El-Damaty (2020).*

## 2.2. SAFFRON PALACE, RENOVATIONS ALONG HISTORY

The renovation history of Saffron Palace reflects a gradual transition in functional adaptation in accordance with context and time. Following its reconstruction in 1901, the palace underwent early modifications in 1930 as shown in Figure 4, to accommodate minor shifts in institutional use, before its conversion into a main university campus in the mid-20th century. These interventions were mainly functional and lacked sustainable conservation strategies, which over time led to material and aesthetic deterioration over time. The building's historical and architectural significance was formally recognised in 1985, when it was listed as a heritage building, marking

the need for a shift towards more sustainable preservation approaches. A major restoration campaign was subsequently implemented in 1994 in collaboration with national heritage authorities, targeting structural stabilization, conservation of decorative elements, and façade rehabilitation, with the aim of preserving authenticity while maintaining functional use. A second phase of renovation around 2010 addressed ongoing degradation, focusing on limited maintenance and service upgrades. Lastly, recent restorations have introduced MEP (mechanical electric plumbing) infrastructure upgrade, structural reinforcements and full conversion of basement floor into an open museum space. Overall, the palace underwent multiple renovations for functional requirements, yet lacking fully sustainable approaches.




*Figure 4: First Photo Documentation perspective view of Saffron palace main façade, maintenance and renovation announcement in local newspaper, 1930, Qasr al Zaafran book, El Damaty (2020).*

## 2.3. SAFFRON PALACE, FUNCTIONAL ADAPTIVE REUSE

One of the defining characteristics of the Saffron Palace is its prolonged adaptive reuse. Originally built as a royal residence, the building was lately transformed into an educational campus for Ain Shams University in 1952. This transition introduced a rare balance of spatial cultural depth and operational flexibility, with rich context allowing the palace to act as a fundamental host for different delegations with diplomatic, cultural and educational purposes, intertwined with its heritage value. It shows a sample of cultural events and ceremonial dinners, reflecting its architectural heritage value and its institutional significance for the government. Figure 5 documents a ceremonial event associated with the visit of the King and Queen of Belgium visit to Egypt. Meanwhile, Figure 6 pictures a royal dinner for Prince M. Reda in honour of then Minister

of Foreign Affairs. These multiple functionalities generated compound pressure on the building environmental comfort.

Consequently, the palace used to host numerous international diplomatic meetings and policy





*Figure 5: Left, Queen Elizabeth, Queen of Belgium, reviews the Honour Guard next to Saffron Palace, Qasr al Zaafran book, El-Damaty (2020).*

*Figure 6: Right, Prince Muhammad Reda Pahlavi at Saffron Palace, during the reception of dinner held by Abdul Fattah Yahya Pasha, Minister of Foreign Affairs, 1939, Qasr al Zaafran book, El-Damaty (2020).*

making events. Figure 7 shows a diplomatic banquet in 1936, hosted by Prime Minister Al Nahhas Pasha. Figure 8 also shows a photograph of a meeting from a series related to the League of Arab States and approval of its Charter hosted at Saffron Palace, with various Gulf and Arab delegates in attendance. These high-profile events required intensive maintenance and a certain standard of environmentally comfortable and sustainable conditions, to preserve the palace's diplomatic and cultural role over years. In its recent function of reusing till the 21st century as an educational campus, the listed palace required less maintenance matching its current state as well for financial sustainability.



*Figure 7: Left, Al-Nahhas Pasha, then prime minister hosts a banquet dinner in honour of Lampson in Saffron Palace, 1936, Qasr al Zaafran book, El-Damaty (2020).*




*Figure 8: Right, Mahmoud Fahmy Al-Narashi Pasha at the closing session of the approval of the Charter of the League of Arab States at Saffron Palace, 1945, Qasr al Zaafran book, El Damaty (2020).*

By the early 2000s and after being listed as a heritage building, Saffron Palace began to host more cultural roles as a cinematic location for multiple movies as shown Figure 9 and Figure 10. Over the years, time distant renovations and less maintenance coupled with climatic changes and modern comfort standards, made the palace critically unsustainable, unable to match nowadays' environmental needs.



*Figure 9: Left, Actor Ahmed Zaki shooting scene from the movie "His Excellency Minister", 2002, Qasr al Zaafran book, El-Damaty (2020).*



*Figure 10: Right, Actor Ahmed Zaki shooting scene from the movie "The days of Sadat", 2000, Qasr al Zaafran book, El-Damaty (2020).*

## 2.4. SAFFRON PALACE FULL CLIMATIC ANALYSIS

### 2.4.1. PALACE FAÇADE ANALYSIS

The four façade elevations presented illustrate the window-to-wall ratio (WWR) distribution of the Saffron Palace, with openings (highlighted in yellow) ranging between 20.0% and 28.7% across different orientations. In Figure 11, the façade demonstrates a balanced proportion between solid and void with a WWR approximately 25.5%. This range is generally considered optimal for public buildings in hot climates, as it allows adequate daylight penetration while limiting excessive solar heat gain. On the south-east orientation, a low WWR of 20% is often recommended to reduce cooling loads while ensuring acceptable indoor illumination levels[17].

The second elevation in Figure 12 has the highest WWR of approximately 28.7%, among all facades. While this increases daylight availability and enhances visual connectivity, it does not cause high solar heat gains as the north orientation admits clear indirect daylight[18]. In the context of a public administrative building serving high-level offices, this could negatively affect thermal comfort and occupant productivity if not mitigated through shading, glazing control, or interior treatments. Thus, this elevation can be considered approaching the upper acceptable limit, with a slight performance deficit under peak summer conditions. Figure 13 shows the third elevation, with a WWR of 20% and a more solid façade composition. From a thermal standpoint, this minimizes heat gain and enhances envelop performance.

However, it may reduce daylight penetration[19], potentially increasing reliance on artificial lighting and causing visual discomfort. in the south-west façade in Figure 14 has a relatively high WWR of 28.2%. Unlike the second elevation, the relatively large openings may admit more direct sunlight from southern angles. In Cairo's climate, a large entrance hall opening may worsen thermal discomfort, as glazing parameters strongly affect daylight and energy performance in heritage buildings[20]. Overall, the façade analysis shows that the building maintains WWR values within a moderate range of 20–30%, aligning reasonably with southern facades, unlike northern elevations which may be considered low for hot dry climates[21]. This variation highlights a possible architectural design bias over indoor environmental quality.

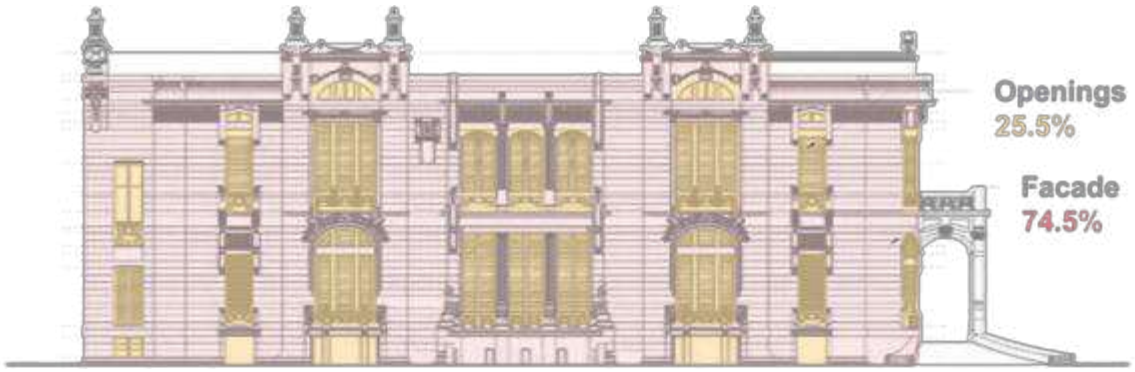



*Figure 11: Side Elevation WWR (Southeast) Saffron palace, Author.*

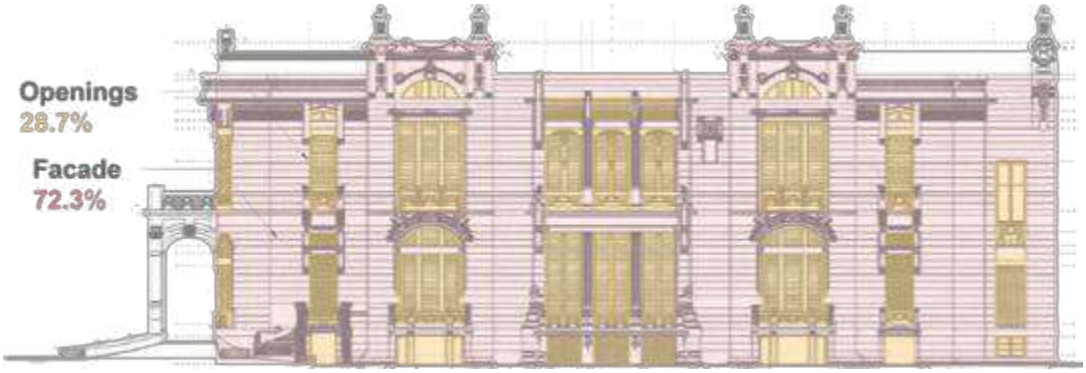



*Figure 12: Side Elevation WWR (Northwest) Saffron palace, Author.*




*Figure 14: Back Elevation WWR (Northeast) Saffron palace, Author.*

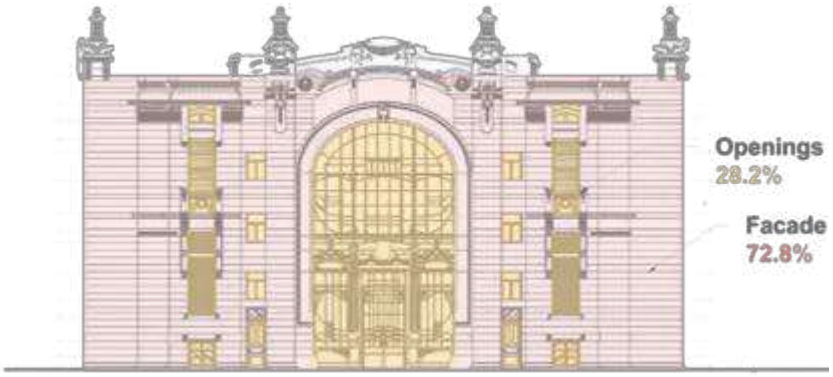



*Figure 13: Front Elevation WWR (Southeast) Saffron palace, Author.*

### 2.4.2. CAIRO CLIMATE

According to the Koppen Geiger classification, Cairo's climate is categorised as a hot desert climate (BWh)[22,23]. Throughout most of the year, Cairo is characterised by a pronounced thermal amplitude and consistently low relative humidity[24]. The monthly mean temperatures range from a minimum of 14.4°C in January to a maximum of 29.2°C in August as shown in Figure 15. The largest daily temperature range is around 16 °C in July, FROM 18.9°C to 35.0°C, while the lowest temperature is recorded in January at 10.1°C. The operative temperature limits recommended by ASHRAE are 2026°C for indoor occupancy, meaning Cairo's climatic conditions fall within the comfort threshold for only four months, two in winter and summer. January and February record extremely low means of 14.4°C and 15.6°C, a 5°C thermal deficit, below the comfort range. In summer, July and August experience extreme mean temperatures of 29.1°C and 29.2°C, 3°C above the comfort range with peaks of 35.0°C.

Taken together, this shows that Cairo has large daily temperature ranges, with average peaks above the comfort threshold in the hot summer months. Relative humidity remains within or below the ASHRAE[25] comfort band of 30–60% for most of the year, with an annual mean RH of 54.2%. The only month in which RH exceeds the upper comfort range is August, at 61%. This underscores the need for sustainable cooling strategies rather than dehumidification. Given the temperature spikes mentioned earlier, August is the most environmentally stressful month. Another vulnerability arises because high temperature ranges within a single day to challenge thermal control systems for heating and cooling cycles.[26]

### 2.4.3. PALACE INDOOR CLIMATE MEASUREMENTS

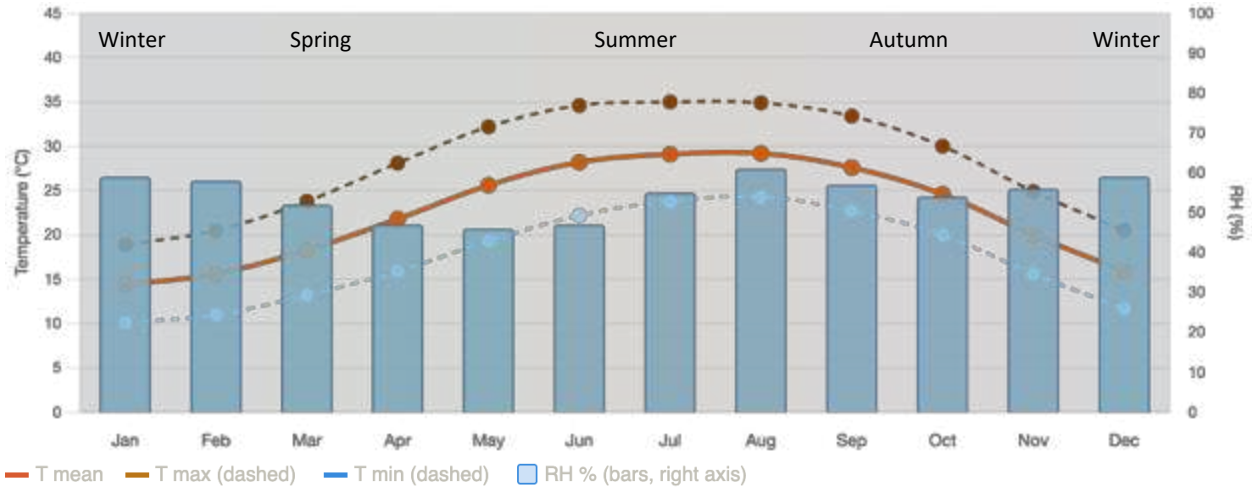



*Figure 15:Monthly Chart for Temperature (T) and Relative Humidity (RH) for Cairo climate, Author.*

The indoor temperature and relative humidity in the palace were recorded at 30-minute intervals throughout the year. excluding February and parts of January for logistical purposes. The measurements were conducted using HOBO U12 data loggers from Onset (Onset, USA; T and RH ranges and accuracy: −20° to 70 °C ± 0.35 °C, RH: 5% to 95% RH ± 2.5%; time accuracy ± 1 min per month at 25 °C). The data loggers[27] were placed in the ground floor gallery and outside the main door of the palace, out of direct contact with the sun and walls and away from windows and other heat sources[28]. The source data with a time step of 30 min was extracted from the data loggers using HOBO software, cleaned, and organised using MS Excel and analysed and visualised by chart as shown in Figure 16. Measurements were taken in 2020, immediately before the renovation works began. Monthly mean indoor temperatures ranged from 18.5°C in March to 27.7°C in August and September. During winter, January recorded a mean indoor temperature of 21.1°C comparted with an outdoor mean of 14.4°C, a surplus of 6.7°C, similarly December showed a gain of 5.5°C gain. However, daily minimum temperatures fell below the comfort range from January to April, with lows of 16.4°C in March. During summer, mean indoor temperatures were 27.3°C in July and 27.7°C in August compared with outdoor means of 29.1°C and 29.2°C, representing a reduction of about 1.7°C.

The annual mean indoor temperature is 23.5°C compared to the outdoor annual mean of 22.5°C. Thermal discomfort was recorded in all months except December, arising from high temperatures. low temperatures, or both. The highest mean temperature was 28.8°C in July with all summer months exceeding the threshold and highlighting thermal stress during this period.

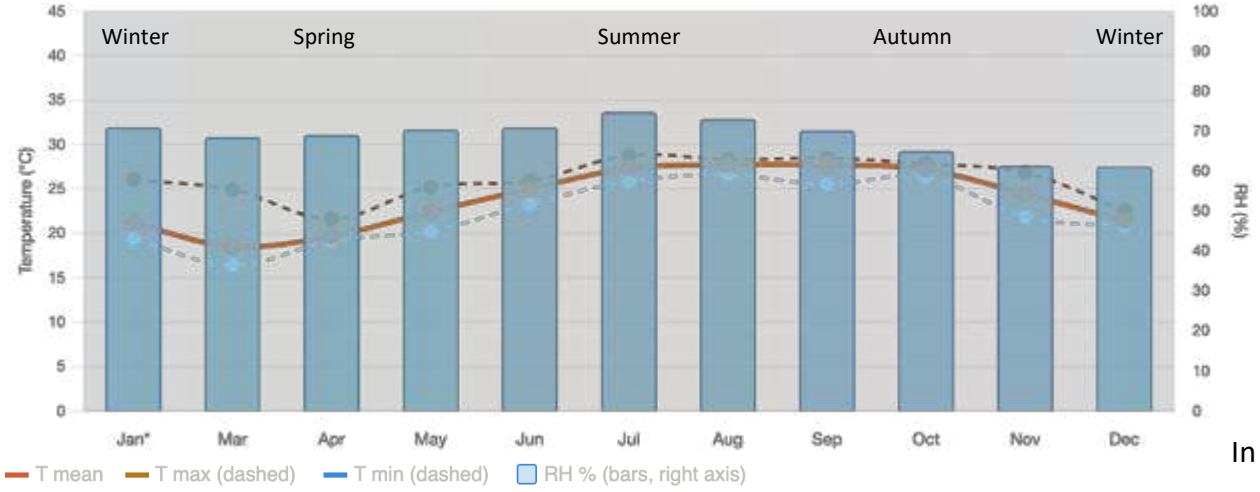



*Figure 16:Monthly Chart for Temperature (T) and Relative Humidity (RH) indoor palace measurements, Jan 2020 – Dec 2020 excluding February, Author.*

In October, the indoor mean of 27.2°C exceeds the outdoor mean of 24.6°C. Indoor RH exceeded the ASHRAE 55 upper comfort threshold of 60% in every recorded month, ranging from a minimum of 61.1% in December to a peak of 74.7% in July. Moreover, indoor RH values in December and January surpassed the outdoor comfortable RH values of 58% and 59%[29].

## 2.4.4. PALACE CLIMATIC COMPARISON AND ANALYSIS

Figure 17 shows a comparison chart between the outdoor climatic environment and the indoor measured climate, including comfort zones of T and RH. The results indicate significant indoor thermal stress during all summer months extending until October. All winter months experience low indoor thermal comfort. The indoor RH exceeds upper comfort range of 60% in almost every month of the year, reaching 75% in July and 73% in August during summer. Analyzing all gathered measurements in comparison, the palace improves thermal discomfort intake from outdoors in four months yet still suffers thermally through the hot season mainly from July to October. Limiting thermal comfort inversely extends relative humidity discomfort to almost the entire year, revealing a design deficit that results in excessive humidity[30]. The thermal improvement is

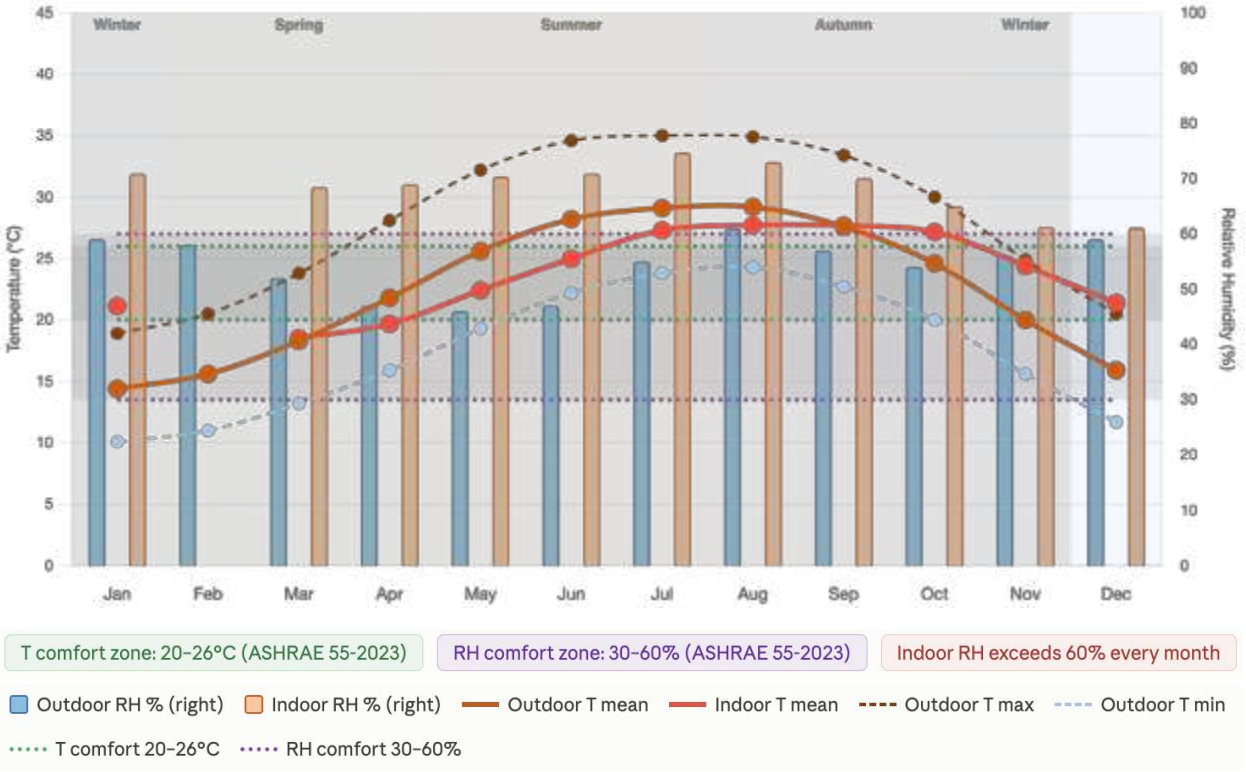



*Figure 17:Comparison Chart between outdoor Cairo climate and indoor palace measurements, Author.*

insufficient yet moderately reduces heat intake, this may be attributed to the thick load-bearing wall structure shown in Figure 18[31], which provides thermal insulation. On the other hand, inadequate ventilation from small openings as shown in Figure 19, combined with possible composite hygroscopic materials may have caused the retention of high humidity, affecting

indoor environmental quality[32,33]. The floors as shown in Figure 20 consist of multilayer concrete and wooden flooring.

## 2.5. PALACE THERMAL AND LIGHT SIMULATION

### 2.5.1. MODEL AND FRAMEWORK

This chapter acts as a detailed procedure to study any possible deficits related to the palace current conditions in terms of thermal loads and light parameters sDA and ASE. Figure 21 shows a basic 3D model simulating the rough outline of the palace, oriented 45° towards North, to imitate the real-life conditions. Glazing percentages were matching the current state, resembling the exact WWR analyzed above.



*Figure 18: Right, Palace structural Bearing walls, renovation process, 2023, Author.*



*Figure 20: Centre, Palace multilayered slab of concrete and wooden flooring, renovation 2023, Author.*



*Figure 19: Left, Palace narrow openings, renovation process, 2023, Author*

Figure 22 illustrates all programs and plugins used. The workflow as shown in Figure 23 consists of two main phases: baseline simulation and multi-objective optimisation. In Phase 01, a parametric 3D base model of the heritage building is developed and simulated to establish its current performance. Daylighting metrics (DA and sDA) are evaluated using OpenStudio, while thermal energy loads (cooling/heating demand) are calculated using EnergyPlus. These simulations generate a baseline dataset describing annual lighting performance and energy consumption.

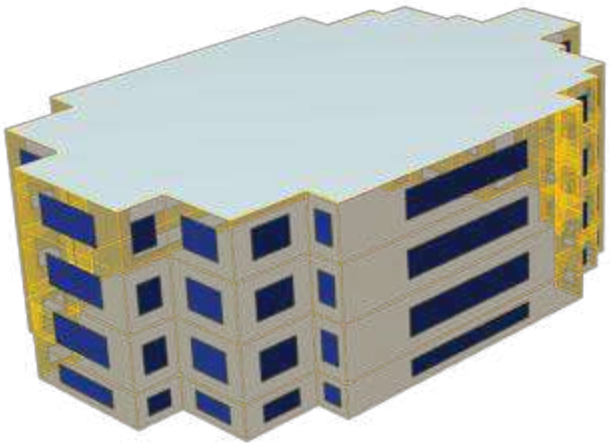


*Figure 22: 3D model in rhino program tracing palace current conditions, Author*

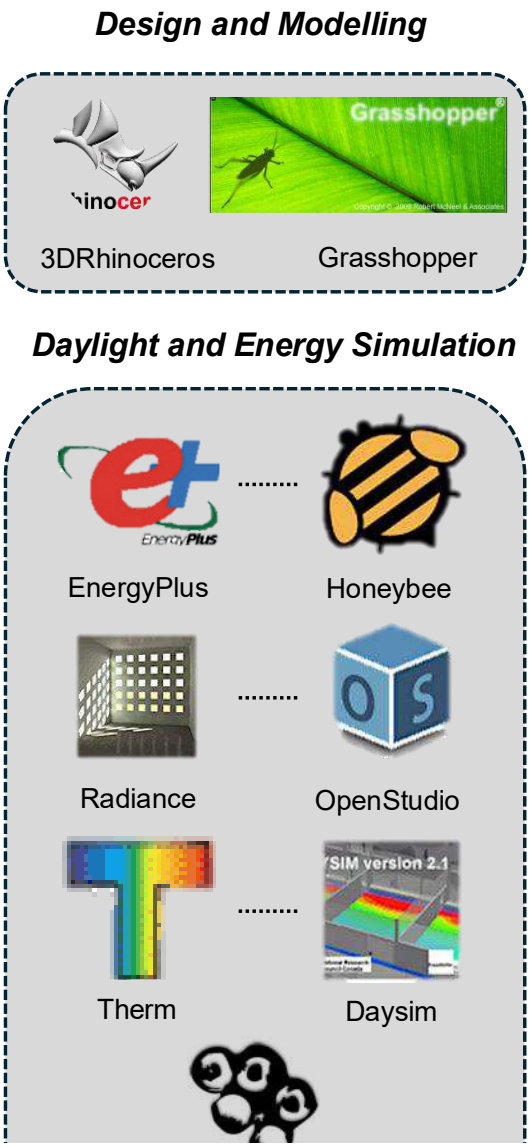



*Figure 21: 3D model in rhino program tracing palace current conditions, Author*

In Phase 02, the model is integrated into a parametric environment using Grasshopper and optimized using Octopus. Multiple design variables are iteratively tested, and simulation results are collected and analyzed. The optimisation process identifies trade-offs between daylight and energy performance, producing a set of optimal solutions (Pareto front). The best-performing configurations are then selected and validated, leading to an optimized design strategy for improved environmental performance.

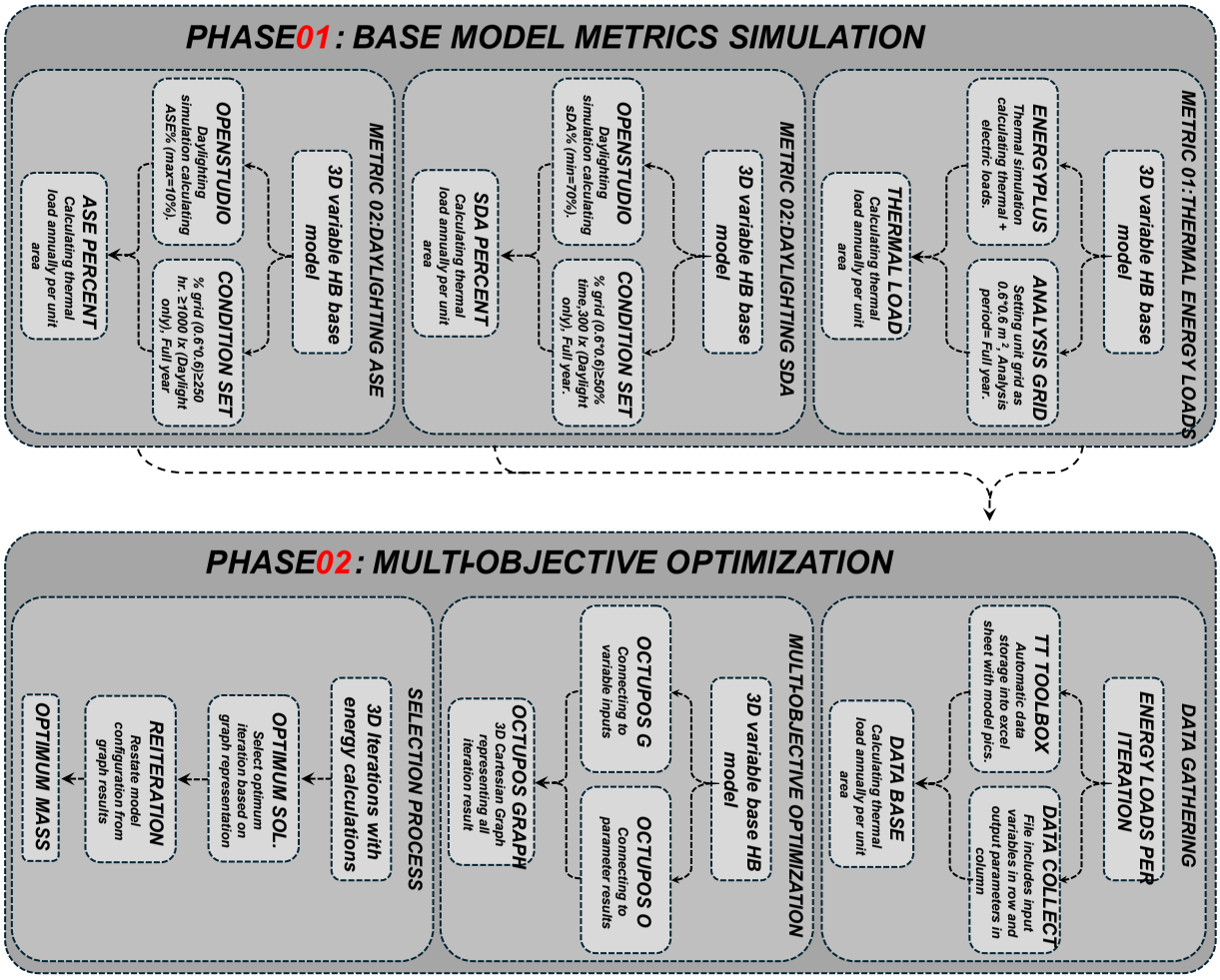



Figure 23: Full Simulation framework, Author.

## 2.5.2. PHASE 01, THERMAL AND LIGHT SIMULATION

This phase shown in Figure 24 a-d, expresses the Annual Sunlight Exposure (ASE) distribution mapped in terms of Direct Sun Hours across four successive floor levels of the subject building; Basement, First, Second and Third Floor respectively. For glazing transmittance, an average 65% transmittance was considered according to current conditions. ASE measures the percentage of

a regularly occupied floor area that receives direct illuminance of 1,000 lux or more for at least 250 hours yearly[13], indicating solar discomfort and overexposure. The IES LM-83-12 threshold for acceptable performance caps a maximum 10% $ASE_{1,000}/_{250}$. Any result further this limit signals thermal deficiency and high glare. All four floors recorded a uniform ASE of 22.4%, indicating inconsistent condition of solar distribution causing poor environmental performance.

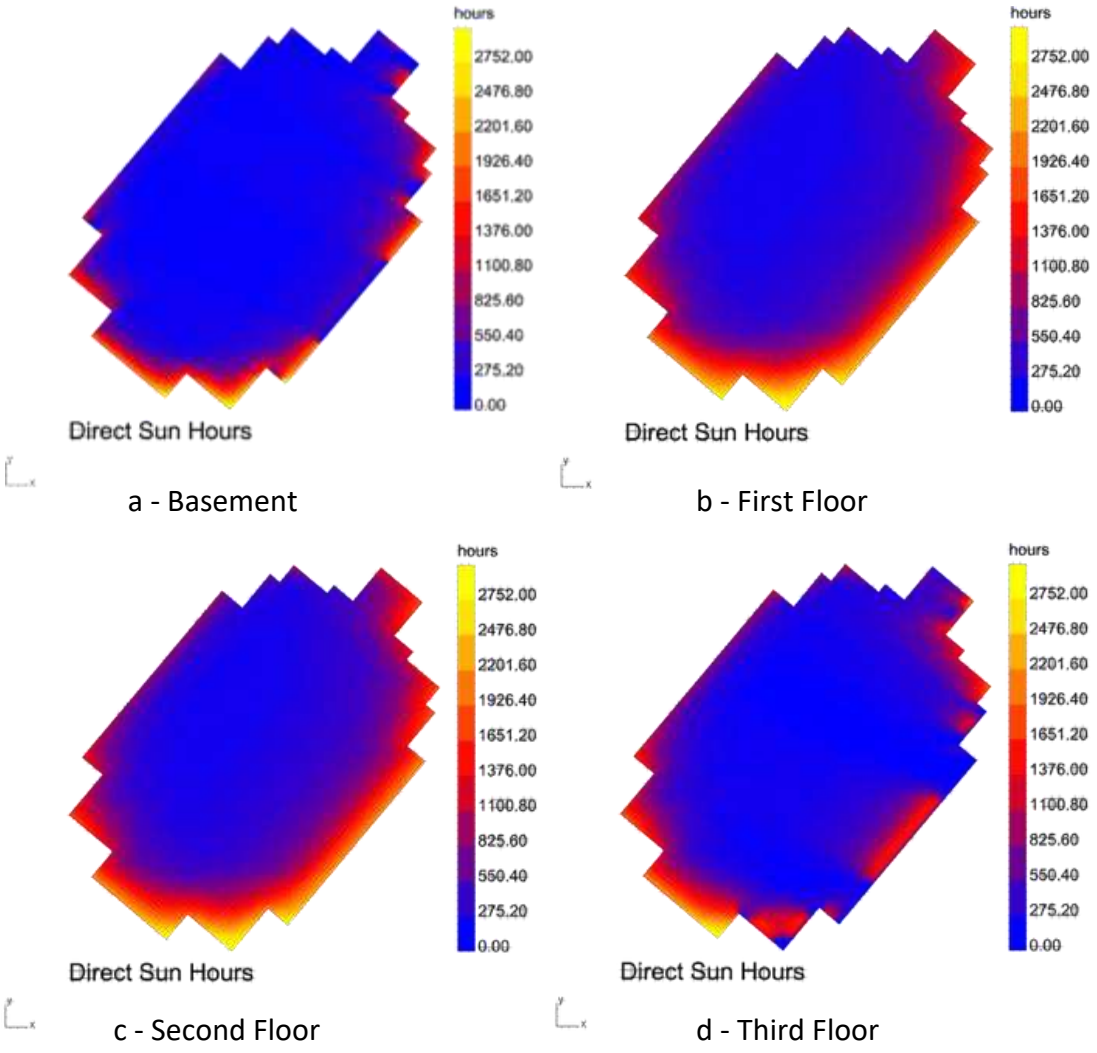



Figure 24: Annual Sunlight Exposure (ASE) distribution mapped in terms of Direct Sun Hours across palace model floor levels, Author.

With north direction parallel to Y-axis, the palace high WWR in southern and eastern facades drives high direct sunlight, when northern facades which absorb clean indirect sunlight show lower sun exposure hours. This results in an imbalance of thermal and visual comfort in the palace, due to inconsistency. In the basement, with high clerestory windows, direct solar hours

are quite limited because of the narrow openings, unlike the third floor which appears to be the inverse on the south-eastern side. The zigzag sections at the edge corners of the south facades act as thermal storage zones as adjacent windows overlap with direct sunlight throughout the day. These results show deficiencies in the positioning of openings and the WWR distribution across the palace facades.

This phase shown in Figure 25 a-d states the Spatial Daylight Autonomy (sDA) distribution mapped across the same four floor levels, in terms of percentage of regularly occupied floor area that achieves a minimum illuminance of 300 lux from daylight alone for at least 50% of annual occupied hours of the palace[34]. The sDA shows the spatial coverage that sustains adequate visual conditions through natural light regardless of artificial lighting. 55% sDA is the minimum, with 75% or above to be considered well-daylit, both adopted under LEED[35] and WELL[36] Building Standard criteria. The four floors recorded markedly different sDA values of 31.69%, 69.51%, 70.10%, and 95.11% for the Basement, First, Second, and Third Floors respectively. The average sDA for whole palace marks 66.67%, below the good daylight standard indicating visual discomfort.

This indicates improved visual performance across the building section vertically upwards. The mass shading of floors above one another affects sDA % as seen as the difference between second and third floor. The same southern and eastern façade dominance that drove the ASE overexposure condition produces an inversely high sDA concentrations. Corner edges limit the light intake especially with consistent window ratios across different facades that absorb sunlight in different angles throughout the day. The contrast between ASE and sDA maps are not coincidental instead of coupled. The façades WWR and fixed openings ratios across the palace generate adequate daylight sufficiency with yet visual inconsistency of high sun glare and poor visual spots. The glazing design shows poor distribution in diffused daylight and concentrated thermal loads.

At the Basement, the sDA of 31.69% represents the most critically deficient condition across the section. High clerestory windows placement limits enough light penetration with irrelevant façade WWR as above makes less use of needed daylight in various spots. This ensures a huge dependence on artificial lighting across most of this level. The First and Second Floors with nearly identical sDA values of 69.51% and 70.10% respectively, are imbalanced with high ASE values. The southeastern walls account for the highest sDA concentrations at both levels, mirroring the ASE thermal hotspots. This reinforces that the palace WWR distribution should be more adjusted to cover any deficits. The Third Floor reassures the same bias of high sDA with poor ASE, which as well, may count to the roof horizontal exposure all day.

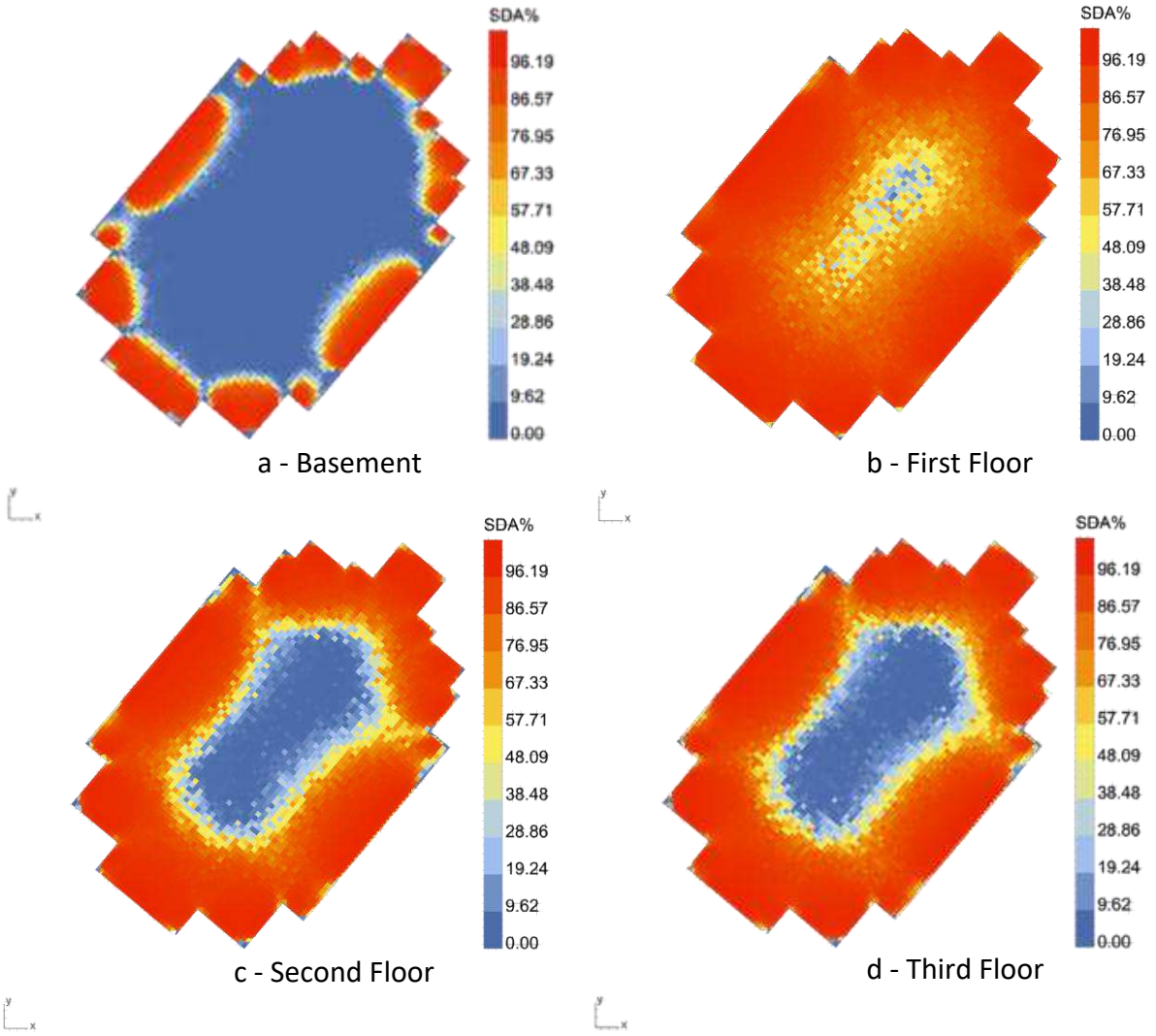
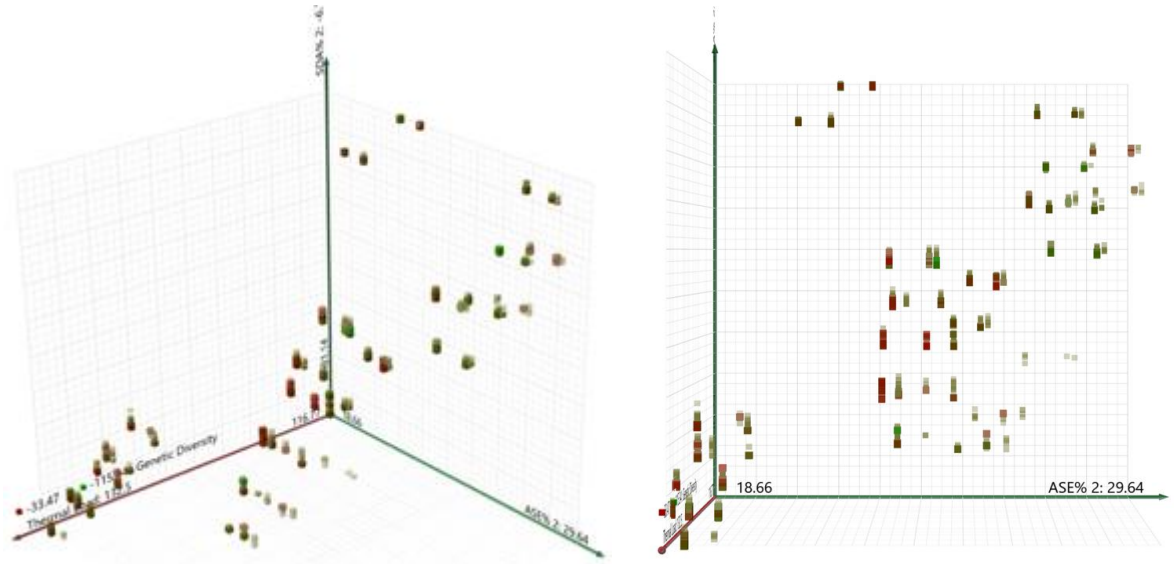



Figure 25: Spatial Daylight Autonomy (sDA) distribution mapped in percent of floor across all palace model floors, Author.

## 2.5.3. PHASE 02, MULTI OBJECTIVE OPTIMISATION

Figure 26 a-b presents the three-dimensional Pareto view generated through multi-objective optimisation conducted by Octopus plugin within Grasshopper. Multi objective optimisation process generates multiple iterations through fluctuating variables related to the study model, with measuring the target parameters each time simultaneously. In this case, unlike conventional buildings the palace is limited to architectural exterior changes due to its aesthetic value and being historical listed. Although façade techniques and mass formation are one of the strong factors influencing indoor energy performance and comfort[37], heritage limitations prohibit any envelope change or adding any shading devices. Other structural limitations as openings increase or reconstructing structural elements are not allowed as well. Instead, to preserve the palace historical value and facades, environmental enhancement would be achieved by certain physical changes as improving regular window transmittance, minimizing sunlight intake at certain façades by adding interior blackouts or uplifting interior finishes in a way that serves the indoor environmental quality for better.




a - perspective b – Side view

Figure 26: Octopus 3D pareto view with multiple solutions across its three axes, sDA, ASE and Thermal load, Author.

ASE, sDA and thermal load were the target parameters to be measured. Through various model generations, six variables were tackled to ranged variations relating to WWR and glazing properties across all facades. The three-dimensional scatter plot reveals a clear topology of solutions, trading off between lowest thermal load, least ASE percent and highest sDA percent.

With X, Y and Z axes in the octopus pareto representing ASE, thermal load and sDA respectively. The top view shows a directly proportional relation between thermal intake and sDA, both increase concurrently. Although optimum thermal load should be at its least, with sDA maximizing above 70% for adequate environmental quality, more WWR shows allowing both to increase putting huge reliance in controlling direct sunlight on different interventions such as mass shading or shading devices on façades, which are restricted for heritage buildings[38,39]. This leaves changes limited to glazing control through properties such as SHGC (solar heat gain coefficient), U-factor of heat transfer insulation and Vt visual transmittance. SHGC ranges 0-1, U factor ranges from 0.2-0.5 and Vt ranges 0.6-0.8. Ranges were considered according to previous trials and results besides minimum environmental criteria as Vt should be at least 55%[40]. These three variables relate to glazing characteristics, while the other three are east-west WWR, north WWR and south WWR, ranging 0-30%, 0-40% and 0-50% respectively.

## 3. RESULTS

The current state of the palace analyzed earlier, when simulated with same real conditions showed a high out of range ASE and poor sDA with relatively excessive thermal load. After a large pool of 549 iterations over 9 generation cycles, various iterations gave significant indications about certain variables parameters correlations, which deficits contribute the most to palace environmental stress and what hypothetical variables respecting heritage limitations would improve most efficiently. Out of all Iterations in Figure 27, the highest 3 (A, B and C) achieving highest sDA were achieved at 79.7%, 79.2% and 77.5%, with ASE values 19.7% ,19.05% and 19.7% respectively. Analyzing these models' variations, model C minimized south façade to 10% (-19%), east-west facades to 20% (-6-8%) and increased Vt to 0.7 (+0.1) with a 2.0 U factor of and a 0.3 SHGC. Model B did same WWR reduction as C, increased Vt to 0.7 (+0.1) with a 1.6 U factor of and a 0.3 SHGC, while model A did same east-west WWR minimizing but reduced south to only 20% (-9%) and increased Vt to 0.8 (+0.2) with a 1.3 U factor of and a 0.3 SHGC.

Since considering adding more WWR to facades is not a possibility, these numbers show that WWR reductions especially in south facade improve the IEQ, with none of these iterations reducing the north WWR. As well, good glazing thermal insulation of low SHGC and U factor with regular Vt is a critical key to affecting positively the thermal performance of palace indoors.

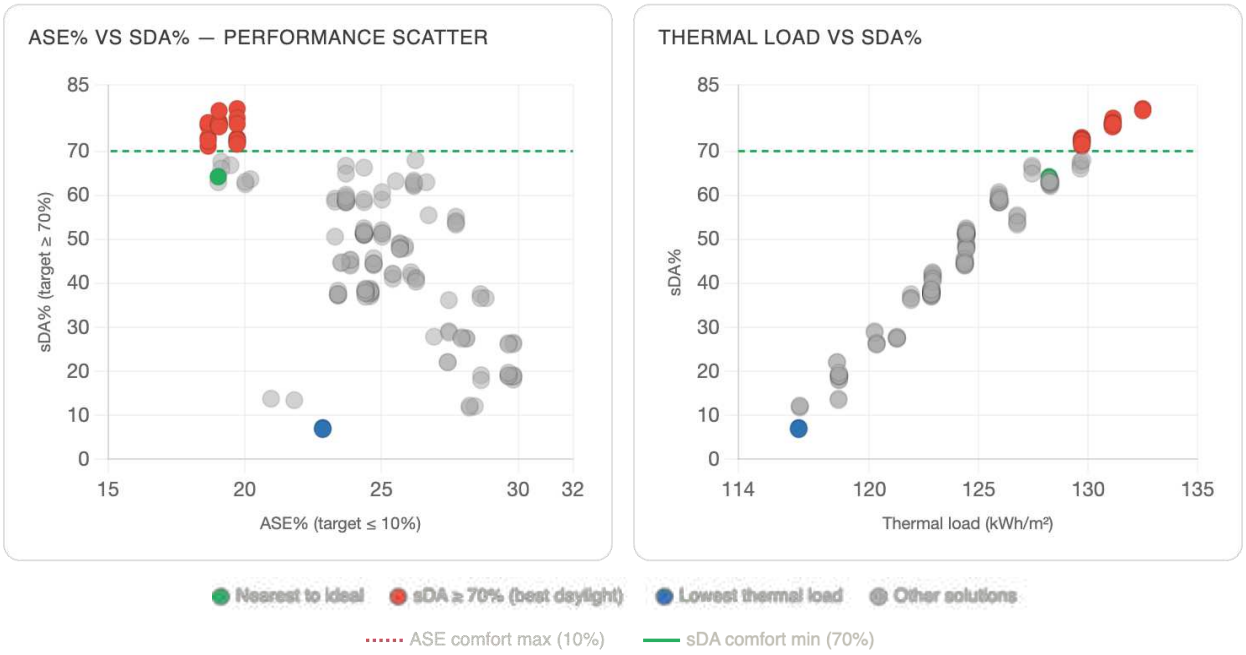



Figure 27: Multi-objective optimization iterations, performance scatter chart, a- ASE-sDA correlation, b- thermal load-sDA correlation, author.

The graph as well shows that out of all possible solutions, achieving an adequate sDA was achievable up to nearly 80%, while the best option would reach a relatively high ASE of 19%, above the maximum 10% limit. This highlights how initial design and mass formation hugely dominate the possible environmental performance later. This highlights the importance of interior environmental refurbishment and that the remaining thermal stress shown in the optimum results suggest further renovation of passive techniques interiorly, regardless of just mechanical ventilation. The analysis shows that the rectangular perimeter of the palace creates a challenging depth, added to the heritage limitations, to reach high sDA levels especially in lower levels with the current WWR, requiring certain techniques as interior light shelves that ensure deeper light reachability or anidolic lighting systems.

The graph in Figure 28 shows how the east-west WWR slight reduction contributed to the best possible outcome for reaching good sDA levels compared to other facades, along with reducing the internal thermal stress. On the other hand, minor changes in glazing properties Vt and SHGC didn't affect much, yet a low 0.2 SHGC and 0.6 Vt proved to be most efficient to reach the best balance of environmental targets. Lowest thermal loads solutions showed very poor and inadequate ASE and sDA levels, while sDA and thermal load expressed high direct correlation, hence emphasizing the importance of openings characteristics. The nearest to best solution is based on balancing all three parameters, however it is considered insufficient in real life practice. The graph in Figure 29 compares the best solutions in terms of ASE reduction, showing the low sDA trade-off, relative to both target thresholds. The graph reveals how these iterations still surpass maximum sDA and barely reach the minimum ASE threshold.

## 4. DISCUSSION

This study is subject to a few limitations. First, the multi-objective optimisation workflow was restricted to envelope-level parameters, specifically window-to-wall ratio and glazing properties




*Figure 29: Multi-objective optimization iterations, mean sDA% chart, a- sDA-glazing correlation, b- sDA-WWR correlation, author.*

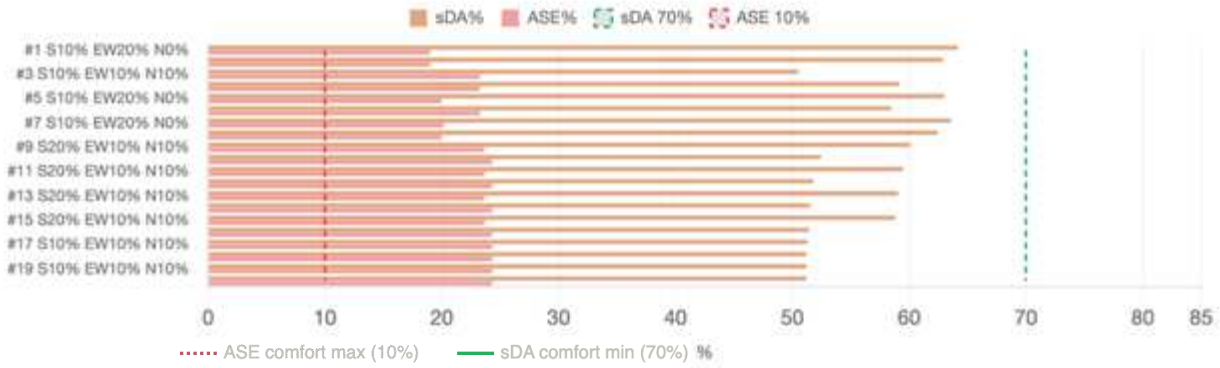



*Figure 28: Multi-objective optimization best iterations, ASE% - sDA% chart, relative to target thresholds, author.*

(Vt, U-factor, SHGC); it did not model interior material interventions such as plaster, flooring, or furnishing changes, which the results suggest may be necessary to resolve the persistent relative humidity discomfort. Second, passive strategies beyond glazing and WWR, such as natural ventilation retrofits, external shading devices, or dehumidification measures, fell outside the scope of the optimisation and remain directions for future research. Finally, the study did not include a cost-benefit or life-cycle assessment of the proposed interventions, which would strengthen its practical value for conservation stakeholders and policymakers. While the building is representative of a broader class of nineteenth-century eclectic palaces in Cairo, caution should be exercised when extrapolating the findings to other heritage buildings. Differences in architectural typologies, construction materials, conservation history, and micro-climatic contexts may influence the applicability of the results.

Concluding up, the study demonstrates that the Saffron palace evaluation by envelope multi objective optimisation within its heritage constraints, reached partial improvement, yet lacked simultaneous compliance of environmental comfort standards. This ensures the need of possible further renovation layers beneath the façade layer, to achieve this environmental balance. As well, it is recommended to study the effect of interior materials refurbishment on indoor environmental comfort, especially for relative humidity. On the other hand, it could be concluded that restoring any heritage building requires achieving these environmental standards for multiple reasons. First, to ensure the operational sustainability of the heritage building energy costs and add longevity to its flexible adaptive reuse of function. Second, this would help need less refurbishments and make wider time interventions between one renovation and another. Last and foremost, restoring environmental considerations, assures the financial sustainability of future renovations either for the same building or similar cases which may deal with more extreme dry hot weather out of climate changes.

## ACKNOWLEDGMENT

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