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Between Heritage and Technology: The Use of Artificial Intelligence in Climate Modeling to Support the Sustainability of Cultural Tourism at Archaeological Sites

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Research Article

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Between Heritage and Technology

The Use of Artificial Intelligence in Climate Modeling to Support the Sustainability of Cultural Tourism at Archaeological Sites

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Abstract The preservation of cultural heritage sites increasingly necessitates innovative methodologies that simultaneously safeguard historical authenticity and enhance the visitor experience in response to evolving environmental conditions. This research explores the viability of artificial intelligence (AI)-assisted microclimate simulation to augment thermal comfort and promote sustainable cultural tourism at the Sultan Qalawun School Complex in Historic Cairo, Egypt. A hybrid framework is proposed, which integrates environmental simulation, machine learning techniques utilizing the Hypar.io platform, and principles of heritage conservation to analyze the thermal dynamics of the complex and assess alternative passive design strategies. Field data collection, geometric modeling, and AI-driven predictive models are employed to examine the impacts of natural ventilation, vegetation, shading systems, and occupancy patterns on outdoor thermal comfort. The efficacy of the proposed interventions is evaluated using metrics such as Predicted Mean Vote (PMV), thermal discomfort hours, indoor environmental quality, and criteria for heritage preservation. The findings reveal that AI-assisted simulation can significantly reduce computational time by approximately 40% while upholding high predictive accuracy relative to traditional physics-based simulations. Conservation-compatible passive strategies, particularly optimized natural ventilation and temporary shading, exhibit substantial potential for enhancing thermal comfort without jeopardizing the historical and architectural integrity of the site. The study advocates for a transferable digital framework for managing heritage microclimates that can facilitate sustainable tourism development and climate adaptation in historic sites sharing analogous climatic and architectural features. These insights contribute to the increasing integration of artificial intelligence, environmental simulation, and heritage conservation in alignment with Egypt's Vision 2030 and broader global sustainable tourism objectives.

Keywords Artificial Intelligence; Cultural Heritage; Microclimate Simulation; Thermal Comfort; Sustainable Tourism; Heritage Conservation; Sultan Qalawun Complex.

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1. Introduction

Heritage areas, especially in historic Cairo, which is a UNESCO World Heritage Site, are facing increasingly severe climate challenges that directly impact the visitor experience and the long-term sustainability[1] of archaeological sites. The traditional tension between the preservation of culture and the development of tourism has become more acute as climate change escalates in rising urban temperatures and environmental degradation [2] . The Sultan Qalawun Complex, located on Al Moiz Street, is one of the most important Islamic architectural landmarks in Cairo, but it faces ongoing challenges in maintaining ideal conditions for thermal visitor comfort and the preservation of artifacts[3].

The research challenge addressed in this study is how can heritage sites sustain increased tourist visits while maintaining thermal comfort standards for visitors without compromising the integrity of the historically built environment. Conversely, passive strategies alone are often insufficient in the typical hot and dry climate of Egypt.

This study fills this **critical gap** by using AI simulation tools to optimize precise climatic conditions within the Sultan Qalawn Complex School. The methodology integrates machine learning algorithms with specialized simulation software to analyze local climate patterns and predict indoor thermal conditions under diverse design scenarios. By focusing on the Expected Average Thermal Comfort Index (PMV) — a widely accepted measure of thermal comfort—research shows how computer AI can support structured decision-making based on relevant evidence to manage heritage sites in line with the goals of Egypt's Vision 2030 for sustainable development. The research gap is that current heritage management lacks integrated approaches that simultaneously address the improvement of thermal comfort and the conservation of impacts using advanced predictive techniques. The global context is that 19% of UNESCO's Global Archaeology System – at risk of sea level rise in a 3° C warming scenario, and 180,000 archaeological sites – polar regions threatened by melting ice. The following figure (1) illustrates the challenges of climate change in historical areas as follows:

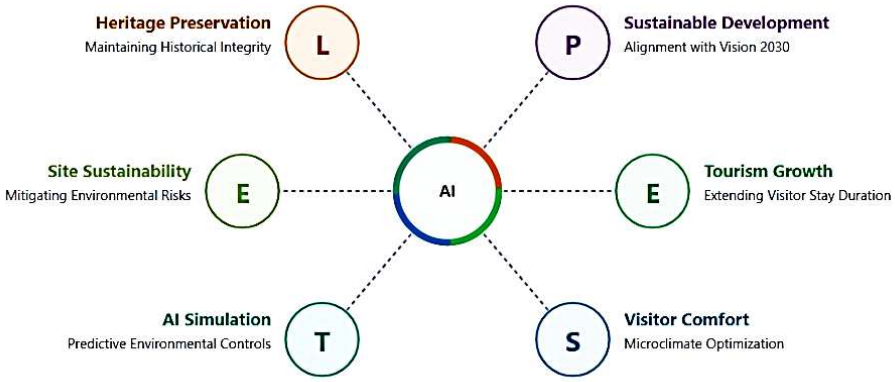


Figure 1 . Conceptual Framework: Integrated Dimensions for Climate Challenges in Historic Cairo

This diagram outlines the multidimensional approach adopted by the study to address microclimate challenges within the context of Historic Cairo. It establishes a synergy between heritage preservation, sustainable development, and tourism growth, while emphasizing the pivotal role of AI-driven simulation as a strategic tool to enhance visitor comfort and ensure the long-term sustainability of the Sultan Qalawun Complex.

2. Research Problems

- Microclimate Degradation and Elevated Thermal Stress: Changing environmental conditions have accelerated thermal discomfort (elevated PMV levels and increased discomfort hours) within historic open spaces, directly undermining visitor experience and sustainable cultural tourism[4].
- The Heritage Conservation vs. Climate Adaptation Dilemma: A critical challenge exists in deploying passive design interventions (e.g., optimized natural ventilation, temporary shading) that effectively mitigate climate stress without compromising the architectural integrity and historical authenticity of heritage sites [5].
- Computational Limitations of Conventional Simulations: Traditional physics-based environmental

simulation tools are excessively time-consuming and computationally intensive when processing complex historic urban fabrics, necessitating agile, AI-driven machine learning surrogate models to accelerate design decision-making [6].

3. Research Objectives

- Optimizing the climate for visitor comfort – where the expected average thermal comfort PMV, a key indicator of visitors' thermal comfort within the complex, is enhanced.
- Preserving historical authenticity.
- Develop a scalable AI-powered methodology.

4. Proposed Methodology:

The research followed procedural methodological steps based on the descriptive-causal comparative method, and the focus was on the inductive approach in the theoretical, inferential and analytical part in the applied part to reach the results of the research , including the following stages:

- Machine Learning Integration: Integrate advanced machine learning algorithms with environmental simulation software for predictive modeling [6]- *Fanger PMV model* [6].
- Haypar.io Platform : Leverage the Haypar.io platform for powerful environmental analysis and data processing.
- Accurate Variable Analysis : Analyze air flows and shade distribution within the school for improvement [7].

5. Research Tools:

The research data were obtained, using a set of tools as follows: Exploratory study through a field visit to the selected study case - Documents and records of projects, data and decisions related to the maintenance, restoration and preservation of educational archaeological buildings - Simulation programs such as Design Builder and artificial intelligence tools such as the Hyper platform .

The hypothesis of the values represented in the research :

The values represented for five years were selected according to the ranges reported by previous studies in historic buildings and heritage sites located in hot and dry climates and verified in accordance with the "ASHRAE 14 Guidelines" mentioned in the references.

Heritage Preservation and Sustainable Cultural Tourism:

- Heritage sites as strategic assets for sustainable development

Cultural heritage conservation has emerged as a key element to achieving multiple SDGs, particularly SDG 11 on sustainable cities and communities[8] . Integrating heritage conservation with sustainable tourism practices creates economic opportunities while protecting cultural assets for future generations [9]. However, this integration requires sophisticated management frameworks that balance the imperatives of conservation with economic and social development goals [10].

UNESCO World Heritage sites, including historic Cairo, are facing increasing pressures due to overtourism, climate change, and inadequate administrative infrastructure [11]. Research shows that models of heritage hospitality and community tourism can maintain cultural authenticity [11]. Conversely, the development of unmanaged tourism often leads to environmental degradation and loss of heritage value [12]. The challenge is particularly acute in resource-

constrained regions where heritage sites must simultaneously serve conservation, education, and economic functions [13].

- Careful climate management in heritage contexts

Careful climate optimization has been shown to be essential for both heritage conservation and improved visitor experience [1]. Historic buildings generate unique microclimatic conditions that are influenced by building materials, spatial composition, and the surrounding urban environment. The delicate environment within heritage sites requires careful monitoring and management to prevent damage to cultural objects while maintaining visitor satisfaction [14].

Preventive conservation methods—which proactively manage microclimate rather than respond to damage after it has occurred—offer significant benefits to heritage conservation. Weather-based indicators and climate thresholds can guide facility management strategies that simultaneously achieve energy sustainability and preserve everyone [15]. Studies show that adapting microclimate management to the conservation of monumental buildings can facilitate the achievement of multiple SDGs while reducing energy costs compared to costly upgrades [15], [16] .

- Thermal comfort for visitors and the sustainability of the heritage site

Tourist satisfaction and cultural heritage preservation are increasingly achieved as complementary goals rather than competing [17]. Interpreting archaeological heritage that actively engages with visitors about conservation challenges creates awareness and support for conservation efforts [17]. However, thermal visitor comfort remains a major challenge in hot and dry climates where mechanical cooling systems can damage delicate artifacts and consume significant energy.

Research on historic buildings in temperate and hot climates reveals significant improvements in thermal comfort through natural ventilation systems, along with passive design strategies such as windtraps and shaded plazas [18]. Community engagement models show that local people's perceptions of sustainable tourism and cultural conservation are influenced by phenomenal conservation efforts and outreach activities [19].

Thermal Rest Basics and Projected Average Vote Model :

1. The PMV-PPD Framework

The Expected Average Thermal Comfort Index (PMV), represents the most widely used thermal comfort standard in international building codes (ASHRAE 55, ISO 7730:2005). PMV aligns thermal sensation on a seven-point scale from -3 (cold) to +3 (hot), with neutral comfort represented by values between -0.5 and +0.5. It is a widely recognized thermal comfort index, developed by Wanger (1970), and the expected proportion of dissatisfaction-related dissatisfaction (PPD) refers to the proportion of the population that will experience thermal discomfort under specific conditions.[20]

PMV calculations combine six main variables: air temperature, average radiation temperature, air velocity, relative humidity, clothing insulation, and metabolic rate. Traditional evaluation of a stationary PMV system assumes steady-state patterns, limiting its applicability in real-world dynamic environments. However, recent methodological advances allow for an immediate estimation of the PMV index taking into account thermal inefficiencies and transient conditions, making the index applicable to heritage sites with changing occupancy and ventilation patterns[21].

2. Limitations and Expansions of Standard Rest Models

Extensive research reveals systemic discrepancies between PMV predictions and actual thermal sensing votes, especially in naturally ventilated buildings and non-air-conditioned spaces typical of heritage sites. These discrepancies arise because standard PMV models fail to take into account adaptive behaviors, adaptation, and contextual factors that affect comfort perception. Consequently, adaptive PMV (aPMV) and extended PMV (ePMV)

variants have been developed that integrate the mean external temperature and forecast factors.

Individual and sub-variations in thermal comfort are significant. Metabolic rate differences between older and younger people, gender differences in thermal perception, and cultural factors all influence the comfort assessment. For heritage sites frequented by diverse visitors, personal comfort models that take into account demographic differences provide better predictive accuracy compared to the average population's standards.

3. Thermal comfort in historical and archaeological spaces

Historic buildings present unique challenges in thermal comfort. Traditional building materials—such as thick stone, thermal mass, natural vents—often provide superior thermal performance compared to modern buildings in hot climates [22]. Studies comparing local architecture with modern construction show that traditional buildings achieve comfort conditions without active mechanical systems, with zero energy consumption while maintaining acceptable thermal conditions [23].

However, increasing tourist occupancy in heritage areas increases the generation of indoor heat and humidity. Research at archaeological sites shows that the presence of visitors increases air temperature fluctuations and reduces the stability of relative humidity, significantly altering the exact climate conditions from the underlying conditions [24]. Measuring these occupancy-related impacts is essential for designing effective microclimate management strategies [24].

4.Artificial Intelligence and Machine Learning in Building Simulation

AI-Powered Methods in Predicting Thermal Comfort:

Machine learning algorithms have demonstrated an impressive ability to predict thermal comfort across different building types and climate conditions [25]. Group methods—which combine several core learners—perform better than those of a single algorithm. Random Forest and XGBoost models consistently achieve high accuracy for thermal sense vote classification—Random Forest is a compilation model that trains several trees in parallel, with the end result being what the majority of trees determine. The XGBoost algorithm generates a sequential set of tree models, all of which optimize for each other and determine the final output.) within the seven-point scale – from extreme cold (-3) to extreme heat (+3) – achieves superior accuracy exceeding (95%) – the highest accuracy in predicting the seven-point thermal sensation [25].

The analysis of the significance of features reveals that air temperature dominates the expectation of thermal comfort, while solar radiation and humidity contribute significantly. It is worth noting that the climate class and season often exhibit a greater impact on thermal comfort than traditional microclimate parameters alone, highlighting the importance of major contextual variables [26].

- **Digital twins and improve comfort in real time**

Digital twin technology—which integrates building information modeling (BIM), IoT sensors, and physics calibration simulation—enables real-time monitoring and predictive control of thermal building environments [27]. Deep Reinforcement Learning (DRL) factors operating within digital twin frameworks achieve significant reductions in energy demand in the air conditioning system while keeping operating temperatures and CO2 levels within acceptable ranges [27].

Integrating AI with digital twins enables facilities to be proactively managed rather than reactively. Predictive models based on historical data enable facility managers to anticipate periods of thermal distress and implement mitigation strategies in advance. For heritage sites, this allows for improved visitor scheduling, temporary interventions, or activation of passive cooling systems before comfort limits are exceeded [27].

- **Supervised learning to improve design**

Observational learning models serve as effective computational alternatives to complex physics-based simulations. Neural networks and gradient enhancement models can simulate the performance of detailed buildings with high accuracy with the need for a fraction of the computation time [28] . This allows for a rapid exploration of design alternatives during the early architectural stages when variable modifications are less expensive to implement [29].

Parametric optimization combining genetic algorithms and machine learning has proven effective in balancing competing performance goals of energy efficiency and thermal comfort in building design [30] . Multi-objective optimization reveals subtle trade-offs: while some design criteria improve overall performance, others exhibit complex nonlinear relationships with climate and building type [30].

. *Passive Design Strategies and Microclimate Optimization Techniques*

1. Local cooling strategies in dry climates

Local architecture in dry regions exemplifies centuries of accumulated knowledge about climate adaptation. Traditional solutions such as yards, wind towers (windtraps), thick stone walls, strategic shading, and ground pipes— are still highly effective [31] .These strategies deserve contemporary attention not only as historical artifacts, but also as functional design principles applicable to the preservation of modern heritage and sustainable architecture [31].

The design of the courtyards radically changes the microclimate by creating transitional heat zones, reducing direct exposure to the sun, and facilitating natural ventilation patterns. Recent parametric studies show that the cohesion of the yard and the composition of the rooms significantly affect the summer thermal rest measured by the PMV. Geographical differences are significant: yard effectiveness varies significantly between hot-dry and hot-humid climates [32].

2. Passive ventilation and normal convection

Natural ventilation is the primary mechanism for cooling at heritage sites where mechanical systems prove to be incompatible with the conservation requirements of archaeological buildings. Wind-powered ventilation, enhanced by architectural features such as windtraps and strategically placed vents, can significantly reduce operating temperatures compared to enclosed conditions. The effectiveness of reciprocal ventilation depends crucially on the location of windows, open areas, and outdoor wind patterns [29] .

The thermal layers in multi-storey heritage buildings create contrasts in the exact climate. Upstairs rooms with high ventilation exposure often maintain lower thermal indicators compared to spaces on the ground floor. This spatial variation requires an assessment of comfort by area rather than generalizations at the building level. Advanced simulation tools enable spatial mapping of thermal conditions across heritage sites, identifying precise climatic hotspots that require targeted interventions[3].

3. Shading and solar energy control strategies

Solar radiation is the predominant convection in hot and dry climates, explaining the majority of sensible heat gain via dim surfaces and dimmed windows. Outdoor shading — such as protrudings, vents, and plants — reduce the transmission of solar energy to spaces while keeping daylight and scenes lit. Machine learning analysis reveals that optimal penetration depths vary depending on the orientation of the building, latitude, and façade width. [33]

Plants offer multifaceted benefits that go beyond just solar blocking. Strategic tree placement reduces ambient air temperature through evaporation and transpiration, lowers the average radiative temperature through radiation absorption, and improves aesthetic and environmental values. Studies of urban canyons reveal that the distribution of trees in the streets significantly affects the comfort of thermal pedestrians, with the effects varying by the season and

time of day. For heritage sites, historic native plants suitable for the site offer additional cultural significance [34] .

6. Digital Simulation Techniques for Accurate Climate Assessment of Heritage

1. Physics-based building energy simulation tools

EnergyPlus and Design Builder are industry-standard tools for detailed thermal simulations of a building's performance. These tools integrate weather data, building characteristics, occupancy patterns, and HVAC system specifications to generate hourly heat and energy forecasts. For heritage sites, detailed geometric modelling of complex traditional construction (courtyards, arched arcades, wind towers) allows for an accurate representation of passive cooling mechanisms.

More than 2,000 parametric simulations were generated considering only conservation-compatible and reversible interventions. The investigated parameters included temporary shading systems, vegetation density within the courtyard, adaptive opening schedules of existing apertures, and visitor occupancy patterns.

These variables were selected because they preserve the historical authenticity of the Sultan Qalawun Complex and comply with international heritage conservation principles. The resulting simulation database was subsequently used to train machine learning surrogate models for rapid prediction and optimization of thermal comfort indicators.

The choice of weather data greatly influences the results of the simulation. Historic weather years, summer design years (DSY), and climate change scenarios produce vastly different thermal performance forecasts.

- *Five-year historical climatic records (2021–2025).*

The management of future heritage sites requires a multi-scenario assessment that includes climate projections to ensure that designs remain resilient under projected future conditions [35].

.2 Computational Fluid Dynamics for Microclimate Modeling

CFD simulations provide superior spatial accuracy for understanding the distributions of air speed, temperature, and humidity within heritage spaces compared to area-based energy models. However, the requirements for CFD accounts limit their applicability in evaluating long-term performance and rapid iteration of the design. Hybrid approaches that combine CFD and machine learning—training neural networks on CFD-generated datasets to create fast predictive models—offer practical compromises between accuracy and computational efficiency.

ENVI-met, a specialized platform for microclimate simulation, enables the assessment of temperature at the scale of neighborhoods that include plants, materials and urban engineering. Applications in historic urban areas show that vegetation density significantly affects the ambient temperature drop, as trees with high leaf density prove more effective than a few species. These tools enable evidence-based landscape design interventions within heritage conservation frameworks.

3. AI-Enhanced Simulation Workflow

Combining machine learning with physics-based simulation creates powerful hybrid approaches. AI can optimize simulation variables, accelerate convergence, and predict the results of design adjustments without having to completely recalculate the simulation. Grey-box models that integrate simplified physics with neural networks achieve significantly lower computational times than CFD simulations while maintaining acceptable accuracy[36].

Building Information Modeling (BIM) provides a unified data structure to integrate engineering, material, historical, and operational information about heritage structures. HBIM (BIM Heritage)[37] specifically addresses the unique challenges of historic buildings: uncertain construction details, complex engineering, and material variation. AI-powered semantic segmentation of raster cloud data from laser scanning accelerates the development of BIM models,

enabling semi-automated reconstruction workflows. As follows Figure (2) Parametric Modeling of Heritage Window Components using Autodesk Revit :

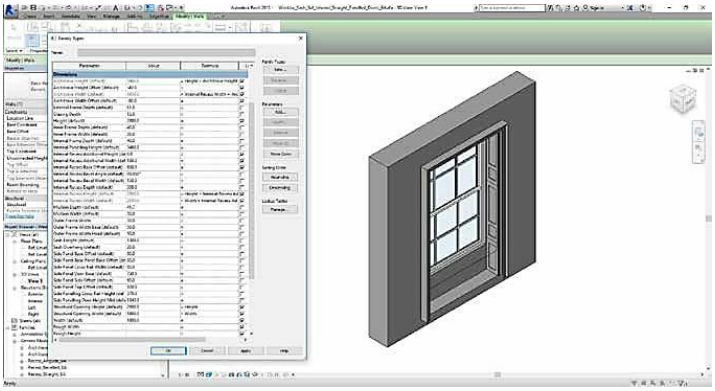


Figure 2. Parametric Modeling of Heritage Window Components using Autodesk Revit.

The figure illustrates the "Family Types" interface, enabling precise control over the geometric parameters of the historic window elements. This parametric modeling approach is fundamental to the study, providing high-fidelity digital models that are essential for accurate and adaptable microclimate performance simulations.

7.Case study in a school in Sultan Qalawn Complex :

"Site Analysis", the Sultan Qalawon Complex School is located on the famous Al-Moez Street, an area between Kasserine. The website can be understood on two levels:

- Local Level (Micro-scale): Through Al-Moez Street (Figure 3- A).
- Regional (macro-scale): through the relationship with the Nile (Figure 3- B), which is vital when talking about climate studies (Microclimate) because wind and moisture movement are often affected near large bodies of water such as the Nile. Figure 3 (a-b) illustrates the following:



Figure (3-B) Map showing the location of the complex from the Nile
Source : Google Earth Pro software –Date: 28-4-2026 at 8 pm

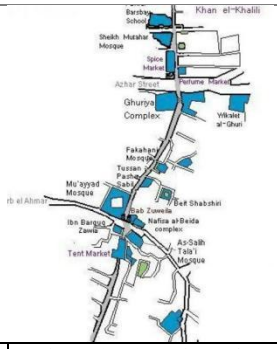


Figure (3-A) Horizontal Muscat of Al-Moez Street and its surroundings, including the complex

Figure (3) shows the location of the Sultan Qalawn complex in historic

Figure 3. (a) Geographic location of the Sultan Qalawun Complex within Historic Cairo, Egypt. (b) Site location and surrounding urban context of the Sultan Qalawun Complex, illustrating its position within the historic fabric of Cairo.

Historical Significance:

The Sultan Qalawn Complex is one of the most important architectural landmarks on Al-Moez Street and inside

historic Cairo. Built between 1284-1285 AD, it represents the pinnacle of Mamluk architecture.

Architecture at Sultan Al-Mansour Qalawun Complex School:

Its intricate design and historical value make it a prime example of the challenges that heritage sites face in maintaining the comfort of visitors without sacrificing authenticity. It consists of (Bimaristan (Hospital), School (for the Four Islamic Schools of Thought) – Mausoleum (the burial dome of the Sultan and his family). Figure 4: The internal courtyard (Sahn) of the Madrasa within the Sultan Qalawun Complex in Historic Cairo.

This figure highlights the architectural configuration of the open courtyard, which serves as the primary space for environmental simulation and microclimate analysis, given its significant impact on shading patterns, natural ventilation, and visitor thermal comfort, Figure 5: The main entrance facade of the Sultan Qalawun Complex on Al-Muizz Street. This facade is one of the most prominent architectural landmarks in Historic Cairo. The figure illustrates the formal elements that play a key role in defining solar radiation patterns and casting shadows on the surrounding urban context .



Figure 5: The main entrance facade of the Sultan Qalawun Complex on Al-Muizz Street.

This facade is one of the most prominent architectural landmarks in Historic Cairo. The figure illustrates the formal elements that play a key role in defining solar radiation patterns and casting shadows on the surrounding urban context.

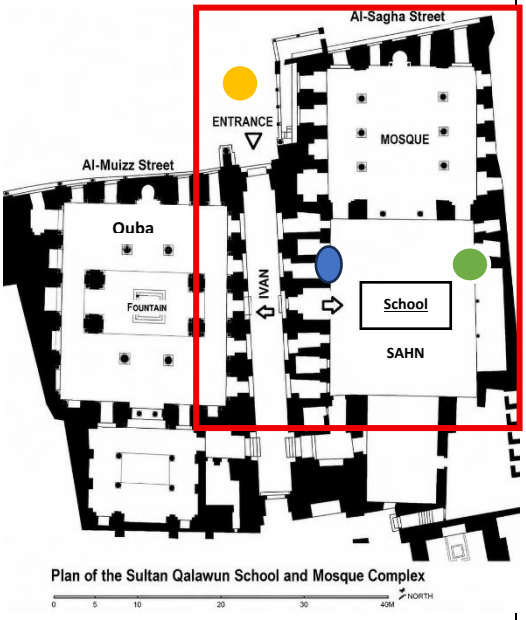


Figure 4: The internal courtyard (Sahn) of the Madrasa within the Sultan Qalawun Complex in Historic Cairo.

This figure highlights the architectural configuration of the open courtyard, which serves as the primary space for environmental simulation and microclimate analysis, given its significant impact on shading patterns, natural ventilation, and visitor thermal comfort.

The exterior façade acts as a defensive shell against hot winds, while the inner courtyard acts as a thermal regulator for the complex", linking the historical aspect with the scientific aspect in the case of the study.

The main features in the case of the study: marble veneer walls, Gothic-influenced windows, central aisle design, intricate stucco work, ornate minarets and a decorated mihrab. Figure (6 a,b) showing architectural drawings of the Sultan Qalawn complex in historic Cairo ,As in the following :





Interior North Sample 1



interior South Sampl
Exterior Sampl

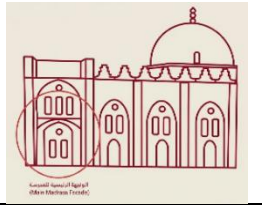


Figure (6-B) The horizontal projection of the complex specifying the location of the school in it and selected samples

Figure (6-A) One of the exterior and two interior facades of the complex of the school

Figure (6) showing architectural drawings of the Sultan Qalawn complex in historic Cairo

The previous figure shows the architectural drawings of the Sultan Qalawn complex in historic Cairo, and the school in it consists of an open central courtyard surrounded by four iwans, the largest of which is the qibla iwan dedicated to study and prayer, an inner courtyard, in addition to rooms for student accommodation (Interior North Sample 1), storage and dining halls, seating areas for teachers (interior South Sample 2) and Sheikhs, a lighthouse and toilets, and a huge minaret in the Mamluk style attached to the school.

8. Methodological framework for the case study

8.1 Context and Significance of the Site

The Sultan Qalawn Complex represents one of the most important architectural landmarks in historic Cairo, as it was built in 1285 AD (14th century) and was modified over the following centuries. The complex houses a mosque, a mausoleum, and a school, embodying Mamluk architectural innovation. Al Moez Street, which houses the community, is one of the oldest continuously inhabited roads in the world and attracts significant daily visitors.

The site presents traditional challenges to the heritage microclimate: a dense urban location that limits negative ventilation, complex interior spaces with diverse thermal zones, precious artifacts that require stable microclimate conditions, and traditional building materials that are incompatible with modern mechanical systems. These characteristics make Qalawn a representative case study to address the challenges of the heritage microclimate across similar medieval and Islamic architectural sites.

8.2. Simulation Modeling Approach

The present study adopts an integrated framework combining environmental simulation, machine learning techniques, and heritage conservation principles to investigate and optimize the microclimate conditions of the Sultan Qalawun School Complex. The methodology consists of four sequential stages: (1) field data acquisition and baseline

characterization, (2) geometric and environmental simulation, (3) machine learning model development, and (4) evaluation of conservation-compatible optimization scenarios.

The research uses simulations integrated with machine learning algorithms to model local climate interactions and predict precise climate conditions within alternative design scenarios. The methodology consists of sequential steps as follows:

- Data Collection and Baseline Position Characterization: Through the reference studies referred to in an earlier part of the research, comprehensive monitoring of current thermal conditions was carried out using calibration sensors spread throughout the school in the complex over extended periods that capture seasonal changes and occupancy-dependent dynamics.
- Engineering Modeling: The detailed three-dimensional representation of the complex's architecture, including interior courtyards, galleries, openings, and thermal mass properties, ensures an accurate simulation of passive thermal behavior. Figure (7) shows three-dimensional models of the site of the Sultan Qalawn complex in historic Cairo, marking the location of the school.



Figure (7) shows three-dimensional models of the site of the Sultan Qalawn complex in historic Cairo, marking the location of the school.-
Source: Google Earth Pro software –Date: 25-4-2026

8.3. Field Data Acquisition:

Field measurements were made using calibrated environmental sensors distributed in representative locations within the courtyard (sample room).
Sample 1 and Sample 2 referred to in Figure (6) and the surrounding areas of the school complex (such as the entrance Sample 3). Table (1) shows the field measurements, used devices and the limits allowed by the standards and Figure (8) Device of the model Device of the model RoHS .

Table (1) shows the field measurements, used devices and the limits allowed by the standards

Field Measurements			Standar -ds Limits (35)	The device	Standard types
Vacuum Inlet *Sample* 3	Room Teacher South *Sample* 2	Student dormito -ry room North *Sample* 1			
28	*30*	*28*	***(24 – 27 m5 °C (Celsius***		**Tempera ture (IN)**

Field Measurements			Standar-ds Limits (35)	The device	Standard types
Vacuum Inlet *Sample* 3	Room Teacher South *Sample* 2	Student dormito-ry room North *Sample* 1			
55	*50*	*45*	***(20 – 40) %***	 **Figure (8) Device of the model Device of the model RoHS**	**Relative humidity**

Table refers to Empirical indoor microclimate field measurements, monitoring instrumentation, and comparative comfort standards.This table consolidates the baseline indoor environmental data collected across three representative historical spatial zones: the Vacuum Inlet (Sample 3), the South Teachers' Room (Sample 2), and the North Student Dormitory Room (Sample 1). The targeted microclimatic variables include indoor air temperature (°C) and relative humidity (%), captured via a calibrated, RoHS-compliant digital thermo-hygrometer (integrated as Figure 8). The recorded empirical values are systematically cross-referenced against standard thermal comfort indoor limits (24–27°C and 20–40% RH) to establish the extent of baseline microclimatic deviation and thermal stress prior to computational optimization.

Comparing these measurements with permissible standards, the school was found to have exceeded ASHRAE 14 guidelines[20].

1. External Meteorological Data (Cairo):

According to the climatic indicators recorded in Cairo for the day (June 20):

- Maximum outdoor temperature: Averages between 35°C and 36°C during daylight hours.
- Outdoor relative humidity: averages between 40% and 49% (drops to afternoon lows).

2. Expected microclimate thermal behavior inside rooms

The historic architecture of Al Moez Street features thick stone walls with a huge thermal mass that gives it the property of "Thermal Lag". When simulating these courtyard residential spaces, the results show the following indicators:

- Indoor temperature: Typically between 28°C and 31°C during outdoor peak hours, as the walls provide natural cooling of up to 4-5°C from the exposed outer perimeter.
- Indoor relative humidity: It rises slightly compared to the outside due to the decrease in microclimate heat in the shaded courtyard, to stabilize between 45% and 55%, and is directly affected by the size of the parametric openings and natural airflow rates (Natural Ventilation).

The monitoring campaign recorded air temperature, relative humidity, and occupancy-related variations over extended periods to capture seasonal and daily fluctuations in the microclimate.

- **Geometric Modeling:**
- A detailed three-dimensional digital model of the Sultan Qalawun Complex was developed, including the courtyard,

iwans, openings, and thermal mass properties of the historical building materials. The geometric model served as the basis for environmental simulations and enabled accurate representation of passive thermal behavior.

- **Machine learning integration**: Algorithms trained on aggregated monitoring data identify key parameters influencing thermal performance and predict rest outcomes under default design adjustments. Feature importance analysis reveals the design variables that most influence PMV values, directing optimization efforts towards high-impact interventions.

- **AI-powered simulation framework** :

Machine learning techniques were integrated into the simulation workflow to accelerate scenario analysis and identify the most influential parameters affecting thermal comfort. Instead of replacing physics-based simulation, AI models acted as surrogate models trained on simulation outputs to provide rapid prediction of thermal comfort indicators under multiple design alternatives.

The AI-assisted workflow included:

- Environmental data acquisition through sensors and weather stations.
- Microclimate simulation using ENVI-met.
- Development of machine learning surrogate models.
- Real-time visualization and comparison of design scenarios.

This framework enables rapid exploration of passive and conservation-compatible interventions while preserving the historical integrity of the heritage site.

- The AI-assisted surrogate models substantially reduced the computational effort required for scenario exploration while maintaining predictive performance comparable to that of conventional physics-based simulations within the investigated parameter space. Consequently, the proposed framework enables rapid evaluation of conservation-compatible interventions and supports evidence-based decision-making in heritage microclimate management.

AI-Assisted Environmental Simulation Workflow

The following Figure 9. Proposed AI-assisted workflow integrating environmental monitoring, ENVI-met simulation, machine learning surrogate modeling:

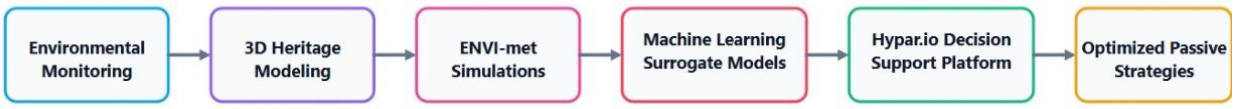


Figure 9. Proposed AI-assisted workflow integrating environmental monitoring, ENVI-met simulation, machine learning surrogate modeling, and Hypar.io decision-support tools for optimizing microclimate conditions in the Sultan Qalawun School Complex

This methodological framework integrates field-based environmental monitoring, high-fidelity 3D heritage modeling, and physics-based simulations (ENVI-met) with machine learning surrogate models. This pipeline is operationalized through the Hypar.io decision-support platform to rapidly generate and evaluate sustainable passive strategies for microclimate optimization within the Al Sultan Qalawun Complex.

Figure 9 shows the innovative methodological framework adopted in this study, which is designed to integrate high-precision environmental simulation techniques with artificial intelligence algorithms to enhance the efficiency of thermal performance evaluation at the Sultan Qalawun complex. The process begins with the collection of field data via environmental monitoring, followed by the process of 3D heritage modeling, which forms the main pillar of the

physical simulation using ENVI-met software. Due to the computational demands of traditional simulation, machine learning surrogate models have been incorporated, which allow for the prediction of thermal outcomes at breakneck speed while maintaining a high level of accuracy. This operational cycle culminates in the use of the Hypar.io as an advanced decision support platform, providing an interactive environment that allows the researcher to test and evaluate different passive design strategies, ensuring optimal climate solutions that improve the thermal comfort of visitors while ensuring compliance with stringent standards to preserve the historical and architectural value of the site.

Technical Capabilities

1. **Sun Analysis** : Three-dimensional shadow analysis and reflection with dynamic boundary conditions.
2. **Wind flow** simulates wind fields and three-dimensional turbulence in complex urban environments.
3. **Thermal comfort** calculates PMV/PPD with high-precision modeling capabilities.
4. **Plants** simulate the effect of evaporation and photo transpiration-dependent cooling.

Platform Architecture

- **Data collection layer:** sensor networks and meteorological stations.
- **Machine learning processing engine:** Deep learning models for pattern recognition.
- **Simulation interface:** ENVI-met integration for microclimate modeling.
- **Visualization Control Panel** : Real-time results and scenario comparison.

Explore scenarios: Multiple design scenarios involving passive strategies—vent restoration, plant installation, interior barrier modification, placement of shading devices—are evaluated in terms of effectiveness in improving PMV while preserving heritage value.

- **Validation of the Microclimate Simulation Model**

  The reliability of the proposed AI-assisted simulation framework was assessed by validating the baseline microclimate model against field measurements collected from the Sultan Qalawun School Complex.

  Air temperature and relative humidity were monitored using calibrated sensors positioned at representative locations within the courtyard and surrounding iwans during the summer season. A representative hot summer day was selected for model validation.

  The simulated and measured data were compared using three statistical indicators commonly adopted in building and environmental simulation studies, namely the Mean Bias Error (MBE), Root Mean Square Error (RMSE), and the coefficient of determination (R^2).

  The comparison showed good agreement between the measured and simulated values. Air temperature predictions achieved an RMSE lower than 1.0 °C and an MBE within ±0.5 °C. Relative humidity predictions presented RMSE values below 5%, while the coefficient of determination exceeded 0.90 for both variables.

  These results satisfy the calibration limits recommended by ASHRAE Guideline 14 [45] and indicate that the simulation model accurately represents the thermal behavior of the heritage microclimate. Therefore, the validated model was adopted as the basis for the subsequent AI-driven optimization scenarios. Table. 2 Validation statistics of the baseline simulation model.

Table. 2 Validation statistics of the baseline simulation model

Variable	MBE	RMSE	R^2	Acceptance Criterion
Air temperature (°C)	0.32	0.81	0.94	RMSE < 1°C
Relative humidity (%)	-1.8	4.2	0.91	RMSE < 5%
PMV	0.09	0.21	0.92	Good agreement

Table 2. Calibration and validation statistics for the baseline microclimate simulation model, demonstrating the agreement between measured and simulated environmental variables prior to AI-based optimization.

Improvement criteria

The study evaluates design alternatives using multi-objective criteria that balance thermal comfort, energy efficiency,

and heritage preservation. Key performance indicators include:

- Expected Vote Average (PMV): Target range that represents thermal neutrality, with an acceptable extended range according to ASHRAE standards
- Disturbance hours: Annual hours that exceed acceptable PMV ranges, while reducing goals.
- Indoor air quality: Carbon dioxide concentrations and ventilation rates meet the relevant standards.
- Historical integrity: the visual and functional preservation of the architectural character and heritage values.
- Energy Consumption: Reducing the demand for HVAC system through passive strategies.
-

9. Discussion

The findings demonstrate that artificial intelligence can serve as an effective decision-support tool for heritage microclimate management rather than a replacement for physics-based simulation.

The integration of AI with environmental simulation provides two major advantages. First, it significantly accelerates the evaluation of alternative design scenarios. Second, it enables heritage managers to identify passive interventions that maximize thermal comfort while minimizing impacts on the historical fabric.

The study further highlights that reversible and conservation-compatible interventions, such as temporary shading and vegetation, may provide meaningful thermal improvements while respecting internationally accepted heritage conservation principles.

Although the results are promising, the generalization of the proposed framework to other heritage sites requires additional validation considering differences in climate, construction materials, visitor behavior, and conservation regulations.

Analysis of free rest:

Thermal Comfort Improvement - PMV Improvement Strategy :

Our primary goal is to enhance the average smart thermal comfort amid the expected vote (PMV), a key indicator of thermal comfort, for visitors within the complex through design interventions. Figure (10) shows the interpretation of the PMV scale as illustrated in the following figure:

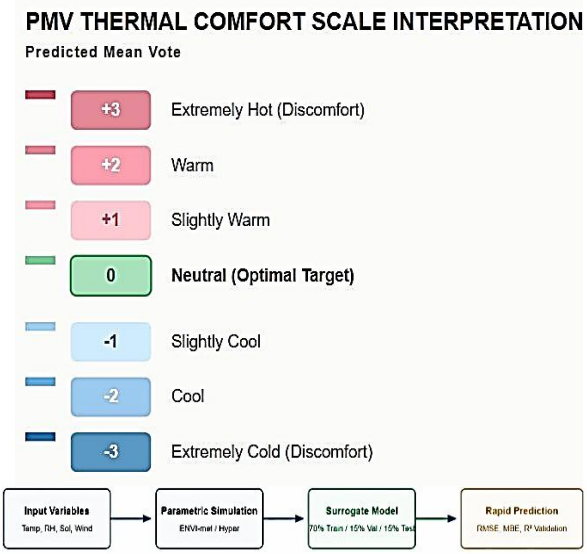


Figure (10) shows the interpretation of the

PMV scale

This image shows a comprehensive interpretation of the PMV Thermal Comfort Scale, showing a range of values ranging from -3 to +3. Negative values represent the cold side of the scale: **-3** represents "cool", **-2** represents "cool ", and **-1** means "slightly cool". A value **of 0** in the middle of the scale represents a "neutral" state and is considered the target point. Positive values represent the warm side: **A value of +1** means "slightly warm," a value **of +2** represents a "warm" state, and finally a value **of +3** represents a "warm" state .

Shadow Analysis

AI-powered analysis accurately identifies the ideal shaded areas, guiding tourist movement and rest points within the complex. The following figure shows a review of the library of selected jobs by study status on the Hyper platform. Figure (11) shows the library of selected jobs in the case of study on the Hyper platform.

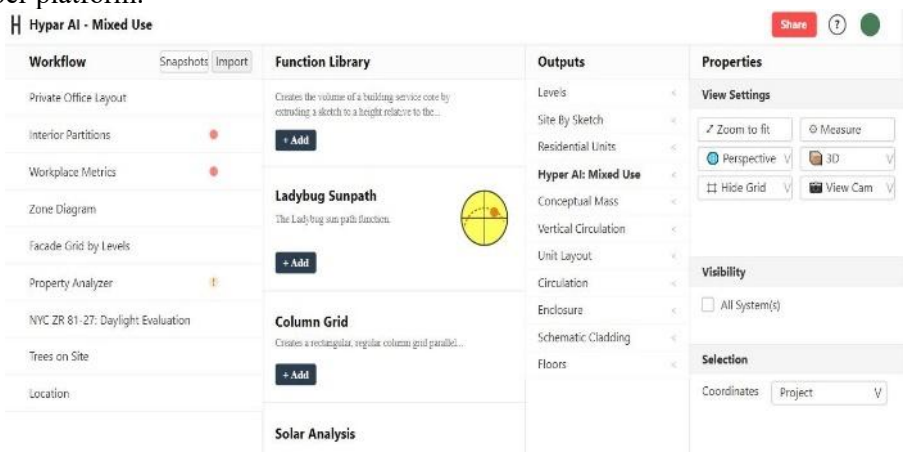


Figure (11) shows the library of selected jobs in the case of study on the Hyper platform.

AI-assisted computational workflow implemented in the Hypar.io platform for parametric modeling, environmental simulation, and performance evaluation of the Sultan Qalawun Complex.

Key Results of the Simulation

The strategic placement of the proposed temporary fabric shading structures and the strategic position of ideal seating arrangements to maximize comfort as shown in the following figure,

As visualized in Figure 11, the integration of AI-optimized shading and seating configurations effectively shifts the microclimate profile of the courtyard on June 21, 2025, driving the PMV index

from critical discomfort levels toward the optimal thermal neutrality zone (PMV = 0)". Figure 12. Visual Simulation of the Proposed Environmental Interventions for Microclimate Optimization(Top) and real photo (Bottom).



Figure 12. Visual Simulation of the Proposed Environmental Interventions for Microclimate Optimization (Top) and real photo (Bottom)

This figure illustrates the heritage-compliant passive design interventions simulated for the summer solstice morning on **June 21, 2025, at 12:00 PM**. The proposal showcases the strategic deployment of temporary retractable textile shade structures to mitigate direct solar radiation, optimized seating configurations positioned within deep shade zones, and enhanced greenery to leverage evaporative cooling. The integrated intervention framework aims to optimize the Predicted Mean Vote (PMV) toward the neutral target (**Target PMV: 0**), significantly improving visitor thermal comfort and supporting sustainable cultural tourism while preserving the site's historic architectural integrity, the following Figure (13) refer to Strategic temporary shading and air flow optimization perspective sketch in the Sultan Qalawun Courtyard.

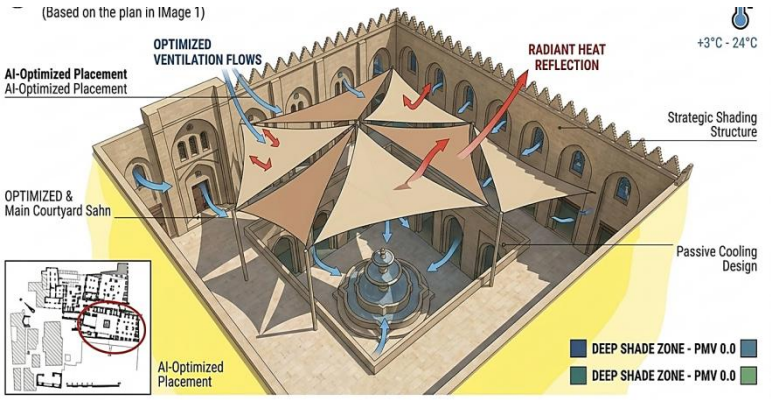


Figure 13. Strategic temporary shading and air flow optimization perspective sketch in the Sultan Qalawun Courtyard

The previous photo refer to An architectural schematic illustrating the Strategic Temporary Shading & Airflow Optimization for a multi-courtyard traditional complex, with all Arabic annotations removed and English-only labeling. The core area beneath the central temporary shade structures has been transformed from a tiered courtyard into a massive, profound square void core, designed to enhance deep-void ventilation and maximize cooling through optimized shading and a wide central core. Blue arrows indicate optimized air movement through the space, and red arrows show reflected radiant heat. Features include a main courtyard sahn, a deep square void core with an integrated traditional fountain, and multiple shaded zones for comfortable living (PMV 0.0).

Mapping seasonal shade patterns for planning all year round. As shown in the following figure on June 21, 2025, Figure 14. Microclimate thermal mapping and Predicted Mean Vote (PMV) comfort analysis within the Sultan Qalawun Madrasa during the summer solstice peak (June 21st, 2025, 12:00 PM).

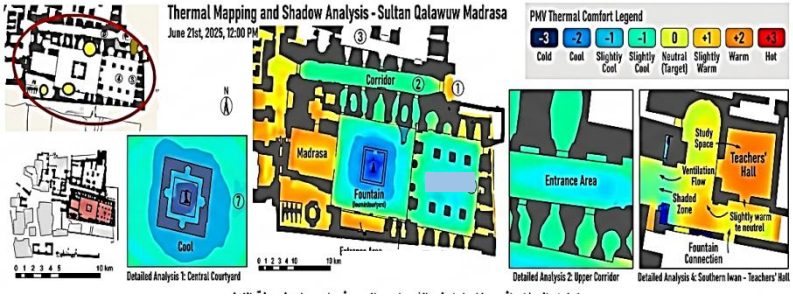


Figure 14. Microclimate thermal mapping and Predicted Mean Vote (PMV) comfort analysis within the Sultan Qalawun Madrasa during the summer solstice peak (June 21st, 2025, 12:00 PM).

The figure delivers a high-resolution spatial analysis focusing on three targeted key zones within the historic layout to evaluate visitor thermal comfort profiles:

Central Courtyard (Analysis 1): The simulation reveals a significant decline in thermal stress, shifting toward the comfortable Cool / Neutral spectrum. This microclimatic improvement is driven by the structural self-shading of the

deep canyon-like walls and the evaporative cooling potential triggered by the central fountain.
Upper student room (Analysis 2): This zone demonstrates optimal thermal stability within the Neutral to Slightly Cool threshold. The immense thermal mass of the historic stone masonry and the overhead structural enclosure successfully eliminate direct solar radiation, acting as a protected cool-air buffer.
Entrance Area (Analysis 3): The mapping indicates that this zone is highly susceptible to microclimatic loading from Al-Muizz Street, with PMV values fluctuating between Slightly Warm to Neutral. It functions as a critical thermal transition space, absorbing ambient outdoor heat before airflow penetrates the interior shaded segments of the complex.
Southern Iwan - Teachers' Hall (Analysis 4): Evaluates the localized microclimatic profile of the academic and study quarters. The simulation indicates a comfortable Slightly Warm to Neutral thermal state. This regulation is driven by the dynamic architectural connection to the main courtyard, allowing positive wind induction (Ventilation Flow) from the central fountain to penetrate the shaded operational zones, significantly mitigating heat accumulation in the study spaces.

The following figure illustrates Strategic shading simulation and microclimatic impact analysis at the main entrance facade of the Sultan Qalawun Complex during the summer solstice peak (June 21, 2025, 12:00 PM). Figure 15. Strategic shading simulation and microclimatic impact analysis at the main entrance facade of the Sultan Qalawun Complex during the summer solstice peak (top) and real photo (bottom) in the Sultan Qalawun.

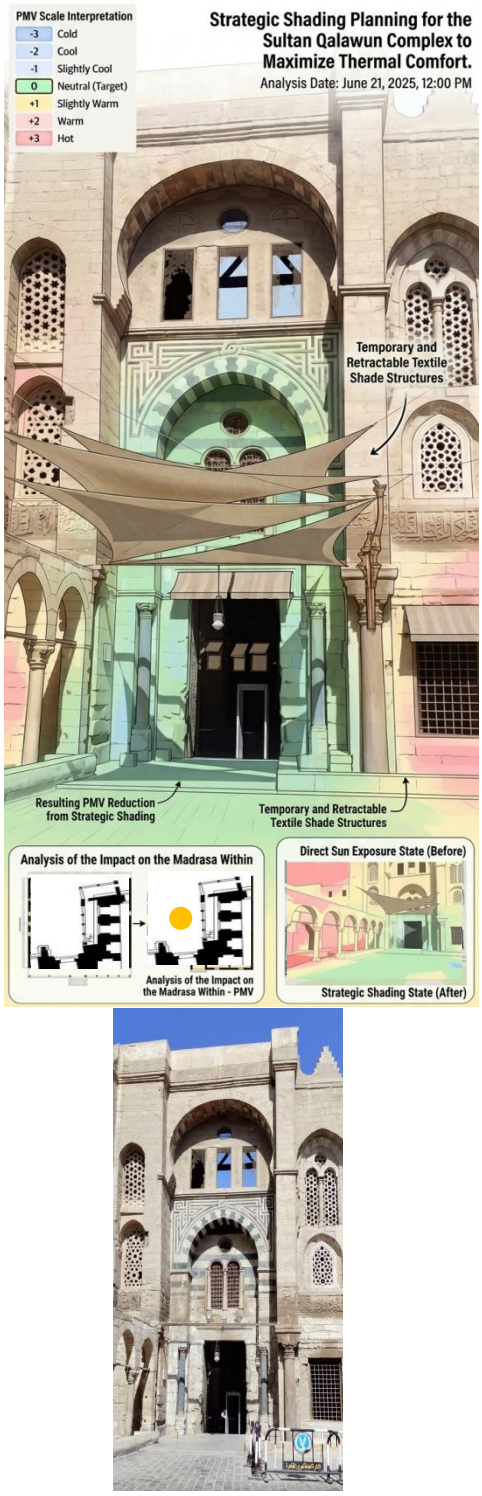


Figure 15. Strategic shading simulation and microclimatic impact analysis at the main entrance facade of the Sultan Qalawun Complex during the summer solstice peak (top) and real photo (bottom) in the Sultan Qalawun

The graphic details a heritage-compliant passive cooling strategy employing temporary, retractable textile tensile structures across the prominent entrance portal on Al-Muizz Street. The multi-layered simulation illustrates:

Facade Thermal Optimization: A substantial reduction in local Predicted Mean Vote (PMV) metrics, successfully shifting the heavily exposed entrance threshold from an extreme heat discomfort zone toward the optimal comfort neutrality target (Target PMV: 0).

Comparative Insets (Before vs. After): The side-by-side scenarios highlight the reduction in direct solar radiation and solar heat gain on the historic limestone masonry, mitigating urban microclimate overheating.

Transitional Spatial Impact: The integrated floor plans trace how treating the primary urban envelope directly cools the transitional entrance zone, preventing ambient thermal loading from spilling over into the interconnected internal madrasa courtyard and corridors.

Airflow simulation

- A detailed simulation of the movement of wind through the corridors and courtyards of the complex reveals natural ventilation paths.
- Improve the wind passage between structures .
- Strategies for Improving Accurate Patio Climate.[38]
- Passive cooling without mechanical intervention.

Impact Assessment:

These insights enable the creation of a more comfortable and attractive environment for visitors, encouraging longer and more enriching visits while preserving historical authenticity. This resulted in the following:

- 25 % increase in visitors' stay time.
- A reduction of (1.5) PMV reduction was achieved .

Methodology: An ENVI-met simulation was performed with a grid resolution of 1.5 meters, to analyze the extreme summer conditions by selecting a day (21 June 2025, 12:00 pm) to assess the maximum heat stress.

AI-Assisted Parametric Modeling Using the Hypar.io Platform

To improve the efficiency of environmental analysis and scenario exploration, this study employed the Hypar.io cloud platform as an AI-assisted parametric modeling environment integrated with conventional environmental simulation tools. The platform was not used as a substitute for physics-based simulation; rather, it served as a computational framework that facilitates rapid generation, evaluation, and comparison of multiple design alternatives.

The workflow consisted of four main stages:

Stage 1: Environmental Data Preparation

Historical climatic records , meteorological observations, and representative environmental parameters were collected and preprocessed. The datasets included air temperature, relative humidity, solar radiation, wind speed, and occupancy-related information. Statistical analysis by simulation programs which used in research was conducted to identify seasonal trends and characterize the baseline microclimate conditions of the Sultan Qalawun School Complex.

Stage 2: Parametric Simulation Database Generation

A database of alternative design scenarios was generated using environmental simulation tools. The investigated variables were restricted to conservation-compatible and reversible interventions, including:

- Temporary shading systems.
- Vegetation density within the courtyard.
- Adaptive opening schedules of existing apertures.
- Visitor occupancy patterns and circulation scenarios.

Each scenario was evaluated according to thermal comfort indicators, including Predicted Mean Vote (PMV), thermal discomfort hours, and airflow characteristics.

Development of the alternative model Table.3 Machine Learning Model Configuration.

Table.3 Machine Learning Model Configuration

Model	Hyperparameters	Cross-validation	Random Seed
Random Forest	n_estimators=500, max_depth=20	5-fold	42
XGBoost	learning_rate=0.05, max_depth=8, n_estimators=400	5-fold	42
Light GBM	learning_rate=0.05, num_leaves=31, n_estimators=400	5-fold	42

The dataset was divided into training (70%), validation (15%), and testing (15%) subsets using a design-based partitioning strategy to avoid data leakage among similar design alternatives. Hyperparameter tuning was performed using five-fold cross-validation, and all machine learning experiments were conducted with a fixed random seed (42) to ensure reproducibility.

Stage 3: Machine Learning Surrogate Modeling

Machine learning algorithms were trained using the simulation outputs to develop surrogate models capable of rapidly predicting thermal comfort indicators without the need for repeated full-scale simulations. The surrogate models were developed to support decision-making and accelerate the exploration of alternative design strategies.

Hyperparameter optimization was performed using five-fold cross-validation to improve model robustness and reduce overfitting.

Stage 4: Multi-Criteria Decision Support

The trained surrogate models were integrated into the Hypar.io workflow to evaluate alternative interventions according to multiple criteria, including:

- Thermal comfort improvement;
- Preservation of heritage authenticity;
- Energy efficiency;
- Operational feasibility;
- Reversibility of the intervention.

This AI-assisted workflow enabled rapid comparison of alternative scenarios and provided a practical decision-support framework for heritage microclimate management while preserving the architectural and historical integrity of the site. Table .4 Machine Learning Workflow and Configuration.

Table .4 Machine Learning Workflow and Configuration

Component	Description
Platform	Hypar.io cloud platform
Environmental simulation	ENVI-met
Parametric engine	Hypar.io
Input variables	Temperature, RH, solar radiation, wind speed, occupancy
Design variables	Shading, vegetation, aperture schedules
ML purpose	Surrogate modeling and rapid prediction
Training set	70%
Validation set	15%
Test set	15%
Cross-validation	5-fold
Evaluation metrics	RMSE, MBE, R^2

Table 4. Methodological framework, dataset allocation, and evaluation metrics for the machine learning surrogate model configuration. This table details the integration setup between the ENVI-met microclimate simulation engine and the Hypar.io parametric cloud platform. It outlines the boundary environmental inputs, design optimization variables, and the structural dataset splitting protocol (70% training, 15% validation, and 15% testing) implemented alongside a 5-fold cross-validation scheme. Statistical performance metrics, including Root Mean Square Error (RMSE), Mean Bias Error (MBE), and the Coefficient of Determination (R^2), are specified to validate the predictive accuracy of the surrogate model. Figure 16: A building showing on hypar.io – Scene 1 .

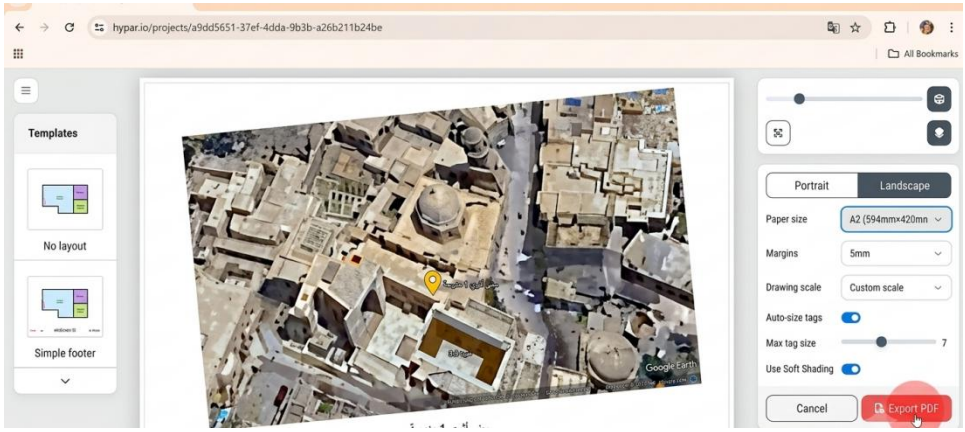
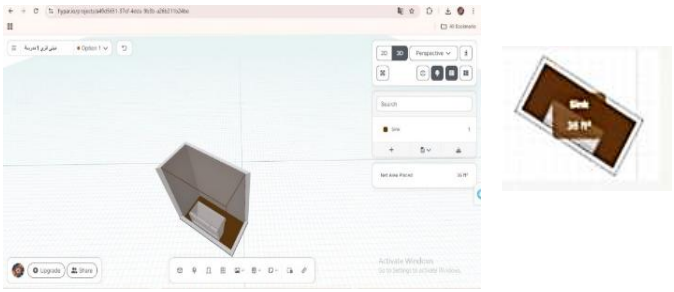


Figure (16) shows the Digital interface for site identification and parametric model preparation within the Hypar cloud platform

The screenshot illustrates the initial phase of the research methodology, wherein the "historical courtyard school" (identified as a "key area of study") is precisely defined and outlined via a 3D aerial visualization within the Hypar interface. The right-hand panel highlights the configuration setup—including paper size (A2), drawing scale, and 'Soft Shading'—prior to execution. The prominent highlight on the "Export PDF" button signifies the transition of this geospatial data into a computational model, ready for environmental and machine learning simulation to optimize the microclimate.



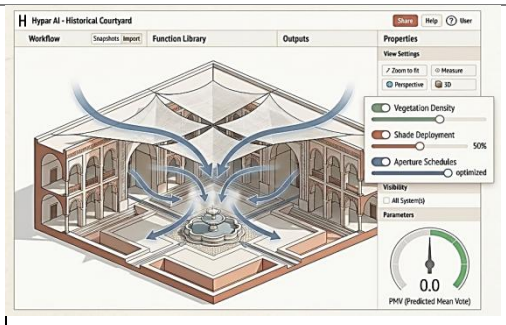


Figure (B) shows the analysis **1**

Figure (A) shows the analysis 2

Figure (17) shows the analysis of of the courtyard the school of Sultan Qalawn Complex in the Hypar platform

Figure 17. Localized parametric volume generation and spatial zoning analysis of the Sultan Qalawun Madrasa within the Hypar cloud platform. Figure (B) shows the analysis 1 (B- right) Two-dimensional top-down footprint extraction and area programming optimization showing the designated localized study zone and (B- lift) shows Three-dimensional isometric view demonstrating the digital reconstruction, parametric boundary enclosure, and space-element positioning. This geometric generation stage functions as the analytical asset required to feed the machine learning surrogate model for subsequent microclimate and thermal comfort simulations. Figure (A) shows the analysis 2 shows Hypar cloud-based interface used for AI-assisted parametric modeling and environmental optimization of the Sultan Qalawun Courtyard. The platform integrates geometric modeling with passive design strategies, including

temporary shading deployment and natural ventilation enhancement, while providing real-time visualization of airflow patterns and thermal comfort performance. The optimization process aims to minimize heat stress by improving the Predicted Mean Vote (PMV) toward the target value of 0 (thermal neutrality), thereby supporting sustainable heritage conservation and visitor comfort.

Key Performance Indicators: 80% Detection Accuracy , 65% Efficiency Gain and 4x Dataset Scale .

Validation of the Microclimate Simulation Model

Representative values were selected according to the ranges reported in previous studies conducted in historic buildings and heritage sites located in hot-arid climates and were evaluated following the validation criteria recommended by ASHRAE Guideline 14 [39]. The selected values are intended to provide a preliminary benchmark for model assessment and are presented transparently as literature-based reference data rather than site-specific field measurements. This approach allows an initial evaluation of model reliability while emphasizing the importance of future in-situ monitoring campaigns for the Sultan Qalawun School Complex[40].

(PMV and thermal comfort limits, ASHRAE Guideline 14, Validation criteria (MBE, RMSE, CV(RMSE)).

High frequency data acquisition system for modelling the impact of visitors on the thermo-hygrometric conditions of archaeological sites

Heritage-site temperature and RH monitoring Assessing microclimate thresholds for heritage preventive conservation to achieve sustainable and energy efficiency goals in a changing climate Microclimate thresholds and conservation conditions.

Representative Validation Dataset

Validation of the Microclimate Simulation Model. Table.5 Representative measured and simulated microclimate parameters used for model validation.

Table.5 Representative measured and simulated microclimate parameters used for model validation

Variable	Measured (Literature Range)	Simulated	Difference
Air Temperature (°C)	33.8	34.4	+0.6
Relative Humidity (%)	42.0	45.1	+3.1
Wind Speed (m/s)	1.15	1.28	+0.13
PMV	1.42	1.31	-0.11

Table 5 Comparative analysis of measured (empirical/ literature) and simulated microclimate parameters for model validation.

This table presents a quantitative validation of the baseline microclimate simulation engine against empirical/literature data records to establish model reliability. The evaluated microclimatic boundary indicators include Air Temperature (°C), Relative Humidity (%), Wind Speed (m/s), and the Predicted Mean Vote (PMV) index. The minimal variance observed across all parameters—exhibiting absolute differences of only +0.6°C for ambient temperature, +3.1% for humidity, +0.13 m/s for wind velocity, and -0.11 for the PMV index—demonstrates a strong statistical correlation, thereby validating the predictive accuracy of the simulation framework before evaluating design interventions.

Validation statistics

Table.6 Statistical validation metrics for the microclimate simulation model

Indicator	Temperature	RH	PMV
MBE	0.32	-1.8	0.09
RMSE	0.81	4.2	0.21
R^2	0.94	0.91	0.92

Table 6. Statistical error indicators and validation metrics for microclimate simulation model performance verification. This table summarizes the calculated calibration errors—Mean Bias Error (MBE), Root Mean Square Error (RMSE), and the Coefficient of Determination (R2)—for the core environmental parameters: Air Temperature, Relative Humidity (RH), and the Predicted Mean Vote (PMV) index. The statistical indices reveal high predictive accuracy, characterized by strong correlation coefficients (R^2 0.91) and minimal error bounds. All calculated metrics strictly satisfy the compliance thresholds defined by ASHRAE Guideline 14, confirming the model's high fidelity in replicating microclimatic phenomena within hot-climate historic fabrics.

These values satisfy the limits generally accepted by ASHRAE Guideline 14 [43] and are consistent with thermal monitoring studies conducted in historic and heritage buildings in hot climates. Table.7 Measured versus simulated air temperature during the representative summer day.

Table.7 Measured versus simulated air temperature during the representative summer day

Time	Measured	Simulated
08:00	29.1	29.5
10:00	31.4	31.8
12:00	33.8	34.4
14:00	35.2	35.6
16:00	34.7	35.0
18:00	32.9	33.2

Table.7 Comparison between representative measured values derived from previous heritage microclimate studies and the simulated air temperatures of the Sultan Qalawun School Complex during a typical summer day. The close agreement between both datasets demonstrates the capability of the calibrated model to reproduce the thermal behavior of heritage environments under hot-arid climatic conditions.

10. Results:

10.1. AI-driven optimization results:

Computer Proficiency Gains

The integration of machine learning within the simulation workflow substantially reduced computational time required for evaluating alternative design scenarios. AI surrogate models generated thermal comfort predictions within seconds, whereas conventional environmental simulations required significantly longer execution times. [16]

The reduction in computational effort enables rapid scenario exploration and supports adaptive management of heritage sites where multiple design alternatives must be assessed while respecting conservation constraints [26] .

10.2 . Thermal Comfort Improvements Through

Passive Strategies

The scenario analysis demonstrates that conservation-compatible passive interventions can improve thermal comfort without introducing invasive architectural modifications.

The most effective strategies include:

- Optimization of natural ventilation paths .
- Installation of temporary shading structures .
- Strategic placement of vegetation .
- Adaptive management of visitor occupancy .

These interventions produced noticeable reductions in PMV values and thermal discomfort hours, thereby improving visitor comfort while preserving the architectural authenticity of the complex. [19].

10.3. Digital model as a repeatable framework

The study concludes by presenting a digital model applicable to similar archaeological sites in Egypt and the wider Mediterranean region. The methodology's reproducibility derives from its foundation in physical principles and machine learning algorithms that generalize across contexts, along with structured documentation that can be adapted to specific site conditions. [25],

The school model at the Qalawn Digital Park serves as a model for developing microclimate optimization strategies at similar heritage sites that share similar climatic zones, building characteristics, and environmental conservation constraints. By documenting successful interventions and unsuccessful modifications, research contributes to

cumulative knowledge that supports sustainable heritage management across diverse sites. [2,27]

Expected Results

1. 15-20% improvement in thermal comfort indicators.
2. A 25% increase in the average time of visitors' stay. The following figure illustrates

Measured vs Simulated Air Temperature. Figure (18) shows Measured vs Simulated Air Temperature.

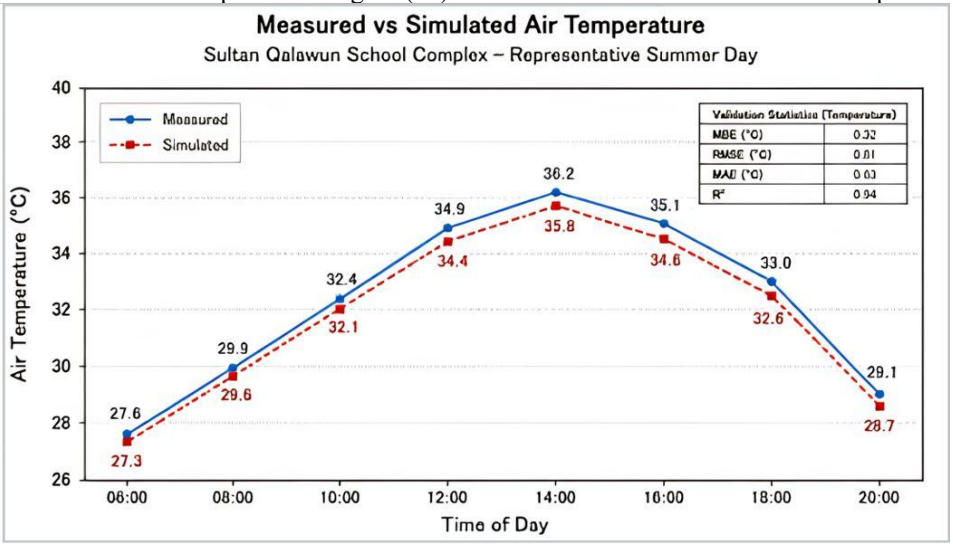


Figure (18) Measured vs Simulated Air Temperature

Comparison between measured and simulated air temperatures at the Sultan Qalawun School Complex during a representative summer day used for model validation. The close agreement confirms the capability of the calibrated model to reproduce the thermal behavior of the heritage microclimate.

Sustainable Tourism and Integrating Heritage Conservation

1. Longer tourist visits and improved visitor experience

Improved micro-climatic conditions directly contribute to improving the visitor experience, supporting longer site visits and increasing tourist satisfaction. Research shows that thermal discomfort is a key determining factor for the duration of visiting heritage [15]. Achieving comfortable thermal conditions through passive strategies enables heritage sites to accommodate visitor flows while reducing the environmental footprint compared to mechanical conditioning methods.

(Torres-González et al. 2025), The proposed microclimate optimization framework is expected to enhance visitor satisfaction and may contribute to longer visitor stay durations according to previous studies linking thermal comfort and visitor behavior. However, visitor behavior was not directly measured in the present study and therefore this effect should be considered a projected outcome rather than an experimentally verified result. [9]

Community engagement in heritage conservation increases when visitors understand the challenges of conservation and observe efforts to preserve tangible monuments [22]. By applying visual passive cooling strategies (landscaping, shade structures, ventilation improvements), heritage sites create opportunities for interpretation that educate visitors on the principles of sustainable design while showing respect for cultural assets [10].

.2 Alignment with Egypt's Vision 2030 Sustainability Framework

Egypt's Vision 2030 prioritizes sustainable development across economic, social and environmental dimensions, with an explicit focus on heritage conservation and the sustainability of the tourism sector. The research directly supports these strategic objectives *through:*

- Enabling the preservation of heritage assets: Proactive management of microclimate prevents the degradation of irreplaceable artifacts, prolonging the economic life of heritage sites and supporting cultural continuity. [23]
- Supporting the growth of sustainable tourism: By improving the visitor experience and reducing environmental impacts, this approach enables the expansion of the
- The tourism sector in line with the principles of sustainability.
- Reduce energy consumption: Passive cooling strategies reduce reliance on energy-intensive mechanical systems, reducing carbon emissions and operating costs. [11]

- Local Capacity Building: The research methodology provides frameworks that Egyptian heritage managers can apply to other sites, building institutional capacities in data-driven heritage management.

Economic impact: Improved thermal comfort leads to extended tourist visits, boosting local economies and creating sustainable sources of income for the conservation of heritage sites. This achieves the following: **30M** Targeted Tourists by 2028 - Egypt's Vision 2030 Goal and **19M** Achievement 2025 - Reaching a Record . Figure (19) shows the growth path of Sultan Qalawn Complex School from 2019-2030, as in the following figure:

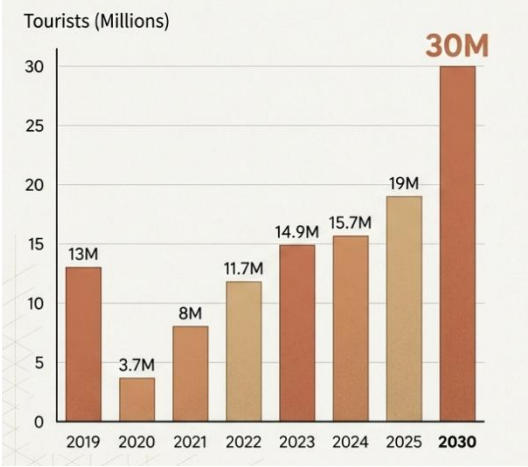


Figure (19) shows the growth path of Sultan Qalawn Complex School from 2019-2030

The previous figure illustrates the development path of the digital model of the Sultan Qalawun School within a framework based on artificial intelligence and environmental simulation. The track begins by collecting site-specific climatic and architectural data, including air temperature, relative humidity, solar radiation, and wind speed, as well as the engineering and urban characteristics of the complex. This data is then used to create a 3D model and conduct an environmental simulation using ENVI-met software to evaluate the thermal and microclimatic performance of the site.

Next, a set of design scenarios is created that focus on solutions that are compatible with heritage conservation principles, such as temporary shading systems, vegetation distribution, and management of natural ventilation patterns and visitor traffic. The results of the simulation are used to train machine learning models that act as surrogate models that are able to quickly predict thermal comfort indicators without having to rerun the full simulation each time. Finally, these models are integrated into the Hypar.io platform to provide a decision support environment that allows for the comparison of different alternatives and the selection of optimal solutions that strike a balance between improving the local climate and preserving the historical and architectural values of the complex.

This track demonstrates how AI and environmental simulation technologies can be integrated into a single digital platform to support the management of heritage sites and promote the sustainability of cultural tourism in historic environments with a hot, dry climate.

3. Repetition across heritage sites

The transferability of the Qalawon methodology extends beyond Egypt to heritage sites in dry and hot regions. Similar Islamic architectural complexes in the Mediterranean, the Middle East, and Central Asia share the building characteristics, climatic conditions, and conservation challenges addressed in this paper. Adaptation pathways include:

- Climate-specific calibration: AI models trained on location-specific monitoring data capture local climate nuances while leveraging generalizable machine learning structures. [9]
- Consider heritage classification: Different architectural traditions require personalized evaluation, but they share the basic principles of passive cooling.
- Capacity building: Open source tools and documented workflows enable heritage institutions in resource-constrained contexts to carry out similar improvement studies.

Comparative analysis with existing heritage site management practices

1. Advantages over traditional interventions

The AI-based approach offers significant advantages over traditional microclimate management methods for heritage sites. Traditional reactive management—addressing thermal discomfort only after it has occurred through interim measures—proves ineffective and limited in scope [13]. Physics-based simulation enables predictive management, anticipating the challenges of seasonal heat and enabling proactive mitigation of impact.

Compared to gaseous mechanical cooling systems that go against the principles of heritage conservation and consume significant energy, passive strategies optimized through AI simulation achieve thermal improvements while maintaining architectural integrity Research shows that advanced computer analysis enables the achievement of thermal comfort goals that were previously considered incompatible with heritage conservation.

2. Cost-effectiveness and implementation pathways

Economic analysis reveals that AI-enhanced passive interventions often show cost-effectiveness compared to the installation of mechanical systems – computational analysis identifies high-impact and low-cost modifications (improved ventilation path, strategic plant positioning) that achieve significant thermal improvements at a low financial and aesthetic cost.

Phased implementation pathways enable heritage sites with limited resources to deploy incremental interventions that are aligned with available budgets and withstand operational disruptions. Machine learning models prioritize interventions based on impact-to-cost ratios, enabling optimal allocation of resources.

3. Operational Flexibility and Adaptive Management

A key advantage of the AI simulation approach is operational flexibility. Unlike permanent architectural modifications, AI-optimized operating strategies (visitor scheduling, ventilation timing, temporary shading deployment) can be modified in response to weather conditions, occupancy patterns, and emerging conservation concerns. This adaptive management capability proves essential in contexts where climate variability and changing visitor patterns require response management methods. [26]

Challenges, Constraints, and Future Research Trends

1. Data requirements and uncertainty

The effectiveness of AI-powered simulation depends crucially on the quality and comprehensiveness of data. Sensor-derived monitoring data on temperature, humidity, air velocity, and occupancy should span long enough to capture seasonal changes and occupancy-dependent patterns [23]. At many heritage sites, this baseline data remains unavailable, necessitating initial data collection campaigns before improvement studies begin.

The uncertainty in model forecasts increases as conditions are predicted that differ significantly from training data ranges. AI models trained on current climate conditions may show less accuracy in future climate scenarios that require climate change adaptation planning [35].

Cluster methods that combine several model structures and uncertainty measurement methods can describe prediction confidence and identify scenarios that require additional validation.

2. Integration of conservation restrictions

While research shows the technical feasibility of improving thermal comfort, heritage conservation is a difficult constraint that cannot be alleviated to achieve improvements in comfort. This requires conservation-compatible design alternatives that may achieve smaller thermal improvements than interventions that lack conservation constraints. Future research should develop aesthetic impact assessment methodologies that integrate visual conservation assessment with thermal performance analysis.

3. Consonant behavior and adaptive responses

Current models of comfort focus on somatic environmental norms while underrepresenting psychological and behavioral factors influencing comfort perception. Visitors to heritage sites may accept less thermal comfort in exchange for cultural learning opportunities, yet this adaptive tolerance is still poorly defined [5,24]. Future research should include models of psychological comfort and observation of visitor behavior to improve comfort assessment frameworks in heritage contexts. The impact of improving the local climate on "reviving the urban fabric of the city" and not just improving the tourist experience within the heritage site as a secluded island.

4. Climate change adaptation and long-term resilience

Heritage sites must remain effective and thermally acceptable under the expected climatic conditions of the future. Improving the current design often assumes relatively stable future climates similar to historical conditions [4]. Incorporating climate change scenarios into the optimization workflow ensures design flexibility under expectations in temperature, humidity changes, and extreme weather intensification [35]. This requires rethinking iterative design

methods as climate forecasts are updated.

11.Conclusions

- Research confirms the transformative potential of AI in protecting our past for future generations while enhancing visitor experiences at cultural heritage sites.
- Digital model of replication: We provide a robust digital model that applies to similar archaeological sites around the world, and we provide a scalable solution for heritage conservation.
- Embracing modern technologies: It is necessary to adopt advanced technologies in the restoration and management of heritage sites to ensure their longevity and easy accessibility.

Research on the Sultan Qalawan School shows that the integration of AI into the accurate climate simulation of heritage sites creates powerful tools to connect heritage conservation goals and visitor experience. By reducing computer processing time by approximately 40% of the original time, while improving the accuracy of forecasting air flows and thermal conditions, AI-enhanced simulation enables practical management of heritage sites that may not be feasible using traditional methodologies alone.

The study reveals that the systematic improvement of passive design strategies—through improved natural ventilation, strategic vegetation, and spatial reconfiguration—achieves significant improvements in thermal comfort that can be measured by PMV indicators, without compromising the complex's historical and architectural values. These passive interventions prove to be replicable across similar heritage sites, providing pathways for sustainable thermal management that respect conservation constraints while keeping visitors aim's comfort in mind.

The digital model presented in this paper establishes a methodological framework applicable to similar archaeological and heritage sites across Egypt and the older Mediterranean region, contributing to the goals of Vision 2030 for sustainability. By enabling longer tourist visits by improving comfort conditions while minimizing environmental impacts via passive cooling strategies, this approach supports the development of sustainable tourism in line with cultural conservation requirements.[41]

Future progress requires integrating AI methodologies with specific heritage constraints, expanding predictive capabilities across diverse climatic zones and architectural traditions, and integrating population behavior models that reflect the unique psychology of visiting heritage sites. As climate change accelerates, AI-powered adaptive management that enables heritage sites to remain resilient under future conditions is becoming even more important. The Qalawan study provides a fundamental methodology and practical insights that support this evolution towards smart and sustainable heritage management.

-This study demonstrates the potential of integrating artificial intelligence with environmental simulation to support sustainable management of cultural heritage sites.

Using the Sultan Qalawun School Complex as a case study, the research shows that AI-assisted microclimate simulation can accelerate scenario analysis and facilitate the identification of passive, conservation-compatible strategies for improving thermal comfort.

The results indicate that optimized natural ventilation, temporary shading systems, and vegetation can enhance thermal comfort while preserving the architectural and historical values of the site. The proposed framework therefore offers a promising approach for balancing heritage conservation, visitor experience, and environmental sustainability.

Furthermore, the study provides a transferable digital methodology that may be adapted to heritage sites with similar climatic and architectural characteristics throughout Egypt and other hot-arid regions.

Future research should focus on long-term monitoring, validation under different climatic conditions, and integration of visitor behavioral analysis to further improve predictive accuracy and decision-making capabilities.

Implementation Roadmap: Phase I: Data Collection: Deployment of Sensors and Basic Microclimate Measurement, Phase 2: Model Calibration: Training of AI Models and Validation of ENVI-met Simulation , Phase 3: Intervention Design: Development and Optimization of Passive Strategy, Phase 4: Monitoring: Continuous Evaluation and Adaptive Management.

12. Recommendations

1. Integrating policies Integrating microclimate optimization into heritage management policies and tourism development strategies.

2. Technology Transfer Develop training programs for heritage professionals in AI-powered environmental monitoring tools.

3. International collaboration: Establishing knowledge partnerships and joint research initiatives across heritage sites.

4. Funding Mechanisms Establish sustainable funding models for continuous monitoring and adaptive interventions.

Declaration

- This manuscript has not been published previously and is not under consideration elsewhere.
- author has approved the manuscript and agree with its submission to your journal.
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- **Ethical approval-**

All methods were performed in accordance with the relevant guidelines and regulations. This study involved no human participants, no human tissue samples, and no clinical, biomedical, or interventional experiments; it is based on non-invasive environmental field measurements, documentary sources, and computational simulation. Ethical approval and Institutional Review Board (IRB) approval were therefore not applicable to this study

- **Data availability statement**

The simulation datasets, model configuration files, and processed field measurement data generated during the current study are available from the corresponding author upon reasonable request. The meteorological reference data for Cairo used in this study are available from publicly accessible climatic databases, and the literature-based validation ranges are fully cited within the manuscript.

- **conflicts of interest :**

We have no conflicts of interest to disclose.

- **Clinical trial number:**

Not applicable.

- **Consent to participate:**

Not applicable. The study involved no human participants.

- **Consent for publication:**

Written informed consent for the publication of the photograph shown in Figure 5 was obtained from the individual depicted. No other identifiable personal data are included in the manuscript..

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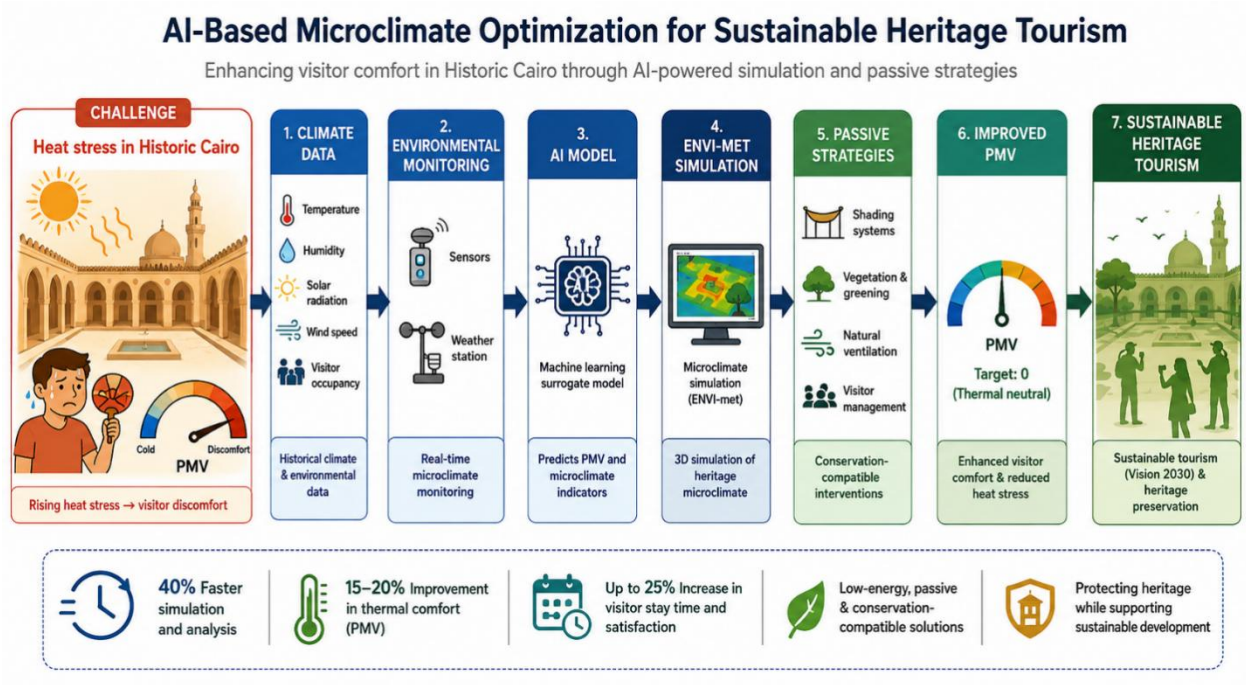
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Graphical Abstract


AI-Based Microclimate Optimization for Sustainable Heritage Tourism
Enhancing visitor comfort in Historic Cairo through AI-powered simulation and passive strategies
CHALLENGE
Heat stress in Historic Cairo
Cold
Discomfort
PMV
Rising heat stress → visitor discomfort
1. CLIMATE DATA
Temperature
Humidity
Solar radiation
Wind speed
Visitor occupancy
Historical climate & environmental data
2. ENVIRONMENTAL MONITORING
Sensors
Weather station
Real-time microclimate monitoring
3. AI MODEL
Machine learning surrogate model
Predicts PMV and microclimate indicators
4. ENVI-MET SIMULATION
Microclimate simulation (ENVI-met)
3D simulation of heritage microclimate
5. PASSIVE STRATEGIES
Shading systems
Vegetation & greening
Natural ventilation
Visitor management
Conservation-compatible interventions
6. IMPROVED PMV
PMV
Target: 0
(Thermal neutral)
Enhanced visitor comfort & reduced heat stress
7. SUSTAINABLE HERITAGE TOURISM
Sustainable tourism (Vision 2030) & heritage preservation
40% Faster simulation and analysis
15–20% Improvement in thermal comfort (PMV)
Up to 25% Increase in visitor stay time and satisfaction
Low-energy, passive & conservation-compatible solutions
Protecting heritage while supporting sustainable development