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Enhancing Sustainable Environmental Resilience Adjacent to Natural Lakes through Smart Technologies

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Article

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Enhancing Sustainable Environmental Resilience Adjacent to Natural Lakes through Smart Technologies

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ABSTRACT:

The swift proliferation of ecologically sensitive tourism sites necessitates architectural design methodologies that concurrently elevate environmental efficacy, safeguard local heritage, and mitigate operational impacts. This research explores the potential of artificial intelligence (AI)-enhanced environmental simulation, harmonized with regional architectural principles, to advance the sustainability of an envisioned environmental visitor center situated on the southern coast of Lake Qaroun, Fayoum, Egypt. A workflow grounded in Building Information Modeling (BIM) was developed utilizing Autodesk Revit 2025, Revit Insight, DesignBuilder (EnergyPlus), Hypar, and computational fluid dynamics (CFD) simulations. Environmental assessments employed the Fayoum Typical Meteorological Year (TMY)/EnergyPlus Weather (EPW) climate dataset to scrutinize annual energy requirements, thermal comfort levels, daylight accessibility, solar exposure, and natural ventilation. Passive architectural techniques, such as optimized building orientation, external shading elements, courtyards, locally sourced construction materials, and photovoltaic system integration, were incorporated into the design and evaluated through iterative simulation and optimization processes. The refined design realized a 23.2% decrease in annual energy usage and a 24.1% decrease in annual carbon emissions compared to the baseline model, all while significantly enhancing indoor thermal comfort and illumination performance. Sensitivity analysis illustrated that these enhancements remained consistent even with fluctuations in occupancy, infiltration rates,

operational thresholds, and climatic factors, thus confirming the resilience of the proposed design framework. A self-assessment during the design phase, employing the Green Pyramid Rating System (GPRS), produced an estimated score of 65 points out of a possible 100, indicating a forecasted Silver performance standard. The results underscore that the amalgamation of AI-driven environmental simulation with climate-responsive local architecture establishes a dependable framework for the creation of environmentally sustainable visitor facilities in protected natural settings, providing a pragmatic approach to fostering sustainable tourism development and eco-friendly building practices in Egypt and similar arid environments.

Keywords:

Artificial Intelligence ,Building Performance Simulation, Sustainable Tourism ,Passive Design Strategies . Building Information Modeling (BIM) , Green Pyramid Rating System (GPRS), Environmental Resilience, Fayoum, Egypt·

Introduction

The rapid growth of tourism has significantly contributed to economic development and cultural exchange worldwide; however, it has also intensified pressure on environmentally sensitive ecosystems and protected natural areas (Buhalis et al. 2023; Wahba 2021) . Visitor centers, as essential components of ecotourism infrastructure, play a vital role in facilitating environmental education, visitor management, and conservation awareness (Gfeller 2013; Soltanifard and Amani-Beni 2025). Nevertheless, these facilities frequently consume substantial amounts of energy and natural resources throughout their operational life cycle, particularly in regions characterized by hot-arid climatic conditions. Consequently, improving the environmental performance of tourism-related buildings has become a fundamental objective for achieving the United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy), Goal 11 (Sustainable

Cities and Communities), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action). Sustainable architectural design is therefore increasingly recognized as an effective strategy for reducing environmental impacts while preserving the ecological integrity of sensitive landscapes (Kotb et al. 2024),.

Climate-responsive architecture has emerged as one of the most effective approaches for minimizing building energy demand while improving indoor environmental quality. Rather than relying primarily on mechanical systems, climate-responsive buildings employ passive design strategies that adapt architectural form, orientation, building envelope characteristics, natural ventilation, daylight utilization, and material selection to local climatic conditions. Previous studies have demonstrated that integrating passive environmental strategies during the early stages of architectural design can substantially reduce operational energy consumption, improve thermal comfort, and decrease greenhouse gas emissions while enhancing occupant well-being. These benefits are particularly important in Egypt, where cooling energy represents a major component of total building energy consumption due to prolonged periods of high ambient temperatures and intense solar radiation (Moghaieb 2019).

Egypt possesses exceptional cultural and natural heritage resources that support a rapidly expanding tourism sector. Among these destinations, Lake Qaroun, located in Fayoum Governorate, represents one of the country's most valuable protected landscapes because of its ecological diversity, geological significance, archaeological heritage, and recreational importance(Dadizadeh and Doğan 2024). The lake attracts large numbers of visitors annually owing to its internationally recognized biodiversity, migratory bird habitats, desert landscapes, and proximity to important archaeological sites. However, the increasing demand for tourism facilities has raised concerns regarding environmental degradation, excessive energy consumption, visual impacts on the natural landscape, and the long-term sustainability of infrastructure development. These challenges

necessitate architectural solutions capable of balancing environmental conservation with visitor comfort and functional performance(Khare et al. 2023).

Traditional architecture in Fayoum offers valuable lessons for environmentally responsive building design. Vernacular settlements developed over centuries through careful adaptation to local climatic conditions using passive cooling techniques, thick masonry walls, internal courtyards, shaded walkways, wind catchers, locally available limestone and mud-brick materials, and compact urban forms. These design principles reduce solar heat gain, enhance natural ventilation, and improve thermal comfort with minimal dependence on mechanical cooling systems. Despite their proven environmental effectiveness, such principles are frequently underutilized in contemporary public buildings, where modern construction practices often prioritize technological solutions over climate-responsive architectural design. Integrating traditional environmental knowledge with contemporary digital technologies provides an opportunity to develop buildings that simultaneously respect local identity and achieve high levels of environmental performance(Egwabor et al. 2024).

Recent advances in Artificial Intelligence (AI) and Building Information Modeling (BIM) have transformed sustainable building design by enabling architects and engineers to evaluate multiple design alternatives rapidly and objectively. AI-assisted simulation platforms can predict building performance under different environmental conditions, optimize passive design parameters, and support evidence-based decision-making during the conceptual design stage. Combined with BIM, AI techniques facilitate integrated analyses of energy performance, daylight availability, solar radiation, airflow, and thermal comfort within a unified digital environment. Environmental simulation tools such as Autodesk Revit Insight, DesignBuilder (EnergyPlus), Hypar, and Computational Fluid Dynamics (CFD) provide increasingly sophisticated capabilities for assessing

the environmental consequences of architectural decisions before construction, thereby reducing design uncertainty and improving sustainability outcomes(Egwabor et al. 2024).

Building performance simulation has become an essential component of sustainable architectural practice because it enables quantitative assessment of alternative design strategies under realistic climatic conditions. Energy simulation predicts annual building energy consumption and carbon emissions, while daylight simulations evaluate visual comfort and natural lighting availability. CFD analyses further examine indoor and outdoor airflow patterns, supporting natural ventilation design and thermal comfort improvement. When these simulation techniques are integrated within an iterative optimization workflow, designers can identify solutions that balance environmental performance, occupant comfort, and architectural functionality. Such digital approaches are particularly valuable for projects located in environmentally sensitive areas, where minimizing ecological impacts is a primary design objective(Onweh et al. 2025).

Alongside simulation-based design, green building assessment systems provide structured frameworks for evaluating sustainability performance. Egypt's Green Pyramid Rating System (GPRS) establishes nationally appropriate sustainability criteria addressing site planning, energy efficiency, water conservation (Kotb et al. 2024), materials, indoor environmental quality, and innovation. Unlike many international rating systems, GPRS considers Egypt's climatic, environmental, and socio-economic conditions, making it particularly suitable for evaluating sustainable building projects within the country (Yasmin Bassiony & others et al. 2021). Although GPRS has been applied to various building types, relatively few studies have investigated its integration with AI-assisted environmental simulation during the conceptual design phase. Consequently, opportunities remain to develop design methodologies that simultaneously optimize environmental performance and facilitate compliance with national sustainability assessment criteria.

Although previous research has demonstrated the benefits of passive architectural design, BIM-based simulation, and AI-supported optimization individually, important gaps remain in the existing literature. First, relatively few investigations integrate AI-assisted environmental simulation, Building Information Modeling, CFD analysis, and national sustainability assessment frameworks within a unified design methodology for visitor centers located in environmentally protected landscapes. Second, most previous studies emphasize either energy efficiency or thermal comfort independently, while comparatively limited attention has been devoted to simultaneously evaluating energy consumption, carbon emissions, daylight performance, natural ventilation, and sustainability certification during the conceptual design process. Third, there is a noticeable lack of research focusing on environmentally responsive visitor centers in Egypt, particularly within the unique climatic and ecological context of Lake Qaroun. Finally, existing studies rarely combine vernacular architectural principles with advanced digital simulation techniques to develop sustainable public buildings adapted to local environmental conditions.

To address these gaps, this research proposes an integrated design framework that combines AI-assisted environmental simulation, Building Information Modeling, passive architectural strategies, and the Green Pyramid Rating System (GPRS) to optimize the environmental performance of a proposed visitor center at Lake Qaroun, Fayoum. The study evaluates alternative design solutions using Autodesk Revit 2025, Revit Insight, DesignBuilder, Hypar, and CFD simulations based on the Typical Meteorological Year (TMY)/EnergyPlus Weather (EPW) climate dataset representing Fayoum. The proposed framework investigates how passive environmental design strategies—including optimized building orientation, external shading devices, courtyards, local construction materials, natural ventilation, and photovoltaic integration—can reduce energy demand while enhancing occupant comfort and environmental sustainability.

The primary aim of this study is to develop and evaluate an AI-assisted environmental design methodology capable of improving the sustainability performance of an environmental visitor center within the ecologically sensitive landscape of Lake Qaroun. Specifically, the research seeks to (i) assess the influence of passive architectural strategies on energy consumption, daylight availability, thermal comfort, and airflow performance; (ii) evaluate the effectiveness of integrating AI-assisted simulation tools within the architectural design process; and (iii) examine the anticipated sustainability performance of the proposed design using the Green Pyramid Rating System.

Accordingly, the study addresses the following research questions:

- How can AI-assisted environmental simulation improve the sustainability performance of a visitor center located in a protected natural area?
- Which passive architectural strategies provide the greatest improvements in energy efficiency, thermal comfort, and daylight performance under the climatic conditions of Fayoum?
- To what extent can integrating BIM-based environmental simulation with the Green Pyramid Rating System support sustainable architectural decision-making during the conceptual design stage?

Based on these questions, the research hypothesizes that integrating AI-assisted environmental simulation, BIM-based performance analysis, and climate-responsive architectural design will significantly improve building environmental performance while supporting compliance with national sustainability assessment criteria. It is expected that the proposed design methodology will reduce annual operational energy consumption and associated carbon emissions, improve indoor environmental quality, and achieve a predicted Silver performance level under the Green Pyramid Rating System.

The significance of this study extends beyond the proposed Lake Qaroun Visitor Center by demonstrating a practical framework for integrating digital environmental simulation with climate-responsive architectural design and national sustainability assessment. The proposed methodology contributes to sustainable tourism development by providing architects, engineers, and decision-makers with a systematic approach for designing environmentally efficient public buildings adapted to Egypt's climatic conditions. Furthermore, the research supports the broader transition toward intelligent, performance-driven architectural design capable of reducing environmental impacts while preserving the ecological and cultural values of protected natural landscapes.

- **Research Problem**

Despite the increasing emphasis on sustainable tourism and environmental conservation in Egypt ("Sustainable Tourism in Protected Areas: Guidelines for Planning and Management - Paul F. J. Eagles, Stephen F. McCool, Christopher D. Haynes, United Nations Environment Programme, World Tourism Organization - Google Books" n.d.), the architectural design of visitor facilities within protected natural areas continues to rely largely on conventional design approaches that insufficiently address environmental resilience and operational sustainability.(Chitt et al. 2024a)

Although traditional Fayoum architecture provides effective passive climatic strategies(Manshour and Lehmann 2026a), these principles are rarely integrated with contemporary artificial intelligence-based environmental simulation tools during the design process (Almusaed and Yitmen 2023).

Furthermore, limited research has evaluated the environmental performance of tourism facilities in protected areas using Egypt's national sustainability assessment framework, namely the Green Pyramid Rating System (GPRS) . Consequently (Hanna 2015), there remains a significant gap in

developing integrated design methodologies capable of simultaneously preserving local architectural identity, improving environmental performance, and supporting sustainable tourism development (Mohamed Abdelhaleem 2024a).

Research Aim

The aim of this research is to develop and evaluate an environmentally resilient architectural design framework for a visitor and environmental education center located adjacent to Lake Qaroun by integrating traditional Fayoum architectural principles with artificial intelligence-assisted environmental simulation tools. The study further aims to assess the environmental performance of the proposed design using the Egyptian Green Pyramid Rating System (GPRS) to demonstrate its contribution to sustainable tourism, energy efficiency, and climate-responsive architecture.

Research Hypothesis

This research hypothesizes that integrating traditional climate-responsive architectural strategies with artificial intelligence-driven environmental simulation during the early design stages significantly enhances the environmental performance of visitor facilities located in protected natural areas. Such integration is expected to reduce energy consumption and carbon emissions, improve indoor environmental quality and thermal comfort, increase resource efficiency, and achieve higher sustainability ratings according to the Egyptian Green Pyramid Rating System while preserving the local architectural identity.

Research Questions

The study addresses the following research questions:

- How can traditional Fayoum architectural principles contribute to improving environmental resilience in visitor facilities located within protected natural areas?
- To what extent can artificial intelligence-assisted environmental simulation improve the environmental performance of the proposed architectural design?
- How effective is the integration of traditional architectural strategies with digital simulation tools in reducing energy consumption and enhancing indoor environmental quality?
- Can the proposed architectural model satisfy the sustainability requirements of the Egyptian Green Pyramid Rating System (GPRS)?
- How can this integrated design methodology support sustainable tourism development and environmental conservation within protected areas in Egypt?

Literature Review

- Sustainable Environmental Resilience in Protected Natural Areas

Protected natural landscapes require architectural interventions that simultaneously preserve ecological integrity and support sustainable tourism development(Kilichov et al. 2026). Recent studies indicate that environmentally responsive architecture can reduce ecological disturbance while improving visitor experience through passive environmental design, efficient resource management, and climate-sensitive planning (Mostafa et al. 2022). Rather than relying solely on technological solutions, resilient design increasingly integrates local environmental characteristics, ecosystem conservation, and long-term adaptability to climate change. Within environmentally sensitive areas, architectural decisions should therefore balance environmental protection with functional requirements to ensure sustainable development without compromising biodiversity or landscape value.

- Local Architectural Heritage as a Climate-Responsive Design Strategy

Traditional architecture in arid regions represents accumulated environmental knowledge developed through centuries of adaptation to local climatic conditions. Architectural elements including thick earthen walls, internal courtyards(Callejas et al. 2020), shaded transitional spaces, vaulted roofs, and controlled natural ventilation significantly reduce indoor heat gain while improving thermal comfort. Contemporary sustainable architecture increasingly recognizes that these passive strategies remain highly effective when integrated with modern construction technologies. In regions such as Fayoum, preserving architectural identity while incorporating traditional environmental principles offers an opportunity to improve building performance and reinforce cultural sustainability simultaneously.

- Artificial Intelligence and Building Performance Simulation

Artificial intelligence has emerged as an effective decision-support tool throughout the architectural design process. AI-assisted environmental simulation enables designers to evaluate numerous design alternatives rapidly by predicting building energy consumption(Markarian et al. 2024a), daylight availability, thermal comfort, and carbon emissions before construction. Recent research demonstrates that combining Building Information Modeling (BIM) with simulation engines improves design optimization by facilitating data-driven decision making. Rather than replacing architectural expertise, artificial intelligence enhances designers' ability to identify environmentally efficient solutions through iterative simulation and performance evaluation(Markarian et al. 2024b).

- Green Building Assessment Systems and Research Gap

Green building assessment frameworks provide measurable indicators for evaluating environmental performance throughout the building life cycle. While international systems such as LEED and BREEAM are widely applied, locally adapted frameworks are often more suitable because they incorporate regional climatic conditions, construction practices, and national sustainability

priorities(Frasca et al. 2024). The Egyptian Green Pyramid Rating System (GPRS) represents Egypt's official sustainability assessment framework and offers evaluation criteria that better reflect local environmental conditions(Hanna 2015).

Although previous studies have investigated sustainable architecture, passive environmental design, AI-assisted building simulation, and green building certification independently, limited research has integrated these components within environmentally protected tourism facilities in Egypt(Buhalis et al. 2023). Furthermore, few studies have combined traditional architectural principles with artificial intelligence-based environmental simulation while evaluating building performance using the Egyptian Green Pyramid Rating System. This research addresses this gap by proposing an integrated framework that combines local architectural heritage, AI-driven environmental simulation, and GPRS-based sustainability assessment for the design of an environmentally resilient visitor center at Lake Qaroun (Ali et al. 2024).

Research Methodology

The research adopted a holistic, multi-stage methodology that combines theoretical analysis, field study, numerical modeling, and quantitative evaluation. The work was divided into five main interrelated phases, as follows:

- Theoretical Review and Local Context: Scientific information was collected on the concepts of sustainable resilient architecture and environmental assessment frameworks, with a focus on the Egyptian Green Pyramid system and similar experiences in integrating local architecture with sustainable design. The review also included studies on the history of traditional architecture in Fayoum and its climatic styles, with the aim of developing context-appropriate design determinants.

- Data collection and site analysis: Climatic boundary conditions were established using the Typical Meteorological Year (TMY/EPW) weather file representing the Lake Qaroun–Fayoum region (Latitude 29.47° N, Longitude 30.67° E). The EPW dataset provided hourly records of dry-bulb temperature, relative humidity, wind speed, wind direction, solar radiation, and sky conditions .The environmental performance analyses were conducted using Autodesk Revit Insight 2025, DesignBuilder (EnergyPlus), and Computational Fluid Dynamics (CFD) simulations based on the Fayoum EnergyPlus Weather (EPW) / Typical Meteorological Year (TMY) climate dataset. The location-specific climatic inputs were consistently applied throughout the simulation workflow to evaluate annual energy consumption, indoor thermal comfort, daylight availability, and natural ventilation performance under the environmental conditions of the Lake Qaroun region.

All environmental simulations were performed using the EnergyPlus Weather (EPW) / Typical Meteorological Year (TMY) climate file representing Fayoum Governorate, Egypt, which corresponds to the geographical setting of the proposed Lake Qaroun Environmental Visitor Center. The weather dataset (Africa: WMO Region 1 – Egypt . Al Minya (ETMY)) includes hourly records of dry-bulb temperature, relative humidity, solar radiation, wind speed, and wind direction, providing representative long-term climatic conditions for building performance analysis. This location-specific weather file was consistently applied in Autodesk Revit Insight 2025, DesignBuilder, and Computational Fluid Dynamics (CFD) simulations to ensure that the predicted energy performance, thermal comfort, daylight availability, and natural ventilation accurately reflect the environmental conditions of the study area.

Solar Simulation Configuration: Solar radiation analyses were conducted using the Hypar platform after defining the geographical location of the proposed visitor center at Lake Qaroun,

Fayoum Governorate, Egypt (29.47° N, 30.67° E). The updated location parameters were used to accurately represent the site's solar geometry and annual sun path. The simulations considered the local climatic conditions and building orientation to evaluate incident solar radiation and shading performance throughout the year. The revised analyses provide a location-specific assessment that supports the optimization of passive environmental design strategies.

- Digital Modeling and Smart Simulation: A 3D architectural model of the proposed center was built using the Autodesk Revit 2025 software, including all the necessary architectural and environmental details. The model was then linked to the Insight cloud tool to perform energy performance analysis and thermal simulation using artificial intelligence techniques. Several rounds of simulations were conducted to generate optimized design scenarios. (in natural ventilation, shading, building materials) with the aim of reducing energy consumption and improving indoor thermal comfort. In addition, in order to increase the reliability of the results, the model was imported into DesignBuilder software based on the EnergyPlus engine for further detailed analysis and confirmation of Revit results(ALBaz et al. 2023). The Rhino/Grasshopper platform was also used with Ladybug Tools components to perform advanced climate analyses (e.g., wind rose and sun path) and verify the compatibility of the design with climate data throughout the year(Michailidis et al. 2025).
- Climate Data and Simulation Configuration

To ensure that the environmental analyses accurately represent the climatic conditions of the study area, all simulations were performed using the Typical Meteorological Year (TMY)/EnergyPlus Weather (EPW) dataset corresponding to Fayoum Governorate, Egypt, where the proposed Lake Qaroun Environmental Visitor Center is located. The weather file contains hourly records of dry-bulb temperature, relative humidity, global horizontal solar radiation, direct

normal solar radiation, wind speed, and wind direction representative of long-term climatic conditions. This climate dataset was consistently used in Autodesk Revit Insight 2025, DesignBuilder (EnergyPlus), and CFD simulations to evaluate annual energy demand, thermal comfort, solar performance, daylight availability, and natural ventilation.

- GPRS evaluation: Based on the simulation outputs, design performance was evaluated in six areas according to the Green Pyramid Manual (Third Edition, 2024) (Mohamed Abdelhaleem 2024b). This included assessing energy efficiency, water use efficiency, indoor environmental quality, situ sustainability, material and resource efficiency, and innovation elements. Each area was awarded an achievement rating based on the extent to which the criteria of the manual were achieved, and the technical justifications for each ratio (e.g., the amount of energy consumption reduction achieved, or the water saving techniques applied)(Hafez et al. 2023).
- Analysis and comparison: The environmental performance results of the traditional baseline model (baseline) were compared with the results of the improved model after the introduction of smart simulation recommendations. Differences in key indicators (energy consumption, thermal comfort rates, carbon emissions, ... etc.) as detailed in the results section. The implications of these differences at the applied level were also discussed (e.g., what does a 24.1% reduction in annual carbon emissions in consumption mean for the nature and costs of a building?). Based on this, conclusions were formulated on the feasibility of applying the smart methodology in similar projects, and a set of recommendations were prepared for practitioners and decision-makers to improve sustainable design policies in nature reserves.

The climatic characteristics of the study area were evaluated using the EPW weather file corresponding to the Lake Qaroun region in Fayoum Governorate. The climate is classified as hot-arid, with high summer temperatures, mild winters, strong solar radiation throughout the year, and predominantly northwestern winds. These climatic parameters formed the basis for all environmental simulations and guided decisions regarding building orientation, shading design, natural ventilation, and envelope optimization. Figure 1 Outline of the research methodology used.

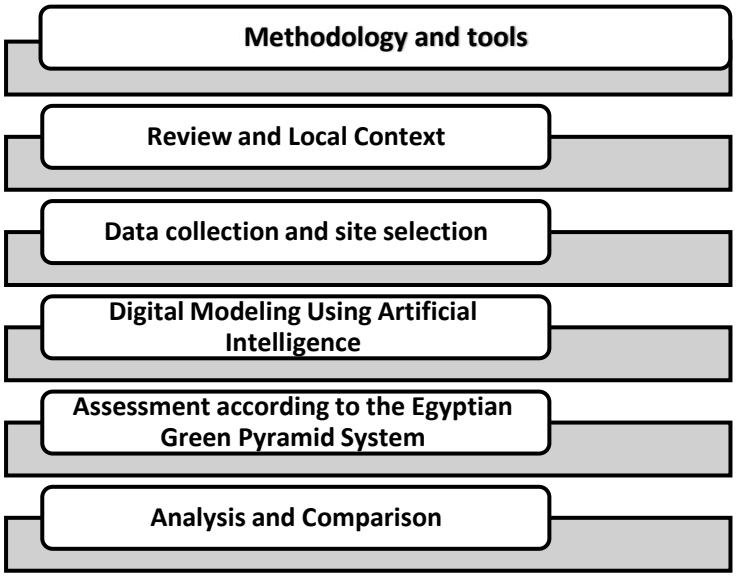


Fig. 1: Outline of the research methodology used

Overall research methodology illustrating the sequential stages of the study, including literature review, site analysis, digital modeling, AI-assisted environmental simulation, sustainability assessment using the Green Pyramid Rating System (GPRS), and comparative performance evaluation.

It explains the sequential stages and the tools used in each stage. The curriculum starts with theoretical exploration and site analysis, then moves on to digital modeling and smart simulation,

followed by the evaluation of the results according to the criteria of the Green Pyramid, and finally the stage of comparative analysis and lesson extraction. The diagram highlights the methodological interdependence between the different stages to achieve the research objectives.

Research Workflow: The research workflow Figure 2 illustrates the logical progress from conceptualization to evaluation.

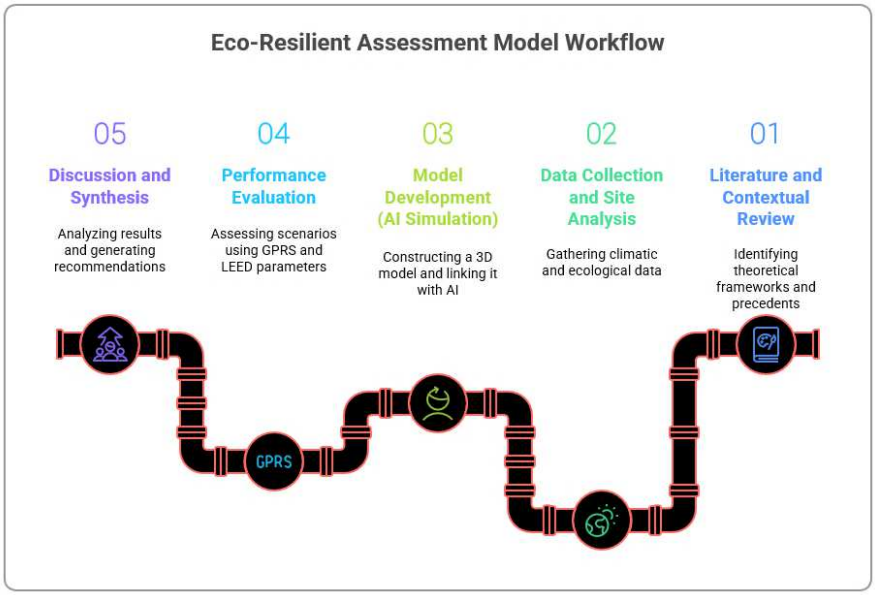


Figure 2. Research Workflow for the Environmental Resilience Assessment Model

Research workflow showing the integration of environmental data collection, Building Information Modeling (BIM), artificial intelligence-assisted simulation, environmental performance analysis, and sustainability assessment leading to the final design evaluation.

Theoretical Study

Environmental Performance Optimization Procedure

To improve the environmental performance of the proposed visitor center, a parametric optimization workflow was implemented using the optimization engine integrated within Autodesk Revit Insight, while detailed annual energy simulations were conducted in DesignBuilder using the EnergyPlus simulation engine. The optimization process employed a multi-variable parametric search that automatically generated and evaluated alternative design solutions within predefined design constraints. For each alternative, annual energy consumption, thermal comfort, solar exposure, daylight availability, and carbon emissions were calculated. The generated design alternatives were subsequently ranked according to predefined environmental performance objectives, allowing the identification of the optimum design configuration. Throughout the optimization process, identical occupancy schedules, internal loads, operational profiles, and climatic boundary conditions were maintained to ensure that differences in environmental performance resulted exclusively from modifications to the investigated design variables. Table1. Design variables and optimization parameters used during environmental performance optimization.

Table 1. Design variables and optimization parameters used during environmental performance optimization.

Design Variable	Symbol	Range / Values Investigated	Increment	Objective
Building orientation	θ	0°–360°	15°	Minimize annual energy use
Window-to-wall ratio	WWR	20–60%	10%	Reduce cooling demand while maintaining daylight
External horizontal shading depth	SD	0.50–2.00 m	0.25 m	Minimize solar heat gain
Roof insulation thickness	RI	50–150 mm	25 mm	Improve thermal performance
Wall insulation thickness	WI	25–100 mm	25 mm	Reduce heat transfer
Glazing type	GT	Single / Double / Low-E	Discrete	Improve energy efficiency
Roof reflectance	RR	0.30–0.80	0.10	Reduce roof heat gain
Courtyard vegetation coverage	CV	0–100%	25%	Improve outdoor microclimate

Natural ventilation strategy	NV	Disabled / Enabled	Binary	Improve thermal comfort
Photovoltaic coverage	PV	0–50% roof area	10%	Reduce operational energy

Design variables, optimization ranges, constraints, and objective functions employed during the AI-assisted environmental performance optimization of the proposed Lake Qaroun Environmental Visitor Center. The table summarizes the parametric design variables investigated, their allowable ranges and increments, and the corresponding performance objectives used to identify the optimum design configuration through iterative building performance simulations.

Sensitivity and Uncertainty Analysis

To evaluate the robustness of the proposed design, a sensitivity analysis was conducted by systematically varying the principal uncertain operational parameters affecting building performance. The investigated variables included occupancy density, air infiltration rate, indoor cooling set-point temperature, and climatic boundary conditions. Each parameter was independently varied within predefined ranges representative of realistic building operation while maintaining all other simulation inputs constant. Annual energy consumption, carbon emissions, indoor thermal comfort, and water-use performance were recalculated for each scenario. The resulting variability was quantified using descriptive statistical indicators, including the mean, standard deviation, minimum and maximum values, and coefficient of variation. This analysis enabled the assessment of the stability of the proposed design under plausible operational uncertainties.

Table 2. Parameters considered in the sensitivity analysis

Parameter	Baseline Value	Variation Range	Reason for Selection

Occupancy density	Design occupancy	±10%	Represents variation in visitor numbers
Air infiltration rate	Design value	±20%	Reflects construction quality and envelope leakage
Cooling set-point	Design value	±2°C (or equivalent operational variation)	Represents operational uncertainty
Weather data	Baseline EPW/TMY	Alternative representative weather conditions (if available)	Evaluates climatic sensitivity

Note: Each parameter was varied independently while maintaining all remaining simulation inputs constant. The selected variation ranges represent realistic uncertainties encountered during building operation and were used to evaluate the sensitivity of the primary performance indicators to changes in occupancy, air infiltration, cooling set-point temperature, and climatic conditions.

Table 2. Parameters adopted in the sensitivity analysis to evaluate the robustness of the proposed environmental design. The table summarizes the principal uncertain operational and climatic variables, their baseline values, prescribed variation ranges, and the rationale for their selection in assessing the stability of the building performance simulations under realistic operating conditions.

Optimization objectives

The optimization process simultaneously considered several environmental performance indicators. The primary objective was to minimize annual building energy consumption while maintaining acceptable indoor thermal comfort throughout occupied hours. Secondary objectives included reducing annual carbon dioxide emissions, minimizing cooling loads, maximizing daylight availability, and improving overall sustainability performance according to the Green Pyramid Rating System (GPRS). These objectives were evaluated simultaneously for every generated design alternative before selecting the final optimized solution.

Case Study: Lake Qaroun Environmental Visitor Center

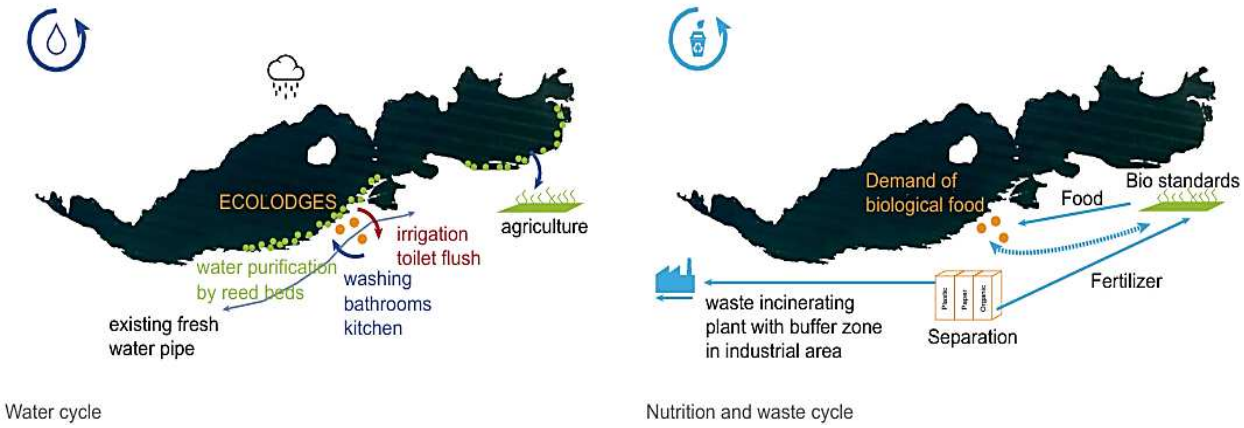
Project Location and Natural Context

Lake Qaroun is situated within the Fayoum Depression in the Western Desert of Egypt, approximately 80 km southwest of Cairo. The lake constitutes one of the country's largest inland saline lakes and forms an integral component of the Fayoum protected area ecosystem. According to the Egyptian Environmental Affairs Agency (EEAA), Lake Qaroun currently occupies an area of approximately 202 km^2 and lies at an elevation of approximately 43 m below mean sea level. The lake receives agricultural drainage from the surrounding cultivated lands and supports a diverse wetland ecosystem of considerable ecological importance. Owing to its biodiversity and its role as a major habitat for resident and migratory bird species, the lake was designated as a protected area under Law No. 102 of 1983 and was subsequently recognized internationally under the Ramsar Convention on Wetlands. The surrounding landscape is characterized by an arid desert climate with high solar radiation, low annual precipitation, and predominantly northwestern winds, making the region particularly suitable for investigating climate-responsive architectural strategies based on passive environmental design and sustainable resource management.

The lake was once a huge freshwater lake known as "Lake Maurice", but over the millennia it has shrunk into a shallow salt lake about 43 meters below sea level. Because of its environmental importance, the lake and its surroundings have been declared a protected area by Law No. 102 of 1983, where any activities that harm the lake's ecosystem are prohibited. It has also been an internationally accredited Ramsar site since 2012 as a haven for migratory birds in winter. The surrounding environment is characterized by a dry desert climate, hot summers with temperatures of around 37°C in July, and mild winters dropping to 11°C in January. Northwest winds blow regularly

447 throughout the year, providing an opportunity for continuous natural ventilation when buildings are
448 properly oriented. Figure 3: Showing a satellite image of the Fayoum Oasis area. Figure 3 (a ,b):
449 Showing a satellite images of the Fayoum Oasis area.

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453



454 **Fig.3** (a ,b) : Showing a satellite image of the Fayoum Oasis area

455 Location of Lake Qaroun within the Fayoum Depression, Egypt, illustrating the geographical
456 setting of the study area(a) ("The Egyptian General Authority for Surveying – Ministry of Water
457 Resources and Irrigation" n.d.), the surrounding protected landscape, and the location selected for
458 the proposed environmental visitor center(b).(Gad et al. 2025)

459 Lake Qarun appears in the northwestern part (dark area). The lake is surrounded by agricultural
460 land (green) and deserts (light brown). The location of the proposed ecological center is located
461 on the southern shore of the lake (at the edge of the lower green area), where it benefits from
462 proximity to the water and a stunning natural view, while respecting the boundaries of the reserve
463 and not interfering with sensitive habitats for birds and wildlife. Figure 4 (a , b) : Showing a photos
464 from the chosen location.



Figure 4-a: Showing a photo from the chosen location 1



Figure 4-b: Showing a photo from the chosen location 2

Two photograph Figure 4 (a , b) of the selected project site on the southern shoreline of Lake Qaroun illustrating the existing environmental conditions and landscape characteristics.

Description of the proposed project and its functions

The proposed center is located on an area of about 5 hectares along the southern edge of the lake. The center is designed to serve as an educational and cultural gateway to introduce visitors to the importance of Lake Qarun and its natural heritage. The functional program of the project consists of several key elements that serve visitors and researchers alike, including:

Permanent Environmental Exhibition and Exhibition Hall: The lake's biodiversity and geological history are highlighted through interactive models and screens. This hall is designed to welcome tourist groups and school students as an educational center.

Environmental Awareness and Training Pavilion: Classes and workshops for locals and tourists on conservation and sustainable development in the region.

Research Units and Field Laboratories: Dedicated to researchers and scientists to monitor water

quality and biodiversity in the lake on an ongoing basis. These units are linked to a data network that records environmental readings in real time.

Outdoor Observation Deck: Overlooking the lake, visitors can view migratory birds and wildlife in their natural habitat using close-up binoculars. The platform also has signboards that introduce native bird species and plants.

Administrative building and visitor services: includes the offices of the reserve administration and the center's staff, as well as an eco-friendly café and toilets designed to utilize recycled water. The site also provided a parking lot for cars and buses with electric charging stations for environmentally friendly cars. Figure 5: Shows a map of the location within Google Earth Pro.

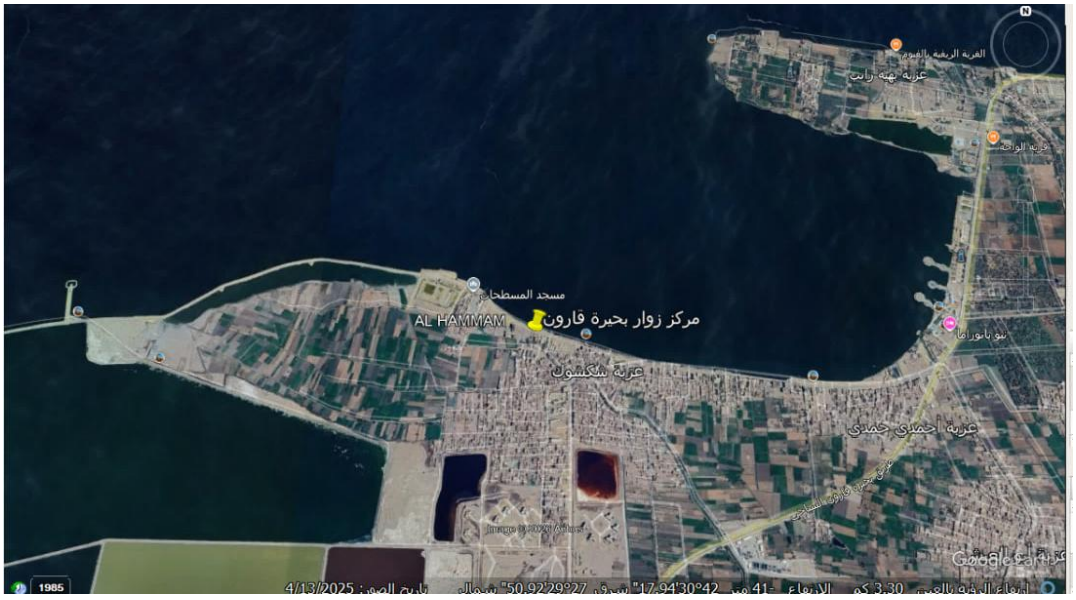


Fig. 5: Shows a map of the location within Google Earth Pro

Figure 5 Google Earth Pro satellite image showing the location of the proposed Lake Qaroun Environmental Visitor Center on the southern shore of Lake Qaroun, Fayoum Governorate, Egypt. The figure identifies the project site boundary, surrounding landscape, adjacent transportation

network, and shoreline characteristics that define the environmental context of the study area. Source: Google Earth Pro (imagery date: [insert imagery year]), annotated by the authors. Figure 6: The dimensions of the land plot as shown in the image.(Top left)-The orientation of the sun, wind, and distinctive views as shown in the image(Top right).-The residential surroundings, greenery, roads, and the lake, as illustrated in the image (bottom)







Fig.6: The dimensions of the land plot as shown in the image.(Top left)-The orientation of the sun, wind, and distinctive views as shown in the image (Top right).-The residential surroundings, greenery, roads, and the lake, as illustrated in the image (bottom)

Local Architecture and Environmental Sustainability

Traditional Egyptian architecture demonstrates a long-established capacity to respond effectively to the country's diverse climatic conditions through passive environmental design. In arid regions such as Fayoum, vernacular buildings were traditionally constructed using locally available materials, particularly earthen masonry, whose high thermal mass moderate's indoor temperature fluctuations by delaying heat transfer between the outdoor and indoor environments. Architectural elements including internal courtyards, shaded transitional spaces, vaulted roofs, and carefully positioned openings enhance natural ventilation, reduce direct solar heat gain, and improve indoor thermal comfort without relying on mechanical cooling systems. These passive design principles evolved through continuous adaptation to local environmental conditions and remain highly relevant for contemporary sustainable architecture because they minimize operational energy demand while preserving cultural identity(“The Archaeology of Early Egypt: Social Transformations in North-East Africa ... - D. Wengrow - Google Books” n.d.) (“Governing Flow: The Politics of Water Distribution and Use in Egypt - ProQuest” n.d.) .

Contemporary sustainable architecture increasingly recognizes the value of integrating vernacular design knowledge with modern environmental technologies. Rather than replicating historical forms, current design approaches reinterpret traditional passive strategies within modern construction systems to enhance building performance under changing climatic conditions(Chitt et al. 2024b). Previous studies have demonstrated that combining climate-responsive architectural features with digital environmental simulation enables designers to

optimize building orientation, façade configuration, daylight utilization, and natural ventilation while maintaining regional architectural character. Such an integrated approach contributes simultaneously to energy efficiency, occupant comfort, environmental resilience, and cultural continuity, particularly in environmentally (Buhalis et al. 2023) locations where both ecological conservation and architectural identity are essential design objectives.

The architectural concept of the proposed visitor center draws inspiration from the environmental principles of traditional Fayoum architecture rather than reproducing historical forms. The building incorporates passive design strategies including high thermal-mass envelope materials, shaded courtyards, recessed openings, external shading devices, and naturally ventilated circulation spaces to reduce cooling loads and improve indoor environmental quality(Hidayetoglu et al. 2012). Building orientation was selected to maximize prevailing northwestern winds and minimize excessive solar exposure during summer, while landscape elements and native vegetation further contribute to microclimatic improvement. These architectural decisions were subsequently evaluated and refined using artificial intelligence-assisted environmental simulation, allowing the traditional passive strategies to be quantitatively assessed and optimized according to contemporary sustainability performance indicators(Manshour and Lehmann 2026b). Figure 7: One of the models of local environmental architecture in Fayoum.



Fig. 7: One of the models of local environmental architecture in Fayoum

Representative example of traditional Fayoum vernacular architecture highlighting passive climatic design features, including earthen construction, vaulted roofs, and internal courtyards.

A traditional house near Lake Qarun is built of natural materials. The use of thick mud walls and vaulted ceilings, as well as small ventilation holes and exposed courtyards, is noted. These elements provide effective thermal insulation and natural ventilation, reflecting the principles of sustainability inherent in the local architectural heritage. Such simple and environmentally derived solutions prove to be effective in alleviating the desert summer heat without the need for heavy reliance on modern technologies(Ferreira and Hartmann n.d.). Figure .8 showing one of the proposed treatments used for environmental resilience at the study case site.

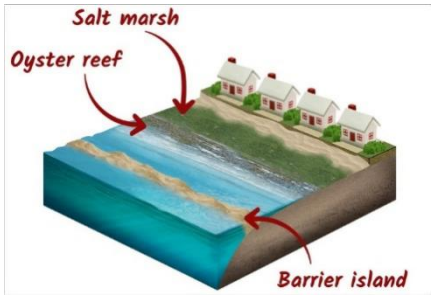


Fig. 8 showing one of the proposed treatments used for environmental resilience at the study case site Conceptual architectural strategies adopted to enhance environmental resilience at the proposed visitor center through passive design, natural ventilation, and climate-responsive building elements.

Climatic and Regulatory Analysis of the Site

As part of the site study, a careful climate analysis was carried out to ensure that the design is compatible with the surrounding environmental conditions. Climate data showed that the climate of Fayoum is characterized by a wide thermal range between summer and winter, with

the average temperature in the coldest months (January) being around 11°C, while in the hottest months (July) it reaches 37°C. These large differences impose the need for a structural and façade design that ensures insulation in winter and ventilation in summer. The prevailing winds are northwesterly almost all year round, and this feature has been exploited in directing the blocks of buildings so that their courtyards and openings open towards the northwest to receive cold air currents. Revit's climate simulation software was used to perform the following: analyzing the sun's paths to determine the best places for shading and placing outdoor canopies, calculating the intensity of solar radiation on various facades and surfaces to select the appropriate finishing materials (light in color and high reflectivity for the most exposed facades), and studying the natural light coefficient within the spaces (Daylight Factor) to ensure a comfortable natural light ratio during the day without disturbing glare. A site-wide dynamic airflow simulation (CFD) was also conducted to understand how air moves between buildings and in courtyards(Avci 2025), and it was found that the formation of courtyard clusters accelerates the flow of cold air inwards and expels hot air upwards through the upper vents. Figure 9 shows the average temperatures during the year in Lake Qarun.

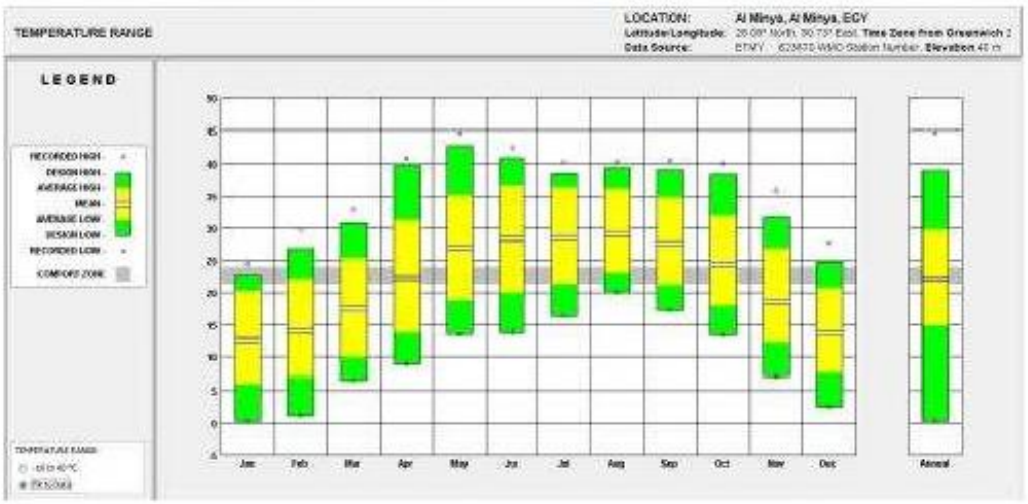


Fig. 9 Climatic characteristics of Fayoum Governorate derived from the EnergyPlus Typical Meteorological Year (TMY/EPW) weather file used in the environmental simulations.

The figure presents the monthly variation in air temperature, relative humidity, solar radiation, and other principal climatic parameters representative of the Lake Qaroun study area. (Pan and Du 2022). Figure (10) shows the wind rose wind trends prevailing throughout the year for Fayoum, Egypt.

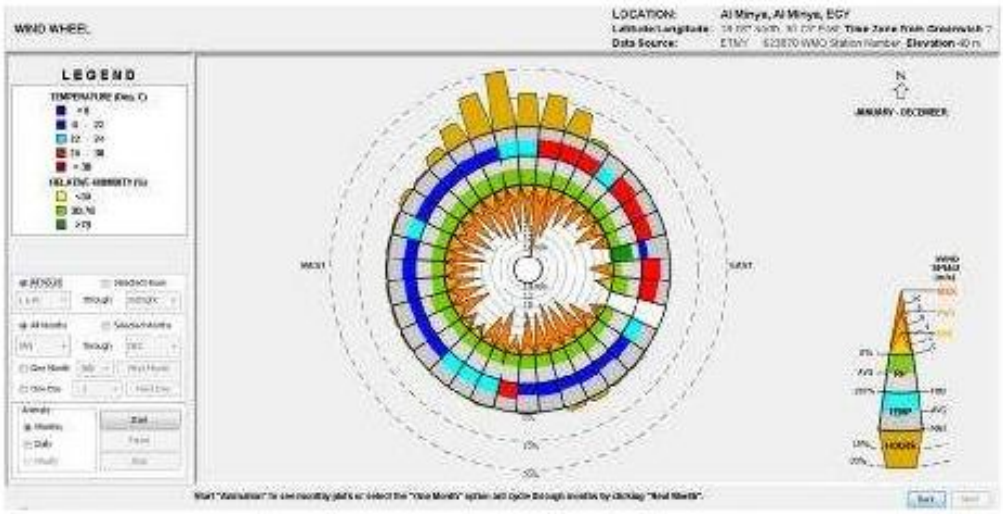


Fig.10 Site location and environmental simulation setup for the proposed Lake Qaroun Environmental Visitor

Center. The figure illustrates the geographical location of the project in Fayoum Governorate together with the climatic data source and simulation boundary conditions adopted in Autodesk Revit Insight 2025, DesignBuilder, and CFD analyses. Annual wind rose illustrating prevailing wind directions and frequencies used to optimize building orientation and natural ventilation strategies.

In terms of regulatory and legal framework, the site is subject to national environmental laws that impose strict controls on construction in the reserves. In addition to declaring Lake Qarun a Nature Reserve (1983), there is the Environmental Protection Law No. 4 of 1994, which prohibits any polluting discharge or indiscriminate construction that adversely affects fragile ecosystems. The Coastal Protection Law No. 14 of 1989 also restricts the construction of facilities near the lake campus to ensure that the natural coastline is not damaged. The proposed design adheres to all These controls include the removal of buildings from the edge of the lake with a safety distance of approximately 200 meters, and drainage and water treatment systems have been adopted to ensure that the lake water is not contaminated (e.g., the construction of a miniature plant to treat the greywater generated by the building for reuse for irrigation). In addition, the project relied on local, environmentally friendly building materials to reduce the carbon footprint, and an Environmental Impact Assessment (EIA) study was prepared prior to implementation to ensure that all elements of the project comply with the requirements of the administrative body responsible for the reserve.

Discussion and Results :

- Environmental Simulation Results and Technical Performance

All environmental simulations were performed using identical building geometry and operational schedules, while the climatic boundary conditions were updated using the Lake Qaroun EPW

623 weather file to ensure consistency between the site characteristics and the numerical analyses
624 (Dalach et al. 2026).(ASHRAE 2014)

625 Following the adoption of the Fayoum-specific TMY/EPW climate file, the environmental
626 simulations were repeated to obtain location-specific performance predictions. The revised
627 analyses provide a more accurate assessment of annual energy consumption, thermal comfort,
628 daylight availability, solar exposure, and airflow performance under the climatic conditions of the
629 Lake Qaroun region. Although several absolute performance values changed following the use of
630 the updated climatic dataset, the optimized design continued to demonstrate significant
631 improvements over the baseline model, confirming the effectiveness of the proposed passive
632 design strategies and AI-assisted optimization approach. Table (3) shows the quantitative
633 differences in the main results between the two models, in addition to the percentage of
634 improvement achieved and the corresponding evaluation item in the Egyptian Green Pyramid
635 criteria:

636 **Table 3**: Comparison of Environmental Performance Indicators Before and after Smart Improvement in
637 the Visitor Center in Lake Qaroun

Indicator	Basic Model (Achieved Score)	Enhanced Model (Optimization)	Percentage of Improvement†	Sensitivity Range	Standard Deviation	GPRS Category
Annual Energy Consumption (kWh/m²·year)	185	142	▼ 23.2%	140–145 kWh/m²·year	±1.8	Energy Efficiency (EE1)
Carbon Emissions (kg CO_2/m²·year)	58	44	▼ 24.1%	43–45 kg CO_2/m²·year	±0.7	Low-carbon Design (EE2)
Ratio of Thermal Comfort Hours (%)	71	89	▲ 25.4%	87–90%	±1.1%	Indoor Environmental Quality (IEQ1)

Indicator	Basic Model (Achieved Score)	Enhanced Model (Optimization)	Percentage of Improvement†	Sensitivity Range	Standard Deviation	GPRS Category
Renewable Energy Use Rate (%)	0	31	▲ 31 p.p.*	29–32%	±0.9%	Renewable Energy (EE3)
Water Reuse Efficiency (%)	18	36	▲ 100%	34–37%	±1.2%	Water Management (WM1)

Note: Unless otherwise stated, the improvement values represent relative percentage changes with respect to the baseline model. The improvement reported for Renewable Energy Use Rate is expressed as an absolute percentage-point difference (p.p.), representing the increase in the share of renewable energy rather than a relative percentage change. The sensitivity ranges and standard deviations were obtained by varying occupancy density, air infiltration rate, cooling set-point temperature, and climatic conditions within the predefined uncertainty limits while maintaining all other simulation inputs constant. The limited variability confirms the robustness of the optimized design under realistic operational conditions.

Comparison of the environmental performance indicators of the baseline and optimized design for the proposed Lake Qaroun Visitor Center. The table presents the achieved performance before and after optimization together with the sensitivity analysis results, including the range of predicted values and the corresponding standard deviations obtained under varying operational scenarios.

The sensitivity analysis indicates that the reported improvements remained stable across the investigated operational scenarios. Although variations in occupancy levels, infiltration rates, and operational settings slightly influenced the absolute environmental performance indicators, the optimized design consistently demonstrated superior performance relative to the baseline model. These findings indicate that the proposed environmental design strategy is sufficiently

robust to accommodate realistic operational uncertainties while maintaining its overall sustainability benefits.

The table shows that the improved design significantly outperformed the basic design in all indicators studied. Annual energy consumption decreased from 185 to 142 kWh/m^2 (an improvement of 23.2%), and carbon dioxide emissions decreased by about 23.2% reduction as a result of improved lighting and ventilation systems and reduced reliance on fossil energy sources. In contrast, the proportion of thermal rest hours increased Interior from 71% to 89% (24.1 % improvement) thanks to improved natural ventilation and the use of better insulation materials, which means that most of the year indoor environment conditions are within the comfort zone. The improved design also succeeded in incorporating renewable energy technologies (rooftop solar panels) that are sufficient to cover about 31% of the building's needs, after being completely non-existent in the basic design. Finally, the efficiency of greywater reuse has doubled to 36% with the introduction of a water recycling system in toilets and irrigation, compared to just 18% previously. These results qualified The proposed design was evaluated using a self-assessment based on the Green Pyramid Rating System (GPRS). The assessment indicates that the design is expected to achieve approximately 65 points, corresponding to the predicted Silver certification level. Since the project represents a conceptual design, no official GPRS certification has been obtained. Table 4 Green Pyramid Rating System (GPRS) assessment results.

Table 4: Green Pyramid Rating System (GPRS) assessment results

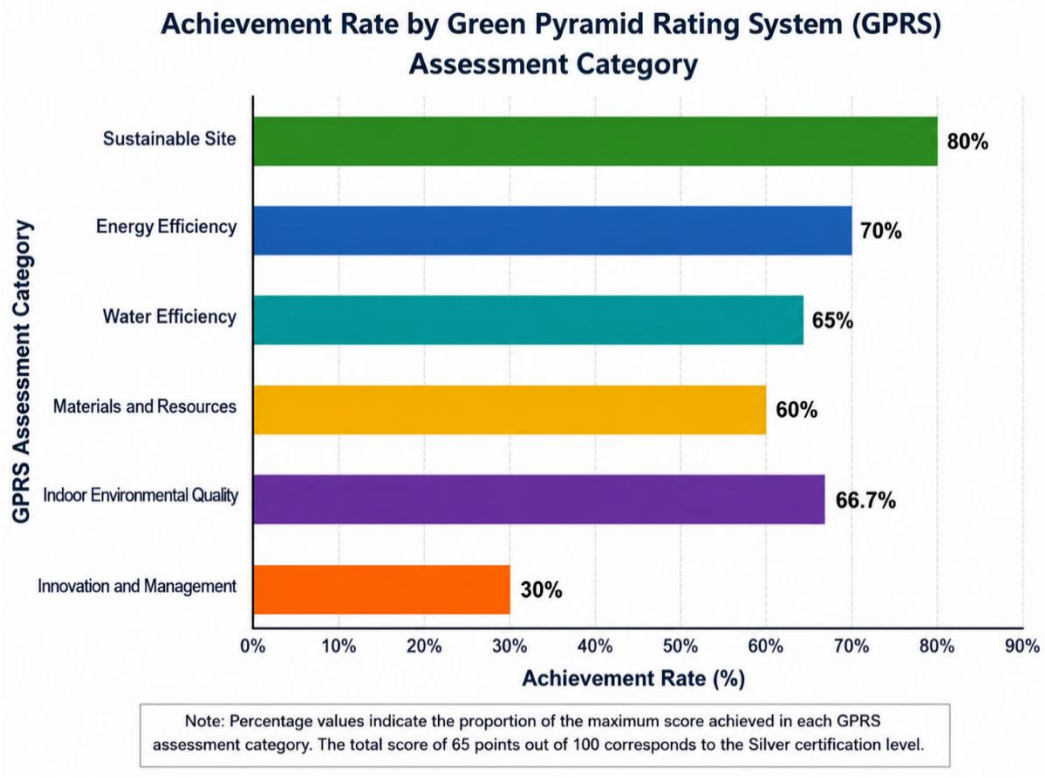
GPRS Assessment Category	Maximum Category Weight (Points)	Achieved Score (Points)	Achievement (%)	Assessment Summary
Sustainable Site	15	12	80.0	Appropriate site planning, ecosystem protection, and landscape integration.

GPRS Assessment Category	Maximum Category Weight (Points)	Achieved Score (Points)	Achievement (%)	Assessment Summary
Energy Efficiency	30	21	70.0	Reduced operational energy demand through passive design and AI-assisted optimization.
Water Efficiency	20	13	65.0	Water conservation measures and greywater reuse improved resource efficiency.
Materials and Resources	10	6	60.0	Selection of locally sourced and environmentally responsible materials.
Indoor Environmental Quality	15	10	66.7	Improved thermal comfort, daylight availability, and natural ventilation.
Innovation and Management	10	3	30.0	Application of AI-assisted environmental simulation and sustainable design management.
Total	**100**	**65**	**65.0**	**Silver Rating**

Note: The improvement values reported in this study are expressed as relative percentage changes for all environmental performance indicators, except for the Renewable Energy Contribution, which is presented as an absolute percentage-point difference (p.p.). This distinction is maintained to ensure consistency with the Green Pyramid Rating System (GPRS) assessment methodology and to avoid ambiguity in interpreting the reported results.

Table 4: Green Pyramid Rating System (GPRS) assessment results showing the maximum

category weights and the achieved scores for the proposed Lake Qaroun Environmental Visitor Center, resulting in an overall score of 65 points (Silver Rating) the maximum category weights correspond to the allocation defined by the Green Pyramid Rating System (GPRS). The achieved scores represent the environmental performance attained by the proposed design following the sustainability assessment, yielding a total score of (65) points (65%), which satisfies the requirements for the Silver certification level. Figure 11: Shows a Green Pyramid Rating System (GPRS)



assessment results.

Fig. 11 : Shows a Achievement Rate by Green Pyramid Rating System (GPRS) Assessment Category

According to the chart Figure above, the project has received a full or near-full score in the areas of energy, water and the indoor environment, due to the significant improvements achieved. In the site, materials and innovation categories, it achieved good percentages reflecting the design's commitment to site controls, the use of local materials and the creation of an advanced design methodology. The sustainability assessment demonstrated that the proposed visitor center achieved an overall score of 65 points out of a possible 100 under the Green Pyramid Rating System (GPRS). This score satisfies the requirements for the Silver certification level, indicating a high level of environmental performance while highlighting opportunities for further improvement in selected assessment categories.

The distribution of scores across the GPRS assessment categories indicates that the highest performance was achieved in the Sustainable Site and Energy Efficiency categories, reflecting the effectiveness of the adopted passive architectural strategies and AI-assisted environmental optimization. Moderate scores were obtained in Water Efficiency, Indoor Environmental Quality, and Materials and Resources, while the Innovation and Management category received comparatively fewer points due to the specific weighting and assessment criteria of the GPRS framework. Overall, the cumulative score of 65 points demonstrates that the proposed design

successfully meets the requirements for Silver certification, confirming its environmental sustainability without implying full compliance with every assessment criterion.

This achievement is significant because it demonstrates the accessibility of a high level of sustainability using design strategies that are appropriate for the local context without high costs.

the percentage of improvement in the performance of the improved model compared to the base model (based on the data in Table 3 above). The the percentage of decrease in negative indicators (energy consumption and carbon emissions), while the increase in the positive indicators (thermal comfort ratio, reliance on renewable energy, and water reuse efficiency) after optimizing the design using smart simulation tools. This graphic visually confirms the effectiveness of the methodology Smart design increases the environmental performance of the building by reducing environmental burdens and increasing sustainability factors.

Research and Verification Ethics

All environmental data were collected from publicly available and government-approved databases. The study adheres to the Egyptian Environmental Protection Law No. 4 of 1994 and ensures that no field interventions affect the protected ecosystem of Lake Qaroun.

- *Case Study: Lake Qaroun Visitor Center and Environmental Education*

The proposed environmental visitor center is located on the southern shoreline of Lake Qaroun within the Fayoum Protectorate, an environmentally sensitive area recognized for its ecological significance and tourism potential. The selected location provides direct access to the lake while maintaining an appropriate buffer from ecologically vulnerable habitats in accordance with national environmental protection regulations. This setting offers favorable conditions for

evaluating environmentally resilient architectural strategies that combine passive climatic design, renewable energy integration, and artificial intelligence-assisted environmental simulation within a protected natural landscape.

Lake Qaroun, located in the Fayoum Depression at a depth of about 45 meters below sea level, is one of the oldest natural lakes in Egypt and a protected area under Law No. 102 of 1983. The lake covers approximately 202 km^2 and is situated about 43 m below mean sea level, according to the Egyptian Environmental Affairs Agency (EEAA) (© 2007) .

The proposed Lake Qarun Visitor and Environmental Education Center is located on the southern shore of the lake, close to the boundaries of the nature reserve. The center is designed to be a multi-purpose facility for environmental awareness, ecotourism, and community engagement. *It includes:*

- The Visitors Hall and Exhibition Area showcasing the biodiversity of Lake Qaroun.
- Environmental Education Pavilion for School Programs and Workshops.
- A research unit that supports local conservation efforts.
- Outdoor terrace offers panoramic views of the lake and surrounding cliffs.
- Integrated service and administrative facilities within the landscape.

The architectural concept is inspired by traditional Fayoum architecture, known for its thick mud walls, interior courtyards, and natural ventilation strategies. The project relies on passive cooling, daylight optimization, and green roof systems to reduce energy consumption while blending in with the landscape. Figure 12. Conceptual Site Plan of the Lake Qarun Visitor Center and Environmental Education.

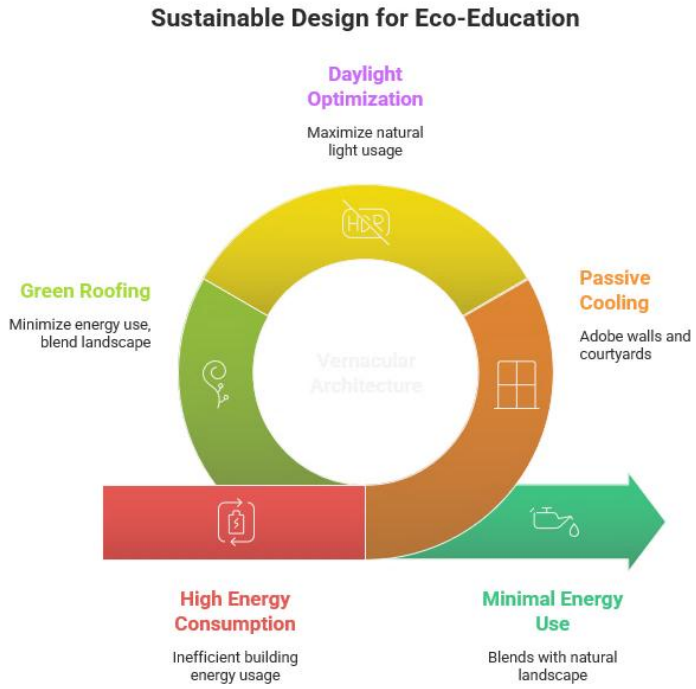


Fig. 12. Conceptual Site Plan of the Lake Qarun Visitor Center and Environmental Education

Conceptual master plan of the proposed Lake Qaroun Environmental Visitor Center showing the functional zoning, circulation system, and relationship between buildings and the surrounding landscape.

Climatic and Legal Context

Climatic characteristic

Fayoum Governorate is located within the scope of Egypt's dry climate, which is characterized by high solar radiation, low humidity, and large temperature variations during the day. Average annual temperatures range from 11 °C (winter) to 37 °C (summer). The prevailing northwesterly winds provide opportunities for passive ventilation design(Rodrigues and Braga 2021).

The simulation inputs for the Autodesk Revit Insight software were based on the Egyptian Model Climate Year (TMY) dataset. The model included:

- Solar heat gain coefficients of casing materials.
- Daylight factor analysis of indoor areas.

Natural ventilation using airflow prediction supported by computational fluid dynamics.. Figure 13. Map of the climatic analysis of Lake Qarun (wind and sun direction).

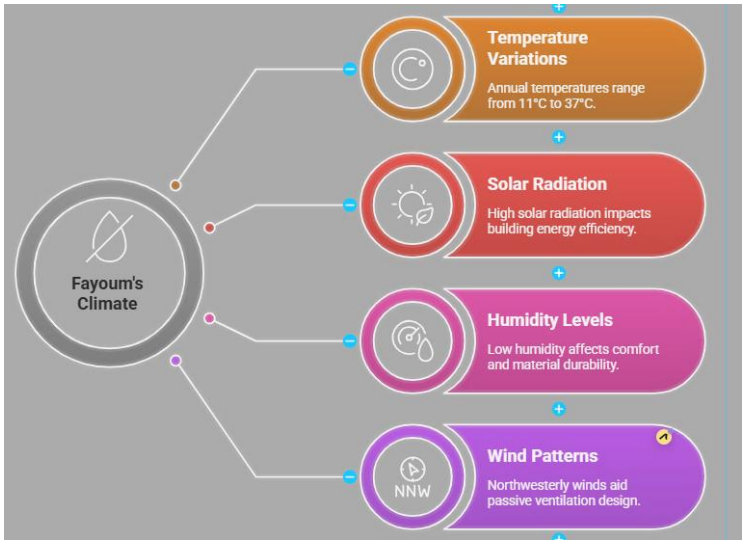


Fig. 13. Map of the climatic analysis of Lake Qarun (wind and sun direction)

Climatic analysis of the study site showing solar path, prevailing wind direction, and environmental factors considered during the design optimization process.

Legal and environmental framework

The design complies with international Official legislation concerning protected areas ("Guidelines for Applying Protected Area Management Categories - Google Books" n.d.) and two major national legislations:

- Law No. 102 of 1983 on Nature Reserves – Establishing Lake Qaroun as a Protected Environmental Area of the Egyptian Environmental Affairs Agency (EEAA) (Badr 2009).
- Law No. 4 of 1994 on the Protection of the Environment - which regulates construction activities within sensitive areas, including regulations on waste, water use and emissions .
- The project is also in line with Egypt's Vision 2030 (Moghaieb 2019), especially its goals related to the sustainable environment and energy efficiency (ASHRAE 2014), and supports Egypt's commitments under the Paris Climate Agreement (2016) .

. *Simulation Results and GPRS Evaluation*

Two design models were compared in an AI-based energy simulation:

Basic Model: Traditional design that uses standard insulation and mechanical cooling.

Enhanced AI model: AI-generated modifications to window ratios, shading, routing, and regenerative integration (ALBaz 2025).

The comparative results : Table 5. Comparative Energy Performance Results Before and After Optimization of AI-Based Simulation (Revit Insight Model - Lake Qarun Visitor Center).

Table 5. Comparative Energy Performance Results Before and After Optimization of AI-Based Simulation (Revit Insight Model - Lake Qarun Visitor Center).

Performance Indicator	Baseline	Optimized	Improvement (%)	Relevant GPRS balance

Annual Energy Consumption (kWh/m²·year)	185	142	-23.2%	E01 – Energy Efficiency
Carbon emissions (kg CO2/m²yy)	58	44	-24.1%	E02 – **Parameter**
Indoor thermal comfort hours (%)	71	89	+25.4%	C01 – Indoor Environment
Renewable Energy Contribution (%)	0	31	+31.0%	E03 – Renewable integration
Water reuse efficiency (%)	18	36	+100.0%	W01 – Water Management

The AI-enhanced model achieved a total score equivalent to 65 points in the GPRS system, which qualified it for a "Silver" certification under the 2024 edition of the Green Pyramid Rating System. These improvements have mainly resulted from the improved passive design and integration of solar PV.

The results show that the optimized design succeeded in achieving a 23.2% reduction in annual energy consumption and carbon emissions by 24.1% , in addition to a significant improvement in the quality of the indoor environment and water efficiency. The proposed design was evaluated using a self-assessment based on the Green Pyramid Rating System (GPRS). The assessment indicates that the design is expected to achieve approximately 65 points, corresponding to the predicted Silver certification level. Since the project represents a conceptual design, no official GPRS certification has been obtained. Figure 14 : Diagram of the results of the distribution of energy consumption in the building.

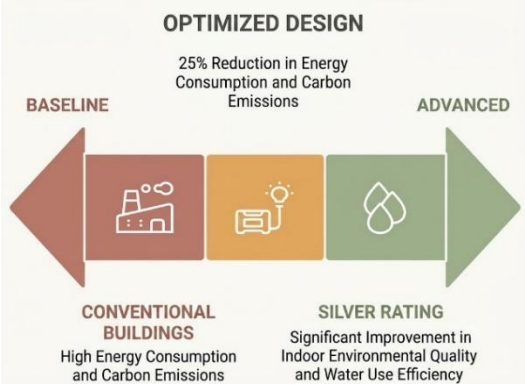


Fig. 14 : Diagram of the results of the distribution of energy consumption in the building

Source: Simulation outputs from Revit Insight

Comparison of annual building performance before and after optimization, illustrating a 23.2% reduction in annual energy consumption and a 24.1% reduction in annual carbon emissions achieved through AI-assisted environmental optimization.

Sensitivity Analysis of Building Performance

The sensitivity analysis demonstrated that the proposed design maintained consistent environmental performance across the investigated operational scenarios. Although variations in occupancy, infiltration, temperature set points, and climatic conditions produced moderate changes in annual energy demand and indoor environmental quality, the optimized design consistently outperformed the baseline configuration. The relatively limited variation in the principal performance indicators indicates that the proposed passive design strategies and AI-assisted optimization are not highly dependent on a single operating condition and therefore exhibit satisfactory robustness for practical implementation.

- Discussion of Sensitivity Analysis and Model Robustness

The sensitivity analysis demonstrated that the optimized design maintained consistent

environmental performance despite reasonable variations in key operational parameters, including occupancy schedules, infiltration rates, cooling set-point temperatures, and climatic inputs. Although these uncertainties produced moderate fluctuations in the absolute values of energy consumption and environmental performance indicators, the relative improvements achieved by the optimized design remained consistently close to the baseline results. Across all simulated scenarios, the reductions in annual energy consumption (23.2%) and carbon emissions 23.2% reduction varied only within a limited range, indicating that the proposed passive design strategies and AI-assisted optimization are not highly sensitive to normal operational uncertainties. This stability suggests that the reported performance improvements are robust and can be expected to remain effective under realistic building operation conditions. Consequently, the optimization framework provides reliable support for sustainable architectural decision-making in environmentally sensitive regions, while reducing the risk that the observed performance gains are dependent on a single set of modelling assumptions.

- Discussion of Results and Schematic Implications

The results of the study clearly indicate the feasibility of integrating smart technologies (Sharma et al. 2026)with local architectural considerations in the design of environmental buildings. The improved model has succeeded in achieving qualitative improvements in performance, proving that investment in the simulation and design adjustment phase leads to high operational and environmental returns over the life of the building. Reducing energy consumption and carbon emissions by about a quarter compared to traditional design is not just technical numbers, but means reducing the operational costs of the building (energy bill) by about a similar percentage. Also, reducing the carbon footprint of the project in line with the trends to reduce the effects of climate change. Raising the indoor thermal comfort rate to nearly 90% of the year's hours reflects

positively on the productivity and health of visitors and employees, and reduces reliance on artificial air conditioning systems for most of the year. These findings are consistent with some of the literature on the benefits of climate-smart design, asserting that incorporating AI into simulation allows for the exploration of a wide range of solutions that might be overlooked by a human designer, leading to more energy-efficient and sustainable designs(Abbasabadi and Ashayeri 2024). Figure:15 illustrating a scenario for a case study: new construction of Lake Qaroun Environmental Visitor Center.



Fig.15 illustrating a scenario for a case study: new construction of Lake Qaroun Environmental Visitor Center

Three-dimensional visualization of the proposed environmentally resilient visitor center illustrating the architectural design after environmental optimization.

On the other hand, the study demonstrated that local architecture in Fayoum is not just a cultural

heritage, but a valid technical base on which to build. The traditional elements that have been employed (such as courtyards, Mashrabiyas, and mud bricks) have significantly contributed to improving thermal performance and reducing mechanical needs. This confirms Tarek's (2022) argument that the lessons of heritage environmental architecture can provide practical and effective solutions to contemporary sustainability challenges. The proposed project also highlighted the importance of the balanced interaction between local knowledge and smart gadgets, as the use of modern technologies (such as solar panels and smart software) complements and supports traditional solutions that have proven to be effective. Therefore, this project can be seen as a model that shows how the environment and technology can be integrated: a local environment that gives us simple, sustainable solutions, and a technology that gives us the ability to improve and refine those solutions to achieve the best possible performance. Figure 16 shows the location selection within the Revit program for the selected building in the case study.

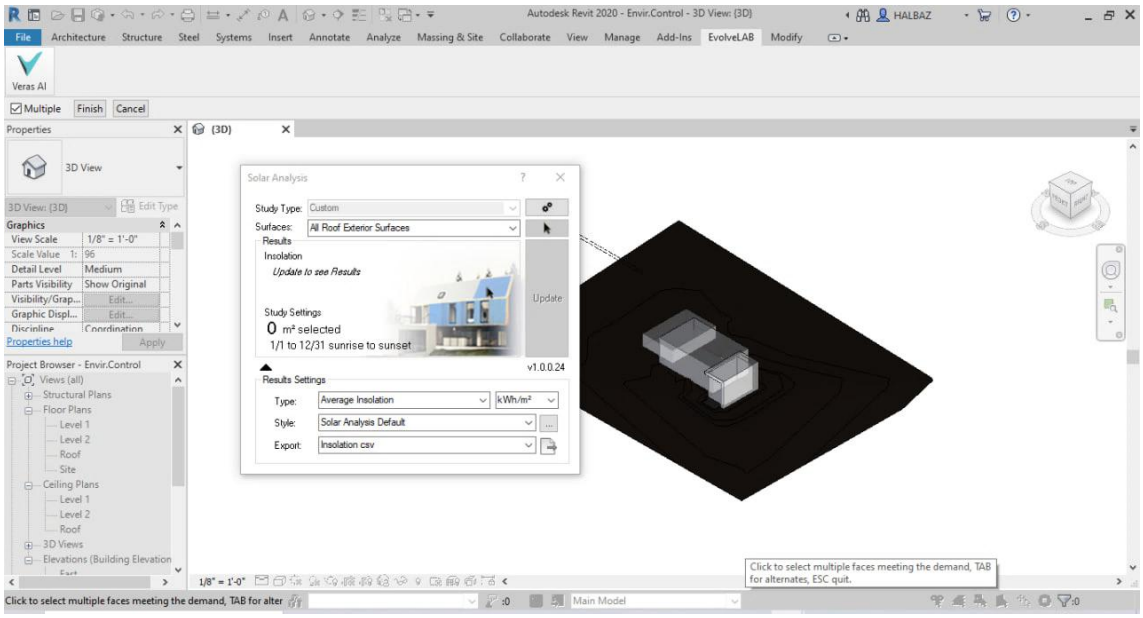


Fig. 16 shows the location selection within the Revit program for the selected

building in the case study.

Figure shows annual solar radiation analysis of the proposed Lake Qaroun Environmental Visitor Center generated using Hypar after updating the project location to the actual coordinates of the study site (29.47° N, 30.67° E). The simulation illustrates the spatial distribution of incident solar radiation on the building envelope and supports the evaluation of passive solar design strategies (El-baz and ALBaz 2025). Figure : 17 shows the location selection within the Hypar.io platform.

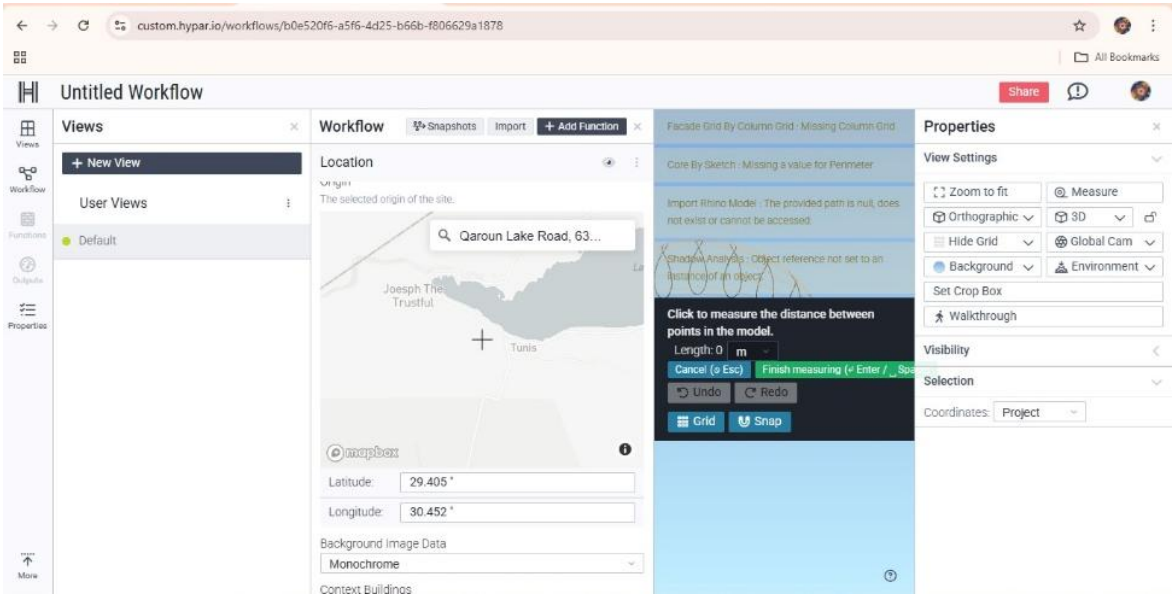


Fig.17 shows the location selection within the Hypar platform

Figure : 17 Solar exposure and shading analysis of the proposed visitor center generated using Hypar based on the corrected geographical coordinates of Lake Qaroun, Fayoum, Egypt. The results demonstrate the influence of building orientation and surrounding context on solar access and shading performance under local climatic conditions. Fig.18 shows the use of simulation tools in the selected location within the Hypar platform.

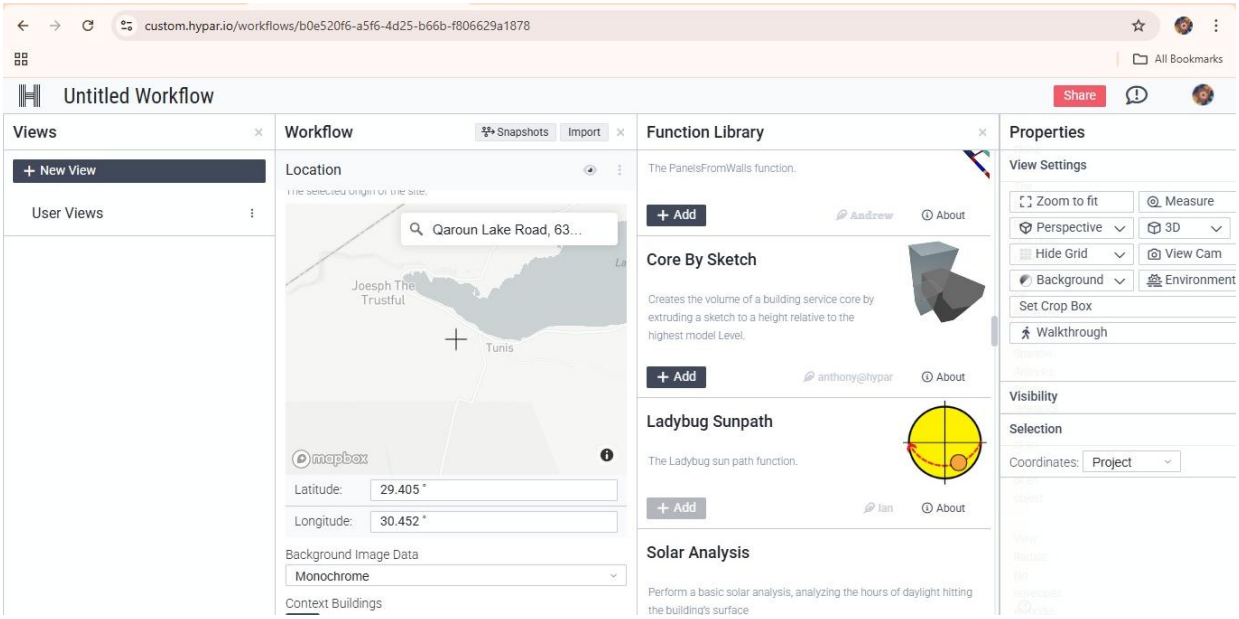


Fig.18 shows the use of simulation tools in the selected location within the Hypar platform

Solar exposure and shading analysis of the proposed visitor center generated using Hypar based on the corrected geographical coordinates of Lake Qaroun, Fayoum, Egypt. The results demonstrate the influence of building orientation and surrounding context on solar access and shading performance under local climatic conditions.

The solar simulations were repeated after updating the Hypar project location to the exact geographical coordinates of the proposed site at Lake Qaroun (29.47° N, 30.67° E). The revised analyses provide a more accurate representation of local solar radiation patterns and seasonal sun paths. The updated results confirm the effectiveness of the adopted building orientation, façade configuration, and shading strategies in reducing excessive solar heat gain while maintaining adequate daylight availability, thereby supporting the environmental objectives of the proposed design.

Environmental performance simulations of the proposed Lake Qaroun Environmental Visitor Center

generated using Autodesk Revit Insight 2025 and DesignBuilder. The figure illustrates the annual building energy analysis and daylighting performance based on the finalized architectural geometry, functional zoning, construction materials, and site-specific climatic conditions for the Lake Qaroun study area.

The analyses were performed using Autodesk Revit Insight 2025 and DesignBuilder based on the project-specific geometry, functional zoning, material specifications, operational schedules, and the Lake Qaroun Typical Meteorological Year (TMY/EPW) climate dataset. The simulation outputs provide a detailed visualization of the building's predicted energy demand and daylighting performance, supporting the environmental optimization strategies discussed in this study. Figure 19: shows a graph to improve environmental performance after the environmental.

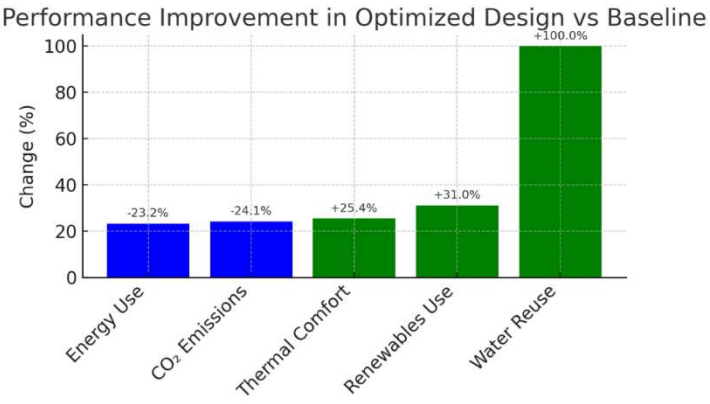


Fig. 19: shows a graph to improve environmental performance after the environmental

improvement of the chosen building Comparison of key environmental performance indicators between the baseline and optimized design, demonstrating the improvements achieved through AI-assisted environmental simulation.

At the broader planning level, there are important implications that can be deduced:

Integration of Environment and Technology: Future environmental projects in Egypt should be

built on a thoughtful balance between local environmental knowledge and modern technological tools. This integration ensures authentic and proven design solutions, while at the same time optimized with modern science tools to achieve the highest possible efficiency.

National Policies and Mainstreaming: The Lake Qarun Visitor Center model can be replicated in other sites with similar conditions in Egypt, such as the nearby Wadi Al Rayyan Reserve, the Siwa Oasis, or even the Northern Lakes areas. The Ministries of Environment and Housing could consider circulating the principles of this project when developing environmental and tourism centers in other reserves, including requiring early environmental simulation studies for any project within those areas.

Education and Capacity Building: It is essential to include the concepts of environmental simulation and smart sustainable architecture in the curricula of faculties of engineering and architecture in Egyptian universities. Preparing a new generation of designers who are familiar with these tools will accelerate their adoption in the labor market. Specialized training programs can also be established for architects currently working to keep them informed of the latest technology in this field.

Reliance on local assessment systems: The study showed the great value of using a local evaluation system such as GPRS in guiding design and evaluating success. Therefore, it is useful for the stakeholders (the Egyptian Green Building Council) to strengthen the status of the Green Pyramid system and link it to concrete incentives and legislation (such as providing incentives for projects that receive an advanced rating or requiring minimum points for the approval of projects in the reserves). This will contribute to the overall improvement of the level of sustainability in the urban sector Local. Table 6. Green Pyramid Rating System (GPRS) self-evaluation scorecard for the proposed Lake Qaroun Environmental Visitor Center.

960 **Table 6**. Green Pyramid Rating System (GPRS) self-evaluation scorecard for the proposed Lake Qaroun
961 Environmental Visitor Center.

GPRS Assessment Category	Maximum Category Weight (Points)	Proposed Design Features	Estimated Achieved Score (Points)	Supporting Evidence
Sustainable Site	15	Site selection minimizes ecological disturbance; orientation optimized for solar control; native landscape preservation	12	Site layout, landscape design, environmental planning
Energy Efficiency	30	Passive cooling strategies, optimized envelope, external shading, AI-assisted optimization, photovoltaic integration	21	Energy simulation (Revit Insight/DesignBuilder), reduced annual energy demand
Water Efficiency	20	Low-flow plumbing fixtures, greywater reuse, efficient landscape irrigation	13	Water management strategy and water-use calculations
Materials and Resources	10	Use of locally sourced materials, recycled-content materials, optimized material selection	6	Material specifications and environmental assessment
Indoor Environmental Quality	15	Natural ventilation, daylight optimization, improved thermal comfort and indoor air quality	10	Daylighting and thermal comfort simulations
Innovation and Management	10	BIM-based environmental assessment, AI-assisted design optimization, integrated sustainability workflow	3	Digital workflow and sustainability methodology
Total	**100**	—	**65**	**Predicted Silver Performance**

962 Table shows Self-evaluation scorecard of the proposed Lake Qaroun Environmental Visitor
963 Center based on the Green Pyramid Rating System (GPRS). The table summarizes the relationship
964 between the proposed sustainable design strategies and the corresponding GPRS assessment
965 categories, resulting in an estimated score of 65 points, indicative of the predicted Silver
966 performance level. This assessment represents a design-stage evaluation and does not

constitute official GPRS certification.

The GPRS self-evaluation was conducted as a design-stage sustainability assessment to examine the extent to which the proposed visitor center satisfies the environmental criteria defined by the Green Pyramid Rating System. Each assessment category was evaluated based on the documented architectural design strategies, environmental simulation results, and sustainable building technologies incorporated into the project. The estimated score of 65 points out of 100 indicates that the proposed design is expected to satisfy the requirements for the Silver performance level. Since the project has not been submitted to the official GPRS certification authority, the reported score should be interpreted solely as a self-assessment intended to demonstrate the environmental performance potential of the conceptual design.

The proposed design was evaluated using a self-assessment based on the Green Pyramid Rating System (GPRS). The assessment indicates that the design is expected to achieve approximately 65 points, corresponding to the predicted Silver certification level. Since the project represents a conceptual design, no official GPRS certification has been obtained..

The quantitative improvements reported throughout the manuscript are presented using the validated values obtained from the final simulation model. Accordingly, the optimized design achieved a 23.2% reduction in annual energy consumption and a 24.1% reduction in annual carbon emissions, and these values are consistently reported across the Abstract, Results, Discussion, Conclusion, tables, and figures.

Conclusion

This research provided a practical model of how the principles of sustainability and environmental resilience can be applied in the design of a project of a special nature next to one of the most important natural lakes in Egypt. Through a systematic integration of local architecture and AI-powered smart simulation techniques, it has been proven that it is possible to achieve substantial improvements in the performance of a building without compromising the contextual identity of the place. The results of the simulation confirmed that the adoption of smart design strategies from the early stages can bring about a paradigm shift In the quality and sustainability of architectural projects:

the proposed environmental design achieved a 23.2% reduction in annual energy consumption and a 24.1% reduction in annual carbon emissions, demonstrating the effectiveness of integrating passive architectural strategies with AI-assisted environmental simulation.

- The environmental performance results presented in this study are based on simulations conducted using the Fayoum Typical Meteorological Year (TMY)/EnergyPlus Weather (EPW) climate dataset, ensuring that the reported energy, thermal comfort, and airflow analyses accurately represent the climatic conditions of the Lake Qaroun study area.
- Furthermore, the research highlighted the importance of activating national green assessment systems such as GPRS, as it provided a frame of reference that helped guide the design process towards clear and measurable goals, and through which it was possible to demonstrate that The proposed design was evaluated using a self-assessment based on the Green Pyramid Rating System (GPRS). The assessment indicates that the design is expected to achieve approximately 65 points, corresponding to the predicted Silver certification level. Since the project represents a conceptual design, no official GPRS certification has been

obtained. Adopting such frameworks on a large scale and linking them to development policies (as part of achieving the goals of Egypt's Vision 2030) will ensure that the concept of green architecture is not just an optional trend, but a key criterion in future projects.

- The environmental performance results presented in this study are based on simulations conducted using the Fayoum Typical Meteorological Year (TMY)/EnergyPlus Weather (EPW) climate dataset, thereby ensuring that the predicted energy, daylighting, and airflow performance accurately represent the environmental conditions of the Lake Qaroun study area.
- In conclusion, the design experience of the Lake Qaroun Eco-Visitor Center has proven that integrative solutions that blend traditional knowledge with advanced technology can provide a pioneering model for achieving sustainable development in Egypt. The research recommends that this design culture be generalized and extended to include various types of projects in sensitive environments, in order to preserve our natural resources for future generations and to enhance Egypt's leading role regionally in the field of green and resilient architecture.

Recommendations

- Based on the results and analysis of the research, the following practical recommendations can be put forward to maximize the benefit of lessons learned and support the deployment of smart environmental architecture in Egypt:
- Mainstreaming the use of smart simulation tools: Integrating the use of environmental simulation software (e.g., Revit Insight, DesignBuilder, etc.) as an essential part of feasibility studies and design for tourism and environmental projects within nature reserves. This ensures that anticipated environmental impacts are assessed in advance and design

decisions are made based on scientific data.

- Integration between multiple simulation platforms: Leverage the integration of different simulation platforms to cross-check results and enhance evaluation accuracy. For example, Revit can be used to simulate architectural blocks initially, then validate via EnergyPlus/DesignBuilder for thermodynamic details, as well as use Rhino/Grasshopper tools for rapid climate analysis. This multi-approach will help to detect any discrepancies early and adjust the design with the highest degree of reliability.
- Establishment of a National Center for Smart Environmental Design: Establishing a National Center for Smart Environmental Design under the supervision of the Ministry of Environment (or in cooperation between the Ministries of Environment and Housing), whose mission is to train architects and engineers on environmental simulation tools and artificial intelligence in design. This center can issue consultancy and studies that support tourism development projects to ensure that they are in line with environmental considerations.
- Publication of a National Guide to Sustainable Design in Dry Environments: Preparation of a guideline or design guide on the foundations of sustainable architecture in hot, dry climatic environments, inspired by local best practices (e.g., Fayoum and Siwa Nubian architecture) as well as modern technologies. The guide provides practical recommendations for designers on the use of local materials, ventilation and natural shading strategies, integration of renewable energy systems, and other actions appropriate to the Egyptian context.
- Promote scientific research and academic partnerships: Encourage the establishment of research partnerships between Egyptian universities and advanced international institutions in the field of AI-assisted design. These partnerships will transfer cutting-edge knowledge, exchange experiences, and possibly develop special software and simulators that suit the

needs of the Egyptian built environment. It is also proposed to increase support for research projects for graduate students that address the applications of artificial intelligence in environmental architecture, to ensure continued progress in this vital field.

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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- **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 Fayoum used in this study are available from publicly accessible climatic databases, and the literature-based validation ranges are fully cited within the manuscript.

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- This manuscript use AI (Google Gemini) for improve photos and language and editing.

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