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Artificial Intelligence in Architectural Design: Toward an innovative digital approach "Using Rhino software applications to analyze a middle school model - A case study"

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الذكاء الاصطناعي في التصميم المعماري: نحو منهج رقمي مبتكر " استخدام تطبيقات برنامج الراينو لتحليل نموذج مدرسة اعدادية - حالة دراسية"

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Abstract:
The field of architecture is undergoing a paradigm shift thanks to the integration of artificial intelligence (AI) into the design and planning processes. This has given architects new tools to analyze data, generate ideas, and predict the performance of buildings before they are implemented. This research aims to explore the role of AI in enhancing the quality of architectural decisions, improving environmental performance, and facilitating the realization of sustainable design solutions, particularly in regions with challenging climates. The methodology relies on the use of generative design software, such as Rhino/Grasshopper, Ladybug & Honeybee environmental analysis tools, as well as the application of optimization algorithms. Through which several design models are generated and analyzed environmentally (lighting, ventilation, energy consumption) to select the optimal model according to specific criteria. The approach was applied to a building design project (case study) in the hot and dry climate of Tripoli. The analysis begins with reading local climate data and then generating prototypes using generative design algorithms. The model was evaluated using environmental simulation tools, resulting in the selection of the most efficient design in terms of reducing heat load, enhancing natural lighting, improving ventilation, and lowering energy consumption compared to traditional models. The results showed that incorporating AI not only enhances environmental performance but also supports creativity and shortens design time.

Keywords: Artificial Intelligence, architectural design, digital approach, generative algorithms, environmental performance, Rhino, Grasshopper, sustainable design.

الملخص :
يشهد مجال العمارة تحولًا نوعيًا بفضل دمج تقنيات الذكاء الاصطناعي (AI) في عمليات التصميم والتخطيط العمراني. أتاح ذلك للمعماريين أدوات جديدة لتحليل البيانات، وتوليد الأفكار، وتوقّع أداء المباني قبل تنفيذها . يهدف هذا البحث إلى استكشاف دور الذكاء الاصطناعي في تحسين جودة القرار المعماري، وتعزيز الأداء البيئي، وتحقيق حلول تصميم مستدامة، خصوصًا في المناطق ذات المناخات الصعبة. تعتمد المنهجية على استخدام برامج التصميم التوليدي مثل Rhino/Grasshopper، وأدوات التحليل البيئي Ladybug & Honeybee، مع تطبيق خوارزميات التطوير ليتم من خلالها توليد عدة نماذج تصميمية وتحليلها بيئيًا (إضاءة، تهوية، استهلاك طاقة) لاختيار النموذج الأمثل وفق معايير محددة. تم تطبيق المنهج على مشروع تصميم مبنى (كدراسة حالة) في منطقة طرابلس ذات المناخ الحار الجاف ويبدأ التحليل بقراءة بيانات المناخ المحلية، ثم توليد نماذج أولية باستخدام خوارزميات التصميم التوليدي. تم تقييم النموذج باستخدام أدوات المحاكاة البيئية، ومن تم التوجيه لاختيار التصميم الأكثر كفاءة من حيث تقليل الحمل الحراري وتعزيز الإضاءة الطبيعية و تحسين التهوية بالإضافة لتقليل استهلاك الطاقة مقارنةً بالنماذج التقليدية. أظهرت النتائج أن دمج الذكاء الاصطناعي لا يعزز الأداء البيئي فقط، بل يدعم أيضًا الإبداع ويختصر الزمن اللازم للتصميم.

الكلمات المفتاحية: الذكاء الاصطناعي، التصميم المعماري، المنهج الرقمي، الخوارزميات التوليدية، الأداء البيئي، Rhino، Grasshopper، Ladybug & Honeybee، التصميم المستدام.

1.Introduction

The integration of artificial intelligence (AI) into architectural design marks a transformative shift in how buildings are conceived, analyzed, and optimized. As environmental concerns and sustainability goals become increasingly central to architectural practice, the need for intelligent, data-driven design approaches has never been more urgent. This is particularly true in regions with extreme climatic conditions, such as Tripoli, where traditional design methods often fail to address energy efficiency, thermal comfort, and environmental responsiveness.

This study aims to explore the role of AI in improving architectural decision quality, enhancing environmental performance, and achieving sustainable design solutions, particularly in areas with challenging climates, by the use of advanced computational tools such as Rhino/Grasshopper, Ladybug & Honeybee, and Galapagos. These tools facilitate parametric modeling and environmental simulations, allowing for rapid iteration and optimization of design parameters to meet complex performance criteria. This integration of AI and architectural design is shaping the future of the built environment, allowing architects to generate multiple design options quickly, save time and resources, and optimize building performance and energy efficiency [3].

The application of AI in architecture is not merely an efficiency gain but a fundamental shift towards more data-driven, environmentally responsive design practices, enabling the creation of energy-efficient, sustainable buildings tailored to specific environmental conditions [31]. By leveraging generative algorithms and simulation tools, architects can now evaluate the environmental impact of design decisions at early stages, leading to more informed and resilient outcomes. This capability is especially valuable in climates where passive design strategies must be carefully calibrated to reduce heat gain, enhance natural ventilation, and improve daylighting. .[18]

The increasing complexity of modern architectural projects, coupled with the urgent need for sustainable practices, necessitates advanced computational approaches to manage the multifaceted interdependencies inherent in building design [28]. AI tools enable architects to integrate climate data, user behavior, and material performance into the design process, allowing them to simulate and optimize building performance before construction begins. This not only reduces the risk of costly post-construction modifications but also ensures that buildings are better adapted to their environmental context.

Furthermore, the study seeks to understand how AI applications, leveraging extensive datasets and complex algorithms, can contribute to more informed decision-making in the early stages of design, thereby fostering designs that are not only aesthetically pleasing but also inherently sustainable and resilient to environmental stressors [3]; [24]. The research presented in this paper applies these tools to a case study in Tripoli’s hot, dry climate, demonstrating how AI-driven design can achieve significant improvements in energy efficiency, natural lighting, and ventilation—ultimately reducing energy consumption compared to conventional designs. The findings highlight AI’s capacity not only to optimize performance but also to foster creativity and streamline the design process [20], [22].

1.1 Research Problem: The architectural design process in regions with challenging climates, such as Tripoli’s hot and dry environment, often struggles to balance creativity, environmental performance, and sustainability. Traditional design methods may not effectively optimize building performance in terms of energy efficiency, natural lighting, and ventilation. There is a need to explore how artificial intelligence (AI) and generative design tools can enhance decision-making and environmental outcomes in architectural practice.

1.2 Objectives: The primary objective is to investigate the efficacy of AI-driven generative design tools in optimizing building performance for sustainable design in hot, arid climates. This includes exploring the use of AI to generate and evaluate architectural designs, identify optimal material selections, and predict energy consumption to enhance environmental sustainability. Also, investigate how AI enhances architectural design quality and decision-making. Use generative design tools (e.g., Rhino/Grasshopper, Ladybug & Honeybee) for optimizing environmental performance. Demonstrate AI’s impact on energy efficiency and sustainability through a case study in Tripoli. Assess AI’s role in boosting creativity and reducing design time in architectural workflows.

1.3 Significance of the Study: This study is significant because it addresses the pressing challenges faced in architectural design within hot and dry climates like Tripoli, where traditional methods often fail to achieve optimal energy efficiency, natural lighting, and ventilation. By integrating Artificial Intelligence (AI) and generative design tools, the research offers a transformative approach to architectural practice that enhances environmental performance while maintaining creative freedom. It demonstrates how advanced computational tools can support sustainable design decisions, especially in resource-limited regions, by providing data-driven, customized solutions to complex design problems. Ultimately, the study contributes to the evolution of architectural methodologies that are better suited to extreme climates and sustainability goals.

1.4 Methodology: This study employs a computational design methodology to investigate how AI-based tools can support architectural decision-making in extreme climates. A building design case study in Tripoli’s hot, dry environment was used to apply and test the approach. Generative design software (Rhino/Grasshopper) was used with environmental analysis tools (Ladybug and Honeybee) to evaluate the model based on lighting, ventilation, and energy consumption. Local climate data informed the simulations. An evolutionary algorithm guided the selection of the optimal design by improving performance outcomes. This methodology demonstrates how AI integration enables informed, performance-driven design decisions in climate-sensitive architectural contexts.

1.5 Literature Review: Architectural design in extreme climates, such as Tripoli's hot and dry environment, demands innovative approaches to balance creativity, sustainability, and environmental performance. Traditional methods often fall short in optimizing energy efficiency, natural lighting, and ventilation. Recent studies highlight the transformative potential of artificial intelligence (AI) and generative design tools in addressing these challenges. AI enhances decision-making and design efficiency by enabling predictive modeling and data-driven optimization of building performance [30]; [3]. Tools like Rhino/Grasshopper, Ladybug & Honeybee, and Galapagos integrate environmental data—solar radiation, wind flow, and thermal comfort—into iterative design processes, supporting sustainable solutions tailored to harsh climates [21]; [26]; [17]. Generative algorithms and machine learning expand design possibilities and help identify optimal configurations that traditional methods may overlook [33]; [11]. These technologies also allow early detection of structural and performance issues, reducing risks and improving project outcomes [3]. Moreover, AI's integration into architecture and civil engineering is reshaping education and practice, with applications in urban design, construction management, and environmental resilience [16]; [27]; [13]. Research emphasizes AI's role in advancing sustainable construction and addressing global challenges like climate change and resource depletion [29]; [14]; [2]; [25].

2. Concepts and Related Terminologies

2.1Generative Design in Architecture: Generative AI, specifically, is rapidly transforming architectural design by enabling the rapid translation of conceptual ideas into visual representations and actionable data for designers [12].

2.2Environmental Performance Optimization: Its application extends to optimizing environmental performance by simulating design scenarios and predicting their impacts on factors such as energy consumption, daylighting, and thermal comfort, thereby facilitating the creation of more sustainable and resilient structures.

2.3Sustainable Design in Extreme Climates:_Furthermore, AI is increasingly leveraged for its predictive modeling capabilities to address critical urban challenges, optimize infrastructure, manage resources, and enhance urban resilience, especially in the face of rapid urbanization and climate change.

2.4Decision-Making in Architectural Design: The application of generative AI models, such as generative adversarial networks, variational autoencoders, and denoising diffusion probabilistic models, is increasingly recognized for its potential to support architectural decision-making processes [20]. This capability extends beyond mere text or 2D image generation to encompass sophisticated 3D architectural design and urban planning applications [9],[19]. These models are particularly valuable for automating 3D city modeling, generating synthetic data for urban monitoring, and facilitating generative urban design and optimization. This includes their application in areas such as transportation, energy systems, and building management, significantly contributing to the development of innovative city initiatives [32].

2.5 Artificial Intelligence (AI):_A field of computer science focused on creating systems capable of performing tasks that typically require human intelligence, such as learning, reasoning, problem-solving, and decision-making.

2.6 Architectural Design& Digital Approach : Architectural design is the conceptual and technical process of planning and creating buildings and structures that balance aesthetics, functionality, and environmental considerations to meet human needs. In contemporary practice, this process is increasingly supported by digital approaches that leverage advanced tools and technologies—such as software modeling, simulation, and data analysis—to enhance design quality, communication, and decision-making. Within architecture, these digital methods enable more precise environmental performance assessments and foster innovative, sustainable solutions, especially in challenging climates.

2.7 Environmental Performance: Generative algorithms are computational methods that use defined rules and parameters to automatically produce complex forms and design solutions, enabling the creation of multiple variations based on input constraints—commonly applied in parametric and algorithmic design. When integrated into architectural workflows, these algorithms support performance-driven design by allowing rapid exploration of environmentally responsive solutions. Environmental performance, in this context, refers to how effectively a building addresses factors such as energy efficiency, thermal comfort, daylighting, and overall sustainability. Together, generative algorithms and environmental performance metrics enable architects to optimize design outcomes that are both innovative and ecologically responsible.

2.8 Rhino/Grasshopper : Rhino, short for Rhinoceros, is a widely used 3D CAD software in architecture, known for its precision in modeling complex geometries. Grasshopper, its visual programming plugin, enables parametric design by allowing users to manipulate geometry through algorithmic and data-driven processes without traditional coding. When combined with environmental analysis plugins like Ladybug and Honeybee, Rhino/Grasshopper becomes a powerful platform for iterative, performance-driven design. These tools allow architects to simulate environmental interactions and assess design alternatives using quantifiable metrics, which is essential for optimizing building forms and systems [19]. The parametric capabilities of Grasshopper, in particular, support the exploration of diverse design options by systematically adjusting parameters, helping identify solutions that balance aesthetics, structural integrity, and environmental performance [10].

2.9 Sustainable Design: An approach to design that seeks to minimize negative environmental impact through energy efficiency, resource conservation, and the use of eco-friendly materials. It promotes long-term ecological balance and human well-being.

2.10 Ladybug and Honeybee : Ladybug and Honeybee are powerful open-source environmental plugins for Grasshopper and Rhino that support climate-responsive and performance-driven architectural design. Ladybug enables designers to visualize and analyze weather data using tools such as sun path diagrams, radiation analysis, and wind rose charts, facilitating climate-based design decisions. Honeybee extends these capabilities by integrating with simulation engines such as EnergyPlus and Radiance, allowing for detailed energy modeling, daylight simulation, and thermal comfort analysis. Together, these tools empower architects to evaluate and optimize building performance across energy efficiency, lighting quality, and occupant comfort—key factors in achieving sustainable design, especially in hot, arid climates.

3. Case Study : Environmental Assessment of a Preparatory" School in Tripoli"

In pursuit of achieving a sustainable architectural design that aligns with local climatic conditions, a proposed preparatory school model in Tajoura, Tripoli (Figs. 1, 2, 3,4,5)
was selected as a case study for the application of environmental assessment methodologies using generative design techniques. This model is part of the "Schools of the Future" initiative, implemented across different regions of Libya under the "Return of Life" plan, and supervised by the Agency for the Development and Improvement of Administrative Centers. The initiative aims to enhance the educational environment and improve the education sector's infrastructure. The case study represents a prototype for a preparatory school with a capacity of 12 classrooms. The objective of the study is to evaluate the environmental and architectural efficiency of this model and to examine its compatibility with the hot-arid local climate before the actual implementation of the project.

A three-dimensional digital model was developed using Rhinoceros 3D, while a parametric design workflow was generated via Grasshopper. Subsequently, the Ladybug and Honeybee plugins were employed to conduct a comprehensive environmental analysis covering the following aspects:

- Daylighting performance
- Natural ventilation
- Thermal performance
- Energy consumption

				
Figure . 1	**Figure . 2**	**Figure . 3**	**Figure . 4**	**Figure . 5**
Figure . 1, 2, 3 ,4 ,5 Architectural Perspectives of the School by Designer Hatem Alaswed (Alaswed,2024)				

This practical application aims to identify design shortcomings and propose architectural strategies to reduce heat loads, improve thermal and visual comfort, and minimize energy consumption.

"Acknowledgment to Mohamed Al-Naffathi for assistance with software configuration".

3.1 Methodology of Environmental Analysis

3.1.1 Digital Model Preparation: A three-dimensional model of the preparatory school was developed in Rhinoceros 3D, incorporating the main architectural elements, including classrooms, windows, roofs, corridors, and open spaces. The model was constructed after importing the executive drawings from AutoCAD. Figure6.

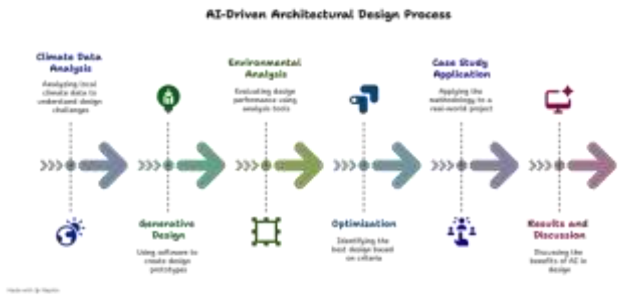


Figure.6 AI Driven architectural design process,(Author,2025)

3.1.2 Parametric Design: Through Grasshopper, a parametric Honeybee model (Figure 7,8) was generated, enabling control over key variables, including:
• Building orientation.
• Window-to-wall ratio.
• Shading depth.
• Wall thickness and material properties.

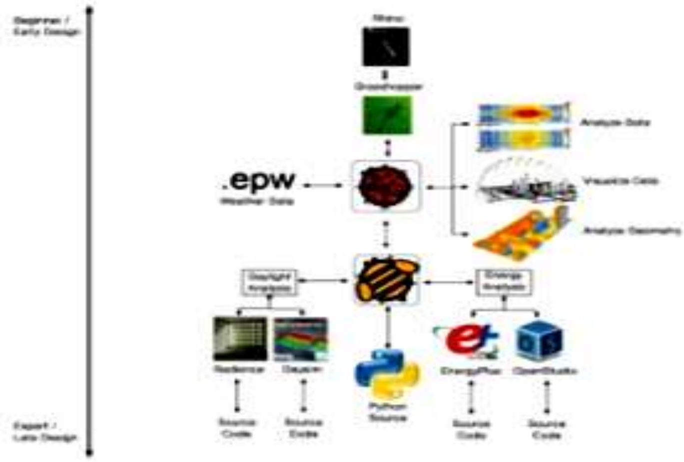


Figure7 Honeybee model ,(Author,2025)

3.1.3 Local Climate Analysis

Using Ladybug, the weather data of Tripoli was imported from the Mitiga meteorological station via an EPW file.

This file served as the primary input for linking the simulations to the actual project location. The climate data analysis focused on:
• Seasonal temperature variations
• Solar radiation
• Wind directions
• Daylight hours

Figure8 Honeybee model ,(Author,2025)

3.2 Environmental Simulations with Ladybug & Honeybee

It is important to note that the simulations were not performed for the entire building. Instead, representative classrooms were selected for each parameter, as illustrated in Figures 9, 10, 11 and 12:
• Daylighting analysis: Classrooms 3 and 6
• Thermal comfort analysis: 6 classrooms distributed across the building
• Energy consumption, natural ventilation, and direct solar radiation: Simulated for the whole building exterior.

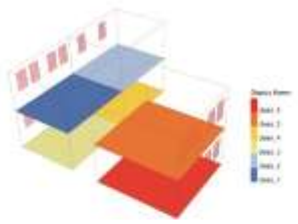


Figure9

Figure10

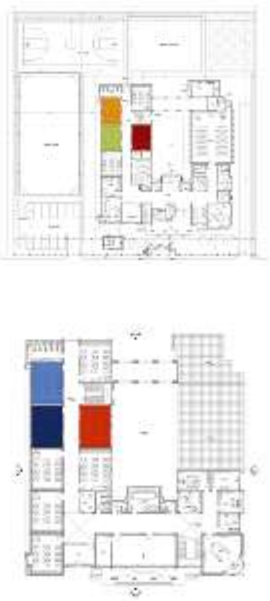


Figure11

Figure12

Figures 9, 10, 11 and 12 : Locations of selected classrooms on the floor plans ,(Authors,2025)

This approach enabled a focused, computationally efficient analysis while providing reliable insights for each environmental parameter. The selected classrooms and simulation zones are highlighted in the referenced figures.

Table1 Definitions of Abbreviated Terms in the Program ,(Authors,2025)

Nomenclature	
PMV	Predicted Mean Vote – thermal comfort index (−3 cold → +3 hot).
PPD	Predicted Percentage of Dissatisfied – % of occupants likely uncomfortable.
T_op	Operative Temperature – weighted avg. of air temp & mean radiant temp.
DA	Daylight Autonomy – % of hours daylight ≥ target (e.g., 300 lux).
sDA	Spatial Daylight Autonomy – % of floor area with DA ≥ 300 lux for ≥ 50% hours.
UDI	Useful Daylight Illuminance – % of time daylight between 100–3000 lux.
EUI	Energy Use Intensity – annual energy use per area (kWh/m²·year).
E_site	Site Energy – total energy consumed on site (electricity + fuel).
E_source	Source Energy – adjusted for generation & transmission losses.
End Uses	Heating, Cooling, Lighting, Equipment, Fans/Pumps, Hot Water.
Peak Loads	Maximum instantaneous heating/cooling demand.

3.2.1 Daylight Analysis

Daylight performance was evaluated by calculating average indoor illuminance (Lux level) and assessing uniformity and distribution. Two classrooms (No. 3 and 6) were selected for detailed daylighting analysis(Figure13,14,15, 16), using the following metrics:

• Daylight Factor (DF%): Ratio of indoor illuminance to outdoor illuminance.
• Useful Daylight Illuminance (UDI): Percentage of time illuminance levels are within the range 100–2000 Lux (comfortable daylight).
• Continuous Daylight Autonomy (cDA): Percentage of time target illuminance is achieved, considering partial values.
• Spatial Daylight Autonomy (sDA): Percentage of floor area receiving at least 300 Lux for 50% of occupied hours.

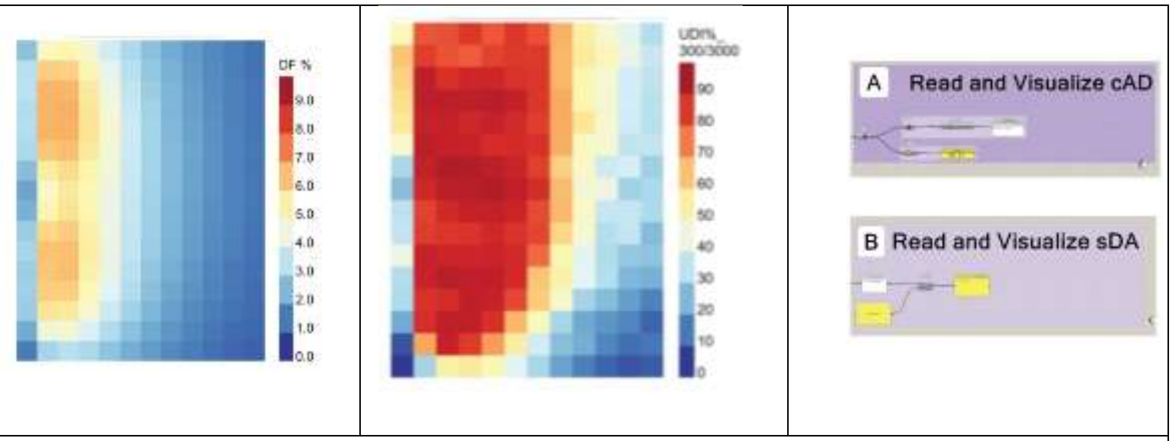


Figure13,14,15 Class 3 location west , Daylight Analysis Simulation – Time Parameters Input (Authors,2025)

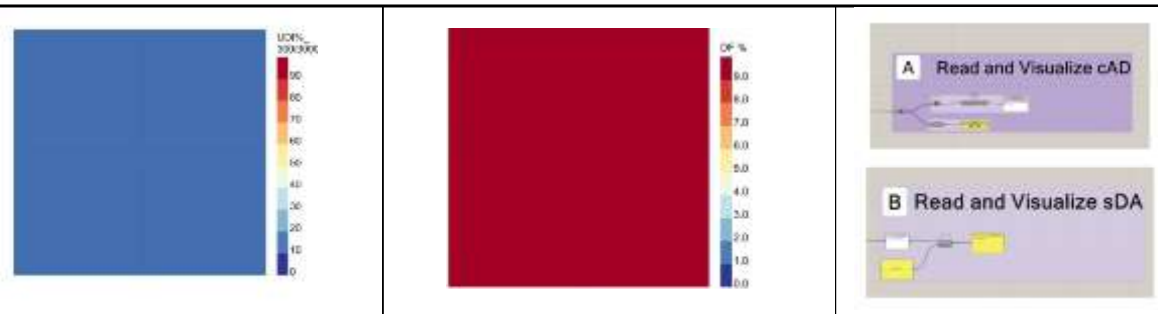


Figure 16 : Class 6 location east,(Authors,2025)

2.4.2 Glare Analysis

Glare analysis was performed using glare graphs and fisheye-lens renderings to visualize daylight distribution inside the classrooms. (Figure17-20)

• Glare refers to visual discomfort caused by excessive brightness or unbalanced light distribution.

• Glare Assessment Percentage (GA%): The percentage of occupants expected not to experience visual discomfort during occupied hours.

Figure 17 : Glare Analysis Class 3 location west
Time day 12 / 6
Clock 1 pm

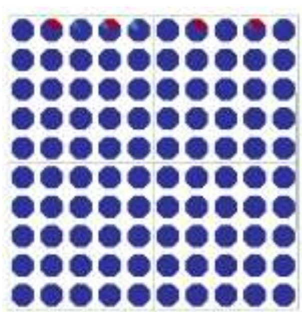


Figure 18 : Glare Analysis Class 6 location east
Time day 12 / 6
Clock 1 pm

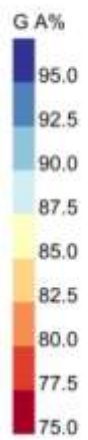


Figure 19 : Glare Analysis-Class 3

Figure 20 : Glare Analysis -Class 6

Figure 17-20: Glare Analysis Simulation – Time Parameters Input

3.2.3 Thermal Comfort Analysis
Thermal performance was assessed by comparing indoor and outdoor temperature variations and identifying hours of thermal comfort or discomfort based on ASHRAE 55 standards. The analysis included:
• Operative Temperature: A combined indicator of air temperature and mean radiant temperature.

•**PMV (Predicted Mean Vote):** Reflects the average thermal sensation of occupants on a scale from –3 (cold) to +3 (hot), with 0 representing optimal comfort. (Figures 21-28).

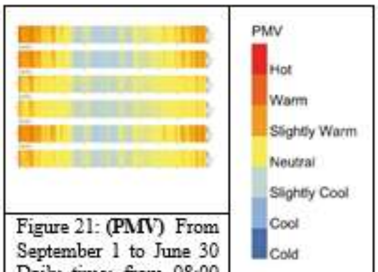
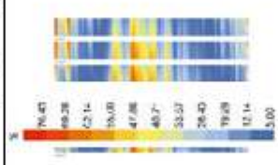
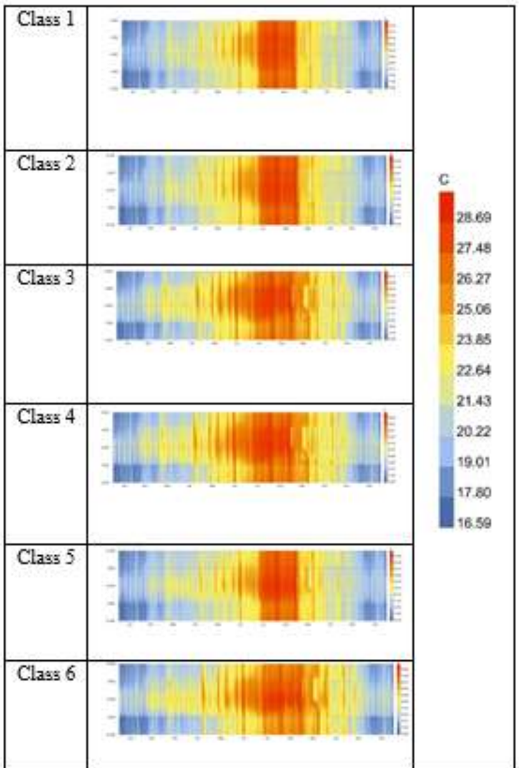


Figure 21: **(PMV)** From September 1 to June 30 Daily time: from 08:00 a.m. to 02:00 p.m.

Figure 22: (PMV) Class1-6





Figures 23,24,25,26,27,28: **(PMV)** Simulation – Time Parameters Input , 1/1 – 30/12 TIME 24H

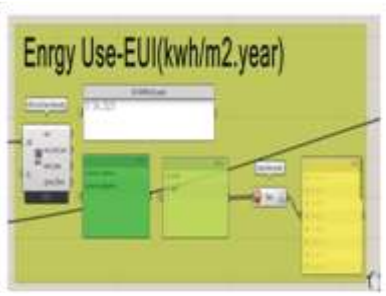
• **PPD (Predicted Percentage of Dissatisfied):** Estimates the proportion of occupants thermally dissatisfied, even under optimal comfort conditions (minimum 5%).

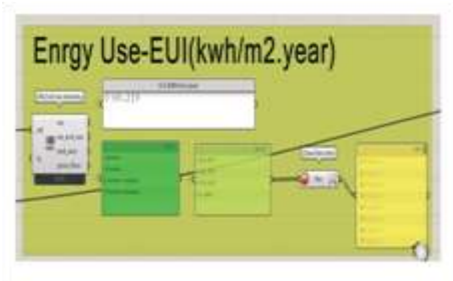
The analysis covered the academic year from September 1 to June 30, during typical classroom hours (08:00–14:00), with an assumed occupancy of 24 students per classroom.

3.2.4 Energy Consumption

Annual energy consumption was simulated using Honeybee, with the following objectives:

• Estimating total energy use (kWh/m²/year).
• Identifying major energy loads (cooling, heating, lighting, ventilation).
• Comparing baseline and improved models.





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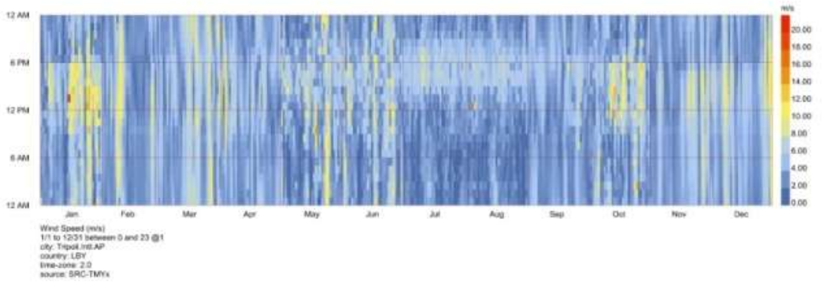
Figures 29,30 Energy Consumption Model – Parameters Input

3.2.5 Natural Ventilation

Natural ventilation was assessed
through airflow simulations, evaluating:

• Air change rate (ACH) for classrooms, with a target of ≥ 6 ACH for optimal indoor air quality.



Figures 31 : Air Change Rate (ACH) Simulation for Natural Ventilation

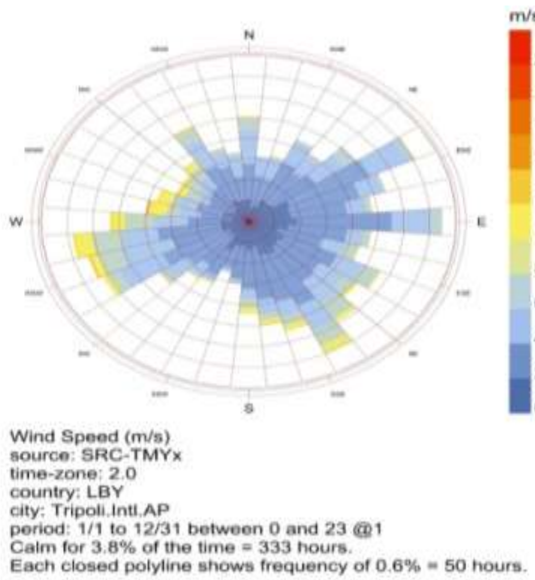


Figure 32 : Wind Rose Diagram Showing Prevailing Wind Direction and Speed3.2.6 Sky Dome and Outdoor Thermal Comfort

A sky dome analysis was conducted to assess direct sun exposure and shading patterns throughout the year. Outdoor thermal comfort was evaluated under different climatic scenarios (sun + wind, sun without wind, etc.) to understand the usability of outdoor spaces for students.

door
Seted 1 / jun to 30 des /24h

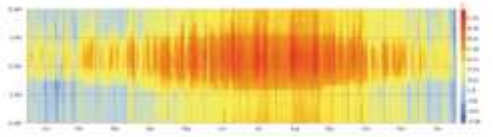


Figure 35:Sun + Wind + Humidity

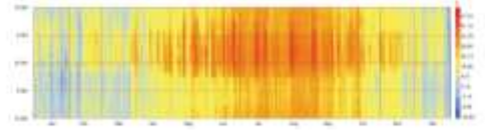


Figure 36:No Sun + Wind + Humidity

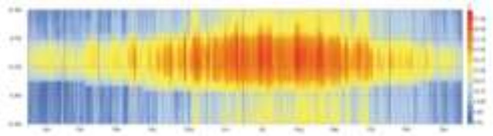


Figure 37:Sun + No Wind + Humidity

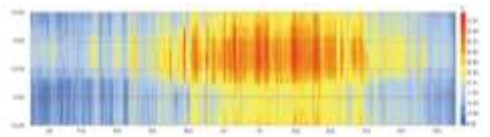


Figure 38:No Sun + No Wind + Humidity

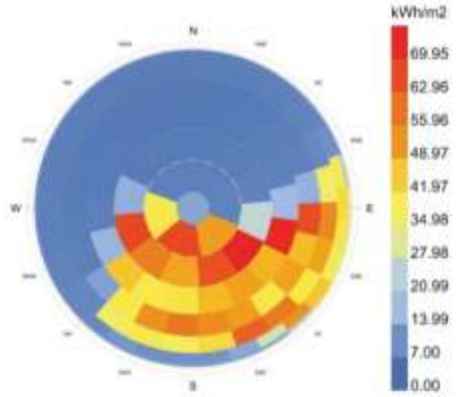


Figure 33 : Sky Dome Radiation Analysis – Direct Sun Exposure Patterns

Figure 35-40:Outdoor Thermal Comfort Evaluation
Thermal comfert out door
standing
Seted 1 / jun to 30 des /24h

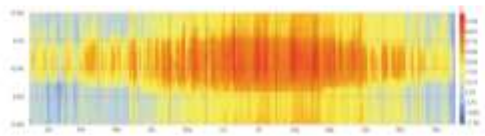


Figure 34:Sun + wind + humidity

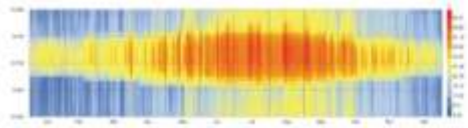


Figure 39:Sun + no wind + humidity

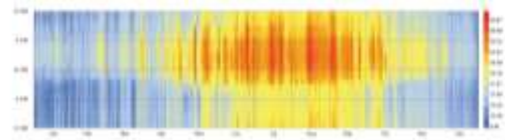


Figure 40:no Sun + no wind + humidity

Incident Radiation

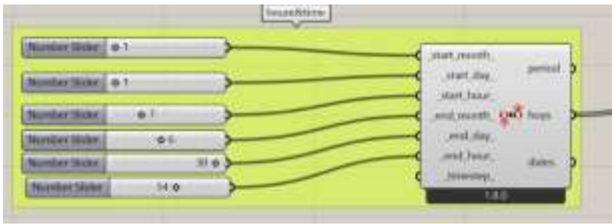


Figure 41: Incident Radiation Simulation – Time Parameters Input

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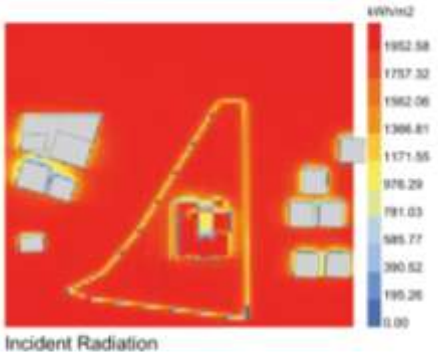


Figure 42: Incident Radiation Results – Base Model

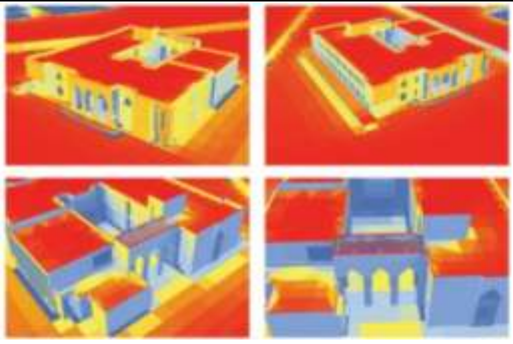


Figure 43: Incident Radiation Results – Base Model

DIRECT SUN HOURS

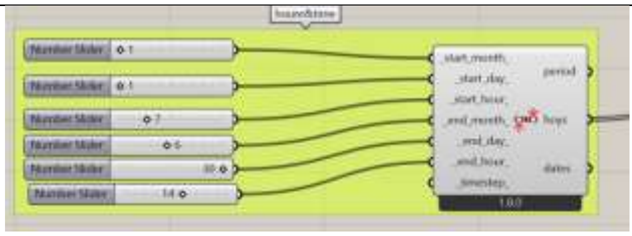
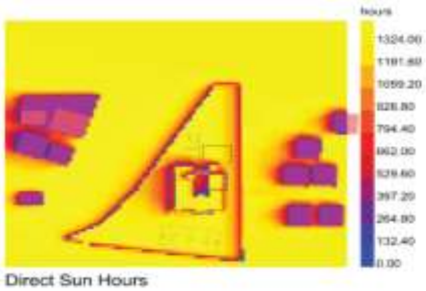
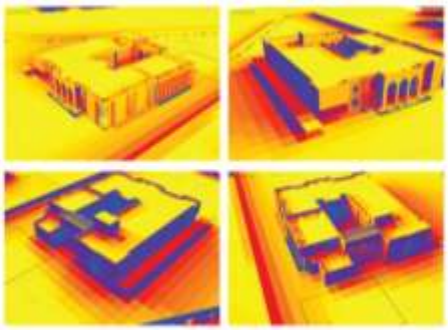


Figure 44: Direct Sun Hours Simulation – Time Parameters Input

Figure 45,46: Direct Sun Hours Results – Base Model





4. Results of the Environmental Analysis

4.1 Model (Before Improvement)

Daylighting (Lux): 230–280 (insufficient)
Thermal Comfort: 35% of occupied hours within comfort range
Ventilation Rate (ACH): 3
Energy Consumption (kWh/m²/year): 92

4.2 Improved Model (After Enhancement)

Improvements applied: reorienting the building, optimizing window locations and adding shading devices, using thermally efficient materials.
Daylighting (Lux): 320–380 (very good)
Thermal Comfort: 62% of occupied hours within comfort range
Ventilation Rate (ACH): 6–8
Energy Consumption (kWh/m²/year): 64

4.3 Comparison Between Baseline and Improved Models

Average Daylighting: ↑ ~30%
Hours of Thermal Comfort: ↑ ~77%
Ventilation Rate (ACH): ↑ 2–2.5×
Energy Consumption: ↓ ~30%

4.4 Key Observations

The baseline design showed insufficient daylighting and ventilation, as well as high energy consumption. Applying generative design and environmental analysis allowed for significant improvements in indoor environmental quality and energy efficiency.

5. Conclusion of the Practical Section

The environmental analysis of the preparatory school prototype in Tripoli revealed that the initial design did not fully respond to the local hot-arid climate. Issues were observed in natural lighting, ventilation, and high energy consumption. However, the application of generative design tools and environmental simulations provided an effective approach to identify design shortcomings and implement targeted improvements prior to construction. The enhanced model demonstrated significant benefits:

-Improved natural lighting levels across classrooms
-Increased thermal comfort for students and staff
-Enhanced natural ventilation and air quality
-Reduced annual energy consumption by approximately 30%.

This case study highlights the importance of integrating digital modeling and environmental assessment tools in the early stages of architectural design, especially for educational buildings, ensuring a sustainable and comfortable learning environment while optimizing resource use and energy efficiency.

Benefits of AI-Enhanced Decision-Making

This approach demonstrates how computational tools can significantly reduce reliance on mechanical cooling systems by integrating climate-responsive principles derived from traditional architectural wisdom [5] ; [6]; [15]. Moreover, the integration of AI allows for the rapid exploration of a vast solution space, enabling designers to discover novel configurations that might not be intuitively apparent [1]. This accelerated exploration capability is crucial for identifying high-performing passive strategies in challenging climates [8].

Challenges and Limitations

Despite the significant advancements and numerous benefits, the integration of AI into architectural design processes also presents several challenges and limitations that warrant careful consideration. One such limitation pertains to the computational intensity required for complex simulations and optimizations, which can be prohibitive for smaller firms or projects with limited resources.

Future research directions:

Building on these findings, future research could explore the integration of real-time sensor data with AI models to enable adaptive building performance in response to dynamic environmental conditions and occupant behavior. This could lead to the development of self-optimizing buildings that continuously adapt their operational strategies to maintain optimal environmental performance and user comfort. Additionally, investigating the scalability of these AI-driven design methodologies to urban planning levels, considering a broader range of environmental and social factors, would provide a more holistic understanding of their potential impact.

Conclusion:

This research demonstrates the transformative potential of AI-enhanced architectural decision-making in optimizing environmental performance and promoting sustainable design, particularly in hot, arid climates like Tripoli. By integrating generative design tools and optimization algorithms into early design stages, architects can incorporate complex environmental data to achieve measurably improved building performance. The study highlights the pivotal role of AI technologies—including machine learning and advanced algorithms—in managing energy consumption and enabling smart buildings to adapt to changing conditions through informed, real-time decisions [14]. It further emphasizes the importance of interdisciplinary collaboration among architects, data scientists, and engineers to fully leverage AI's capabilities in creating resilient, resource-efficient built environments [3]. These findings support a paradigm shift in architectural practice toward AI-augmented design processes, advancing environmental governance and long-term sustainability goals [25].

Results and Recommandations:

The study found that Ladybug and Honeybee offer a dynamic and flexible approach to building performance simulation, particularly suited to early design stages. Unlike traditional simulation tools, their parametric and visual programming environment encourages experimentation and supports interdisciplinary design thinking. These tools successfully provided performance feedback on lighting, ventilation, and energy consumption, helping guide design decisions.

- The simulations demonstrated that Ladybug and Honeybee can effectively reduce heat gain, enhance natural lighting, and improve ventilation, contributing to more energy-efficient design outcomes. Their integration within Rhino/Grasshopper allowed for a seamless workflow, enabling iterative design and optimization using evolutionary algorithms.
- However, while powerful, the tools the study uses present a learning curve for users unfamiliar with computational design. Additionally, due to the limited scope and subjective nature of the research, certain aspects, such as interoperability and complex design scenarios, were not fully explored.
- Ladybug and Honeybee are powerful tools for simulating environmental performance in architecture, especially during early design stages. Integrated with Rhino/Grasshopper, they allow designers to explore multiple options and assess factors like solar exposure, daylighting, ventilation, and energy use. Their flexibility makes them especially valuable in academic and research contexts where experimentation is essential.
- Recent updates have expanded Ladybug and Honeybee's capabilities, including seamless integration with advanced simulation engines like Radiance, EnergyPlus, and OpenFOAM. They now also support interactive 3D graphics and data visualizations, making environmental feedback more intuitive and visually engaging.
- Educational Integration: Ladybug and Honeybee should be incorporated into architectural education to familiarize students with performance-based design in parametric environments.
- Early Design Use: These tools are best utilized during the conceptual and early design phases, where performance feedback can inform creative decisions without the constraints of finalized models.
- Professional Training: For broader adoption in practice, training programs should be developed to bridge the gap between traditional design workflows and parametric simulation tools.
- Tool Development: Continued development of Ladybug and Honeybee should focus on improving usability, enhancing interoperability, and supporting whole-building simulations for certification and financial assessment.
- Invest in Training for Broader Adoption
- Provide training for architects and students to overcome the learning curve associated with parametric design and visual programming interfaces.
- This study recommends beginning the architectural design process with a clear understanding of environmental factors and site context to guide responsible early-stage decisions. Designers should adopt parametric tools like Rhino/Grasshopper to enable flexible, iterative workflows and integrate environmental analysis plugins such as Ladybug directly into the design environment. These tools provide real-time feedback, helping designers make informed choices that enhance sustainability. Ensuring accessibility and usability of these open-source tools promotes wider adoption and fosters collaboration, ultimately supporting the creation of resilient, energy-efficient buildings.
- The study advocates for a deeper integration of AI in architectural pedagogy and practice, emphasizing the development of interdisciplinary curricula that equip future architects with the necessary computational skills and ethical frameworks to leverage these transformative technologies effectively. This necessitates a paradigm shift in architectural education to prepare students for a future where AI plays a central role, ensuring human insight and creativity remain paramount [4], [7]. This shift must also acknowledge the potential for AI to lead to standardization if not approached with critical engagement, thereby risking a reduction in creative depth rather than fostering vertical growth in architectural epistemology [23]. Moreover, the pedagogical adoption of AI tools, has been shown to significantly enhance students' creative expression, technical mastery, and overall design understanding, providing a new technological perspective for architectural design education [32].

Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare that they have no conflict of interest.

References

1. Abro, R. S. (1994). Recognition of passive cooling techniques. Renewable Energy. https://doi.org/10.1016/0960-1481(94)90142-2

2.Akter, Most. S. (2024). Harnessing Technology for Environmental Sustainability: Utilizing AI to Tackle Global Ecological Challenge. Deleted Journal, . https://doi.org/10.60087/jaigs.v2i1.97

3. Almaz, A. H., El-Agouz, E. A. E., Abdelfatah, M. T., & Mohamed, I. (2024). The Future Role of Artificial Intelligence (AI) Design's Integration into Architectural and Interior Design Education is to Improve Efficiency, Sustainability, and Creativity. Civil Engineering and Architecture . https://doi.org/10.13189/cea.2024.120336

4.Asfour, O. S. (2024). How Artificial Intelligence Could Affect the Future of Architectural Design Education. Resourceedings, . https://doi.org/10.21625/resourceedings.v4i2.1113

5.Bouabdallah, N., Houda, M., & Alkama, D. (2016). Biomimicry as an approach for sustainable architecture case of arid regions with hot and dry climate. AIP Conference Proceedings, . https://doi.org/10.1063/1.4959379

6.Fardeheb, F. (2008). Examination and Review of Passive Solar Cooling Strategies in Middle Eastern and North African Vernacular Architecture. In Springer eBooks (p. 2511). Springer Nature. https://doi.org/10.1007/978-3-540-75997-3_508

7.Fareed, M. W., Nassif, A. B., & Nofal, E. (2024). Exploring the Potentials of Artificial Intelligence Image Generators for Educating the History of Architecture. Heritage, . https://doi.org/10.3390/heritage7030081

8.Foudazi, F., & M'Rithaa, M. K. (2013). Sustainable cooling solutions for application in Western Cape Province, South Africa. International Journal of Sustainable Development . https://doi.org/10.1504/ijsd.2013.056565

9.Fu, Y. (2025). Towards AI Urban Planner in the Age of GenAI, LLMs, and Agentic AI. https://doi.org/10.48550/ARXIV.2507.14730

10.Furmanek, A. F. (2021). Basic reflections on the implementation of different 3D technologies co-operating in the architectural design process. IOP Conference Series Materials Science and Engineering. https://doi.org/10.1088/1757-899x/1203/3/032137

11.Feng, G., & Yan, W. (2024). Text2VP: Generative AI for Visual Programming and Parametric Modeling. arXiv (Cornell University). https://doi.org/10.48550/arxiv.2407.07732

12.Gupta, R., & Kyaw, A. H. (2025). Insights Informed Generative AI for Design: Incorporating Real-world Data for Text-to-Image Output. https://doi.org/10.48550/ARXIV.2506.15008

13.He, M., Liang, Y., Wang, S., Zheng, Y., Wang, Q., Zhuang, D., Tian, L., & Zhao, J. (2025). Generative AI for Urban Design: A Stepwise Approach Integrating Human Expertise with Multimodal Diffusion Models. https://doi.org/10.48550/ARXIV.2505.24260

14.Iluyomade, T. D., & Okwandu, A. C. (2024). Smart buildings and sustainable design: Leveraging AI for energy optimization in the built environment. International Journal of Science and Research Archive. https://doi.org/10.30574/ijsra.2024.12.1.1049

15.Izadpanahi, P., Farahani, L. M., & Nikpey, R. (2021). Lessons from Sustainable and Vernacular Passive Cooling Strategies Used in Traditional Iranian Houses. Journal of Sustainability Research, 3(3). https://doi.org/10.20900/jsr20210014

16.Jin, S., Tu, H., Li, J., Fang, Y., Zhang, Q., Xu, F., Liu, K., & Lin, Y. (2024). Enhancing Architectural Education through Artificial Intelligence: A Case Study of an AI-Assisted Architectural Programming and Design Course. Buildings . https://doi.org/10.3390/buildings14061613

17.Khidmat, R. P., Fukuda, H., Kustiani, K.-, & Wibowo, A. P. (2021). A Benchmark Model for Predicting Building Energy and Daylight Performance in The Early Phase of Design Utilizing Parametric Design Exploration. IOP Conference Series Earth and Environmental Science. https://doi.org/10.1088/1755-1315/830/1/012008

18.Komatina, D., Miletić, M., & Ružičić, M. M. (2024). Embracing Artificial Intelligence (AI) in Architectural Education: A Step towards Sustainable Practice? Buildings . https://doi.org/10.3390/buildings14082578

19.Ko, J., Ajibefun, J., & Yan, W. (2023). Experiments on Generative AI-Powered Parametric Modeling and BIM for Architectural Design. arXiv (Cornell University). https://doi.org/10.48550/arxiv.2308.00227

20.Li, Y., Chen, H., Yu, P., & Yang, L. (2025). A Review of Artificial Intelligence in Enhancing Architectural Design Efficiency [Review of A Review of Artificial Intelligence in Enhancing Architectural Design Efficiency]. Applied Sciences. Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/app15031476

21.Lee, S., Choi, B., Maia, C., Park, J., Youm, S. H., & Lee, S. (2021). Integrating simulation into design: an experiment in pedagogical environments. International Journal of Technology and Design Education. https://doi.org/10.1007/s10798-021-09682-6

22.Maksoud, A., Al-Beer, H. B., Mushtaha, E., & Yahia, M. W. (2022). Self-learning Buildings: integrating Artificial Intelligence to create a building that can adapt to future challenges. IOP Conference Series Earth and Environmental Science. https://doi.org/10.1088/1755-1315/1019/1/012047

23.Moussaoui, M. E. (2025a). Future Illiteracies -- Architectural Epistemology and Artificial Intelligence. https://doi.org/10.48550/ARXIV.2507.23434

24.Netser, Y., Hameen, E. C., & Tang, P. (2025). Socio-Sustainable Architectural Design Through Ethical Implementation of Generative Design and Artificial Intelligence. 1(1). https://doi.org/10.7771/3067-4883.1095

25.Nishant, R., Kennedy, M., & Corbett, J. (2020). Artificial intelligence for sustainability: Challenges, opportunities, and a research agenda. International Journal of Information Management. https://doi.org/10.1016/j.ijinfomgt.2020.102104

26.Panya, D. S., Kim, T., & Choo, S. (2020). A Methodology of Interactive Motion Facades Design through Parametric Strategies. Applied Sciences. https://doi.org/10.3390/app10041218

27.Parekh, R., & Mitchell, O. (2024). Progress and obstacles in the use of artificial intelligence in civil engineering: An in-depth review. International Journal of Science and Research Archive. https://doi.org/10.30574/ijsra.2024.13.1.1777

28.Płoszaj-Mazurek, M., & Ryńska, E. (2024). Artificial Intelligence and Digital Tools for Assisting Low-Carbon Architectural Design: Merging the Use of Machine Learning, Large Language Models, and Building Information Modeling for Life Cycle Assessment Tool Development. Energies. https://doi.org/10.3390/en17122997

29.Regona, M., Yiğitcanlar, T., Hon, C. K. H., & Teo, M. (2024). Artificial intelligence and sustainable development goals: Systematic literature review of the construction industry. Sustainable Cities and Society. https://doi.org/10.1016/j.scs.2024.105499

30.Rane, N., Choudhary, S., & Rane, J. (2023). Leading-edge technologies for architectural design: a comprehensive review [Review of Leading-edge technologies for architectural design: a comprehensive review]. SSRN Electronic Journal. RELX Group (Netherlands). https://doi.org/10.2139/ssrn.4637891

31.Roudsari,m .pak,m.smith,a. (2013) Ladybug: A parametric environmental plug-in for Grasshopper to help designers create an environmentally-conscious design . Gordon gill Architecture. Chicago.USA

32.Xu, C. Q., & Huang, Y. (2024). Technological Innovation in Architectural Design Education: Empirical Analysis and Future Directions of Midjourney Intelligent Drawing Software. Buildings,. https://doi.org/10.3390/buildings14103288

33.Xie, X., Yang, N., & Zhang, T. (2025). Machine-Learning-Enhanced Building Performance-Guided Form Optimization of High-Rise Office Buildings in China’s Hot Summer and Warm Winter Zone—A Case Study of Guangzhou. Sustainability, . https://doi.org/10.3390/su17094090