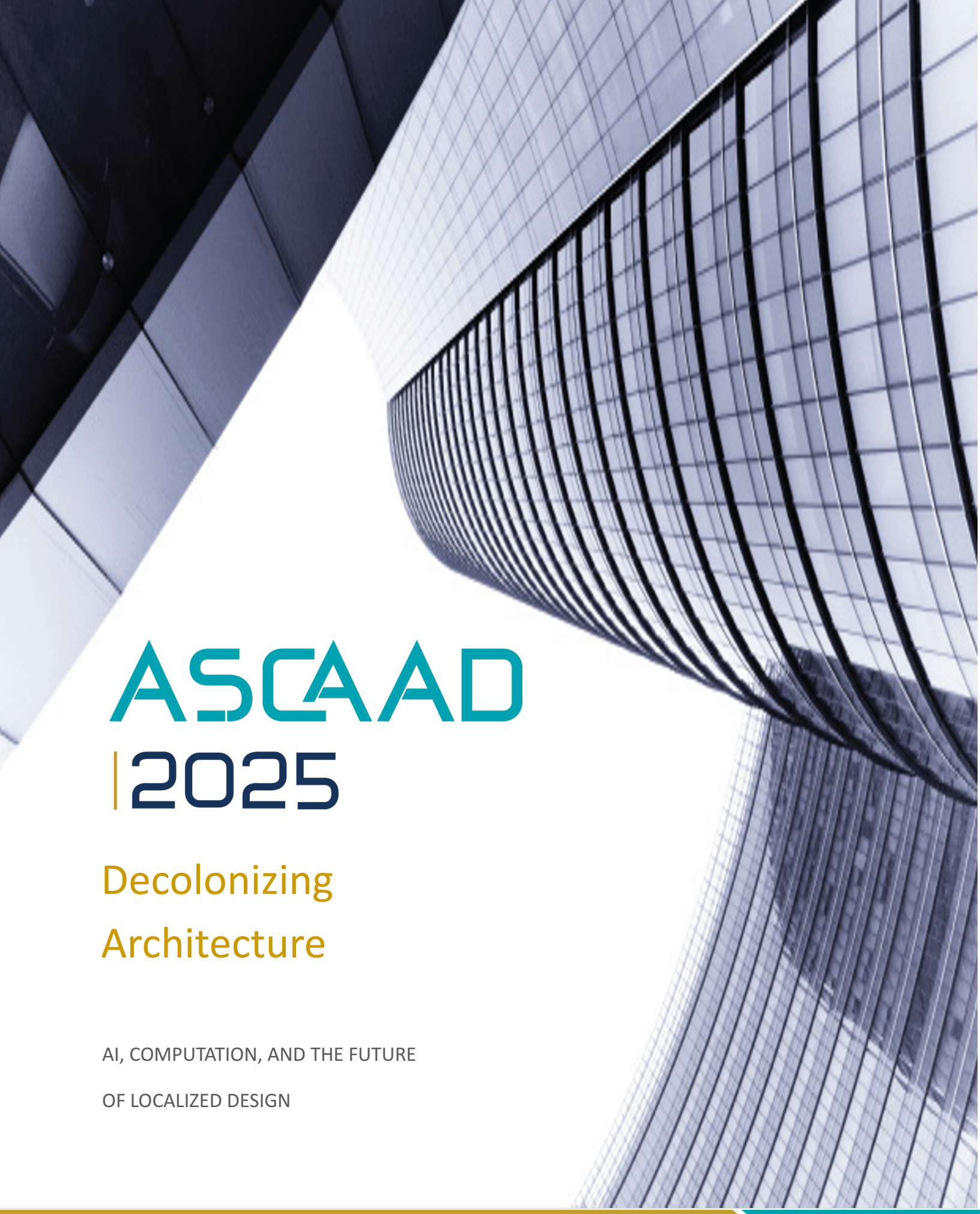


ASCAAD 2025

Decolonizing Architecture

AI, COMPUTATION, AND THE FUTURE

OF LOCALIZED DESIGN



PROCEEDINGS

The 13th ASCAAD Conference

Decolonizing Architecture

AI Computation and the Future of Localized Design

IN-PERSON CONFERENCE

21-23 October 2025

Riyadh, Saudi Arabia

Alfaisal University

EDITED BY

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Articles edited in this volume were refereed by members of the International Scientific Review Committee in a process that involve detailed reading of the papers, reporting of comments to authors and modifications of manuscripts by authors. The re-evaluation of resubmitted articles was done by the scientific committee members to ensure quality of content.

ORGANIZATION





ASCAAD
ARAB SOCIETY FOR COMPUTATION IN ARCHITECTURE, ART, AND DESIGN

ABOUT ASCAAD

ASCAAD is a society of those who teach, conduct research and practice in computer-aided architectural design (CAAD) in the Arab World regions of West Asia, and North Africa. ASCAAD is also active in Central Asia, Sub-Sahara Africa, and the Mediterranean. The society holds conferences and educational events that will be hosted by a different University each time. The output of the conferences and contributions from the educational events be published as a Conference Proceedings book. ASCAAD aims to facilitate communication and information exchange regarding the use of digital design technology in architecture, planning and building science that are dramatically challenging our fundamental assumptions, theories, and practices of conventional design paradigm.

أسكاد هي جمعية لأساتذة التدريس و المهندسين و القائمين بالبحث في مجال التصميم المعماري بمساعدة الحاسوب في كليات العمارة والتصميم والهندسة في العالم العربي بشطريه في غرب قارة آسيا و شمال إفريقية. ينشط أسكاد كذلك في مناطق وسط آسيا و جنوب الصحراء الافريقية و حوض البحر الأبيض المتوسط. تعقد الجمعية المؤتمرات والفعاليات التعليمية التي ستستضيفها جامعة مختلفة في كل مرة، و يتم نشر مخرجات المؤتمرات والمساهمات من الأحداث التعليمية ككتاب وقائع المؤتمر. وتهدف أسكاد إلى تسهيل التواصل وتبادل المعلومات فيما يتعلق باستخدام تكنولوجيا التصميم الرقمي في الهندسة المعمارية والتخطيط وعلوم البناء التي تتحدى بشكل كبير افتراضاتنا ونظرياتنا وممارساتنا لنموذج التصميم التقليدي.

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PREFACE

This book comprises the Proceedings of the 13th International Conference of the Arab Society for Computation in Architecture, Art and Design (ASCAAD 2025), held as an in-person event, from October 21-23, 2025, at Alfaisal University, Riyadh, Saudi Arabia. The proceedings contain the 43 accepted papers. All papers will also be available digitally at CumInCAD (Cumulative Index of Computer Aided Architectural Design) – http://papers.cumincad.org.

Conference Theme

The ASCAAD 2025 theme focuses on ***Decolonizing Architecture: AI, Computation, and the Future of Localized Design.*** Architecture has long been shaped by Eurocentric narratives, from the dominance of Western architectural styles to colonial planning models that continue to influence cities worldwide. These biases extend into contemporary design, often marginalizing local identities, indigenous knowledge, and vernacular traditions. With artificial intelligence (AI), computational design, and data-driven methodologies rapidly transforming the built environment, there is an urgent need to assess whether these technologies will reinforce or dismantle architectural hegemony. AI has the potential to serve as a tool for decolonization by fostering localized, inclusive, and sustainable design practices, shifting digital tools from mechanisms of globalized homogeneity to platforms for cultural empowerment.

Indigenous architectural traditions, shaped by centuries of adaptation and deep ecological understanding, have often been overlooked in mainstream architectural discourse. AI can help integrate and elevate these traditions by learning from indigenous spatial arrangements, passive cooling strategies, and biomimetic design principles. Generative design tools can incorporate handcrafted elements and local construction techniques, ensuring that contemporary architecture does not erase cultural identity but rather builds upon it. Similarly, computational design presents an opportunity to encode traditional motifs, spatial configurations, and historic morphologies into AI-generated models. When thoughtfully guided, these digital tools can act as powerful instruments of cultural storytelling, preserving and evolving heritage rather than erasing it.

One of the significant challenges in AI-driven design is the bias embedded within its training datasets. Since most AI models are trained on predominantly Western architectural data, they often fail to recognize or adequately represent non-Western forms. This perpetuates a cycle where AI-generated designs reinforce existing aesthetic and spatial hierarchies rather than diversifying architectural expression. Overcoming this bias requires actively curating diverse datasets that include non-Western typologies and materials. Furthermore, it is essential to address the ethical implications of AI-driven design, ensuring that indigenous and vernacular architectural elements are not appropriated without proper attribution.

Colonial urban planning models have left lasting legacies of spatial segregation, inequitable land distribution, and environmental degradation. AI and spatial analytics can play a critical role in reimagining cities with a focus on inclusivity, sustainability, and cultural specificity. By identifying and addressing post-colonial spatial injustices, AI can aid in reclaiming and regenerating urban spaces in ways that align with local needs. However, smart city initiatives must

be critically examined to ensure that they do not simply impose another layer of technological colonialism but instead integrate indigenous and community-driven planning principles. Digital twin technologies offer additional potential, allowing for the reconstruction and reinterpretation of urban morphologies to reflect more equitable and historically conscious planning approaches.

AI-driven material optimization and digital fabrication provide further opportunities to rethink construction practices in ways that align with local sustainability goals. Traditional building materials and methods, often dismissed in favor of industrialized Western alternatives, can be revived through machine learning applications that optimize their structural and environmental performance. 3D printing, CNC machining, and robotic construction can empower regional material economies, reducing reliance on imported materials and fostering localized innovation. By repositioning AI and digital fabrication as tools for ecological and cultural sustainability, architecture can move away from imposed, unsustainable practices toward more context-driven solutions.

The decolonization of architecture through AI is not solely a technological issue—it is fundamentally about agency and ethical responsibility. The critical question remains: who controls the design process, and who benefits from AI-driven advancements? Ensuring that AI-generated designs include local voices, community participation, and culturally responsive methodologies is crucial to avoiding digital colonialism. Regulatory frameworks must be established to guide the ethical deployment of AI in architecture, ensuring that computational design empowers rather than marginalizes communities.

Ultimately, AI and computational tools are not inherently colonial or decolonial; their impact depends on how they are developed and implemented. This theme envisions a future where AI is not merely a tool for efficiency but a means to critically interrogate, reconstruct, and amplify architectural traditions that have been historically marginalized. By embracing localized intelligence, cultural specificity, and ethical AI deployment, the future of architecture can move beyond inherited biases to create more inclusive, resilient, and contextually rich built environments.

The ASCAAD 2025 conference invites submissions of original research papers to address the following topics including but not limited to:

1. AI & Computational Design in Architecture

- AI-driven generative design
- Computational design methodologies
- parametric modelling
- Graph machine learning
- Bias in AI training datasets
- AI-assisted sustainable and energy-efficient

2. Digital Fabrication & Construction Technology

- 3D printing, CNC machining, and robotic fabrication
- Integrating AI with digital fabrication

3. Decolonizing Architecture & Localized Design

- Challenging Eurocentric architectural narratives
- AI as a tool for promoting indigenous.
- Localized material innovation
- Ecological sustainability
- Ethical implications of AI on cultural preservation

4. Building Information Modeling (BIM) & Graph Machine Learning

- Safety data into BIM and CAD models
- AI-enhanced decision-making in construction management

5. Urbanism & Smart Cities

- AI and spatial analytics in urban planning
- Smart cities and their potential risks of digital colonialism
- Post-colonial spatial injustices and AI-driven urban regeneration
- Digital twins for historically and culturally conscious urban design

6. Architectural Education & Pedagogy

- Integrating AI and computation into architectural curricula
- Balancing traditional and digital design skills in education
- AI as a pedagogical tool in architecture and urban studies
- Interdisciplinary approaches in architectural education

7. Energy & Sustainability in Architecture

- ML applications for energy
- AI optimization for carbon footprint reduction
- Adaptive and climate-responsive architecture

8. Decolonizing Architecture & Localized Design

- Situating Architecture within Philosophy of Technology

9. Digital Space and Virtual Environments

- Architecture of the Metaverse
- Virtual Architecture
- Transformations in the Nature of Architectural Space
- Architectural Space in Digital Games
- The Future of Architectural Spatiality

10. AI in Art & Geometry

- AI-generated artistic and geometric.
- AI exploration geometric patterns.
- Algorithmic design and computational aesthetics
- AI, art, and architectural expression

11. Research & Industry Collaboration

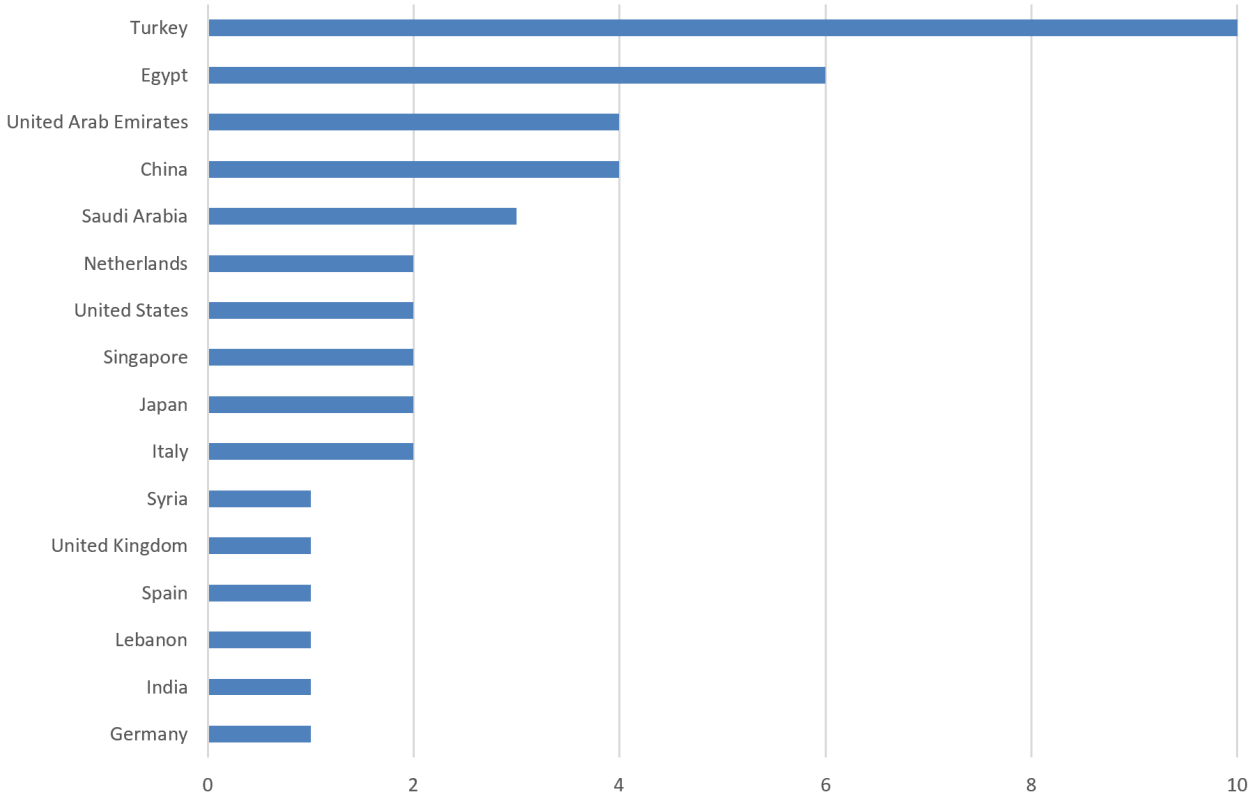
- Industry-academia partnerships.
- Bridging research gaps between architecture and digital technology
- Policy frameworks for ethical AI in architecture

Submissions and Statistics

The conference theme of ASCAAD 2025 at Alfaisal University, Riyadh, Saudi Arabia, has incited wide interest regionally and globally. A double-blind peer review process was implemented using the *OpenConf* system. In the first round of submissions, authors were asked to send abstracts (in English or Arabic) with a maximum of 500 words and one figure. We received in this stage **117 abstracts**. All abstracts were sent anonymously to at least 2 international referees per abstract and were checked in accordance with the quality measures set out for submissions by ASCAAD.

As a result, a total of **109 abstracts** were forwarded to the second round of peer review process, where they were invited to submit full paper submissions that describe well-developed or completed research (max. 3000-5000 words). Full paper submissions were sent anonymously and were reviewed by two to three international referees. The review process was only possible with the generous and professional contribution of the reviewing committee consisting of a total of **55 expert referees** from around the globe.

A final number of **43 full papers** by **110 authors** representing **16 countries** from the Middle East, Europe, Asia, and North America were identified by the ASCAAD 2025 scientific committee and were invited to submit camera-ready papers.



ASCAAD 2025 full paper submissions by country (based on contact author data)

Out of the 43 full paper submissions, 7 papers (**16.28%**) were predominantly focused on "**Topic 1: AI & Computational Design in Architecture**", involving aspects related to AI-driven generative design, computational design methodologies, parametric modeling, graph machine learning, bias in AI training datasets, and AI-assisted sustainability and energy efficiency.

7 papers (**16.28%**) were predominantly focused on "**Topic 2: Digital Fabrication & Construction Technology**", involving aspects of 3D printing, CNC machining, robotic fabrication, and integrating AI with digital fabrication.

7 papers (**16.28%**) were predominantly focused on "**Topic 6: Architectural Education & Pedagogy**", involving aspects related to integrating AI and computation into architectural curricula, balancing traditional and digital design skills in education, AI as a pedagogical tool in architecture and urban studies, and interdisciplinary approaches in architectural education.

5 papers (**11.63%**) were predominantly focused on "**Topic 3: Decolonizing Architecture & Localized Design**", involving aspects related to challenging Eurocentric architectural narratives, AI as a tool for promoting the indigenous, localized material innovation, ecological sustainability, and the ethical implications of AI on cultural preservation.

5 papers (**11.63%**) were predominantly focused on "**Topic 4: Building Information Modeling (BIM) & Graph Machine Learning**", involving aspects related to safety data into BIM and CAD models, and AI-enhanced decision-making in construction management.

5 papers (**11.63%**) were predominantly focused on "**Topic 9: Digital Space & Virtual Environments**", involving aspects related to the architecture of the metaverse, virtual architecture, transformations in the nature of architectural space, architectural space in digital games, and the future of architectural spatiality.

4 papers (**9.30%**) were predominantly focused on "**Topic 5: Urbanism & Smart Cities**", involving aspects related to AI and spatial analytics in urban planning, smart cities and their potential risks of digital colonialism, post-colonial spatial injustices and AI-driven urban regeneration, and digital twins for historically and culturally conscious urban design.

3 papers (**6.98%**) were predominantly focused on "**Topic 7: Energy & Sustainability in Architecture**", involving aspects related to machine learning applications for energy, AI optimization for carbon footprint reduction, and adaptive and climate-responsive architecture.

FOREWORD – ASCAAD

Dear ASCAAD friends,

The 13th International Conference of the Arab Society for Computation in Architecture, Art and Design (ASCAAD 2025) has invited scholars, researchers and students worldwide to address methodologies, approaches, and processes within the framework of computational design and how it addresses decolonizing architecture and the future of localized design.

The ASCAAD community has been highly motivated to join this special gathering of the CAAD community, which has attracted researchers from around the world in a unique opportunity and venue, thanks to the host of this special event at Alfaisal University, in Riyadh, Saudi Arabia. The unwavering support provided by the host for this year's ASCAAD conference has been unmatched. This conference has opened the door for a diverse platform for engagement and opportunities for closer partnerships in the CAAD community.

Special thanks to the esteemed keynote speakers for this conference who have enriched and enticed the conversations and debate around the role of computational in this part of the world in such challenging times. Thanks to Marcelo Spina, Robert Woodbury, Wassim Jabi, Florian Wiedmann, and Neil Leach. Many thanks to the sponsors of this event whose generous support has made this conference a success. Thanks go to all workshop moderators and facilitators, especially *Wassim Jabi*, *Mehdi Mostafavi*, *Abdulrahman Fahmy*, *Mohamed Noeman*, *Ramez Sorial* and *Mohamed Alaa* for their progressive and innovative ideas and exciting workshops.

As president of ASCAAD, I cannot but express my deep gratitude and optimism working side by side with a highly enthusiastic, active and committed group of researchers and scholars within the Arab World and the Middle East. This conference would not have been possible without the year-round dedication and commitment from ASCAAD Vice President *Amar Bennadji*, treasurer *Zaki Mallasi*, and board members *Mostafa Alani* and *Sema Alacam*, whose spirit of cooperation and generosity throughout the previous years and the preparation for this conference has been exceptionally rewarding and key to the success of this event.

I cannot but thank deeply all members of the CAAD community who have offered consistent support to ASCAAD. Special thanks and gratitude to presidents of ACADIA Marc Swackhamer, president of eCAADe Anetta Kepczynska-Walczak, president of CAADRIA Rudi Stouffs, and president of SIGraDi Paula Gomez for their endless endorsement and encouragement.

Sherif Abdelmohsen
President of ASCAAD

FOREWORD – Host

It is my great pleasure to welcome you to the 13th International Conference of the Arab Society for Computation in Architecture, Art and Design (ASCAAD 2025), hosted by Alfaisal University in Riyadh, Saudi Arabia. As Chair of both the Scientific and Organizing Committees, I am deeply honored to present this year's proceedings, which reflect the collective vision, creativity, and dedication of an extraordinary community of scholars, practitioners, and educators.

This year's conference theme — "Decolonizing Architecture: AI, Computation, and the Future of Localized Design"— invites us to critically examine the intersections between technology, culture, and identity in architectural thinking. It challenges us to rethink how emerging computational tools, artificial intelligence, and digital design systems can become instruments of empowerment rather than homogenization. The theme encourages a dialogue on how we, as architects and researchers, can harness technological innovation to reinforce cultural specificity, contextual intelligence, and environmental responsibility.

The papers presented in this volume represent a wide spectrum of ideas and experiments that embody this year's theme. From AI-driven generative processes and machine learning in design, to heritage preservation through computational analysis and digital fabrication, these contributions demonstrate the dynamic evolution of architectural practice across the Arab region and beyond. They remind us that computation is not merely a technical language — it is also a cultural and philosophical medium through which we can reimagine our built environment.

I would like to express my sincere gratitude to all authors, reviewers, and members of the ASCAAD community for their invaluable efforts in advancing our shared mission. Special thanks are also due to the ASCAAD Executive Board, keynote speakers, and sponsoring partners whose support and collaboration made this conference possible. I would also like to extend my heartfelt appreciation to Dr. Muhammad Anan, Dean of the College of Engineering and Advanced Computing at Alfaisal University, for his continuous support, leadership, and encouragement throughout the preparation and hosting of this conference.

May these proceedings inspire further dialogue, innovation, and collaboration in shaping an architectural discourse that is both technologically advanced and culturally grounded.

Dr. Abdulrahman Alymani
Chair, Scientific and Organizing Committees
ASCAAD 2025
Alfaisal University, Riyadh – Saudi Arabia

ACKNOWLEDGMENTS

First and foremost, we thank all paper authors whose work was featured in this conference for their hard work, dedication and commitment during the whole process and specifically with the challenging circumstances of changing conference venue. We would also like to extend our thanks and gratitude to all session chairs who represented different CAAD sister organizations. Thanks also to sister organization presidents who provided the conference committee with supporting material and announcements for upcoming CAAD activities around the world. Without the support of *eCAADe*, *ACADIA*, *CAADRIA*, *SIGraDi*, and *CAAD Futures* and their generous support of all ASCAAD 2025 activities, this conference would not have achieved this success and global recognition. Many thanks to the 55 members of the international reviewing committee who have worked tirelessly to support the double-blind peer review process and the evaluation of 117 abstracts and 43 full papers. Such a demanding task in a tight timeline and working within challenging circumstances is highly appreciated. Special thanks to our esteemed keynote speakers and conference sponsors for enriching and empowering this special conference.

More specifically, ASCAAD will remain grateful to this unique opportunity enabled by the Alfaisal University and would like to thank specifically the conference chair Professor *Abdulrahman Alymani* for his outstanding support and collegial spirit in hosting ASCAAD 2025, and to all members of the scientific and organizing committees at the Alfaisal University. Thanks to this generous support, ASCAAD could hold its conference in Riyadh, Saudi Arabia in October 21-23, 2025, in what was an extremely unique event. Such partnership has truly increased the conference exposure to a wider audience, participation, new perspectives and offered a great conference experience. Such genuine collaborative efforts and spirit further underscore the growing and well-knitted nature of the support system of the CAAD community.

October 2025
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I. AI & COMPUTATIONAL DESIGN IN ARCHITECTURE

A SOFTWARE FOR GENERATING DIMENSIONED LAYOUTS FOR GIVEN ADJACENCIES

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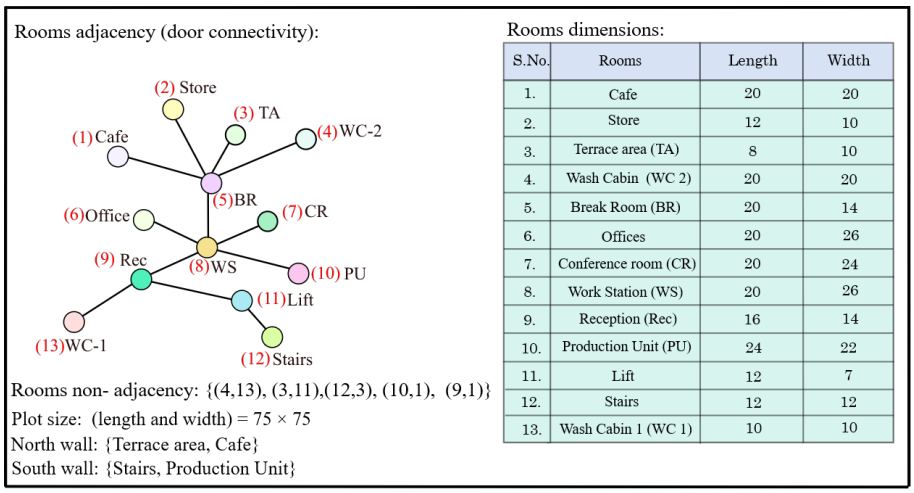
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Abstract. Designing a building layout involves carefully planning the size, shape, and arrangement of rooms. This paper introduces a software tool that utilizes a graph-based approach to generate automated building layouts based on user-defined input constraints. The tool accepts specific parameters, including door adjacency (defining door connections between rooms), non-adjacency (ensuring certain rooms do not share common walls), room dimensions, and plot size. The dimensions of the room specify the width and length of each room, and the size of the plot establishes the dimensions of the rectangular boundary. Leveraging these inputs, the software produces floor plans that fulfill the specified adjacency, non-adjacency, and dimensional criteria, rendering it a valuable resource for architectural design. The layout generation process consists of several steps: First, biconnected, plane-triangulated graphs are generated from given door connectivity to represent the necessary room adjacencies and separations. From these graphs, the software generates distinct dimensionless floor plan configurations, which are subsequently adjusted to fit within the specified plot dimensions using up to 30% variation in room sizes and then integrates circulation into the generated dimensioned layout based on user requirements. This process yields a range of optimized layouts, with optimality determined by compliance with the given requirements. While the software is currently limited to rectangular plots and layouts with rectangular rooms, future enhancements aim to expand its capabilities by incorporating non-rectangular rooms and boundaries, thereby increasing its versatility and design potential.

Keywords: *Bi-connectivity, wall adjacency, circulation, floor plan, graph theory.*

1. Introduction and Related Work



S.No.	Rooms	Length	Width
1.	Cafe	20	20
2.	Store	12	10
3.	Terrace area (TA)	8	10
4.	Wash Cabin (WC 2)	20	20
5.	Break Room (BR)	20	14
6.	Offices	20	26
7.	Conference room (CR)	20	24
8.	Work Station (WS)	20	26
9.	Reception (Rec)	16	14
10.	Production Unit (PU)	24	22
11.	Lift	12	7
12.	Stairs	12	12
13.	Wash Cabin 1 (WC 1)	10	10

(a)

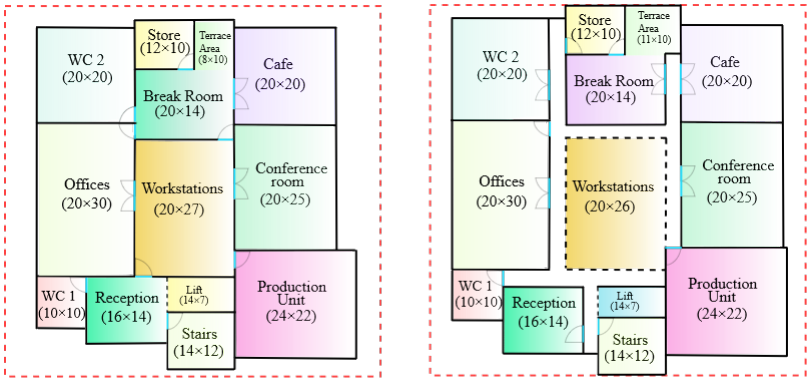


Figure.1: (a) User-defined input constraints. (b) and (c) Layouts generated by the proposed software

In architectural design, floor planning plays a crucial role in shaping the functionality and efficiency of a building, requiring designers to strike a balance between diverse and often conflicting objectives. Architects and engineers are responsible for developing plans that meet client requirements such as room sizes, orientations, and adjacency preferences. For the past few

decades, floor planning within a given plot size, while meeting specific room requirements, has posed a complex problem both for designers and automated systems. This complexity arises from the vast number of possible configurations and the input constraints that must be explored to find an optimal solution. The combinatorial nature of these tasks makes the problem difficult to solve in a reasonable amount of time. In addition, the optimal arrangement of rooms and spaces can affect the use of materials, leading to more sustainable and resource-efficient construction. In this context, computational methods and optimization algorithms become essential tools for navigating the intricacies of modern floor planning.

The existing literature outlines a step-by-step algorithm for room dimensioning through bubble diagram implementation, as originally proposed by Roth et al. [1982]. Over the past few decades, substantial research has concentrated on the automated generation of floor plan layouts, employing a range of optimization methods such as genetic algorithms, simulated annealing, and integer programming (Nagy et al. [2017]; Bahrehmand et al. [2017]; Bausys et al. [2005]). Additionally, parametric and generative design techniques (Wu et al. [2018]) along with machine learning and artificial intelligence, have been applied to improve the automated creation of floor plans within specified plot boundaries (Wu et al. [2019]; Nelson et al. [2021]; Feng et al. [2016]). Researchers have also been investigating graph-theoretic approaches alongside optimization techniques to get dimensioned layouts according to specified requirements (Upasani et al. [2020]; Bisht et al. [2022]).

Despite ongoing research, creating floor plans remains a complex architectural challenge. This complexity arises from numerous interconnected sub-problems and distinct sub-domains. Key considerations include boundary layout, circulation, and energy optimization. Additionally, each sub-domain, whether residential, office, or hospital design, requires specialized expertise and tailored approaches. As a result, developing a comprehensive methodology that effectively addresses the diverse challenges across these various sub-domains presents a significant obstacle. The construction of layouts using optimization techniques has a slower convergence rate towards the solution. Machine learning approaches rely on input datasets to generate the best-fit housing layout through supervised learning, resulting in architecturally significant and realistic floor plans. However, the reliability of these outputs can be compromised when datasets are not peer-reviewed or properly curated to account for architectural, spatial, cultural, or environmental considerations, leading to unpredictable results. Additionally, these methods often lack control over room shapes, outer boundaries, and room dimensions, and discussions on circulation are often insufficient. There is no control over the shape of the room, outer boundary, and room dimensions, and there needs to be more discussion on circulation. Ultimately,

striking a balance between computational efficiency, architectural authenticity, and user-specific requirements remains the key to evolving automated floor plan generation into a more robust and practical tool for real-world applications.

This paper discusses a graph-theoretic approach to creating an optimal basic floor plan for architecture, focusing on minimizing the dimensions of the rooms. The algorithm considers factors such as plot size, room adjacency, non-adjacency, and door connectivity. The goal is to produce floor plans that meet practical design requirements specific to users (see Figure 1).

While adjacency constraints are essential for compiling floor plans,

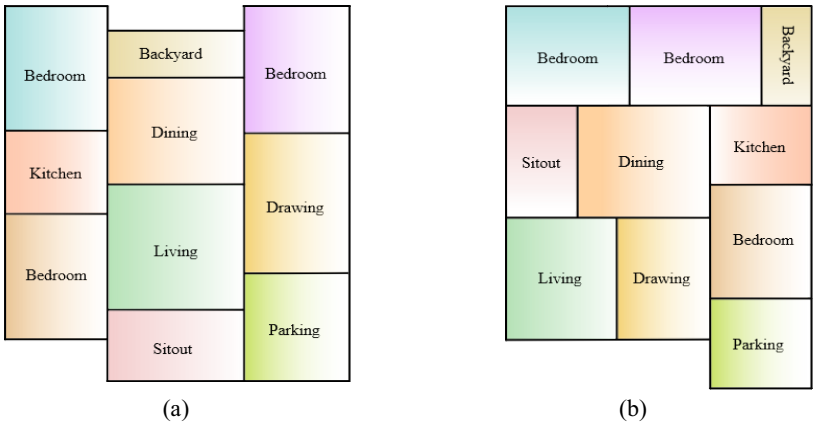


Figure.2: Floor plans illustrating the influence of cardinal direction preferences. (a) Layout satisfying adjacency, dimensional, and non-adjacency constraints without cardinal preferences. (b) Layout additionally incorporates cardinal direction requirements, placing the sit-out in the west and the backyard in the east.

practical design considerations often require the inclusion of non-adjacency constraints. These restrictions ensure that certain rooms are not located next to one another, which is essential for reasons such as privacy, noise control, and functionality. By incorporating non-adjacency constraints, the floor plan generation process becomes more precise and adaptable, allowing for better fulfillment of specific user needs. Another important consideration in floor plan design is the preference for certain boundary rooms to face specific cardinal directions. Such preferences often arise from practical concerns, such as ensuring adequate sunlight exposure, enhancing natural ventilation, or situating the building entrance/exit in a particular direction. In some cases, this requirement can be accommodated simply by rotating the generated floor plan. However, there are situations where rotation alone is insufficient to satisfy these directional preferences (see Figure 2). Therefore, explicitly incorporating this requirement into the input constraints of the generation process enables the methodology to produce floor plans that better adhere to

such practical and aesthetic considerations. We refer to this directional preference as the "cardinal requirement", which is formally included as part of the input constraints in the proposed methodology to enhance both the functionality and the visual appeal of the generated layouts.

2. Terminology

This section introduces key terms used consistently throughout the paper:

2.1. FLOOR PLAN (RINSMA [1988]):

A floor plan (*F*) refers to the division of a polygonal space into multiple rooms or regions that meet the adjacency requirements specified by an associated graph. The exterior outline of a floor plan (layout) is known as its boundary, while the internal subdivisions are referred to as rooms, separated by walls. Two rooms are considered adjacent when they share a wall segment.

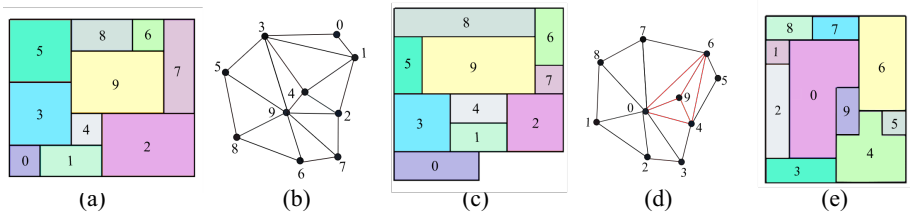


Figure.3: (a) Rectangular floor plan corresponding to the PTPG graph in (b). (c) Non-rectangular floor plan associated with the graph in (b). (e) orthogonal floor plan corresponding to the graph in (d), having a separating triangle (0,4,6).

Floor plans can be categorized based on the geometry of their boundary and the shapes of the rooms they contain: A rectangular floor plan (RFP) features a rectangular boundary with all rooms also shaped as rectangles (see Figure 3a); an orthogonal floor plan (OFP) has a rectangular boundary, but the rooms may include non-rectangular shapes such as L, T, or C forms (see Figure 3e); and a non-rectangular floor plan (NRFP) is distinguished by a non-rectangular boundary, allowing for varied rectilinear outer shapes (see Figure 3c).

In architecture, every floor plan is linked to an adjacency graph that illustrates the relationships between rooms. Each room is represented as a vertex, and shared walls between rooms are shown as wall adjacencies (edges) connecting these vertices. By converting floor plan designs into graph structures, analysis and optimization become more efficient.

2.2. GRAPH (BHASKER ET AL. [1988]):

A plane graph *G* is a graph drawn so that edges only intersect at their endpoints, ensuring no overlapping except at the vertices.
This graph structure includes various faces or regions, with one unbounded exterior face and all other faces designated as internal.
The vertices on the boundary of the exterior face are called exterior vertices, while those within are considered internal vertices.

In graph G, a three-vertex cycle that encloses at least one internal vertex is referred to as a separating triangle (see Figure 3d). A Properly Triangulated Plane Graph (PTPG) is a connected plane graph in which all internal faces are triangular, with a length of three, and it contains no separating triangles (see Figure 3b).

3. Overview of the Methodology

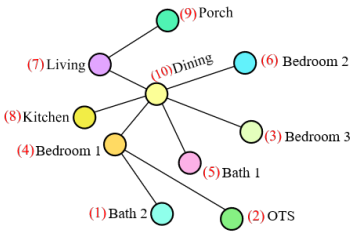
This section briefly overviews our graph-theoretic approaches for generating optimal floor plans, detailing the step-by-step procedure, underlying assumptions, and implementation specifics.
The process begins with inputting the door adjacency graph and adding wall adjacencies to ensure the generated layout is connected and has proper interior wall placement.
The method includes removing separating triangles and then generating dimensioned floor plans using the provided room dimensions and plot size. The final output is a set of dimensioned layouts that satisfy the given requirements (refer to Section 3.4) and integrate circulation into the generated dimensioned layout based on user requirements (see Figure 1c, incorporating circulation in the floor plan shown in Figure 1b).

3.1. BI-CONNECTIVITY (ADDITION OF WALL ADJACENCIES)

The significance of connectivity in the design of rectangular floor plans is immense, as it dramatically enhances accessibility and flexibility. This, in turn, promotes efficient movement and allows for straightforward navigation within the building. A study by Kozminski et al. in [1985] demonstrated that the layout graph must be biconnected and triangulated to create a rectangular floor plan. Therefore, to produce a rectangular floor plan based on user-provided door connectivity (a one-connected layout graph), it is necessary first to add additional wall adjacencies to transform the input one-connected graph into a biconnected graph and then triangulate it.

We presented an approach for creating a biconnected graph that is flexible enough to adhere to specific restrictions. By inserting new edges as needed, we aim to maintain the connectivity of the graph even if any node is deleted. The method identifies articulation points and their corresponding blocks. A 'Room Non-Adjacency' list is provided as input, detailing rooms that are not adjacent, along with the existing door connectivity. The approach carefully connects several nodes within the blocks while ensuring that none of the edges from the non-adjacency list are included. Note that any graph in Figure 4b does not contain edges from the "Room Non-Adjacency" list in Figure 4a. It identifies acceptable edges among the blocks and incorporates them only when necessary and permissible.

Rooms adjacency (door connectivity):

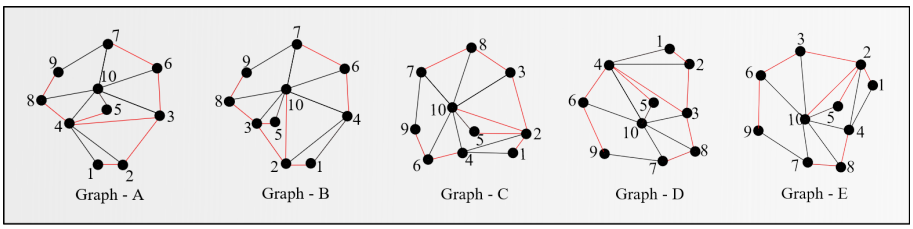


Rooms non- adjacency: {(1,8), (5,8), (9,2), (10,1), (1,5)}
Plot size: (length and width) = 30 × 40
North wall: {Porch}
South wall: {OTS}

Rooms dimensions:

S.No.	Rooms	Length	Width
1.	Bath 2	8	4
2.	Open to Sky (OTS)	10	4
3.	Bedroom 3	12	14
4.	Bedroom 1	12	10
5.	Bath 1	6	10
6.	Bedroom 2	9	9
7.	Living	14	11
8.	Kitchen	8	10
9.	Porch	12	11
10.	Dining	10	10

(a)



(b)

Figure.4: (a) User-provided input constraints. (b) Introducing wall connectivity while preserving door connectivity: Bi-connectivity

The result is a restricted set of new edges that enhance connectivity while adhering to the established constraints. This ensures the effective strengthening of the graph in line with the input requirements (refer to Figure 4b, Graph A). In this figure, eight additional wall adjacencies (edges) have been added to the original door connectivity graph. These newly established

wall relationships are highlighted in red, illustrating the expanded spatial connections within the layout.

The input door connectivity graph has various options for incorporating wall adjacencies to create a bi-connected layout graph, resulting in multiple possible biconnected graphs (see Figure 4b, Graphs A-E). Therefore, based on the provided door connectivity graph, we initially create several biconnected graphs and subsequently use these generated graphs for triangulation.

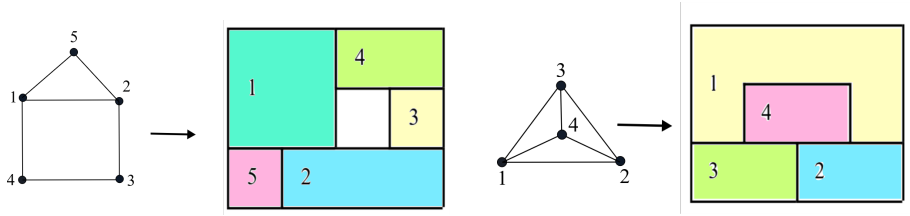
3.2. TRIANGULARITY (ADDITION OF INTERIOR WALL ADJACENCIES)

Once biconnected graphs are generated based on user-provided door connectivity, the subsequent phase is triangulation, which entails incorporating additional interior wall adjacencies to remove any extra space within the created rectangular floor plan. When the generated bi-connect graph is not triangulated, meaning it contains a non-triangular face, the method of creating the floor plan (corresponding to that graph) may inadvertently produce unused areas, resulting in inefficiencies (see Figure 5a). We proposed a method for triangulating a biconnected graph with user-defined non-adjacency restrictions between rooms. The method prioritizes ensuring that non-triangular faces are fully triangulated while avoiding certain edges that users wish to avoid. It starts with a list of non-triangular faces and a set of non-adjacency edges, and then iteratively divides each face into triangles. The procedure begins by attempting to add edges using an ear-clipping method (Mei et al. [2013]) while ensuring that no limited edges are generated. We determine if valid edges may be added without violating the constraints for each face. If valid edges are identified (while satisfying the input constraints), then add an edge to the non-triangular face (in Figure 6a: Graph-A, two additional interior wall adjacencies (edges) are incorporated into the generated bi-connectivity graph. These newly established wall connections are highlighted in blue, demonstrating the expanded spatial relationships within the layout. Suppose all possible valid edges are also in the non-adjacency set; then, we temporarily ignore the limits and complete the triangulation, nevertheless. This fallback approach ensures that the entire graph gets triangulated, even when limitations limit edge additions. After generating valid edges for non-triangular faces, there could be multiple

options for adding wall adjacencies, which led to multiple triangulated graphs (see Figure 6a: Graph A-E).

3.3 REMOVAL OF SEPARATING TRIANGLE

After generating several biconnected and triangulated graphs, the next critical step is to address separating triangles in these graphs. A rectangular floor plan requires each room and boundary to be a rectangle, which means that every



(a) (b)

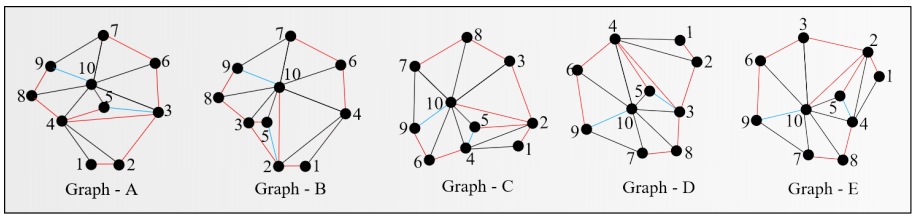
Figure.5: (a) Additional space is created in the floor plan corresponding to the graph with a non-triangular face (1,2,3,4). (b) A non-rectangular room (Room 1) appears in the floor plan due to the presence of a separating triangle (1,2,3) in the input graph.

sub-region must be rectangular and contiguous along clear, straight bounds. As a result, three rectangular rooms cannot be arranged to form a triangular cycle enclosing an interior vertex (refer to Figure 5b: It is not possible for three rectangular rooms to create a triangular cycle that encloses a central interior room). Furthermore, Rinsma [1988], illustrated that to construct a rectangular floor plan, the related layout must be free of separating triangles. Following the identification of a separating triangle using the method proposed by Johnson [1975], we introduced a technique for its removal. The process begins with the enumeration of all separating triangles and a collection of non-adjacent edges (provided by the user). The process begins by selecting one edge from the three outer edges of the chosen separating triangle. The objective is to add a new edge while simultaneously removing one of the outer edges of the selected separating triangle. It is important to ensure that the removal of this edge, followed by the addition of the new edge, does not result in the new edge being included in the non-adjacency list or forming a new separating triangle. If it does, the procedure advances to consider the next potential edge for removal (In Figure 6a (Graph-A), the separating triangle (4, 3, 10) prompted the removal of the edge connecting nodes 4 and 3. Consequently, a new edge was added between nodes 5 and 10, becoming part of the overall connectivity and triangulated structure, as shown in Figure 6b (Graph-A). The newly introduced edge (5,10) is highlighted in pink. Hence, we generate graphs without separating triangles, i.e., PTPG graph generation

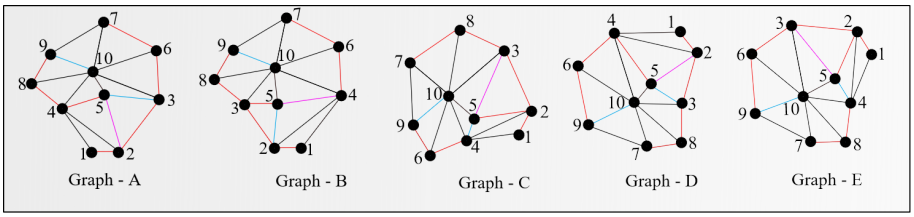
(see Figure 6b: Graph A-E), and next, we proceed to the floor plan generation phase.

3.4. GENERATION OF DIMENSIONLESS FLOOR PLANS

A preliminary floor plan representing the arrangement of rooms within a rectangular plot is referred to as a dimensionless floor plan. Dimensionless floor plans offer architects and designers the ability to visualize spatial interactions without being limited by exact measurements. This visualization facilitates the assessment of room flow, orientation in cardinal directions, and overall building functionality. Ultimately, generating dimensionless floor plans provides a versatile, adaptable, and strategic starting point for further refinement and detailed planning.



(a)



(b)

Figure.6: (a) Triangulation. (b) Removed separating triangles to generate PTPG.

As discussed earlier, the PTPG offers an efficient representation of the adjacency and connectivity between various rooms or spaces within a building layout. A given PTPG G corresponds to a set of RFPs, where each RFP satisfies the adjacency relations encoded in the PTPG and shares the same outer boundary as the PTPG.

To determine this set of RFPs, where each plan also adheres, as far as possible, to specified cardinal direction requirements, we begin by identifying feasible outer boundaries. This is achieved by computing paths along the boundary of each PTPG (as shown in Figure 6b), ensuring that these paths preserve the rectangularity constraint of room modules in the final layout. Let this set of paths be denoted by P. These paths must be avoided in the subsequent construction. Next, we identify vertices along the graph boundary that correspond to user-defined cardinal orientation requirements. If multiple vertices are specified for a particular direction, we attempt to connect them via boundary paths, ensuring these paths do not fully overlap with any in the set P. If such a condition is violated, the problematic vertex or vertices are discarded from consideration.

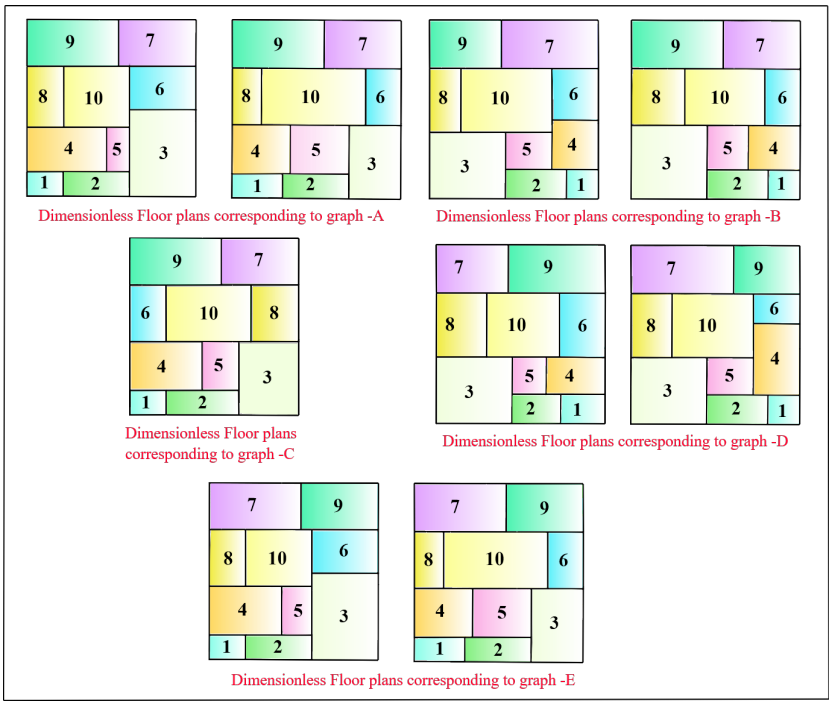


Figure.7: Multiple dimensionless floor plans satisfying door adjacencies and wall adjacencies.

If fewer than four cardinal requirements are specified, the remaining required vertices are selected randomly from the boundary while preserving the order of cardinal directions. For instance, let the selection for north and west be done, then the selection for south and east is done by following an order of tracing the outer boundary and the order of cardinal directions. For each such vertex or path, we explore extensions in both clockwise and

counterclockwise directions. At each step, we ensure that the growing four paths do not entirely contain any path from the forbidden set P.

This process ultimately yields a set of four connected paths forming a valid boundary for the floor plan, one that is consistent with both the PTPG structure and the rectangularity constraints. This boundary is then used to construct a dimensionless floor plan using the algorithm proposed by Bhaskar and Sahni [1988], which serves as a fundamental blueprint for further refinement.

For the PTPGs illustrated in Figure 6b, the resulting dimensionless layouts are presented in Figure 7. In the layout corresponding to Graph A of Figure 6b, the two selected floor plans differ in the way the "Dining" and "Bedroom 3" rooms share wall segments. In the first layout, the shared wall is vertical, while in the second, it is horizontal. These variations highlight how alternative floor plans derived from the same PTPG can differ either in room placement or in the orientation of shared wall segments.

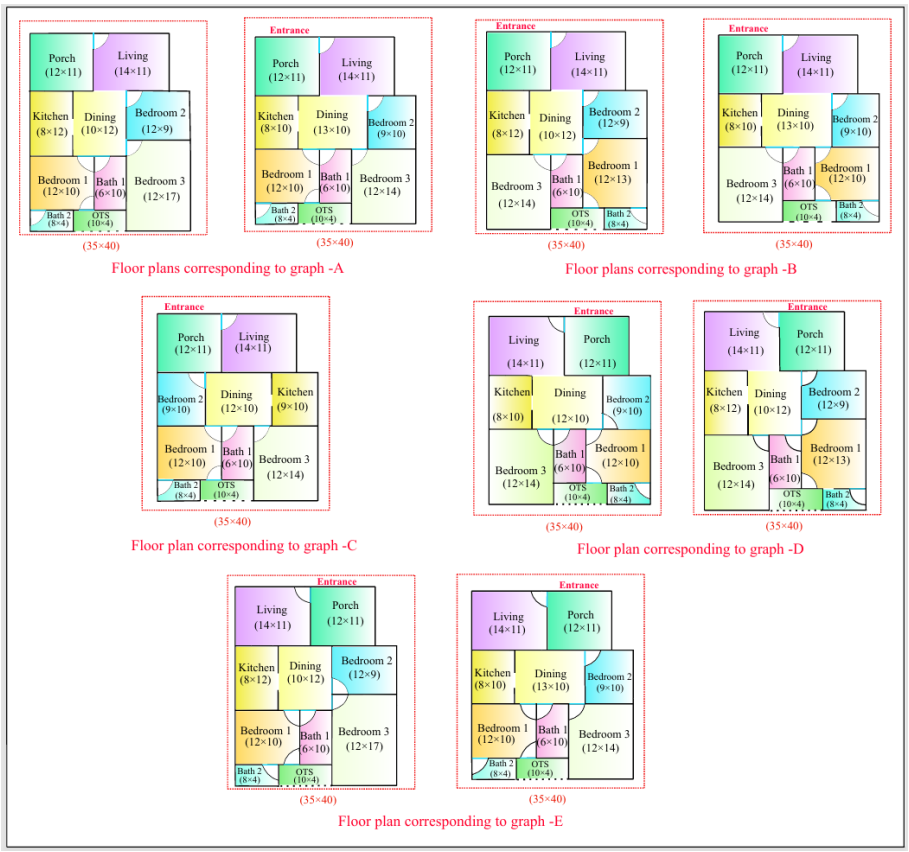
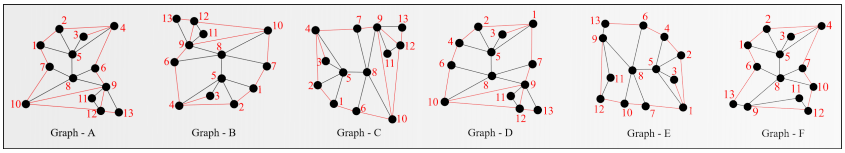


Figure.8: Multiple dimensioned floor plans satisfying door adjacencies and wall adjacencies.

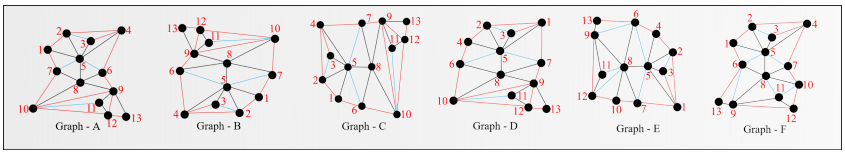
3.5. GENERATION OF DIMENSIONED FLOOR PLANS

Dimensioned layouts provide precise measurements for each room and space, translating conceptual designs into actionable blueprints that can be used for construction. This allows architects, engineers, and builders to implement the design accurately on-site. They help verify that spaces are functional and meet (e.g., ensuring enough space for furniture and circulation) and that pathways serve their intended purpose. They allow designers to confirm that rooms are proportioned for their designated use, and connections between rooms are appropriately sized for smooth movement. By providing minimum room dimensions, plot size, and door adjacency, designers can ensure an efficient layout that balances aesthetic appeal with practicality. In conclusion, generating dimensioned layouts is crucial for transforming abstract design concepts into detailed, buildable plans. It ensures compliance with standards, optimizes functionality, supports effective communication, and enables practical execution, making it an indispensable part of the architectural design process.

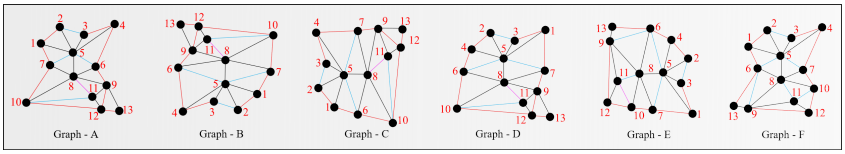
To generate a dimensioned floor plan, a dimensionless floor plan is refined using input data, which includes the minimum required dimensions for each room and the specified plot size. Modifications based on the work of A. Schwarz et al. [1994] were incorporated to enhance this method. Among the proposed modifications is a minimum door width of 3 feet for connecting rooms, allowing for adjustments to accommodate specific design requirements. Additionally, this approach includes setting permissible limits for adjustments to room dimensions, and for the plot, this threshold is set to zero. This ensures that room dimensions can be stretched up to a defined threshold to optimize the fit within the overall layout. In this implementation, the limit was set to allow up to a 30% increase in room size. In Figure 4a, the minimum specified width for the “Dining” area is 10 feet. The algorithm allows the width to be extended up to a maximum of 13 feet. As illustrated in Figure 8, all the dimensioned layouts for the “Dining” room have a width ranging from 10 to 13 feet. This flexibility in adjusting dimensions allows for creating a layout that best meets the specified criteria, accommodating up to a 30% variation from the original minimum dimensions while maintaining the integrity of the selected dimensionless floor plan. Since it is a general approach to plan generation, it can be used to generate not only housing layouts but also automated office layouts, depending on user-specified constraints (see Figures 10 and 11, which show the process of generating a garment manufacturing and designing office).



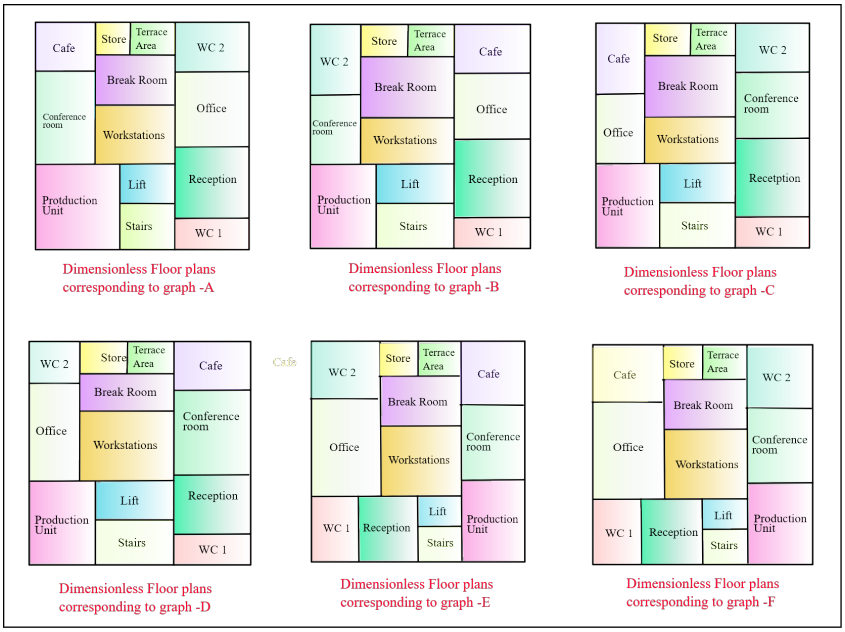
(a)



(b)



(c)



(d)

Figure.9: Processing phases of the methodology applied to the inputs shown in Figure 1a: (a) Establishing bi-connectivity. (b) Triangulation. (c) Removing separating triangles. (d) Dimensionless layouts corresponding to PTPGs in Figure 9c.



Figure.10: Dimensioned floor plans for the given inputs in Figure 1 and corresponding to dimensionless layouts in Figure 9d.

3.6. GENERATION OF CIRCULATION WITHIN DIMENSIONED FLOOR PLANS

For the smooth movement of people and connection of spaces within a building, properly designed circulation is crucial. It supports the purpose of the building, whether for residential, commercial, or public use, by creating a practical and visually appealing environment. Once a dimensioned floor plan was obtained, a graph theoretic approach discussed in Shiksha K. et al. [2025] for getting circulation in the layout was applied to integrate circulation into the layout. For the specific case of a garment manufacturing and designing office for the inputs in Figure 1a, where door adjacency, non-adjacency constraints, room dimensions, and plot size were given, dimensionless and dimensioned layouts were produced (see Figures 10 and 11). Applying the method in the mentioned study, circulation paths with a width of 3 feet were generated in a selected floor plan from Figure 1 (Dimensioned floor plan corresponding to Graph-B), as shown in Figure 1c.

3.7. ASSESSMENT OF CONSTRAINT SATISFACTION IN GENERATED LAYOUTS

This section evaluates the outputs presented in Figures 8 and 11 in terms of their ability to satisfy the given input constraints, quantified through error percentages.

3.7.1 For adjacency constraints:
Consider the generated PTPG graph based on the provided door connectivity graph. Let the edge set of the generated graph be Graph A, and that of the input door connectivity graph be Graph B. Define $/B/ = m$.

Case (i): If there are no extra edges in A (i.e., $B - A = \emptyset$), it means all adjacency requirements are fully satisfied, leading to an error of 0%.
Case (ii): If there are additional edges ($B - A = C$, where $/C/ = r$), the error is calculated as:

Adjacency Error (%) $\delta_A = \left(\frac{r}{m}\right)100$

Refer to Figures 10 and 11: In Example 1 and Example 2, each generated floorplan (Graph A–F) achieved an error of 0%, indicating that the adjacency constraints were perfectly met.

3.7.2 For non-adjacency constraints:
Let the edge set of the generated graph be set A, and the input non-adjacency constraints be set S, where $/S/ = p$.

Case (i): If none of the prohibited edges from S appear in A (i.e., $A - S = A$), then all non-adjacency constraints are satisfied, resulting in an error of 0%.
Case (ii): If some prohibited edges do appear in A (let $S - A = C$, with $|C| = q$). The error is given by:

Non-adjacency Error (%) $\delta_N = \left(\frac{q}{p}\right)100$

As shown in Figures 10 and 11, for Example 1 and Example 2, the generated floorplans (Graph A–F) resulted in an error of 0%, meaning that the non-adjacency constraints were completely respected.

3.7.3 For dimensional constraints of the plot and rooms:
A threshold of 30% deviation for room dimensions and 0% deviation for plot dimensions is enforced during the transformation of filtered dimensionless layouts into dimensioned layouts (refer to Section 3.6). During the application of the dimensioning procedure, room dimensions are allowed to increase by up to 30% relative to the original input values, while plot dimensions must remain unchanged. Any dimensionless layout that leads to room dimensions exceeding this allowable limit is discarded. As a result, all accepted dimensioned layouts exhibit a maximum deviation of 30% in room dimensions and no deviation in plot dimensions with respect to the original specifications. This is evident in the outputs shown in Figure 8 and Figure 10, where all layouts conform to the plot boundary, and the height and width of rooms increase by up to 30% of the original input values.

3.7.4 For cardinal requirement:
Every generated dimensionless floor plan has a set of four paths associated with it (refer to section 3.5), whose first path corresponds to north, second to east, third to south, and fourth to west; name these paths as P_1, P_2, P_3, and P_4. Let the given requirements for north, east, south, and west be C_1, C_2, C_3, and C_4, respectively. Let $|C_i| = m_i$.

Now, find $r_i = |C_i - P_i|; 1 \leq i \leq 4$.
Then, the error in satisfying the cardinal direction for a generated dimensioned layout is given by

Cardinal error (%) $\delta_C = \left(\frac{\sum_{i=1}^{4} r_i}{\sum_{i=1}^{4} m_i}\right)100$

In Figure 4a, the cardinal requirement is Porch in the north and OTS in the south. From the boundary of each layout in Figure 7, we have, $m_i - r_i = 0$, this gives $\delta_C = 0$.

4. Conclusion, Limitations, and Future Enhancement

This study describes software that employs graph-based algorithms to generate multiple building layouts based on user-supplied limitations. The software allows users to specify critical requirements such as which rooms should connect directly for door addition (adjacency), which should not share walls (non-adjacency), the particular measurements of each room, and the total plot size. The software processes the inputs and starts by generating bi-connected, plane-triangulated graphs that satisfy specific user-defined adjacency and nonadjacency requirements. These graphs (i.e., PTPG) serve as the foundation for creating unique, dimensionless floor plan layouts. Subsequently, these layouts are modified to fit the user-specified plot size, allowing the given room dimensions to vary by up to 30%. This adjustment yields optimized, fully dimensioned layouts that adhere to the specified design criteria and then integrate circulation into the generated dimensioned layout based on user requirements. Future enhancements will introduce non-rectangular rooms in the dimensioned floor plans, incorporate corridor elements based on user specifications, and improve the user interface for easier adjustments.

Currently, it only supports rectangular room shapes, which makes it easier to convert graphs into floor plans. However, this limits its use for real buildings that often have irregular shapes or plots. In such cases, it becomes more difficult to handle room placement, direction, and size requirements. Another issue is scalability, since the number of possibilities grows quickly when more rooms, floors, or rules are added, which slows down the process.

In future work, this study could be improved by allowing non-rectangular room shapes, creating better ways to fit layouts on irregular sites, and using optimization methods like heuristics or evolutionary algorithms to handle larger and more complex designs. Additional features like door placement and 3D layout visualizations could enhance functionality, transforming it into a comprehensive tool for architecture.

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SETEASY

A Multi-Modal Classroom Engagement Assessment and Seating Optimization Framework

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Abstract. SetEasy optimizes classroom engagement in fixed seating grids. It fuses multimodal sensing (wristband physiology, 4K video, environmental data) and trains a v-Gage model grounded in a revised ISEQ. Each week, two-week engagement forecasts are mapped to a student–seat utility matrix, and CP-SAT generates seating plans under visual-access and social-dynamics constraints. In a four-week deployment (23 students, 331 classes), v-Gage converged across affective, behavioral, cognitive, and overall dimensions, cutting RMSE from 0.75 to 0.53. Optimization raised mean engagement from 0.30 to 0.70, with over two-thirds of seats reaching high engagement and back-row low-activity patterns markedly reduced. These results show that, without hardware changes, interpretable, data-driven seating strategies can substantially enhance engagement. The multimodal "assessment + optimization" paradigm offers a transferable, sustainable path to culturally responsive, differentiated spatial design amid global homogenization.

Keywords: *Machine Learning, Educational Space Optimization, Computational Design, Multimodal Sensing, CP-SAT Optimization*

1. Introduction

Under the wave of global educational standardization, schools worldwide have largely retained the "grid-based" seating arrangements originating from Western educational systems. This practice frequently results in mismatches between classroom furniture dimensions and students' body types or cultural needs(Castellucci, Arezes and Viviani, 2010).

In recent years, primary and secondary education reforms have called for a shift in learning environments from unidirectional instruction to learner-centered models that emphasize individual differences and foster active collaboration(Barrett et al., 2015). Extensive research indicates that classroom seating arrangements and spatial design have a significant impact on students' learning outcomes and classroom engagement(Mäkelä and Leinonen, 2021). For example, Barrett et al. found that simply optimizing seating layout can yield up to a 16% improvement in learning efficiency. However, limited by school infrastructure and funding, most schools still rely on fixed desk layouts, making it a practical challenge to optimally assign "who sits where" within the existing grid(Peponis et al., 2007).

Currently, seat assignments in classrooms primarily rely on teachers' experience—either by making manual adjustments based on guidelines and shortest-path methods(Meller and Gau, 1996), or by iteratively experimenting with adjacency matrices in CAD software(Liggett, 2000). When balancing multiple objectives such as capacity, visibility, and social dynamics, this process is time-consuming and rarely achieves a globally optimal outcome. Fixed seating layouts have also been shown to inhibit collaboration and behavioral engagement(Kariippanon et al., 2019).

In response to these limitations, research in computationally intelligent seat assignment has advanced rapidly. Genetic algorithms are capable of searching thousands of combinations at once, significantly improving satisfaction(Shin-Ike and Iima, 2016); Merrell et al. mapped interior design principles into probability density functions to interactively recommend seating positions(Peponis et al., 2007); deep reinforcement learning has modeled seat swaps as a Markov process, converging on multi-objective optima(Kakooee and Dillenburger, 2024); and the EDU-AI framework applies attention heatmaps in closed-loop seating optimization(Kariippanon et al., 2019). However, most existing methods depend on single behavioral factors or static preferences and lack real-time integration of multimodal data—physiological, behavioral, and environmental.

Meanwhile, educational scholars have long criticized "one-size-fits-all" classroom models for undermining students' cultural identity and learning motivation(Ladson-Billings, 2014). Culturally responsive teaching stresses a deep understanding of learners' sociocultural backgrounds(Gay, 2002), and

self-determination theory emphasizes that environments must satisfy students' needs for autonomy, competence, and relatedness(Pekrun and Linnenbrink-Garcia, 2012). The OECD likewise advocates for locally data-driven design to break the homogeneity of seating arrangements(OECD, 2013). Yet, teachers working in classrooms with fixed desks and chairs still lack quantitative tools for implementing differentiated seat assignment.

To bridge this gap, we present SetEasy—an intelligent framework for classroom seating optimization. The system first integrates physiological and behavioral data from students and teachers, as well as environmental information, and incorporates questionnaire results to construct an engagement prediction model. Combined with seat calibration data, these inputs are used to generate a student-seat utility matrix, enabling the generation of optimal seating plans through a weekly closed-loop iteration. In real-world deployment, after seven cycles, overall classroom engagement increased by approximately 45%, validating that data-driven seat assignment can significantly enhance educational outcomes in traditional fixed seating environments. Furthermore, SetEasy provides a scalable and replicable technical pathway for implementing localized and culturally responsive classroom practices.

2. Methodology

SetEasy is an intelligent, multimodal perception-based framework for optimizing seating arrangements within fixed classroom grids. The system first collects data from wristband physiological sensors, 4K behavioral video, and environmental monitors, and integrates these with ISEQ questionnaire responses to build the v-Gage engagement prediction model. Engagement predictions from the previous two weeks are fused with seat calibration data to generate a student-seat utility matrix. Finally, CP-SAT integer programming is used to maximize utility under teacher-defined constraints, such as vision and social dynamics, outputting the optimal seating plan in a weekly closed-loop iteration (see Figure 1).

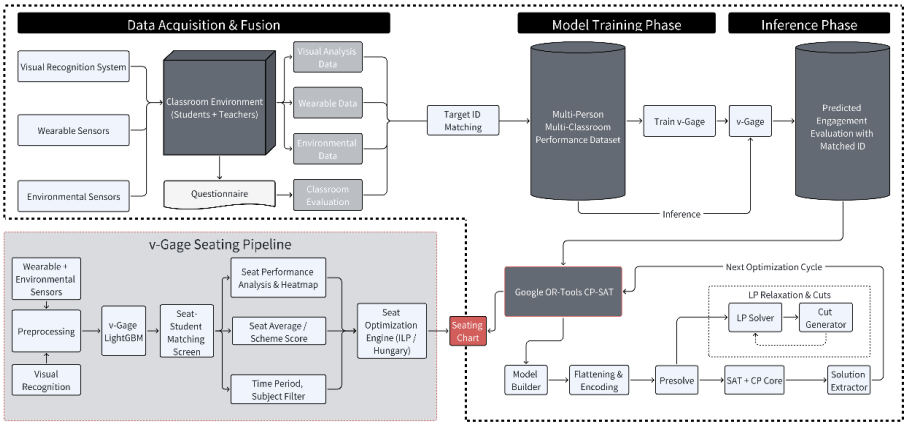


Figure 1. Classroom Engagement & Seating Flow.

2.1 DATA COLLECTION

Data were collected in June 2025 from a standard classroom at a secondary school in a medium-sized city in southern China. Over a four-week period, 23 first-year high school students (13 female, 10 male) and 6 teachers participated as study subjects, resulting in 331 valid classroom session datasets.

2.1.1 Physiological and Behavioral Data Collection

Three types of sensors were deployed for data collection (see Figure 2). First, each student wore an Empatica E4 wristband to continuously capture multi-channel physiological signals during class, including electrodermal activity (EDA) at 4 Hz, blood volume pulse (BVP) at 64 Hz (used to derive heart rate variability, HRV, metrics), 3-axis acceleration (ACC) at 32 Hz, and peripheral skin temperature (ST) at 4 Hz(Gao et al., 2020).

Second, to obtain fine-grained behavioral data, the system followed the approaches of the StuArt model(Zhou et al., 2023) and the open-source Student Classroom Behavior dataset(Yang, Wang and Wang, 2023), performing real-time recognition of five key classroom behaviors—hand-raising, standing, writing/reading, dozing, and mobile phone use—at a frequency of once per second. A 4K wide-angle camera was mounted at the top front of each classroom to continuously record and analyze classroom dynamics at one frame per second.

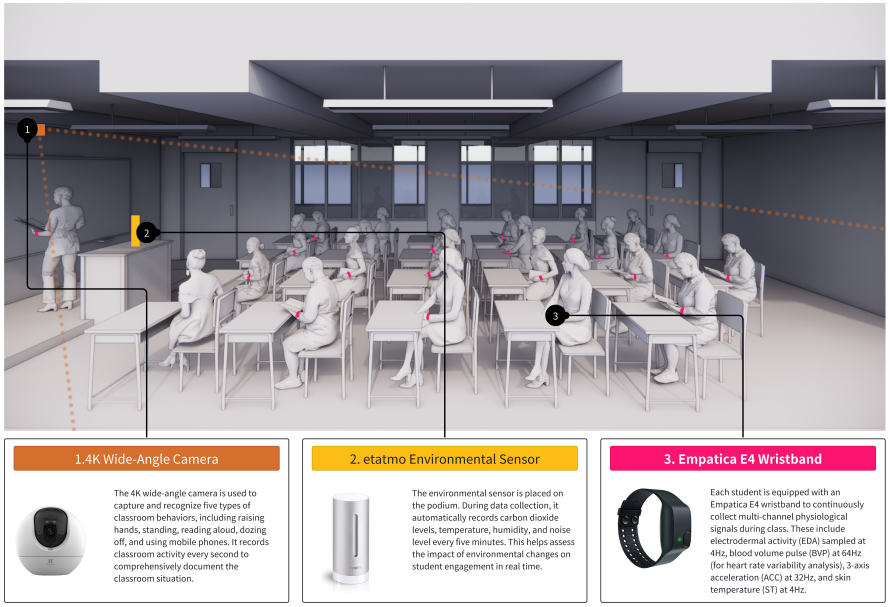


Figure 2. Diagram of Physical Deployment in Classroom.

Additionally, each classroom was equipped with a Netatmo environmental sensor, automatically recording indoor CO_2 concentration, temperature, humidity, and noise level every five minutes to provide real-time assessment of environmental impacts on students. The overall data sensing timeline is shown in Figure 3.

We implement multiple privacy safeguards: (1) guardians and students provide written informed consent; (2) video and wearable data are processed exclusively via on-premises, offline inference on school computers—raw data are never written to disk and are immediately deleted, with only de-identified weekly features and seat scores retained; (3) students participate under randomly assigned ten-digit IDs, reducing re-identification risk.2.2

2.1.2 Engagement Annotation and Ground Truth Construction

In this study, "classroom engagement" is defined as a composite of students' focus and willingness to participate in classroom activities across three dimensions:

(1) Cognitive engagement: the depth of students' understanding and critical thinking about classroom content;

(2) Affective engagement: the level of interest and enjoyment students experience during lessons;

(3) Behavioral engagement: students' attentiveness and active participation in class.

Although multimodal sensor data provide objective measurements of students' behaviors and physiological states, subjective self-report measures remain crucial for supervising the predictive model. To ensure reliable ground truth, we adopted the validated In-Class Student Engagement Questionnaire (ISEQ)(Fuller et al., 2018).

Consistent with previous research using wearables in classroom settings, which adapts survey items for different age groups(Di Lascio et al., 2017), we simplified the original ISEQ—designed for college students—to better suit the cognitive level of high school students.

Additionally, based on recommendations from Moore and Lippman regarding positive development indicators, we replaced the ISEQ item "the activities really helped my learning of this topic" with "I asked myself questions to make sure I understood the class content," thereby minimizing scoring bias in courses with limited in-class activities.

Table 1 presents the questionnaire items used to assess multidimensional engagement: items 1, 3, and 5 measure behavioral, affective, and cognitive engagement, respectively, while items 2 and 4 reflect disengagement in behavior and emotion(Skinner, Kindermann and Furrer, 2009, Fuller et al., 2018).

All items were rated on a five-point Likert scale (− 2 to +2), and students completed the questionnaire immediately after each class to minimize recall bias. The questionnaire data collection process is illustrated in Figure 3.

TABLE 1. Self-report items for measuring in-class engagement in online survey.

Questions (please describe your engagement in the last class)	Subscales
1. I paid attention in class.	Behavioural
2. I pretended to participate in class but actually not.	Behavioural (-)
3. I enjoyed learning new things in class.	Emotional
4. I felt discouraged when we worked on something.	Emotional (-)
5. I asked myself questions to make sure I understood the class content.	Cognitive

Note: (-) means the reversed score.

During data processing, all reverse-coded items were first adjusted by inverting their scores, after which the raw scores were linearly transformed to a 1–5 scale. The arithmetic mean of the cognitive, affective, and behavioral scores was then calculated to yield the overall engagement ground truth for each class session.

2.2 DATA PREPROCESSING

To accurately determine the start and end times of classroom sessions, we applied Information-Gain based Temporal Segmentation (IGTS)(Sadri, Ren and Salim, 2017). This method automatically differentiates between instructional and break periods based on student activity patterns, ensuring that all subsequent analyses are strictly confined to genuine classroom teaching intervals.

To address prevalent motion artifacts and environmental noise in the physiological data, we implemented a multi-stage cleaning process: EDA signals were first smoothed using a 5-second median filter to suppress transient noise, then decomposed into tonic and phasic components via the cvxEDA algorithm. For BVP data, linear interpolation was employed to repair intervals with suboptimal heart rate quality.

Following the removal of flat segments and artifact contamination, we validated a total of 331 high-quality, usable class sessions, which served as the foundational dataset for further analysis.

2.3 FEATURE-ENGAGEMENT ENGINEERING

The central goal of this study is to construct effective features for precise classroom engagement prediction. Building on related work such as n-Gage(Gao et al., 2020, Zhou et al., 2023), we replicated and enhanced the multidimensional engagement prediction pipeline to fit our research context, resulting in the new v-Gage system module.

From physiological signals, we extracted 36 features, including the amplitude and number of peaks in EDA signals, proportion of arousal, and HRV indices in both time (SDNN, RMSSD, pNN50) and frequency (LF/HF ratio, etc.) domains(Shaffer and Ginsberg, 2017). For behavioral patterns, we calculated the mean and variance of motion intensity from accelerometer data, and constructed synchrony features with both teachers and peers using Dynamic Time Warping (DTW) and Pearson correlation coefficients (8 features total).

From classroom environmental data, we extracted 8 features—mean and peak values of CO_2, temperature, humidity, and noise during lessons—to quantify environmental impacts on students(De Dear and Brager, 2002).

The visual behavior recognition stream further enriched the system with direct classroom behavioral features: for each class session, we detected the frequency and duration of the five most common behaviors, hand-raising-to-teacher-response latency, and cumulative dozing time, resulting in 10 behavioral features per session. Altogether, this yielded a comprehensive feature set with 62 dimensions.

We employed a LightGBM (Luxburg et al., 2018)regression model to model the relationship between the feature set and students' classroom engagement. The LightGBM-based v-Gage automatically predicts three-dimensional engagement, offering a rapid, efficient, and quantifiable alternative to traditional subjective scoring. Model training followed a nested cross-validation scheme: the inner loop used three-fold cross-validation for hyperparameter tuning and feature selection, while the outer loop applied five-fold cross-validation (grouped by student ID) to ensure generalizability and prevent information leakage.

2.4 CONSTRUCTION OF THE STUDENT–SEAT UTILITY MATRIX

To map multimodal predictions of individual classroom engagement to actual teaching space, we constructed a student‑seat utility matrix that quantitatively evaluates the potential effects of every possible seating arrangement on classroom outcomes. First, we performed spatial calibration of the classroom using a single overhead 4K camera and ARUCO marker technology(Garrido-Jurado et al., 2014), enabling one-time calibration of the classroom layout and seat grid and assigning spatial coordinates and unique indices to each seat. During each class session, the visual model ran a real-time head tracking algorithm and employed the SORT multi-object tracking method(Bewley et al., 2016) to accurately map student IDs in every frame to their respective seats, allowing the system to automatically generate and store student‑seat assignment sequences for each session.

Based on these spatial calibration and seat-matching results, we aggregated the predicted engagement of each student for every seat over the preceding two weeks. Specifically, we calculated the average predicted engagement ($\bar{E}_{i,j}$) for each student‑seat pair to reflect long-term trends in classroom performance, and computed the standard deviation (σ_j) for each seat to quantify the stability of engagement across different students. We then combined these metrics to define a comprehensive utility score:

$$U_{i,j} = 0.8\bar{E}_{i,j} + 0.2\left(1/\sigma_j\right) \quad (1)$$

The weighting coefficients of 0.8 and 0.2 were selected based on sensitivity analysis and cross-validation, emphasizing the long-term performance of individual seats while appropriately considering the consistency and reliability of each seat's engagement level. This utility matrix serves as a crucial input for the subsequent seat optimization model, quantifying the influence of classroom spatial configuration on overall classroom engagement.

2.5 SEAT OPTIMIZATION SOLVER

Building on the established seat utility matrix, we rigorously modeled the seat assignment as an integer linear programming problem and solved it using the Google OR-Tools CP-SAT solver(Martinelli Tabajara and Y. Vardi, 2019) for efficient optimization. The decision variable $x_{i,j} \in \{0|1\}$ is set to 1 if student i is assigned to seat j, and 0 otherwise. The objective function is to maximize the total weighted utility across all students:

$$\max \sum_{i,j} w_i \, U_{i,j} x_{i,j} \tag{2}$$

Here, the weight w_i is customizable by the teacher to address specific pedagogical needs—such as assigning higher weights to students with learning difficulties or attention deficits—enabling proactive support for these students through the optimization process.

The optimization is subject to the following constraints:

(1) Each student must be assigned to exactly one seat (student-seat uniqueness);

(2) Each seat may be assigned to at most one student (seat-student exclusivity);

(3) Vision and height constraints: students with impaired vision or shorter stature are prioritized for front-row seats with unobstructed views;

(4) Social and collaboration constraints: avoid seating students who are prone to mutual distraction or negative interactions next to each other, while promoting proximity among students who collaborate effectively;

(5) Accessibility and special needs: ensure that students with disabilities or special requirements are seated in accessible locations;

(6) Teacher-specified reserved or restricted seating zones, providing teachers with necessary intervention capabilities.

2.6 MODEL DEPLOYMENT

To evaluate the usability of the system in authentic classroom settings, all algorithm modules were deployed on the standard classroom computer used by teachers, with automatic data synchronization and analysis handled over the local area network(Xie et al., 2019, Liu et al., 2022).

The classroom was equipped with a standard teaching computer (Intel Core i5, 16 GB RAM, NVIDIA RTX 3060, Ubuntu 20.04), serving as the central computation and storage node. All wearable physiological sensors, environmental monitors, and classroom cameras were connected to the same Wi-Fi LAN and configured to automatically upload collected data to a designated directory on this computer after each class, ensuring comprehensive and centralized data management.

A unified Python 3.8 virtual environment was created on the deployment machine, with required dependencies—including PyTorch, OpenCV, LightGBM, Scikit-learn, and OR-Tools—installed sequentially. The final model weights and configuration files for the behavior recognition, engagement prediction, and CP-SAT seat optimization modules were synchronized locally. Each configuration file specified the data input directory, model path, and output directory to guarantee that inference results matched those obtained during the laboratory phase.

Once configured, the system operates automatically according to the following workflow:

(1) After each class, all devices upload data;

(2) The classroom computer sequentially performs behavior recognition, engagement prediction, and seat optimization;

(3) Results are saved in the local database and reports are generated.

2.7 PERIODIC CLOSED-LOOP OPTIMIZATION

SetEasy is designed not as a one-time static deployment but as a periodic, closed-loop system supporting continuous, dynamic optimization in real classroom settings.

At the end of each week, SetEasy automatically launches a complete data update and optimization workflow. The ETL pipeline aggregates logs from wearable devices, raw data from environmental sensors, and outputs from visual behavior recognition into a unified time-series database. Data preprocessing—including normalization, missing value imputation, and feature selection (such as moving average smoothing and PCA-based dimensionality reduction)—is applied within the data warehouse(Moreno-Marcos et al., 2019, Choi, Yang and Chung, 2021). The engagement prediction model is incrementally updated using gradient descent, employing sliding window cross-validation on data from the past seven days, with optional small-scale hyperparameter tuning (e.g., learning rate adjustment, regularization tuning) to maintain model stability.

The updated model generates utility scores for each student at each seat, creating a new sparse matrix as input to the Google OR-Tools CP-SAT solver. The solver aims to maximize the overall mean engagement, incorporating linear constraints (such as group distance, special-needs seat masks, and front‑back row ratios) and binary decision variables, and conducts time-limited heuristic search to output optimal or near-optimal seating solutions.

The system's frontend component visualizes the results as a heatmap covering the entire classroom, accompanied by key decision prompts. Teachers can confirm or manually adjust the recommended arrangement, with all changes recorded and integrated into the next cycle's dataset—thus closing

the loop. Through incremental model updates, matrix reconstruction, CP-SAT solving, and visual analytics, SetEasy delivers a robust and reproducible workflow for ongoing dynamic seat optimization:

(1) After each cycle, the engagement prediction model is automatically updated using the previous week's classroom data;

(2) The student – seat utility matrix for the next cycle is recalculated according to the updated model;

(3) The CP-SAT optimization engine generates seating recommendations and corresponding heatmaps, providing intuitive explanations for each suggestion;

(4) Teachers can confirm the layout or interactively adjust the recommendations provided by the system.

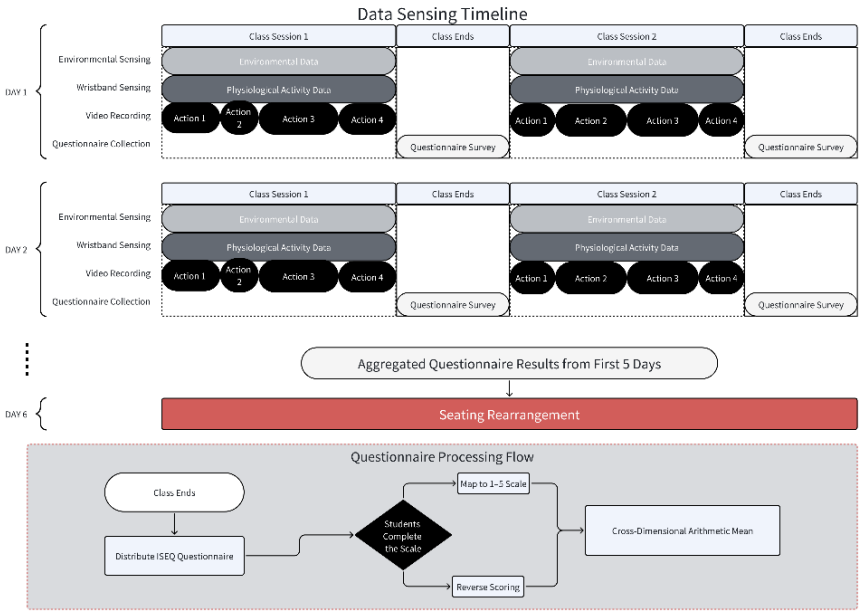


Figure 3. Data & Questionnaire Flow.

3. Results

3.1 DATA COLLECTION OUTCOMES

In a representative lesson—a 45-minute mathematics class during week 1, session 1—the SetEasy system automatically captured and de-duplicated five categories of classroom behaviors, retaining seat numbers (RxCy): hand-raising, standing, yawning, smiling, and brief episodes of dozing (see Table 2). Across the session, the 23 students collectively exhibited 230 hand-raises

(an average of approximately 10 per student), 45 instances of standing (about 2 per student), 60 yawns (about 2.6 per student), 180 smiles (about 7.8 per student), and 8 dozing events (about 0.3 per student). Hand-raising activity peaked between the 10th and 30th minutes, coinciding with periods of teacher explanation and class interaction; standing events were primarily associated with roll call or demonstration scenarios, averaging 5.5 seconds in duration; yawning and dozing occurred mainly in the second half of the class, suggesting a decline in student attention over time.

Further spatial analysis revealed systematic differences in behavioral frequency by seat location (see Table 2). Students seated in the front row (e.g., R1C2, R1C3) raised their hands 11 – 12 times on average, while those in the back row (R5C3, R4C1) did so only 8 – 9 times. In contrast, yawning and dozing were more frequent in the back rows; for example, R3C4 recorded 3 yawns and 1 dozing event, whereas R1C1 in the front row recorded no sleep behavior. Smiling also showed a front-row-high, back-row-low pattern: R1C2 and R2C3 registered 9 – 10 instances, while R4C3 in the back row registered only 6. These results objectively demonstrate that, within a fixed seat grid, spatial distance significantly influences students' active participation and fatigue-related behaviors.

TABLE 2. Seat-ID-Behavior Statistics.

Seat (RxCy)	Stu ID	Raising Hands	Standing	Yawning	Smiling	Sleeping
R1C1	S01	9	2	1	8	0
R1C2	S02	12	2	0	10	0
R1C3	S03	11	1	1	9	0
R1C4	S04	10	3	2	7	1
……	……	.....	……	.....	.....	.....
R6C3	S23	9	1	1	9	0

3.2 V-GAGE MODEL EVALUATION

As shown in Figure 4, the MAE and RMSE curves for v-Gage in emotional, behavioral, cognitive, and overall engagement dimensions exhibit a steady, monotonic decline, with no oscillations or inflection points, indicating stable convergence and controlled overfitting risk during training. Compared to n-Gage—which utilizes only physiological and environmental features—the addition of behavioral features in v-Gage yields consistently lower prediction errors across all dimensions. The most notable improvement is in cognitive

engagement: after 80 training epochs, v-Gage achieves an RMSE of approximately 1.00, while n-Gage remains at 1.11. The overall engagement RMSE also drops from 0.75 to around 0.53, demonstrating superior generalization. This improvement is mainly attributable to the incorporation of behavioral features such as acceleration intensity and group synchrony, which are highly correlated with cognitive workload and thus effectively enhance the expressive power of physiological and environmental signals.

3.3 SEAT HEATMAP EVALUATION

A comparison of seat heatmaps before and after optimization (Figure 4) clearly demonstrates that reassigning seats substantially increased overall class engagement while reducing spatial variability. Prior to optimization, most seats had engagement scores in the 0.20 – 0.40 range, with a global average near 0.30 and the highest value barely reaching 0.60. The third row recorded the lowest average ($\approx$ 0.35) and included near-zero "non-participation" seats, reflecting a significant proportion of low-activity locations.

After optimization, every seat except row 4, column 2 exceeded 0.60, lifting the overall class average to approximately 0.70. More than two-thirds of seats registered scores above 0.80, with continuous "high-engagement bands" appearing in rows 1, 3, and 6, indicating clear convergence in engagement distribution. The change in average engagement (0.30 → 0.70) represents an increase of over 130%, and only a single seat remained at an extremely low value, showing that "low-participation islands" were nearly eradicated.

Overall, data-driven seat optimization shifted engagement from "low and dispersed" to "high and concentrated," providing teachers with clear targets for further improvement and validating the effectiveness of seating optimization in enhancing classroom engagement.

4. Discussion

4.1 SUMMARY OF RESULTS

Applied in mainland Chinese secondary classrooms—across both Chinese- and English-language lessons—SetEasy received positive feedback: The results demonstrate that SetEasy uncovers significant temporal and spatial stratification in classroom engagement: student participation exhibits a "rise-then-fall" pattern over the course of a lesson, and positive behaviors become sparser and signs of fatigue more evident with increased distance from the teacher. The v-Gage model achieves stable, smooth convergence in

multidimensional engagement prediction; the integration of behavioral features substantially enhances the identification of deep cognitive states, validating the complementarity between physiological–environmental signals and overt behaviors. With this detailed engagement profile, integer programming reallocates high-potential students to key sightlines, elevating overall classroom engagement and leading to a more balanced distribution: previous patterns of "low participation in the back row" are effectively alleviated, with high-engagement areas clustering into continuous bands and low-activity "islands" significantly reduced.

In summary, whether in Chinese or English classes, SetEasy first diagnoses seat-induced disparities in participation and then, through data-driven seat assignment, consolidates engagement from a scattered state to one that is concentrated and sustainable—demonstrating the synergistic effect of multimodal sensing and optimization strategies in reconstructing classroom motivation dynamics.

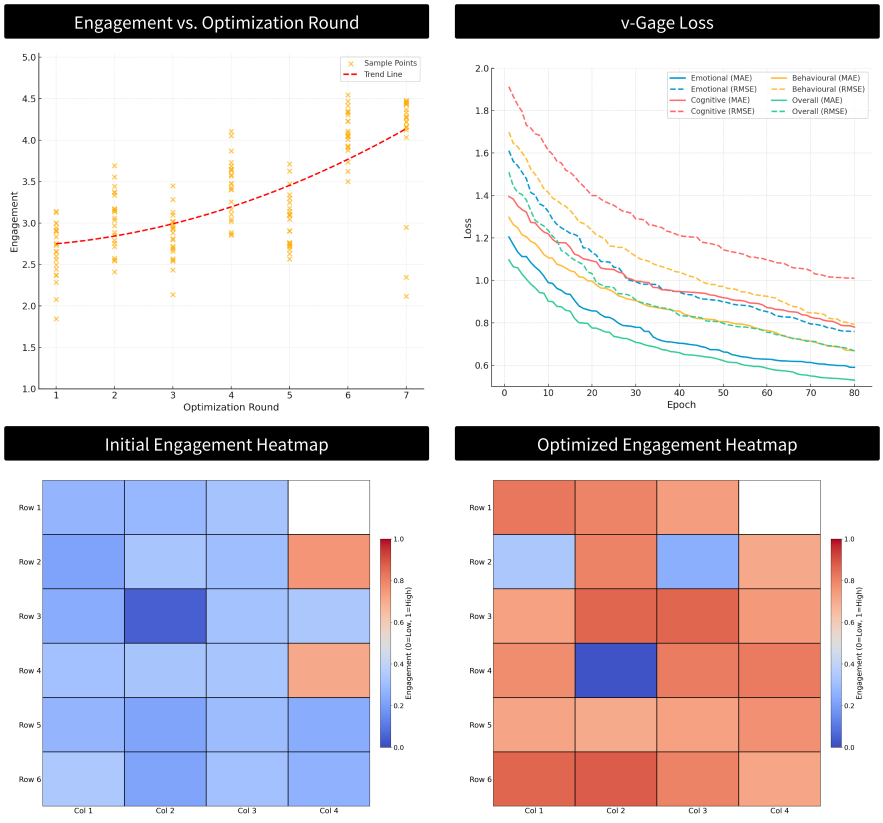


Figure 4. Visualization of Model Training and Seating Optimization Outcomes.

4.2 LIMITATIONS

SetEasy focuses on lecture classrooms because the seating and visibility gaps it corrects rarely occur in seminars or labs. In this context, this study has four primary limitations. First, the model was trained mainly for standard lecture classrooms and has not yet been validated in diverse instructional contexts such as inquiry-based or discussion-oriented classes, nor has its adaptability to different teaching styles been established. Future work should broaden the range of classroom types and teacher samples to enhance generalizability. Second, the engagement ground truth relies in part on student self-assessment, which may be affected by fatigue and social desirability bias; future studies should include multi-source evaluations from peers and teachers, along with more objective metrics, to mitigate subjective error. Third, data collection was limited to a small number of campuses and grade levels; thus, the model's robustness in other locations, educational stages, or non-standard classroom layouts remains to be demonstrated. Systematic evaluation of cross-context transferability, enabled by cross-school collaboration and data sharing, will be necessary for further refinement. Fourth, data collection required many wristbands and an ambient sensor, so large-scale rollout is costly.

4.3 CONCLUSION

SetEasy integrates multimodal sensing, v-Gage engagement prediction, and CP-SAT integer optimization, enabling the calculation of "student–seat" utility within fixed seating grids and providing weekly, class-wide seat assignment strategies that maximize collective benefit. This framework equips teachers with interpretable, quantifiable, and rapidly updatable seating strategies, replacing labor-intensive manual adjustments and enhancing both individualized support and instructional efficiency. Instructors reported increased interaction and reduced management burden with higher student engagement, aligning with our quantitative results. More importantly, this study demonstrates that even when physical layouts cannot be altered, computational design can reshape spatial dynamics and mitigate the suppression of local cultural identity and motivation imposed by globalized, homogenized layouts—laying a data-driven foundation for culturally responsive and differentiated design in educational architecture. This "multimodal assessment–integer optimization" paradigm is equally applicable to other fixed-seat environments, such as meeting rooms, control centers, and medical waiting areas, offering a transferable technical template for smart space management and equitable resource allocation.

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UNLOCKING CERTAINTY IN COMMERCIAL DEVELOPMENT

A Data-Driven Model for Site Selection and Market Differentiation

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Abstract. The spatial distribution of commercial activities in the Egyptian market is shaped by two contrasting perspectives: a top-down, government-led regulatory approach and a bottom-up, developer-driven market approach. Each operates with its own methodology, challenges, opportunities, and degrees of certainty in decision-making. At the macro scale, national urban regulations govern the distribution of commercial services in both existing and new urban areas. This regulatory perspective treats commercial functions as service components within planned zones, driven by standardized variables such as catchment area ratios, built-up area limits, and life safety parameters, based on historic planning models and development priorities. In contrast, the meso and micro scales reflect a more dynamic market reality. Here, developers approach commercial activities as businesses operating in competitive environments, where site selection becomes a critical decision influencing customer reach, long-term sustainability, and brand growth. These decisions must factor in a wide range of tangible and intangible internal and external variables often without clear, data-driven guidance. A key challenge for the bottom-up approach is the lack of clear evidence-based insights into what drives successful site selection and asset characteristics. Many decisions are still based on intuition or limited past experience rather than systematic analysis. This research addresses that uncertainty by applying digital technologies and data science tools to one of the fastest-growing sectors in Greater Cairo: coffee shops. Coffee shop commercial activity has been selected as a pilot case to model broader commercial activity analysis through big data science. Through the hedonic

valuation model, this study uses descriptive and diagnostic analysis to support decision-making through: (1) Mapping current distribution patterns of coffee shops across Greater Cairo for the purpose of understanding the current domain and (2) Identifying and weighting internal and external success factors using machine learning feature importance. The study analyzes over 16,000 data points from diverse sources including Google Maps, social media, and real estate platforms covering 28 national and international coffee shop brands over a 20-year period. Success is modelled as a function of combined individual attributes, classified into external (location-based) and internal (in-store) characteristics. The random forest model was applied to identify and rank the features most strongly correlated with success. The study found that in-store operational and branding factors had significantly higher impact on coffee shop success than external location-based attributes. Second generation retail features in form of digital readiness (Retail 02 status) was the top predictor, followed by average pricing, brand maturity, and social media engagement highlighting that consumer perception, tech-enabled operations, and market differentiation are stronger success drivers than geographic location.

Keywords: *Hedonic Valuation Model, Big Data, Cairo Coffee Shop Market, Market Differentiation.*

1. Literature Review

1.1. COMMERCIAL SERVICES VERSUS RETAIL BUSINESS: A REVIEW

1.1.1. Commercial Services

From a top-down perspective of Egypt's national government, through the General Organization of Physical Planning (GOPP) and its Urban Planning Standards - Volume 11 (2017), defines commercial services as essential public services. Their provision remains a pressing issue in Egypt's urban development landscape. The main challenges identified include:(1) severe shortage of commercial services compared to optimal benchmarks or global standards, (2) Poor site selection processes that fail to meet population needs equitably and (3) Misalignment between allocated space sizes and contemporary service standards. Public-sector planning tools emphasize: (1) Alignment with other public services, (2) Centralized, accessible, and safe locations, (3) Avoiding hazardous zones, (3) Efficiency based on *minimum threshold* and *maximum range* concepts and (4) Promoting co-location and inclusion (e.g., disability access).

1.1.2. Retail Business

From a bottom-up perspective adopted by investors, commercial activity is approached as a retail business driven by return on investment (ROI) and long-term sustainability. Based on interviews and podcasts featuring Egyptian investors, three key challenges to retail success within Egyptian context have been identified (1) Understanding the local market dynamics, (2) Designing hospitality features that meet evolving customer expectations, and (3) Adapting to experiential retail new approach that emphasizes immersive, personalized in-store experiences that go beyond traditional transactions. (Million Pound Menu EG, n.d.), (Egypt's Entrepreneur Awards, n.d.).

Given the dynamic nature of market conditions, successful retail site selection and the prioritization of architectural, experiential, and intangible features to adopt can benefit from up-to-date crowdsourced data and big data analytics. Effectively identifying, quantifying, and ranking key location and hospitality attributes and understanding their interdependencies can help bridge the uncertainty gap that often challenges retail decision-making. The use of big data and machine learning techniques across industries has shown strong potential for generating precise, data-driven insights. By shifting focus from manual data collection to advanced analysis, these tools support better identification of high-impact variables, enabling more confident and optimized investment decisions in the retail sector.

1.2. HEDONIC VALUATION MODEL: A REVIEW

The hedonic pricing model is an economic framework established based on consumer theory, initially introduced by (Lancaster,1966). Hedonic valuation model hypothesizes that the value or, in this research, the success of a product or service is derived from the combined worth of its individual attributes. These attributes, whether tangible or intangible, are often not directly traded in the market but significantly influence consumer satisfaction, demand, and perceived value (Rosen, 1974; Freeman, 1979; Herath and Maier, 2010; Greene, 2019). In the context of coffee shops, pilot study for commercial activities, these attributes are categorized into external factors (e.g., location and neighbourhood context) and internal or in-store characteristics (e.g., architectural design, services, and digital engagement). Within the hedonic valuation model, these serve as independent variables,

allowing overall success to be deconstructed into measurable components that reflect what consumers are willing to pay for or respond positively to.

1.3. COFFEE SHOP INDUSTRY IN GREATER CAIRO: A REVIEW

According to Statista (2024), Egypt's hot drinks market which includes tea, roasted and instant coffee, and cocoa in dry form is divided into at-home consumption, valued at EGP 2.4 billion, and out-of-home consumption (cafés and coffee shops), valued at EGP 1.6 billion. This study focuses on the latter. While overall revenue and revenue per capita continue to grow, consumption volumes have stagnated for tea and coffee, with only minor increases for cocoa. Volume per capita is projected to remain stable (Statista, 2024), suggesting deeper shifts in consumer behaviour and market dynamics.

Such status in terms of revenue can be interpreted as follows: (1) Demographic shifts: Egypt's younger population, entering their peak earning years, is contributing to higher spending on coffee and cafe experiences (Savills, 2024). (2) Evolving consumer behaviour: There is a rising appetite for premium, innovative, and experience-driven products, contributing to the premiumization of the market (Savills, 2024). (3) Supply-side disruptions: As highlighted by Al Mashhad (2024), global investment surges 168% in cocoa and 70% in coffee signal rising input costs and international supply chain challenges. Given these dynamics, macroeconomic indicators alone are insufficient. It becomes critical to understand the specific internal and external attributes of coffee shops that shape consumer preferences and business success. This study, therefore, investigates these characteristics within Cairo's increasingly competitive coffee shop market.

2. Methodology

2.1. DATABASE CONSTRUCTION

This research used publicly available data from Google Maps as the primary source for exploring 30 selected coffee shop brands in Cairo. TABLE 1 below outlines the data entry points and their analytical purposes:

TABLE 1. Data Entry Points from Google Maps and Their Analytical Usage in Coffee Shop Success Evaluation (Authors, 2025)

Data Explored	Scope of Usage

Longitude & latitude	• Location classification (East, Central, or West Cairo) • Competition Density analysis.
Address & hyperlink	• Contextual classification (Commercial, residential, admin, Road network or special-use area) • Store Type identification & Classification (specialized coffee shop, plug-in to conventional store, plug-in to library) • Parking availability
Working Hours per Branch	• Quantifying Impact of total Operating Hours per Day
Top Reviews	• Exploring key positive features to be considered in Hedonic Model
Ratings & Number of Reviews	• Constructing the success indicator
Popularity Times	• Measuring weekly visitor interest in each branch for success Indicator analysis

According to recent Egypt Digital 2024/2025 reports (DataReportal, 2025; NapoleonCat, 2025) Facebook platform is being used by 56.4 million users (48.3% of the population), primarily aged 25–34 (31.4%) and 18–24 (31%). Rapid growing TikTok has reached 41 million users (35.1%), dominated by aged 18–24. Instagram follows with 19.4 million users (16.6%), where 41.7% fall within the 18–24 age group. These figures highlight a young, digitally active audience, especially between 18 and 34 years old.

Reflecting this strong engagement with social media platforms, the number of followers and likes across each coffee shop brand's official Facebook, Instagram, and TikTok pages was collected and used as input in the Success Indicator analysis. Additionally, the average number of posts per active year was used as a proxy indicator of brand–customer engagement and marketing activity, under the Digital Popularity & Brand Creation framework. As individual branch establishment dates are often unavailable,

each brand was assigned a constant year of establishment, based on official websites, news articles, or the earliest social media presence.

To reflect the socio-economic level of context neighbourhoods, average prices for 2-bedroom units were extracted from the following real estate platforms Property Finder, Nawy, and Dubizzle Egypt. These values were averaged across platforms and incorporated under Average Income feature in the External Factors framework. Menu pricing data (including cappuccino, highest, and lowest item prices) was sourced from Talabat, ElMenus, and brand websites. The presence of second-generation retail features such as apps, websites, in-store Wi-Fi, loyalty programs, and trend-aligned offerings was verified through platform listings and digital store audits, informing the In-Store Factors framework.

2.2. CONSTRUCTION OF SUCCESS INDICATOR

This research presents a **proof of concept** for applying **big data analytics** within a **hedonic valuation model** to evaluate factors influencing the success of coffee shops, using a **Random Forest machine learning approach**.

The **dependent variable (Y)**: **Success Indicator** was developed as weighted combination of three key parameters:

1. **Customer Ratings and Reviews**: collected from Google Maps for each branch

2. **Popularity Time**: measured by average weekly popularity data (24/7) from Google Maps for each shop[1].

3. **Social Media Engagement**: calculated as the average number of followers per year (total active brand years) across Facebook, Instagram and TikTok.

Due to the absence of publicly available revenue or sales data, financial performance parameter was excluded. Each parameter was **normalized** and **weighted** to reflect its relative contribution to user interest and satisfaction. **Branch specific parameters** (Ratings and Popularity) were assigned a

[1] Due to time and knowledge limitations, popularity data was directly extracted for 20% of each brand's branches, while the remaining values were reliably estimated using same conceptual method.

weight of **0.35** each, while the **brand parameter** (Social Media Engagement) was assigned **0.30**.

Success Indicator (Y) = 0.35 × Rating + 0.35 Popularity × + 0.30 × Social Media Engagement (1)

2.2.1. MinMax Normalization Method

A. **Normalized Rating** = (Weighted Rating -1) / (5 - 1) (2)

i. Where **Weighted Rating** = (Rating Count / (Rating Count + 10[2])) x (Rating + (10 / Rating Count + 10)) x 4.2[3] (3)

B. **Normalized Popularity** = Average Popularity/100 (4)

C. **Normalized Social Media Engagement** = (Facebook Followers Per Year /Max) +(Instagram Followers Per Year/ Max) + (TikTok Followers Per Year/ Max)/3 (5)

2.3 CONSTRUCTION OF HEDONIC MODEL FACTORS

Through the hedonic valuation model approach, 19 internal and external factors[4] shown in TABLE 2 were identified for the use in a Feature importance analysis. A random forest machine learning algorithm was then applied to determine the relative weight of each factor in influencing coffee shop success.

TABLE 2. Constructed Hedonic Model Factors (Authors, 2025)

Variable Name	Definition and Reflection	Type of Data
External Factors		

[2] The Bayesian weighted rating formula was applied, incorporating 10 as a minimum review threshold to adjust for varying sample sizes.

[3] The overall sample average rating that is used as a baseline.

[4] Defined groups and categories are based on literature review, reviewing collected data and research's evaluation for prospective affecting attributes.

1	Development Location	Geographical development zone: East, West, or Central Cairo	Categorical
2	Store Location	Land use/zoning type (e.g., Residential, Commercial, Mixed)	Categorical
3	Parking Availability	Parking access: No (0), Limited (1), Yes (2)	Ordinal
4	Competitive Density	Number of coffee shops within a 500m radius from each shop	Continuous
5	Average Area Income	Average price for 2-bedroom units in the area	Continuous
6	Street Visibility	Casual visibility from the street: Yes (1), No (0)	Dummy
In Store Factors			
Design / Operational			
7	Type of F&B	Shop concept: Specialized, Plug-in to Restaurant, to conventional store, to Truck, or Cultural space	Categorical
8	Average Price	Average beverage price across the menu	Continuous
9	Total Working Hours	Total hours open per day	Continuous
10	Brand Expansion Level	Local (0), National (1), Regional (2) or Global (4) classification	Ordinal
11	Number of Branches	Total number of operational branches	Continuous
12	Outdoor Seating Availability	Whether the shop has outdoor/open seating area: Yes (1), No (0)	Dummy
13	No. of Active Years	Years since brand establishment	Continuous
14	Trend Interaction	Whether the menu reflects current trends (e.g., matcha, new packing): Yes (1), No (0)	Binary

15	Retail 02 Status	Presence of website, app, and/or in-store Wi-Fi	Binary
Digital Popularity & Brand Creation			
16	Average Popularity	Review-based or foot traffic-based popularity score	Continuous
17	No. of Instagram Posts	Total number of posts by the shop's Instagram account	Continuous
18	No. of Tiktok Likes	Total likes on TikTok account (used as a proxy for engagement and virality)	Continuous
19	Loyalty Features	Whether a loyalty program / promotions exists: Yes (1), No (0)	Binary

3. Analysis and Discussions

3.1. MAPPING THE COFFEE SHOP SCENE IN GREATER CAIRO CONTEXT

As shown below in Figure 1, the sample has included 503 coffee shops branches for 28 brands.

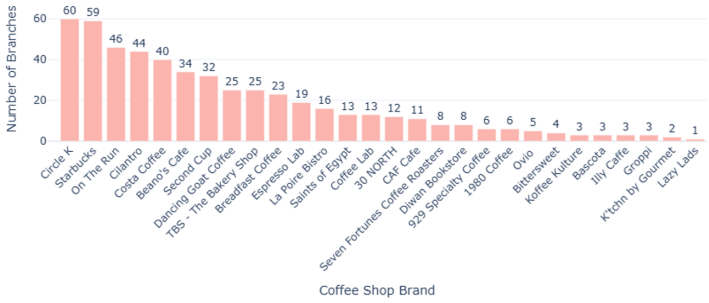


Figure 1. Distribution of 503 Branches of 28 Coffee Shop Brands in the Study Sample (Authors, 2025)

Through exploring brands origin and their spatial distribution in greater Cairo and their scope of expansion, it reveals that the Egyptian coffee shop market highly welcomes international brands along with National ones. National brands hold the largest share in Greater Cairo, accounting for 45.9% of all branches. Among international brands, the top three franchised brands originate from the USA 20.1%, Canada-USA 11.5%, and the UK 7.65%, as illustrated in Figure 2.

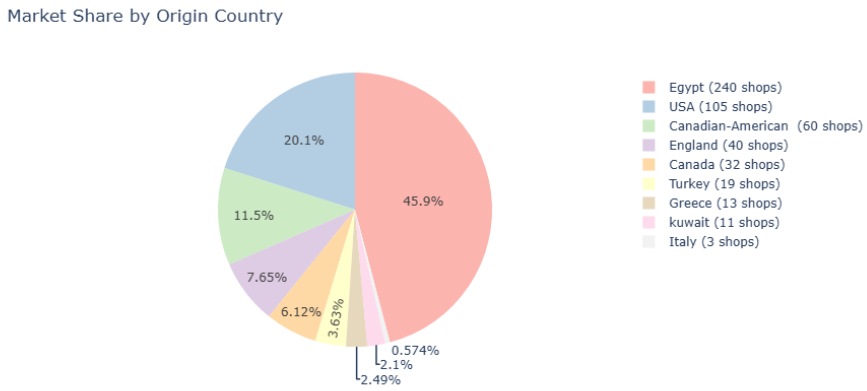


Figure 2. Market Share by Origin Country (Authors, 2025)

Of the 28 coffee shop brands operating in Greater Cairo, 6 are localized within the city, 11 have expanded to other governorates across Egypt, 3 operate within the MENA region, and 8 are global brands, as illustrated in Figure 3

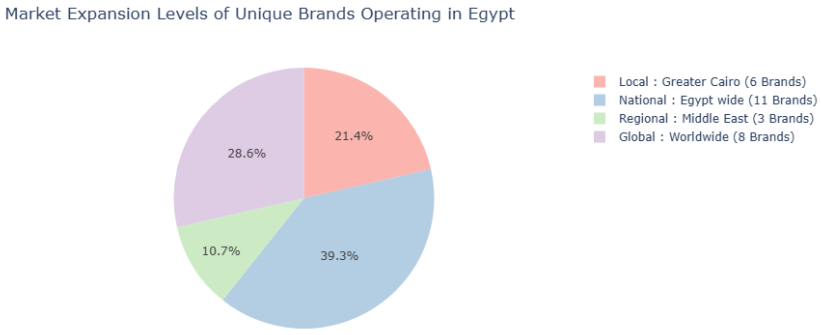


Figure 3. Level of Operation Expansion for Coffee Shop Brands (Authors, 2025)

Among coffee shops operating in Greater Cairo, 209 branches (41.55%) are located in Central Cairo, 171 branches (34%) in East Cairo, and 123 branches (24.45%) in West Cairo, as illustrated in Figure 4 and Figure 5.

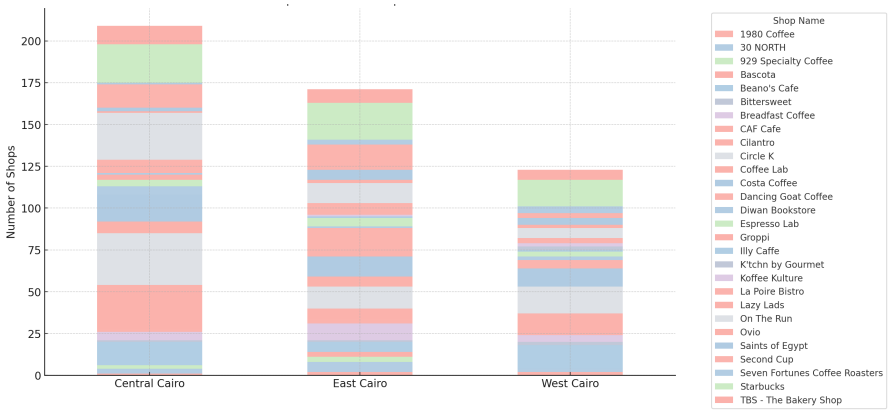


Figure 4. Distribution of Coffee Shops Across Greater Cairo (Authors, 2025)

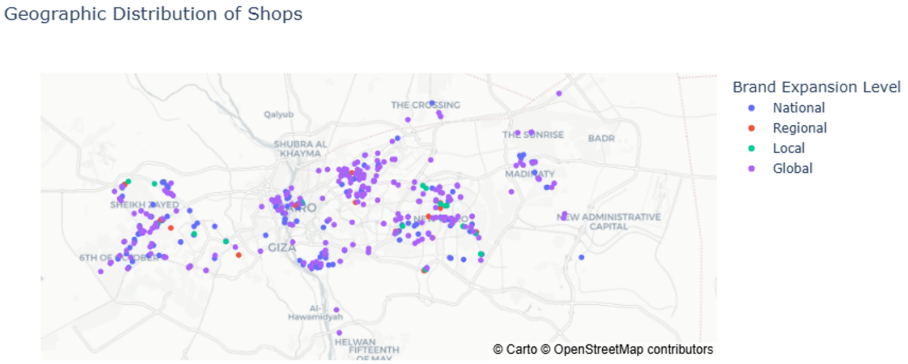


Figure 5. Geographic Distribution of Coffee Shops Across Greater Cairo (Authors, 2025)

3.2. FEATURE IMPORTANCE ANALYSIS OF INTERNAL AND EXTERNAL SUCCESS FACTORS

Through applying Random Forest machine learning algorithm to the selected features, achieving an R^2 score of 0.979 the following results was achieved as shown in TABLE 3: the nine In-Store Design and Operational Factors accounted for 86.63% of the total feature importance, followed by the four

In-Store Digital Popularity & Brand Creation by 8.45%. The six External factors contributed the remaining 4.94% of the feature importance.

TABLE 3. Feature Importance by Category (Authors, 2025)

Feature Category	Importance Percentage
• In-store Factors Design / Operational	86.63%
• In-store Factors Digital Popularity & Brand Creation	8.45%
• External / Contextual Factors	4.94%

Although location was initially expected to be one of the top influential factors in coffee shop success, the analysis revealed otherwise. Findings show that in-store characteristics outweigh external/ contextual ones, indicating that how a brand design and operational features are more critical than where it is located. The most successful coffee shops were those that were tech-enabled, appropriately priced, digitally visible, and focused on experiential offerings highlighting these as the pillars of competitive advantage.

The relatively low weights assigned to external factors may be explained by the homogeneity of the sampled locations and in Cairo in general. Many shops in the study are situated in similarly high-end, planned developments with shared advantages such as sufficient parking, street visibility and commercial clustering. For example, the sample included eight coffee shops in Westown and nine in District 5, similar in garden 8, all affluent, newly developed areas offering comparable physical and contextual features. In such cases, operational differentiation, rather than geographic distinctiveness, becomes the key success factor.

One particularly notable finding was the dominant importance of the Retail 02 Status, which accounted for 40.72% of the total weight—the highest among all features as shown in TABLE 4. Even after reclassifying this variable into a binary format to test robustness, it remained the top predictor of success. These insights uncovered through big data analytics underscores that digital readiness, even in its simplest form, acts as a clear indicator that Retail 02 is less about technology use and more about market positioning and brand ambition.

These results underscore the fact that Retail 02 which represents a second-generation approach to retail that includes digital infrastructure, loyalty programs, and trend responsiveness is not merely about technology

usage, but about brand positioning and consumer perception. Contrary to expectations that Retail 02 features would have little effect due to widespread mobile internet usage, their presence appears to act as a signal of professionalism, modernity, and brand ambition. Their impact lies less in their technical function and more in the message they send to customers.

TABLE 4.Coffee Shop Success Feature Importance – Full Model (Authors, 2025)

	Feature	(%)		Feature	(%)
1	Retail 02 Status	40.72	16	Type of F&B_Coffee Shop	0.3
2	Average Price	26.03	17	Development Location_West Cairo	0.3
3	Number of Branches	8.17	18	Street visibility	0.15
4	No of Active Years	6.13	19	Type of F&B_Plug-in to a convenience store	0.13
5	No. of Tiktok Likes	3.62	20	Store Location_Administration Area	0.12
6	No. of Instagram Posts	2.5	21	Outdoor Seating Availability	0.11
7	Total Working Hours	2.45	22	Type of F&B_Plug in to Burger Truck	0.09
8	Average Area Income	2.26	23	Type of F&B_Plug-in to a restaurant	0.04
9	Brand Expansion Level	2.09	24	Development Location_East Cairo	0.03
10	Average Popularity	1.74	25	Store Location_Residential Area	0.01
11	Trend Interaction	0.93	26	Parking Availability	0.01
12	Competitive Density	0.85	27	Development Location_Central Cairo	0.01
13	Loyalty Features	0.59	28	Store Location_Special Nature	0
14	Type of F&B_Plug-in to Grocery Shop	0.33	29	Store Location_Road Network	0
15	Store Location : Commercial Agglomeration	0.31	30	Type of F&B_plug_in to Bookstore	0

4.2.1. Average Price – 26.03%

Shops with higher average beverage prices tend to be more successful. This suggests that pricing reflects the perception of quality and brand positioning.

4.2.2. Number of Branches – 8.17% & No. of Active Years – 6.13%

The presence of multiple branches enhances a coffee shop's success, where it reflects wide presence and increases accessibility that builds loyalty, popularity and long-term sustainability.

Older coffee shops shown to perform better, likely due to brand maturity, refined operations, and loyal customer bases. Longevity builds credibility and local reputation.

4.2.3. No. of Instagram Posts – 2.5% & No. of TikTok Likes – 3.62%

Social media engagement both passive and active has become a defining element of modern consumer culture across industries, and the coffee shop market is no exception. Feature importance analysis confirms that frequent posting and consistent digital presence are strong indicators of success. These behaviours reflect effective visual branding, ongoing marketing efforts, and sustained audience engagement, all of which enhance a coffee shop's perceived relevance particularly among Gen Z and experience-oriented consumers.

4.2.4. Total Working Hours – 2.45% & Average Popularity – 1.74%

As per the study, positive correlation between Longer opening hours that provides higher accessibility and customer responsiveness and the increase of average popularity exists in coffee shop industry. Shops that open longer can serve more customers and adapt to different lifestyles.

4.2.5. Brand Expansion Level – 2.09 % & Competitive Density – 0.85%

A high concentration of surrounding coffee shops whether expanding locally or nationally or franchised from regional or global markets may indicate a vibrant café scene, but also reflects intense competition. This helps explain why in-store factors received the highest importance scores, where shops

that thrive in dense markets are likely those offering greater value, stronger differentiation, or a more compelling customer experience.

4.2.6. Trend Interaction – 0.93% & Loyalty Features – 0.59%

Being responsive to market dynamics through embracing emerging trends like matcha or seasonal drinks has proven to positively impact performance and keeping the success of coffee shop in highly competitive markets.

Additionally, loyalty programs proved its ability as well to play a role in maintaining a returning customer base and supporting long-term retention, keeping its status in the market.

4.2.7. Type of F&B– <0.5% combined

As per analysis outcome, format of market entry whether as a standalone coffee shop or a plug-in concept (e.g., within a grocery store, restaurant, or bookstore) has minimal direct impact on success. This suggests that performance is driven more by in-store features than by format. However, some types may align with specific audiences that need to be considered while typical target customer analysis is being conducted.

4. Conclusion

This study demonstrates that in Cairo's competitive coffee shop market, success is not defined by location only. Instead, a brand's digital presence, pricing strategy, operational maturity, and in-store customer experience are the dominant drivers of success. Using a hedonic valuation model and machine learning analysis, the research identifies internal operational and in-store factors as the primary drivers of performance outweighing location-based variables.

Feature importance analysis revealed that internal operational and in-store factors far overshadow external location-based factors in determining the success of coffee shops in Greater Cairo. In particular, digital readiness measured through Retail 02 Status (e.g., having a website, app, or Wi-Fi) emerged as the most influential factor, contributing 40.72% to the model. This indicates that the perception of digital presence, more than its actual use, strongly impacts consumer trust and brand positioning.

Average beverage price followed with a weight of 26.03%, suggesting that pricing reflects perceived quality and plays a key role in market differentiation. Indicators of brand maturity (including number of branches (8.17%) and years of active years (6.13%)), also significantly influenced success, reflecting the importance of operational experience and expansion capacity.

Social media two-way engagement metrics such as TikTok likes (3.62%) and Instagram posts (2.5%) demonstrated the growing importance of visual branding and youth engagement, particularly among Gen Z consumers. Extended opening hours and higher popularity scores (2.45%) & (1.74%) respectively, highlighted the role of accessibility and customer responsiveness. Contrary to expectations, external factors such as development zone, income levels, and competitive density had limited predictive power, likely due to the homogeneity of high-end, planned developments in the sample. In such contexts, operational differentiation becomes the key to success. These findings emphasize that success in Cairo's coffee shop sector is increasingly driven by how a brand operates, not just where it is located.

These insights offer a data-driven framework for developers, investors, and policymakers to inform retail strategy—guiding decisions in location selection, branding, pricing, and service design. While this study focuses on coffee shops as a pilot case, the methodology and findings are applicable to other forms of commercial activity that rely on customer-facing physical spaces and digital engagement. Future research can build on this by expanding the dataset, testing across different retail segments or applying the model in other cities and urban contexts for broader generalization.

5. Recommendations for Further Studies

Future research could expand the hedonic framework by incorporating a broader set of external and internal features, including those less commonly quantified, from both successful and underperforming coffee shops. Exploring the interactions between these variables using advanced regression techniques and machine learning models would enhance the model’s depth and accuracy. Such an approach could uncover hidden patterns within the market ecosystem, offering a more comprehensive set of indicators to support decision-making. Over time, this would contribute to building a more stable, predictable, and mature coffee shop market.

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ARTIFICIALLY AUGMENTED OTTOMAN BAROQUE

Ornament as a Radical Agent for Change

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1. Abstract

This project uses artificial intelligence to reinterpret and revive Thessaloniki's ornamental heritage, focusing on baroque and Islamic-inspired motifs from the city's interwar architecture. Following the Great Fire of 1917, architects trained in Istanbul's École des Beaux-Arts brought a richly hybrid design language to the city — blending late Ottoman traditions with European styles such as Baroque Revival, Art Nouveau, and early Modernism. Their ornamental expressions, often dismissed by modernist purists, became acts of cultural resilience and identity.

To explore how this ornamental legacy might inform contemporary design, a dataset of 1,784 architectural elevation images (from 1924–1937) was collected from buildings in Thessaloniki.

The final prototypes serve as 3D collages of the past. They can be viewed as contemporary expressions of a forgotten urban syntax that retrace cultural narratives discovered through ornament. This project seeks not only to

preserve, but to reactivate ornamentation as a meaningful architectural tool — one augmented by machine learning and rooted in local memory.
By positioning ornamentation as a site of digital heritage experimentation, the project challenges the long-standing dichotomy between form and function. It leverages AI not as a neutral tool, but as a creative collaborator capable of mediating between archival data and future form-making. The resulting artifacts function as speculative restorations — not of specific buildings, but of a societal aesthetic sidelined by modernism, nation building and political narratives. In this case, the omission of ornament coincides with the founding of the new Greek Nation and the dismantling of the Late Ottoman Empire. Ultimately, this work contributes to a broader discourse on how computational design can reconcile aesthetic memory with contemporary fabrication and ecological awareness, particularly in cities with complex colonial and cultural histories like Thessaloniki.

2. Introduction

Thessaloniki, a city located in Northern Greece, holds a unique and layered architectural identity shaped by centuries of complex history. Once a vital port of the Ottoman Empire until its annexation by Greece in 1912, the city witnessed dramatic transformation in the early 20th century. A pivotal moment came with the Great Fire of 1917, which destroyed a significant portion of the historic center, leaving thousands homeless and erasing centuries of built heritage (Karadimou-Yerolympou, 1985). In the aftermath, an urgent reconstruction process began, especially after 1924, amid geopolitical shifts, population exchanges, and a growing need for modern infrastructure, which led to a prolific decade for many refugee architects (Theodoridou-Sotiriou, 2006).
Due to a shortage of local engineers and architects capable of handling the scale and complexity of reconstruction, Thessaloniki attracted a wave of professionals educated in Istanbul. Many of them were trained at the Ecole des Beaux-Arts in Istanbul, now known as Mimar Sinan University (Tsilenis, 2009). These architects brought with them a rich blend of architectural traditions — rooted in the late Ottoman context — combined with emerging styles of the early 20th century, including eclecticism, baroque revival, Jugendstil (Art Nouveau), and the nascent ideas of modern architecture (Theodoridou-Sotiriou, 2006).
The result was a highly distinctive architectural expression: buildings that incorporated Islamic ornamental elements, Ottoman and European spatial organization, and a flair for decorative detail that stood in contrast to the modernist rejection of ornament famously championed by figures such as Adolf Loos. In his 1908 essay “Ornament and Crime,” Loos asserted that the

evolution of culture is synonymous with the elimination of ornament from architecture. Yet, in 1920s Thessaloniki, ornament emerged not as an obsolete relic, but as an active, radical agent in the city's rebuilding — a language of continuity, identity, and creative hybridity.

This project seeks to rediscover and amplify this unique design language through the lens of contemporary artificial intelligence. By documenting and analysing architectural ornaments found in Thessaloniki's buildings constructed between 1924 and 1937, a dataset of 1,784 images was considered as the basis and used to extract further details and information valuable for this research project. These ornaments capture the nuanced aesthetics of the city's Ottoman and Islamic heritage, reflecting the designers' sensitivity to both their formal education and the cultural memory embedded in their surroundings.

Using this dataset, the team trained a diffusion model to generate new ornamentations inspired by the historical motifs. These artificially generated 2D designs serve not as replicas but as speculative extensions of a historical narrative. Multiple different ways of generating new forms were tested and evaluated. After picking some 2D forms based on the evaluation and through using a custom Meshy.ai API, these 2D images are translated into 3D geometries — utilizing neural networks that simulate depth and volume — which can then 3D printed and prototyped.

The goal of this initiative is not merely preservation, but activation: to reintroduce ornamental language into contemporary construction in Thessaloniki's historic center. By doing so, the project proposes a new mode of architectural continuity — one that is technologically innovative yet deeply rooted in local memory. In an era where cities often struggle to balance heritage with progress, artificially augmented Ottoman Baroque offers a poetic, data-driven path forward, where ornament once again becomes a tool for cultural expression and urban identity.

Architecture acts as the material expression of social, financial, and technological advancements of an era. Within that context, the first Industrial Revolution resulted in an explosion of creativity for designers and artists alike (Frampton, 1988). The use of tools and techniques developed for mass-production gradually infiltrated architecture and design at all levels. The "modern man" of the twentieth century, living in newly developed industrial metropolises, was the foundation upon which modernist architecture was developed. More precisely, in that era, Portland cement and reinforced concrete were invented, which led to a major shift in building technology and construction. Consequently, the architecture produced was heavily influenced and directed by the opportunities but also the limitations that this newly introduced structural material offered (Hastaoglou-Martinides, 2015).

The fourth Industrial Revolution, more than two centuries later, has been a turning point in architectural production, as it enabled architects to move past parametric design and into exploring the creative boundaries of computer–human interaction (Henriques et al., 2020). During this era, the proliferation of advanced and highly anthropomorphic technological means such as artificial intelligence and robotics is at the epicenter of changes in the way architecture is defined. The exploratory realm of artificial neural networks is of particular interest in architecture, as the produced results can at times feel contradictory rather than realistic, which leaves room for interpretation and further development of design ideas (Cantemir & Kandemir, 2024).

3. Ornament in Architecture

Due to a shortage of local engineers and architects capable of handling the scale and complexity of reconstruction, Thessaloniki attracted a wave of professionals educated in Istanbul. Many of them were trained at the Ecole des Beaux-Arts in Istanbul, now known as Mimar Sinan University. These architects brought with them a rich blend of architectural traditions — rooted in the late Ottoman context — combined with emerging styles of the early 20th century, including eclecticism, baroque revival, Jugendstil (Art Nouveau), and the nascent ideas of modern architecture (Theodoridou-Sotiriou, 2006).

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Geometrical and floral patterns are the most important ornaments in Islam, since human representation is forbidden (Cenani & Cagdas, 2006).

In Seljuk tradition, ornament is mostly applied in portal facades to embellish entryways into buildings (Cenani & Cagdas, 2006).
In the digital realm, the development of bump and later displacement maps by Jim Blinn took over the representation of ornament as texture due to computational and processing power limitations (Elys, 2007). Nowadays, multiple different strategies of representing ornamentation have proliferated.
Architects who have explored the use of digital surface as ornament include Caruso St. John's Architects. They were one of the early examples of digital appropriation of historical ornaments and vocabularies as a means of architectural expression (Elys, 2007).
Technological use and provocation of emotion are in the epicenter of the digital neo-Baroque emergence (Januszkiewicz & Paszowska, 2015). The Deleuzian fold is also another way Leibniz's mathematical theories collide with the emotive world of Baroque artefacts.
The architectural legacy is revisited today under the conditions of the Fourth Industrial Revolution. This era has marked a turning point in architectural production, moving beyond parametricism and into deeply creative computer-human interaction. The proliferation of anthropomorphic tools such as artificial intelligence and robotics has reshaped how design is conceived. In particular, artificial neural networks offer a speculative design capacity, generating forms that oscillate between the historical and the unfamiliar.
Research on the use of AI in architecture has been gaining ground in the past decade, showcasing the potential to contribute to every stage of architectural conception, ideation, and creation. Moreover, research has discussed artificial intelligence's potential to undertake profoundly creative and resourceful tasks in light of new technological advancements. The architectural community has been analyzing to what extent the architectural profession can be realistically overtaken by AI algorithms (Mrosla and von Both, 2019). Moreover, the psychological effects of viewing artificially generated images have been described through terms like "estrangement," "ostranenie," and "defamiliarization" (Leach, 2022).

4. Related Work

Architecture in the 21st century took up the role of the role of experimenting with computational, topological explorations. Due to the renewed interest in geometric manipulations, a new and digitally emerging interpretation of Baroque has been ongoing in cities since the late 1990s (Januszkiewicz & Paszowska, 2015).
The intersection of artificial intelligence and architecture has become a growing field of inquiry, with multiple studies exploring the generative

capabilities of AI for both form-making and heritage conservation. Digital tools enable architects to move beyond the constraints of human cognition, leading to what he describes as "post-human design intelligence" (Carpo, 2017). In the context of architectural heritage, AI is increasingly being applied not only for documentation and analysis but also for the creative reimagination of lost or incomplete design languages. Researchers are starting to value the aesthetic qualities of historic styles. In efforts to quantify and measure the appeal of these bygone archetypes and spatial configurations, researchers have employed Birkhoff's aesthetic measure M. This measure is based on the calculation of symmetry and order (O) and complexity (C) to evaluate whether a space or element is aesthetically pleasing Hartanto et al., 2024).

More recent developments, such as StyleGAN and DALL-E, have enabled speculative design rooted in aesthetic cues from training data. Within the domain of heritage restoration, efforts such as the RePAIR project (2022) have employed deep learning to digitally reconstruct fragmented artifacts. Similarly, in the urban conservation sphere, GAN-based models have been used to predict and visualize missing architectural components in historic districts.

Within ornamentation specifically, AI-based generation remains underexplored. While parametric tools like Grasshopper have allowed procedural modeling of decorative forms, few projects have harnessed diffusion models to speculate upon stylistic continuities within a historical context. This research distinguishes itself by focusing not on style transfer but on culturally situated generation: training models not to mimic, but to extend the grammar of architectural heritage.

5. Methodology

The project began with the digitization and classification of architectural ornaments sourced from Thessaloniki's Historic Center Archive. From an initial collection of over 1,784 facade scans, a focused dataset of 300 door elevations was curated. The emphasis on doors was strategic: these elements offer high symbolic and compositional consistency, making them suitable for training generative models.

Each selected ornament was cleaned and vectorized. A vocabulary index was developed relating to the geometry, style, quantitative attributes, material indications and contextual nuances.

The dataset of doors was augmented through flipping horizontally and used first to fine-tune a Diffusion Probabilistic Model to generate new designs. As the number of samples was limited, the new AI-generated designs appeared similar to the ones provided as a training set.

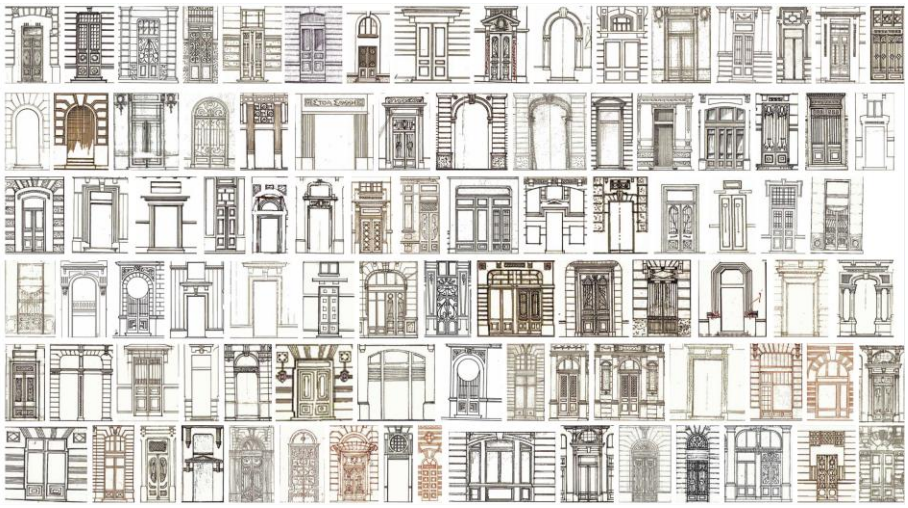


Figure 1. Sample of the Baroque Door Dataset

The image dataset was then used to create a personalized channel into Midjourney, a popular diffusion probabilistic model capable of synthesizing new forms based on learned patterns. Midjourney's ability to interpolate between aesthetic references made it ideal for generating historically resonant yet novel compositions. Prompts were carefully engineered to balance Ottoman Baroque influences with speculative design, and outputs were manually reviewed and curated.

Once high-quality 2D forms were selected, they were fed to MeshyAI to create 3D volumetric translations. These were then imported into Rhino and Grasshopper for minor adjustments and cleanup before 3D printing prototypes using PLA material. The prototypes served as both proof-of-concept and potential templates for new architectural elements that could be inserted into restoration or adaptive reuse projects in the city.

Additionally, textural layers were added to enhance realism using AI-powered rendering engines. These high-resolution visualizations simulate materiality, wear, and lighting conditions, allowing stakeholders to evaluate how the designs would appear in real-world architectural settings.

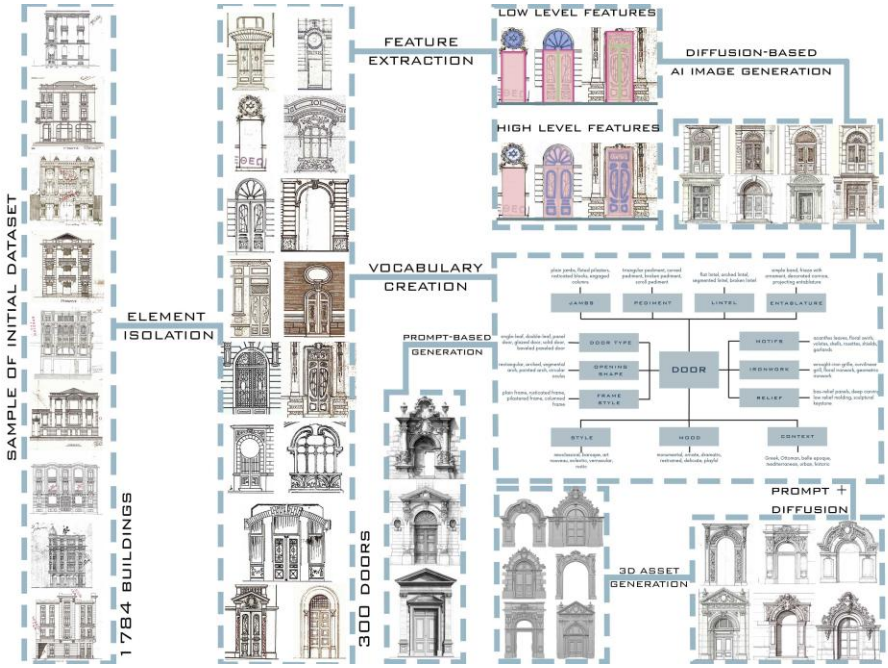


Figure 2. Workflow Diagram

6. Results

The final curated dataset of 300 doors enabled the creation of AI-generated door frames in three different ways (Figure 3). Of these, approximately 20 were selected for depth translation and 3D modeling. A remixing process led to the creation of a subset of 6 doorway ornaments that reflect the breadth of the baroque vocabulary found in Thessaloniki (Figure 4).

The AI-generated doors exhibited a unique capacity to fuse traditional elements in unexpected ways: Ottoman muqarnas blended with European pediments, floral arabesques interlocked with neoclassical scrolls, and symmetrical layouts often featured baroque flourishes in asymmetrical arrangements. These hybrids challenge the dichotomy between tradition and innovation.

The volumetric renderings were presented to stakeholders in Thessaloniki's urban planning and architectural preservation community in an effort to. Initial feedback suggested interest in integrating some of the proposals into restoration efforts where original ornamentation is missing or has been destroyed. Several of the designs also sparked conversations about redefining guidelines for "appropriate" restoration aesthetics in protected urban zones.

Moreover, the capacity of making 3D geometries using a custom Meshy.ai API was assessed using both the AI-Generated line drawings as well as the AI-Renderings. What was riveting was that the best results in depth translation were not yielded from photorealistic but rather technical drawing style 2D depictions.

Furthermore, the use of the 3D geometry exercise is to infuse the archival material with latent qualities which can emerge via verbal input to accompany the initial pictorial training dataset.



Figure 2. Different AI-Image Generative Methods



Figure 4. Final AI-Generated Door Design Proposals

7. Contribution

The center of Thessaloniki is protected as a historic place by the Ministry of Culture and the Committee of Archeological Heritage. With that being said, it is important to note that any new construction and renovation or restoration work is subject to the approval of the aforementioned agencies.
The breadth of the accepted forms, materials, colors and designs is usually determined by the state officials who are employed by the ministry for this region. It is a highly intuitive and subjective process which can at times be laborious and require a lot of redlining. Based on the forms found in the archive and through utilizing the latest Generative Artificial Intelligence Algorithms, it is possible to pave the way for breadthening the formal vocabulary and revitalizing the Ottoman Baroque heritage encountered in the city. Many of the artifacts depicted throughout the archive have been demolished in the 1950s and 1960s when new laws favored the sale and vertical development of multistory residential buildings as a response to the real estate market pressure and the rapidly growing population of the city.
By leveraging artificial intelligence trained on lost or under-documented heritage, architects and preservationists gain access to a broader set of tools that reflect the city's pluralistic history. The project demonstrates how AI can complement rather than challenge traditional preservation by offering informed, imaginative proposals rooted in historical data.
Furthermore, the method is replicable and adaptable. Other cities with layered architectural histories could adopt similar workflows to reconstruct or reimagine their lost ornamental heritage. The approach balances innovation with cultural sensitivity, making it a valuable contribution to the discourse on digital heritage and the future of architectural ornamentation.
Future work would enclose further specifying or narrowing down the task at hand for specific projects and realistic conditions in city planning within the historic center. A pamphlet of proposed and approved forms could be formulated to distill the architectural vocabulary of mid-war era heritage.

8. Conclusions

This project illustrates the potential of artificial intelligence to reawaken architectural languages that have been silenced by time, disaster, and modernization. In Thessaloniki, where the richness of Ottoman Baroque has often been overwritten by generic postwar development, AI offers a way to not just remember, but to reimagine.
The fusion of data-driven generation with manual curation and fabrication enables a collaborative workflow between human and machine. This hybrid process yields results that are historically grounded yet radically inventive.

AI is not simply a tool for automation, but a partner in speculative heritage-making.

By focusing on doors as symbolic thresholds, the project underscores architecture's role as a mediator between eras, ideologies, and communities. Reintroducing ornamentation into contemporary construction opens new avenues for identity formation, placemaking, and urban storytelling.

Moreover, this quest is particularly riveting for the city of Thessaloniki as the Ottoman Heritage had strategically been erased to give room to the emergent new Greek nation's narrative. This approach has started to fade societally and politically with more and more people embracing Asia Minor and Ottoman heritage in linguistics, gastronomy, music and the visual arts. To further elaborate, the city of Thessaloniki had been under Ottoman law for almost 500 years, which led to the city becoming a melting pot and a meeting point for various civilizations and religious groups which practiced commerce and businesses freely under the same jurisdiction.

In a broader context, this research contributes to the emerging field of computational heritage. It invites architects, historians, and technologists to think critically about how machine intelligence can participate in the cultural life of cities. As we enter a time of profound interdisciplinary collaboration where critical thinking and crystallized knowledge reigns supreme over technological advancements; the question remains as to what makes human intuition stand out from its synthetic counterpart. The use of archival material is particularly important in this case as it prevents to a certain extent the results from being flattened by the vast domain of pretrained Diffusion Probabilistic Models and Transformers. Through the lens of Thessaloniki, the project poses a simple yet profound question: what if the past was not something to be preserved in amber, but something we could continue to design with?

Acknowledgements

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MOTION AS A DRAWING MEDIUM

Reinterpreting Architectural Drawing Through Computational Approaches

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Abstract. This study reinterprets architectural drawing as an active and performative process rather than a static representation, focusing on the act of drawing itself emerging between the visible and the conceptual. It investigates how motion-based and code-driven systems can function as dynamic drawing tools by transforming the act of drawing into a spatial event shaped by real-time data and physical responses. Arduino-based drawing machines serve as the foundation of this experience, creating distinctive traces through both code-based and user-directed movements. These movements are recorded and converted into digital lines using the Grasshopper platform, enabling workflows that connect human intention with system autonomy. The process redefines the line as a manipulative agent and a spatial mediator by interacting with other lines and the environment, leading to emergent relationships. By combining mechanical motion, algorithmic behavior, and spatial visualization, the study introduces a new dialect for drawing that converts meaning into action and interaction. Ultimately, it explores how motion, both conceptual and physical, can transform drawing practices.

Keywords: *line generation, motion-based drawing, code-driven drawing, computational drawing, drawing machine.*

1. Introduction

The evolution of architectural drawing indicates the progression of the line from a pure representational element to an active carrier of meaning, eventually becoming a dynamic force capable of altering and transforming the space. This change is not only a chronological series of actions but also a vital sign of the evolution of architectural philosophy through its elements and media of articulation. As architectural drawing progresses, the line is no longer viewed as a fixed margin or an inactive mark; rather, it is regarded as a dynamic entity that interacts with its environment, influences spatial perception, and stimulates innovative thought. This transition illustrates an intellectual development in design thinking as the line has transcended its conventional characteristic as a representational tool and now acts as a cognitive agent that combines abstract approaches with spatial reality. Also, it has been acknowledged that drawing is a deeply situated action that includes perception, physical reality, and the interpretation of meanings that are not distinguishable at first glance.

With the integration of computers into architectural drawing techniques in the latter part of the 20th century, the methods of line production and the contexts in which lines were generated gained significance (Tanrıverdi Çetin & Dülgeroğlu Yüksel, 2020). Although the discussion between hand drawing and Computer Aided Design (CAD) continues in architectural education and practice, it is now widely accepted that drawing plays a crucial role in design thinking. Rather than focusing solely on the medium of drawing, our discussion should address the manner of drawing itself and, in parallel, the mind of drawing, the ways of conceiving and making sense of the act and movement it entails. Today, this duality has largely dissolved; while it is hardly possible to claim that hand drawing is uninfluenced by a digitalized mindset, it is equally evident that drawings produced in digital environments cannot be abstracted from the embodied practices of drawing by hand. The line has evolved into a representation of thought or a diagram that involves a genetic code, acting as an active component that influences the design process (Edwards, 2008). In this framework, lines go beyond just being simple representations or abstractions; they are active constructs that capture relationships, actions, and possibilities. With the rise of computational design and motion-based tools, this already intricate comprehension of drawing has been further enhanced. Digital technologies do not eliminate traditional drawing but rather recontextualize and broaden its possibilities by introducing elements of temporality, interactivity, and novel methods of spatial manipulation. Consequently, the contemporary exploration of motion as a medium for drawing reveals innovative approaches to the conception, execution, and representation of space, enriching our engagement with the drawing experience in architectural illustration.

Today, lines generated by computational methods do more than just form visual patterns that interact and confront one another; they have the capacity to transform the topological features of space. A growing body of research evaluates how digital tools can bridge the formal language of programming with visual representation, linking geometric and algebraic operations (Alaçam et al., 2014). Accordingly, the line transforms into a data-driven artifact, no longer a fixed mark on paper, but a dynamic component that can be reinterpreted in real time. So that, the act of drawing itself experiences a conceptual transformation, increasingly characterized by algorithmic processes rather than manual movements. In other terms, the algorithm, which is defined as a new alphabet of the digital era, evolves into a new form of drawing, shifting the emphasis from visual representation to a framework of computational description. (Carpo, 2011).

In summary, the line can be redefined not only as a generator of shape but also as a self-sufficient, active agent that engages with its surroundings and other agents, lines, modifying the framework and interpretation of space. This research demonstrates a bidirectional connection between the physical trace and its digital duplicate through the simultaneous operation of an Arduino-based drawing machine and a Grasshopper simulation. In doing so, it reconceptualizes the line not merely as representation, but as an operative agent that manipulates boundaries, attracts and repels neighboring points, and generates spatial patterns.

2. Theoretical Foundation

During the Renaissance period, when drawing (disegno) primarily emphasized its symbolic content, it was not yet regarded as a neutral repository of information or a simple reductive tool for architecture. Instead, it was conceived as an intellectual and liberal art form, an embodiment of conceptual intent realized through the act of accurately assembling lines and angles (Perez-Gomez, 1982). However, a radical shift in the perception of drawing occurred in the late 18th century with Gaspard Monge's work on descriptive geometry (Grattan-Guinness, 2005). Monge's approach transformed architectural thinking into a prevalent representation, positioning drawing as a neutral and objective means of representation. In addition, descriptive geometry changed the role of an architect from a craftsman to an active designer who communicates by drawing. This historical evolution indicated a shift in the behavior of the line, transitioning from a representative element of concepts to a precise interpretation of functional and mechanical directions. As Perez-Gomez mentioned (1982), this shift was supported by theoretical progresses such as projective geometry, especially in the contributions of Poncelet, who perceived space not as a constant Euclidean domain where parallel lines never intersect, but as a flowing system formed

by transformations, through reinterpreting the line as an active ingredient within that framework. Artists such as Paul Klee have completely changed the understanding of the line, considering it not just as a structural element but as an active entity that embodies motion, process, and transformation. Further, Klee (1953) defines line as "A dot that went for a walk," referring to a point that acquires direction and continuity through its movement across a surface **(Figure 1)**. Accordingly, Kandinsky (1947) mentioned that a point represents disruption and non-existence, while also acting as a connection between different states of being, and this encapsulates its deeper meaning. In this process, the line activates passive surfaces, creating force fields in space through its interactions. Despite Klee's metaphorical explanation, in architectural practice the line often emerges with clear intent (Edwards, 2008). In this context, randomly distributed points or lines may generate relational patterns based on an algorithm, forming sequences of spatial events (Allen, 1999).



Figure 1. An active line on a walk, moving freely, without goal on the left and the same line accompanied by complementary forms on the right (Klee, 1953).

Stan Allen's (1999) infrastructural urbanism emphasises the relationship between the line and its environment at an urban scale. In this work, randomly scattered metal bearings, conceived as points or micro-agents, roll across a surface according to specific rules, leaving behind traces. These traces, whether intersecting or running parallel, form sequences of events. Le Va's work **(Figure 2)** further exemplifies how randomness and order can coexist, demonstrating that the collective behavior of independent agents can generate complex interactions and dynamic systems in process.

Within this framework, the line can be considered a manipulative agent, capable of bending, pushing, pulling, and causing displacement. As Edwards (2008) notes, it is no longer merely a carrier of form but acts as a diagram containing a genetic code, directly producing space. In light of this, computational methods have a significant potential for understanding the ways of behavior of lines. Instead of directly producing visual representations, these lines perform as active agents with the capacity to modify the topological features of space through either collaboration or conflict. The relationships they establish build the foundation for complicated systems and fluid interactions, raising questions about how these lines engage with each other, establish relationships, and generate new interpretations or structures. Deleuze and Guattari's (1987) notion of the rhizome offers a vital viewpoint for

comprehending this complex role. Unlike conventional structures like trees or roots, the rhizome suggests a non-linear order where any point can attach to any other and it lacks a defined path, it advances by exploring different routes on its own. This model provides a guideway to comprehend systems in which lines form, divide, branch, and reconnect. This new role encompasses three propositions: (I) it views the drawing surface as a topos or "drawing space"; (II) it interprets drawings as contextual figures; (III) and it sees lines as evolving processes. Together, these three propositions create the "performative paradigm," framing every component of the drawing process as a developing dynamic in which imaginative inhabitation and aesthetic sensitivity are crucial factors (Paans, 2024).



Figure 2. Bearings rolled (six specific instants; no particular order) by Barry Le Va (Allen, 1999).

Similarly, architectural sequences are not merely successive arrangements of events or spaces. They are dynamic processes that continuously transform through spatial sequences which may reinforce, oppose, or remain indifferent to one another, functioning as spatial programs (Tschumi, 1994). Tschumi's approach demonstrates that linear events in architecture extend beyond spatial orientation, establishing new layers of meaning through the interaction between space and action **(Figure 3)**.

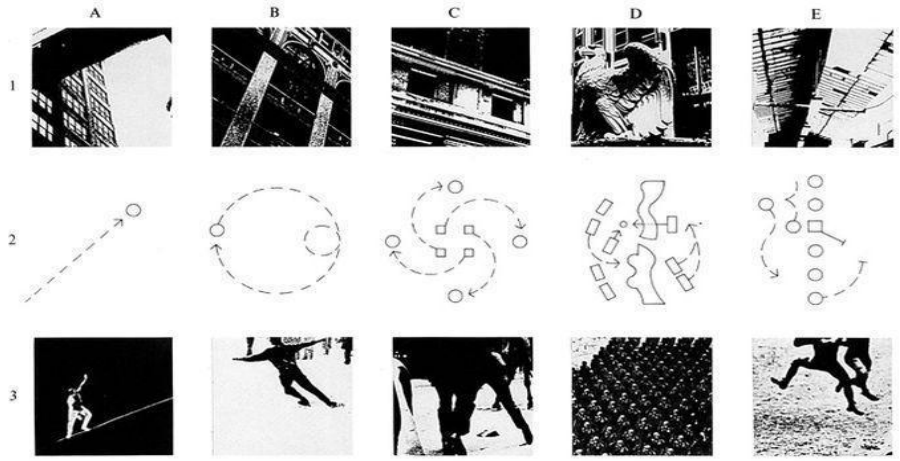


Figure 3. Events and diagrams (Tschumi, 1994).

According to Negroponte (1975), early computational design experiments, notably Sutherland's SKETCHPAD, initiated a shift from passive drafting instruments to intelligent design systems capable of interpreting user input. Building upon this trajectory, the HUNCH sketch recognizer conceptualizes drawing as a dynamic negotiation between evolving design intentions and their graphic articulation **(Figure 4)**. By capturing parameters such as speed, pressure, and spatial coordinates, HUNCH infers underlying cognitive and behavioral patterns, distinguishing rapidly sketched forms from those rendered with deliberation, thus making explicit the otherwise implicit aspects of the design process.

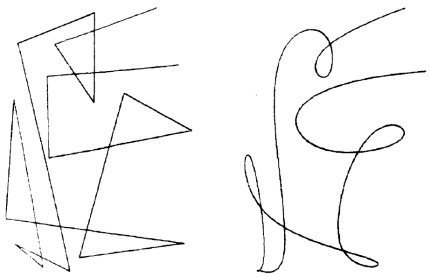


Figure 4. Curve recognition (Negroponte, 1975).

Another study was related to Lego Mindstorms–based tracked drawing robots, sequentially reprogrammed and reconfigured, to explore robotic beauty and ultimately bring the Plotter to life as a separate work of art, pens of various thickness and color rigidly mounted upon cars outlining their course on A2 paper for 10–45 minutes, the duration truncated at the artist's creative

intention **(Figure 5)**. Autonomous robots capable of generating their own art through basic rules, unpredictability, and stigmergy provide human observers the chance to comprehend life and aesthetics beyond the anthropocentric framework and the confounding divisions it generates (Moura, 2016).

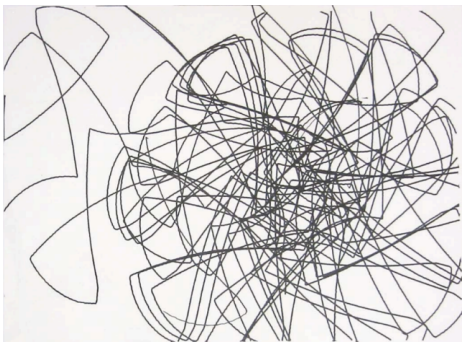


Figure 5. Robot drawing from the preliminary study (Wanner, 2011)

Together, all these perspectives reinforce the view that the line should no longer be regarded as a fixed or rational construct, but rather as a dynamic system shaped by complicated interactions. Within this framework, the line ceases to be a passive representation and instead becomes a manipulative agent: actively generating form, organizing space, maintaining continuous dialogue with other agents, and transforming spatial coordinates by bending, pushing, pulling, or displacing them in accordance with the algorithm.

3. Methodology

This study adopts an experimental and research-through-design method to explore the line as an autogenic (Negroponte, 1975) and manipulative agent in architectural drawing, combining a theoretical foundation with both physical and computational drawing experiments. The process (flowchart) of the work can be seen in **Figure 6**.

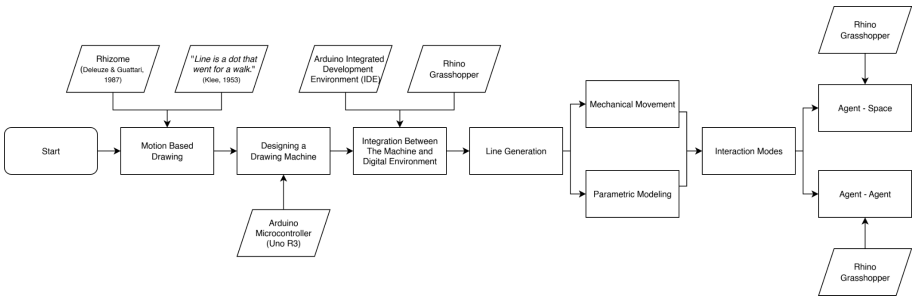


Figure 6. Flowchart.

The methodological framework is structured in four interconnected stages:

- Designing a drawing machine
- Connecting the drawing machine to digital environment
- Line generation
  - physical drawings through mechanical movement
  - simulation by parametric modeling
- Interaction modes
  - agent-space
  - agent-agent

In the first stage, a low-resolution drawing machine, referred to as a line-maker, was developed by assembling and coding Arduino-based mechanical components. This physical machine served as both a generator and a performer of the lines, illustrating the transformation of the line from a static mark to a dynamic agent.

As part of the second stage, the drawing machine was interfaced with computational environments such as Arduino Integrated Development Environment (Arduino IDE) and Rhino Grasshopper.

In the third stage, both physical and digital lines were generated through mechanical movement of the drawing machine and parametric modeling in Grasshopper.

The fourth stage focuses on examining the behavior of the generated lines as manipulators, especially how they communicate with their environment (agent-space) and with other lines (agent-agent). These interactions can be considered to investigate how lines, driven by mechanical movement and computational approach, can lead to emergent spatial sequences, echoing the theoretical notions from Stan Allen's infrastructural urbanism and Deleuze and Guattari's rhizomatic systems.

3.1. DESIGNING A DRAWING MACHINE (LINE-MAKER)

In this phase, a simple mechanical system that generates physical lines was developed. Components such as Arduino Uno R3 microcontroller, DC gear motors, jumper wires, a L298N dual motor driver board, a 9V battery, 2WD robot chassis, wheels, a HC-06 bluetooth module, a ball bearing caster, a joystick and a pen were assembled into a drawing unit capable of producing lines through code-driven operations **(Figure 7)**.

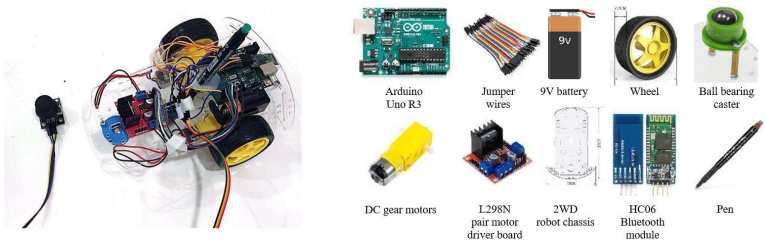


Figure 7. The drawing machine and its components.

3.2. CONNECTING THE DRAWING MACHINE TO DIGITAL ENVIRONMENT

This part examines the mutual interaction between the drawing machine and the digital environment, encompassing the Arduino IDE and Rhino Grasshopper. The aim is to generate and analyze lines through both algorithmic and motion-driven inputs, and to process them within a digital framework. The drawing machine was programmed by using C++ scripts developed in the Arduino IDE, incorporating parameters such as microcontroller pin configurations, wheel radius, distance between wheels, speed, duration and random movement commands **(Figure 8)**.



Figure 8. Arduino IDE interface.

In this phase, the code developed within the Arduino IDE was verified and subsequently uploaded to the Arduino Uno R3 microcontroller. By means of the microcontroller, both physical and digital lines were generated through the random movements of the drawing machine. During the drawing process, the positional data of the machine was simultaneously transmitted to the Grasshopper algorithm as x and y values via the HC-06 bluetooth module connected by the *Open/Close Port* component which is part of the *Firefly* plug-in in Grasshopper **(Figure 9)**.

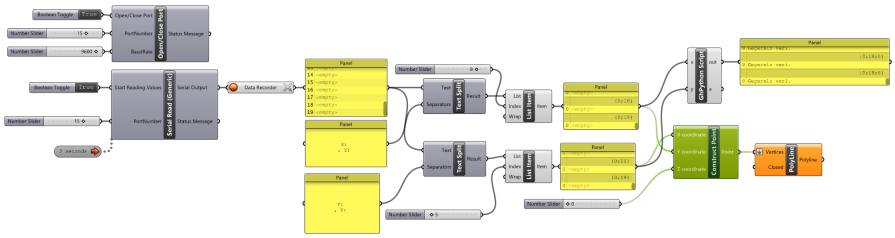


Figure 9. The Grasshopper algorithm connects the Arduino microcontroller to Grasshopper while simultaneously recording positional data.

Through the *GhPython Script*, a component of the Grasshopper algorithm, the positional data were recorded in the target file **(Figure 10)**. An example of the positional data format is 31.03, 17.42 (X, Y).

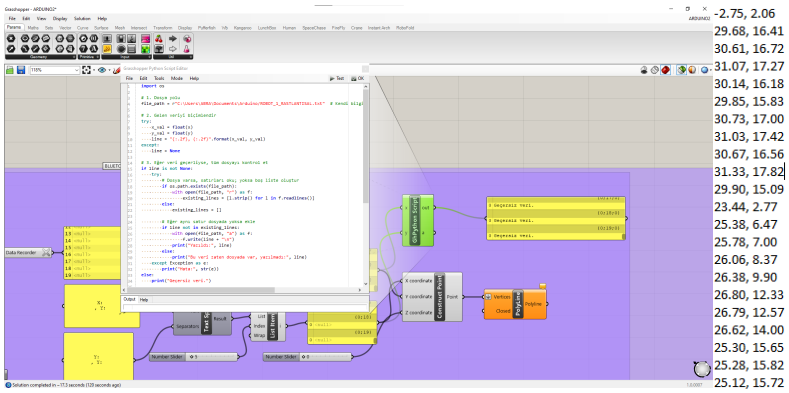


Figure 10. *GhPython Script* records the positional data that can be seen on the right.

3.3. LINE GENERATION

This section examines the line generation methods including physical drawings through mechanical movement and simulation by parametric modeling. The first method investigates how algorithmic instructions can generate physical drawings, while the simulation process examines the ways of reinterpretation of lines digitally. In either case, the drawings were digitized through parametric modelling, translating linear gestures into spatial and manipulative configurations.

3.3.1. Physical Drawings through Mechanical Movement

Using the Arduino IDE and Grasshopper, code-based commands were transmitted to the drawing machine to generate physical lines **(Figure 11)**. This method demonstrated that lines can be generated not only as visual

representations but also as behavioral constructs, emerging through coding and algorithmic processes.

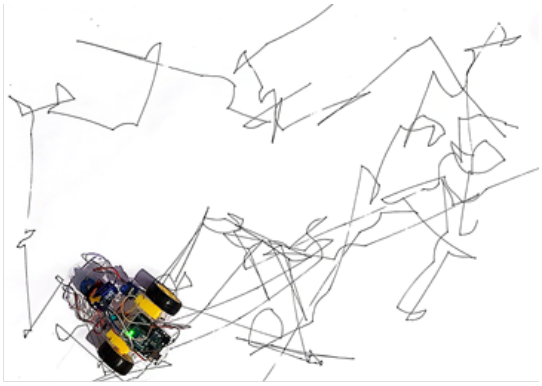


Figure 11. The drawing machine in action.

To deepen the investigation of the human-machine interaction, a workshop was conducted in which architecture students actively engaged with the drawing machines. Participants were introduced to the technical and conceptual framework of the system, and were encouraged to generate drawings through direct manipulation. A roll of paper was laid on the floor to provide a drawing surface for the machines. While two of the machines were moving autonomously, the leading one was manipulated by the user through joystick-based movement commands, which were subsequently translated into physical traces **(Figure 12)**. Within the studio context, students perceive the line not merely as a compositional result, but as a medium for regulations and feedback, fostering a novel cognitive approach along the representation-to-production spectrum. This process enabled a critical exploration of authorship, control, and the performative role of the line.

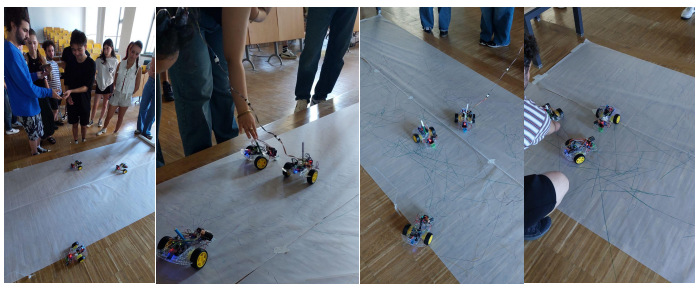


Figure 12. Three drawing machines: one joystick controlled, and two operating autonomously through random movement.

Participants operated the drawing machine using a joystick, while the other two machines were moving autonomously. The movement of these autonomous machines manipulated the user's decisions. So, the lines generated by user decisions (green) and drawings generated by random movements (black) can be seen in **Figure 13**.

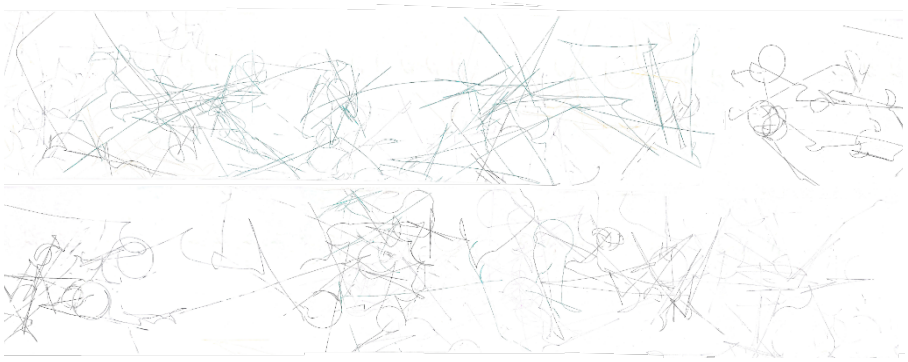


Figure 13. Lines generated through the mechanical movement of the drawing machines.

3.3.2. Simulation by Parametric Modeling

Within the scope of the workshop, the movement of the drawing machine was monitored in real-time and was recorded as spatial coordinates by using Grasshopper. The recorded data was then employed to generate a digital model of the physical drawing **(Figure 14)**, allowing for a synchronized and precise digital depiction of the drawing process as it transpired in the physical world.

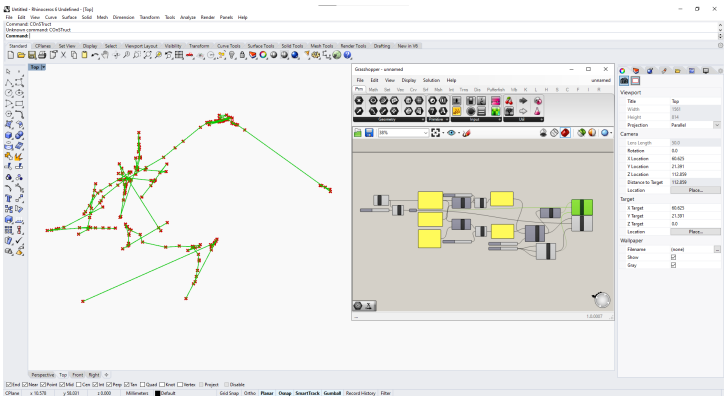


Figure 14. Grasshopper algorithm that simulates the movement of the machine in real-time.

The positional data previously recorded to the target file were subsequently imported into Grasshopper. For **Figure 15**, the red area represents the line

generation by positional data while the green area provides the spatial points around the generated lines.

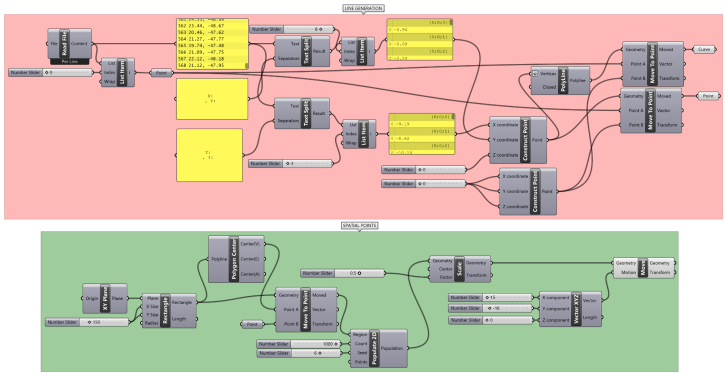


Figure 15. The Grasshopper algorithm that generates lines using the positional data.

Parallel with the physical generation of lines, the spatial points and the digital counterparts of the physical lines were reinterpreted in Rhino Grasshopper based on the real-time coordinates derived from the mechanical movements of the drawing machine **(Figure 16)**. Each unique movement of the machine was recorded as a control point, and this set of points was transformed into lines through a Grasshopper algorithm.

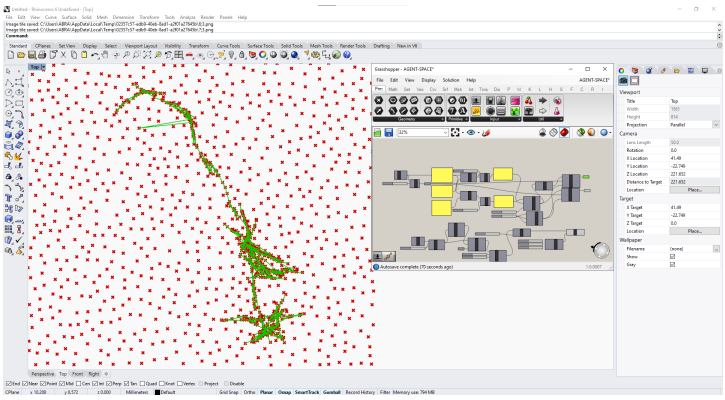


Figure 16. Control points (red) and lines (green) generated in Grasshopper using real-time positional data.

The lines generated by the drawing machines were digitally simulated in Grasshopper using location data **(Figure 17)**. While the blue and green lines were generated by the autonomous movement of the machines without human intervention, the red one was generated by manipulation with the help of a

joystick. These digital outcomes can be considered as reinterpretations of the physical ones.

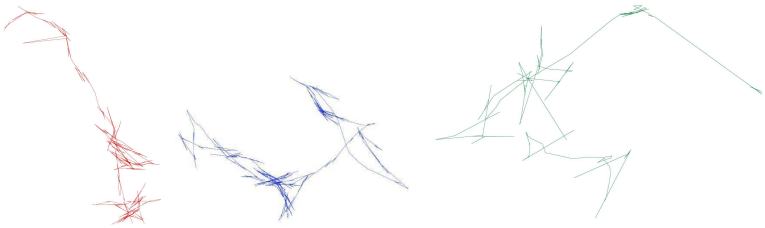


Figure 17. Simulation of the physical lines generated by Grasshopper algorithm.

3.4. INTERACTION MODES

This section investigates how the generated lines interact with one another and with the space. The focus is not only on the form of the line, but also on its relational behavior, including how it influences, responds, and reconfigures spatial conditions through proximity, directionality, and intensity. In this context, the line was examined not merely as a graphical element, but as an active participant in spatial negotiation, capable of initiating force relationships, defining boundaries, and altering the perception and organization of the environment in which it operates.

3.4.1. Agent – Space

The generated lines and spatial points were digitized and reinterpreted with Grasshopper algorithm **(Figure 18)** to create an interactive model. The Interpolate component simulated the digital lines through positional data and spatial points were generated by the *Populate 2D* component in Grasshopper. These models represent the transformation of mechanical movements into spatial forms.

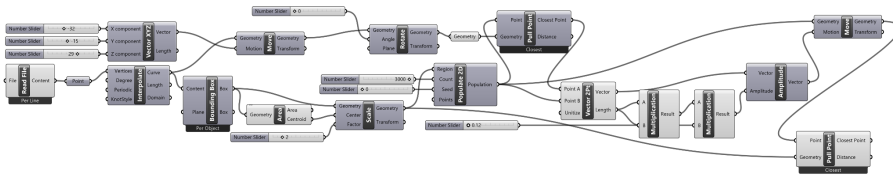


Figure 18. Grasshopper algorithm that generates the agent-space interaction.

Accordingly, how the lines engage with boundaries, voids, and surrounding space was examined and the line was conceptualized as an agent that transforms or reorganizes the spatial field in which it operates. The generated lines manipulate the space by applying pulling force to the adjacent points,

whereby the intensity of this force decreases as the distance increases, thereby reshaping the field they inhabit **(Figure 19)**.

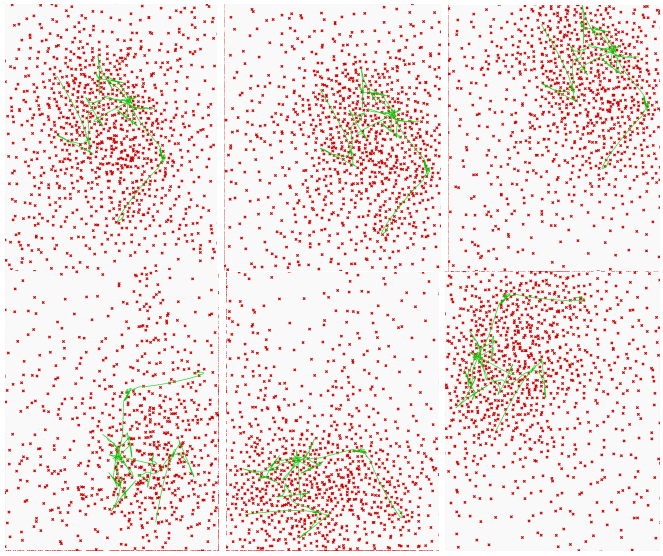


Figure 19. Generated line (green) and adjacent points (red).

Beyond the planar studies, the line was placed in a limited three-dimensional space (a prism) to mimic how it might behave in space. Subsequently, environmental points within the prism were incorporated and the system was simulated in the Grasshopper environment. For each point in space, a segment was constructed along the shortest path to the nearest point on the line (nearest-point projection). The resulting network explicitly invokes the rhizome concept with reference to Barry Le Va's work (bearings rolled), producing a rhizome-like, irregular and unpredictable set of lines **(Figure 20)**.

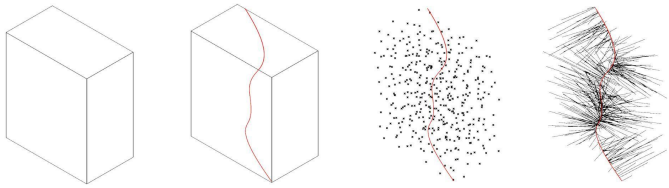


Figure 20. Agent-space interaction in three-dimensional space.

Following the simulation, the line's density (mass) was progressively reduced in the Grasshopper environment to observe how the agent influenced surrounding points. As agent (line) density decreases, the magnitude of its attraction field decays, and spatial points transition from clustered to dispersed configurations within the bounded domain. **(Figure 21)**.

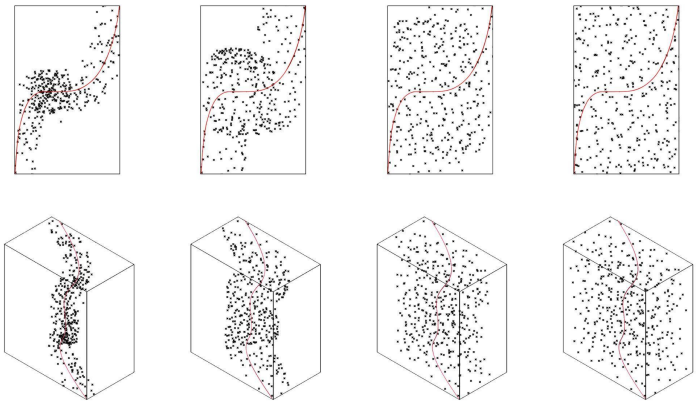


Figure 21. Relationship between agent density and spatial point distribution.

3.4.2. Agent – Agent

Interactions such as intersection, overlap, pulling or pushing between the agents were simulated through an algorithm **(Figure 22)**. These behaviors were evaluated in relation to Stan Allen's concept of event sequences, where spatial meaning is not predetermined but emerges through the dynamic interaction of the elements.

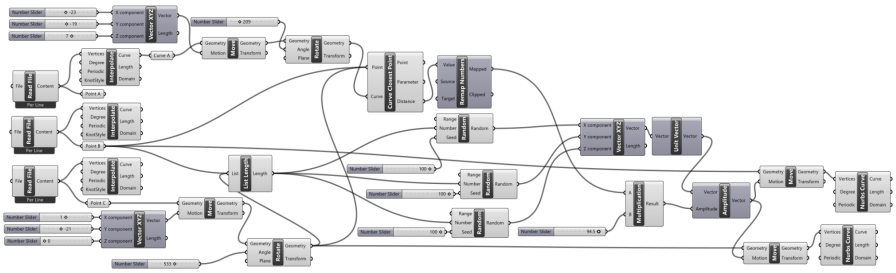


Figure 22. Grasshopper algorithm simulating the interaction between the lines.

In this framework, each line acted as an agent capable of initiating, modifying, or responding to other agents within the system **(Figure 23)**. Their interactions generated a field of contingencies, moments of collision, alignment, or resistance, that produced new spatial logics. Rather than functioning as isolated entities, the lines participated in a distributed network of influence, in which agency was shared, negotiated, and continuously redefined through their mutual engagement.

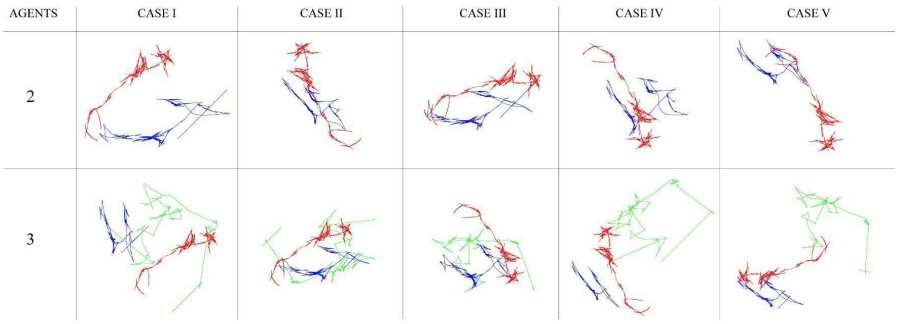


Figure 23. Interactions of the agents related to movement and rotation of the red one.

4. Results and Discussion

The experimental part of this study showed that the line changed from a representational mark to a manipulating agent. Accordingly, the physical drawings through mechanical movement and simulation by parametric modeling showed that abstract algorithmic rules may make both physical traces and their digital counterparts. This meant that the line was treated as a behavioral entity instead of just a visual output. Simultaneously, the workshop showcased the active negotiation between human intent and machine independence, presenting the act of drawing as a performative experience. The user guides the drawing machine with a joystick through the spontaneous operations of other machines, which manipulates the user in the drawing process. While this action was unpredictable, the physical lines also depict a particular sequence. Also, in the agent-space interaction model, the lines reshaped their surroundings by attracting nearby spatial points. For the interactions between agents, where programmed behaviors like pushing and pulling deformed each other, led to new spatial arrangements. As the red line adjusted its position or angle, the control points of the other lines shifted, resulting in the lines bending or extending. This deformation illustrated that the lines acted as manipulative agents. That result shows how Stan Allen's notions about infrastructure urbanism and event sequences work in real life. As opposed to drawings and colors being completely auto-generated (Balcı and Alaçam, 2022), we show that human participation functions as an operative co-agent, modulating algorithmic behavior and reframing authorship in line production. All these interactions transformed the drawing into an interconnected, rhizomatic system aligned with the concept of Deleuze and Guattari. Finally, the findings revealed that when mediated by computational and mechanical processes, the line transforms from a passive entity to an autogenic force capable of generating, structuring, and transforming space using its own embedded logic and dynamic behavior.

5. Conclusion

From the intellectual intentionality of Renaissance drawings to the mechanical precision of the 19th century, and later to Paul Klee's dynamic expressions and Stan Allen's field-based strategies, the line has continuously redefined its ontological status in architectural thought. This research examines the evolving agency of the line through a set of experimental methods such as generation of physical lines by the Arduino-based drawing machine and simulation by parametric modeling. The line is no longer a passive trace; it becomes an active force that manipulates boundaries, attracts surrounding points, and generates spatial configurations in real time. Therefore, this study affirms the line not only as a conceptual tool but as an operative entity that questions authorship, embraces unpredictability, and opens up new possibilities for architectural speculation in the algorithmic age.

Acknowledgements

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AI-DRIVEN CYMATIC ARCHITECTURE

Integrating Generative AI and Sound Data for 3D Concrete Printed Façade Design

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Abstract. Advancements in Artificial Intelligence have transformed computational design, opening new possibilities for performance-driven methods. However, the opportunity to develop tailored workflows that turn sound data from cultural heritage sites into environmentally adaptive facades remains largely unexplored. This paper proposes an AI-augmented process that uses cymatic equations to translate the soundscape of specific cultural heritage locations into self-shaded architectural facade modules, designed for 3D Concrete Printing. The process involves four key steps: (1) sound data capture through recordings from AlSeef in Dubai, (2) data decoding with ChatGPT to extract time, frequency, and amplitude data from the compiled audio file, (3) façade generations using a custom Python script co-created using ChatGPT in Grasshopper that converts these parameters into a facade mesh, and (4) Multi-objective optimization using Wallacei for self-shading and cost assessment. The workflow was validated by printing a prototype, demonstrating the feasibility of translating natural phenomena into architectural forms. The findings emphasize the potential of AI-integrated workflows to create customized workflows. Future efforts will focus on site-specific façade applications and creating a plugin to expand this approach for adaptive, data-driven architecture.

Keywords: *Artificial Intelligence, Cymatics, Digital Fabrication, 3D Concrete Printing, Facade Design, Computational Design*

1. Introduction

In recent years, interest has grown in developing computational design workflows that integrate design with digital fabrication to enhance the design

process. The emergence of AI-driven workflows has created new opportunities for culturally aware design, data-based optimization, and fabrication strategies tailored to specific materials and individual fabrication companies. Furthermore, interpreting embedded cultural elements such as soundscapes provides an opportunity to narrate spatial stories through materiality (Oxman, 2019). This paper explores how technological advancements, such as Artificial Intelligence (AI), can be allocated to develop a customized workflow. This workflow transforms soundscape data into culturally embedded facades that are both cost-effective and environmentally responsive.

In recent years, there has been a growing awareness that the soundscape constitutes a vital component of our intangible cultural heritage. The concept of soundscape varies across numerous countries and encompasses human and social sciences as well as physical measurements (Schulte-Fortkamp et al., 2016). In 1978, the soundscape was defined as “the acoustic environment as perceived, experienced, or understood by a person or people, within a given context,” in the “Handbook for Acoustic Ecology" as part of “The World Soundscape Project” initiated by Schafer (Schafer, 1993, Truax & D., 1978)

Sound vibrations can be observed when applied to physical media, such as sand, water, or solids. Cymatics is the scientific study of this phenomenon. It was inspired by Ernst Chladni's 18th-century experiments, which revealed hidden sound geometries using vibrating metal plates (Khan, 2024). In more recent explorations, the potential of cymatics, which integrates art, science, and technology, has been utilized in a manner that allows sound vibrations to be employed in creating responsive environments (Khan, 2024). Tseng and Hou investigated the conversion of two-dimensional sound patterns into three-dimensional geometries. They employed Chladni's principles to transform vibrations into a three-dimensional point cloud, which was subsequently converted into solid forms. (Tseng and Hou, 2020). Other studies have explored how sound can be visually represented through strategic spatial design and material choices. (Çalışır, 2016). Advances in cymatic research demonstrate sound's potential as a driving force behind sculptural output. However, the integration of digital fabrication-informed design with performance-based optimization remains to be thoroughly investigated.

The integration of parametric modeling and robotic fabrication tools in the 3D concrete printing design process (3DCP) has expanded the possibilities of façade systems and contributed to the development of more material-informed designs (Leschok et al., 2023; Yabanigül and Gulec Ozer, 2025). Mass customization has become increasingly prominent through the integration of computational design, which explicitly addresses the sustainability aspects of façades, while also improving material precision and optimizing geometries. Multi-objective evolutionary solvers, such as Wallaei, enable a more efficient design filtering process through customized design iterations, allowing the

creation of 3DCP geometries that incorporate multiple performance criteria, including self-shading, structural optimization, and material efficiency (Fleckenstein et al., 2023; Shan and Junghans, 2023).

Computational designers can now enhance their capabilities by incorporating generative AI into their design workflows. Through the adoption of ChatGPT or diffusion-based models, the entire design workflow is improved, spanning from conceptual design to final fabrication by streamlining the process (Cheung et al., 2025; Cao et al., 2024). The co-creation of designs utilizing AI as a collaborative partner presents a significant opportunity for more innovative and responsive designs that align with specific contextual needs. Design can be improved through increased cultural awareness, which is embedded with contextual significance and developed in relation to fabrication strategies (Jang et al., 2025). Real-time code generation using AI tools like ChatGPT can enable practical data analysis and produce outputs within the designer's parametric environment. This supports further exploration of sound-driven architecture and how sound data can transform into geometries (Institute of Acoustics, 2024).

This research investigates the development of a streamlined workflow that integrates AI-enhanced computational design with multi-objective optimization for efficient fabrication. It facilitates the translation of culturally embedded soundscapes into material-driven geometric expressions, rather than perceiving sound as an atmospheric afterthought. The following section outlines the application of the workflow for creating environmentally and cost-optimized 3DCP facades.

2. Method and Tools

In this research, a custom plugin has been developed using Python/ChatGPT integration within Grasshopper, taking sound data and other parameters as inputs. The process involves extracting sound data in terms of time, frequency, and amplitude, which are used in a Cymatic equation. The output consists of multiple facade generations that undergo multi-objective optimization based on specific criteria, including environmental analysis and cost analysis. As shown in Fig. (1) below, the framework is divided into four main categories: sound data capture, data decoding, facade generation, and multi-objective optimization. Each step of the process integrates AI and computational design methods to translate sound data into location-specific architectural output.

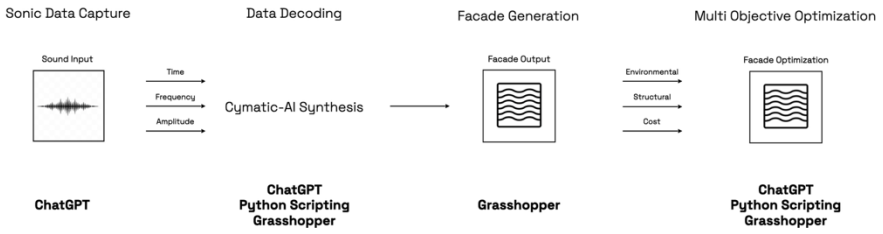


Figure 1. AI Cymatic Workflow for 3DCP Facades

2.1. Sound Data Capture

This study focuses on AlSeef in Dubai as a cultural heritage site for sound data collection. Audio recorded on-site can be defined as ambient sounds that represent daily urban life and natural noises that highlight ecological and biodiversity features throughout the day. Traditional sounds, such as regional music reflecting the area's history and social significance, were also collected from recordings of local events. These varied sounds are combined to form a distinctive acoustic profile of the site. This profile serves as the primary input for a specially developed workflow, which directly affects the façade output.

2.2. Data Decoding

Time, frequency, and amplitude values are extracted from the collected sound data, as these are the primary parameters needed for the cymatic equation. ChatGPT was initially used to extract these parameters as an Excel file, which can then be directly input into the Python script.

$$Z(t) = \Sigma A_i \cdot \sin(2\pi f_i t + \varphi_i) \quad (1)$$

Z(u, v): Displacement at point (u, v)
t: Time
φ_i: Phase offset of the i-th wave
Σ: Sum over all contributing frequencies or sound sources

Additional parameters, such as u, v counts, and distance values, are also considered, as they determine the final façade's dimensions. Settings such as scale factor, harmonic intensity, wave decay rate, and displacements influence the pattern's level of detail. The values chosen for these settings were based on the layer-to-layer distance proposed and tested by Layn, the 3DCP company. While these parameters affect the pattern's complexity, the time parameter impacts the entire pattern, since the current time corresponds to a

specific point in the input acoustic data, including seconds before and after. As shown in Fig. (2), this process was implemented in Grasshopper with a custom plugin developed using ChatGPT for Python scripting, creating a flexible script capable of generating diverse façade dimensions and patterns that meet design requirements and site constraints.

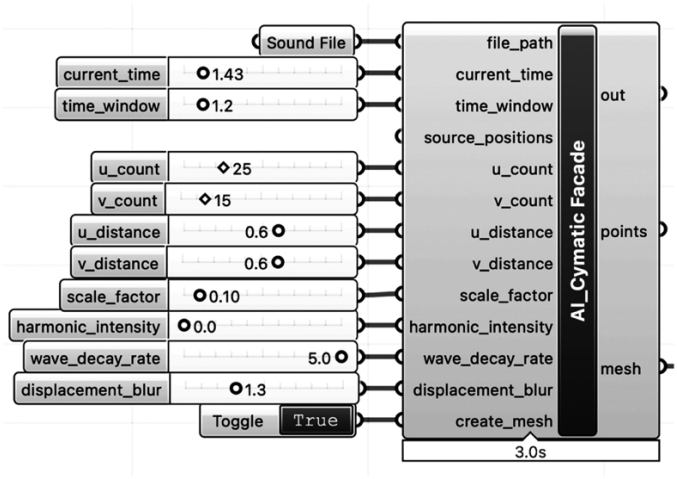


Figure 2. AI-Cymatic Workflow for 3DCP Facades Custom Plugin in Grasshopper

2.3. Façade Generation

The script outputs the façade as a mesh, demonstrating the potential of AI for 3D generation within Grasshopper. Since it is a generative process, multiple variations are created for a single location based on the sound input. As mentioned earlier, the detailed pattern of the façade can be adjusted using input parameters. The façade is then contoured according to the 3DCP layer height and extruded based on the toolhead width. This produces a visual representation of the final façade, helping with visual assessment before printing, as shown in Fig. (3).

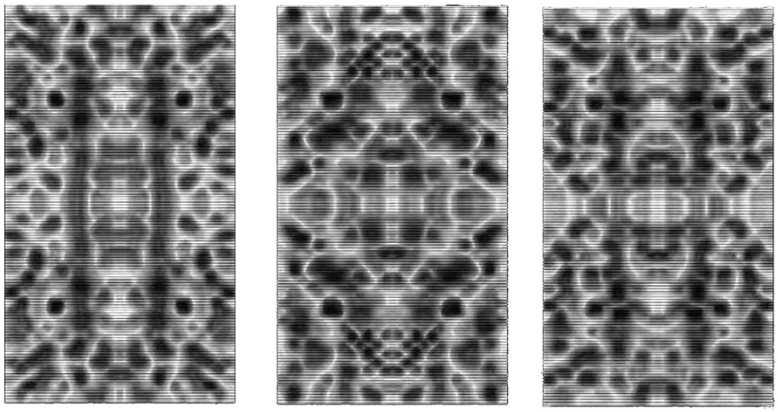


Figure 3. 3DCP Facades Visualization

2.4. Multi-objective Optimization

The generated façades are optimized through environmental analysis to enhance self-shading and cost analysis to reduce expenses. This results in a façade pattern that improves self-shading, leading to better indoor thermal comfort and a 25% decrease in cumulative radiation compared to a flat 3DCP façade. Using the Cyclops plugin in Grasshopper, as shown in Fig. (4), the façade's self-shading performance is assessed, and the most effective designs are chosen. Fig. (5) displays one of the optimized façades illustrating the self-shading of the 3DCP pattern.

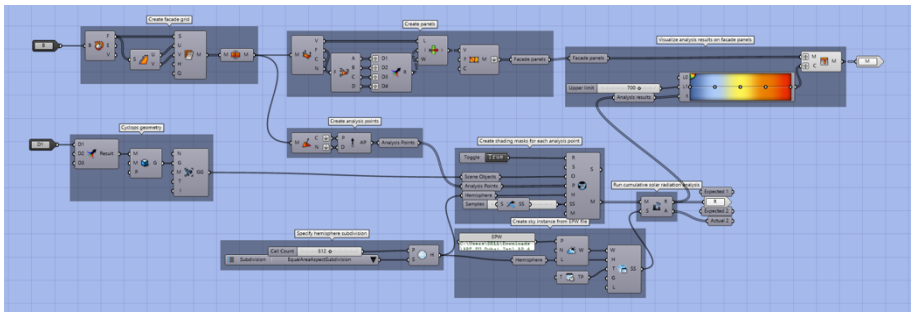


Figure 4. 3DCP Facades self-shading assessment using Cyclops in Grasshopper

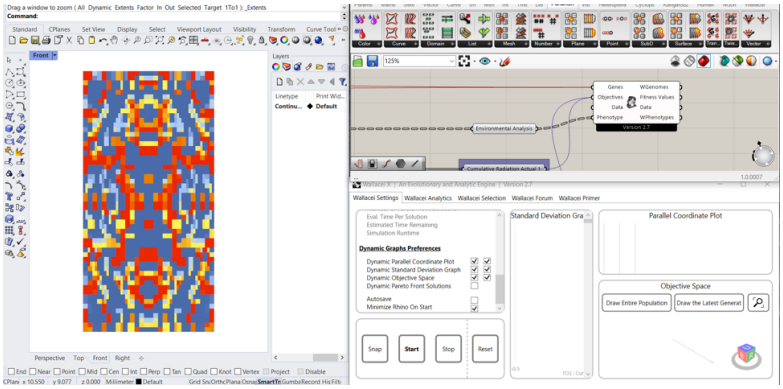


Figure 5. 3DCP Facades self-shading assessment using Cyclops in Grasshopper

ChatGPT was used to create a customized cost analysis plugin in Grasshopper for Layn, a 3D Concrete Printing firm in Egypt. The 3DCP costs depend on printing time, length, and concrete volume, which vary across prints, as illustrated in Fig. (6). The Python script incorporates fixed factors like profit margin and material costs. The facade's accumulated radiance, influenced by Dubai's environment, along with printing and profit costs for Layn, serve as input parameters for the Wallacei plugin in Grasshopper. These inputs help filter design options to identify those that improve self-shading at lower costs.

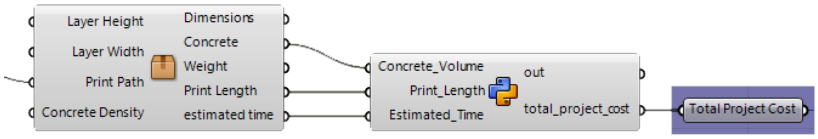


Figure 6. 3DCP Facades Cost Analysis

The Wallacei Plugin was employed to iterate through design options, selecting those with the lowest total radiation and cost. Fig. (7) illustrates the entire workflow, which includes the Custom façade generation cluster, façade modifications, print path creation, environmental analysis cluster, and the cost calculation Python script.

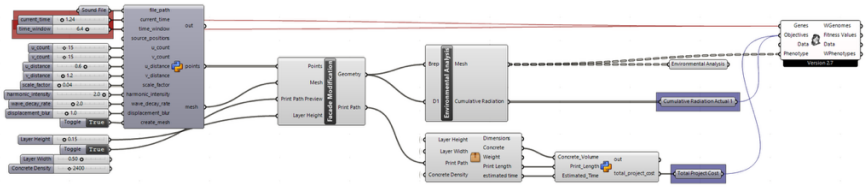


Figure 7. 3DCP Facades Generation and Multi-Objective Optimization

This computational design workflow is versatile across various scales and disciplines. It was tested on a small prototype inspired by the sound of sea waves and printed at Layn in Cairo, Egypt, to find the best pattern depth. The initial testing was based on the company's printing factors, especially the layer-to-layer offset, to create more complex geometries beyond simple horizontal seams. As shown in Fig. 8, the layer-to-layer offset of the pattern extrusions was optimized to prevent concrete buckling under weight, allowing us to identify the maximum extrusion depth suitable for optimization.



Figure 8. 3DCP Prototype

4. Conclusion

This paper explores the adoption of AI-powered computational workflows that integrate science, technology, and architecture. It describes how soundscapes from cultural heritage sites are extracted and converted into 3DCP façade units using a custom ChatGPT/Python script in Grasshopper, optimized for self-shading and cost efficiency. The pattern depth analysis, influenced by printing factors from Layn, has been tested on a prototype to verify the stability of pattern parameters in the Python script. Moving forward, developing context-aware architectural components through AI as co-designers can streamline the design process. This method aligns systems with site constraints and fabrication limits, resulting in more efficient, contextually suitable construction solutions. Future research should include additional structural factors, apply the design to a specific site for contextual evaluation, and optimize the infill pattern based on location, as the current study standardized the infill pattern.

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TOWARDS AN INTELLIGENT WORKFLOW FOR HISTORICAL BUILDING RESTORATION, NON-DESTRUCTIVE CRACK DETECTION & PROSPECTS DATABASE

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Abstract. As preserving historic buildings becomes more critical in protecting cultural heritage, the necessity for practical approaches to catalog and assess these structures grows. Non-destructive image processing methods, including high-resolution digital cameras and deep learning algorithms, have improved crack identification in building documentation, enhancing accuracy and efficiency in structure monitoring. Suppose technological advancements will improve the accuracy and speed of documenting and restoring historical monuments. In that case, it necessitates the development of existing tools to accommodate new methods of accuracy and engagement. This paper examines the existing literature on documentation methods for historical buildings, evaluating current technologies while identifying potential areas for improvement and innovation to develop a workflow strategy that serves as a database for generating AI tools in the domain. The study shows that while some methods effectively document building cracks, human intervention remains essential for accuracy, such as mechanical surveying. A comprehensive database incorporating precise specifications for historic building restoration and crack documentation has been developed as a result of this study. SQL is used to build this database, enabling the effective management and retrieval of data. In addition to expediting the documentation and evaluation process, the integration provides a strong foundation for future AI-driven heritage conservation solutions. To achieve the best results in the recording and restoration of heritage buildings, a hybrid strategy that combines cutting-edge technology tools with skilled human assessment is recommended.

Keywords: *Survey modeling, Crack detection, SQL, Artificial intelligence.*

Introduction

Historic structures symbolize architectural triumphs and connect to the past, telling stories of cultural relevance and human experience. Due to environmental factors, negligence, and the passage of time, many structures deteriorate, necessitating regular inspection and maintenance. Historic buildings have been documented using physical measurements, photographs, and drawings. While comprehensive, these methods are time-consuming and prone to human error. The introduction of digital technology offers more precise and thorough documentation.

Despite advancements, identifying and documenting structural concerns, especially cracks, remains a challenge, particularly in generating backend databases. Combining contemporary technologies with conventional restoration brings benefits and challenges. Studies are underway to enhance image processing in structural diagnostics and crack identification in heritage conservation. Using technologies such as surveying, simulation, and image processing improves understanding of structural conditions and supports restoration planning.

This research investigates the use of an SQL database system as essential for documentation. It evaluates existing methods for documenting historical structures, including strategies for detecting cracks and assessing their structural integrity. The study discusses techniques in architectural conservation, focusing on advanced surveying methods and their application in identifying flaws. It aims to assess current documentation practices and explore the use of high-resolution imagery and machine learning for crack identification, converting the findings into a database.

The primary goals are to develop a comprehensive approach to heritage documentation and restoration. This includes creating an SQL database architecture for documentation and crack detection, as well as an integrated process linking technologies to the database. The paper aims to lay the groundwork for an AI-powered tool to detect and assess cracks in historical buildings, leading to a balanced approach that integrates traditional techniques with modern solutions.

The techniques employed in this study are both qualitative and quantitative. The qualitative approach involves reviewing the literature on digital technology in historical documentation, examining surveying, simulation, photogrammetry, laser scanning, HBIM, and image processing for crack identification, and identifying gaps to inform future research. The quantitative approach focuses on data implementation, generation, and collection.

The research combines quantitative analysis of image data with experimental machine learning, ensuring accurate data processing and pattern identification for fracture detection. This approach generates comprehensive documentation of existing conditions. The database structure organizes and standardizes data, serving as a foundation for future AI-powered heritage protection. SQL's structuring and querying capabilities provide a platform for developing analytical tools and automated detection systems.

1. Review of Existing Workflow Strategies

Over the past decade, substantial progress has been made in documenting and restoring historic structures. This allowed for a shift away from traditional manual approaches and toward integrated digital workflows. This progress is a sign that heritage protection standards, as well as the advancement of digital technology, are becoming increasingly more challenging and complex. According to recent research by Zhang et al., the incorporation of artificial intelligence and machine learning has profoundly altered the approach to document creation and restoration tactics (ZHANG et al., 2022). This change needs a thorough examination of current techniques to find best practices and areas for improvement. Current workflow techniques in legacy documentation can be categorized into three main types: conventional documentation workflows, digital documentation workflows, and hybrid systems. (MAROUN, 2022)

1.1. TRADITIONAL DOCUMENTATION WORKFLOW

Conventional methodologies in workflow management, despite their established history, frequently depend on manual documentation processes and physical record-keeping systems. These established practices encompass various forms of manual measurement techniques, technical drawings, and photographic documentation protocols. Although such methodologies yield comprehensive observational data, they present notable inefficiencies in terms of temporal resources and remain vulnerable to human inconsistencies. Nevertheless, in contexts where technology is constrained or in specialized scenarios involving historically sensitive buildings requiring meticulous handling, these conventional approaches retain their significance, particularly. (MARTINEZ, 2020)

Modern research has revealed several irreplaceable elements within traditional documentation methodologies. In the domain of tactile evaluation protocols of historical buildings, restoration specialists or restorers use direct physical examination approaches to analyze material compositions. These established methodologies enable detailed assessment of artisanal qualities through time-validated conservation protocols

(ANDERSON, 2024). Documenting knowledge of specifications remains crucial, encompassing the interpretation of architectural forms, the examination of historical significance, and the evaluation of cultural impact. Its knowledge base is also relevant to traditional building techniques. However, physical verification procedures still perform this basic function: they include empirical measurements, systematic material analysis protocols, detailed evaluations of the environment, and comprehensive visualization, which are much more complex than automated systems currently can.

1.2. DIGITAL DOCUMENTATION WORKFLOWS

In recent years, the digital has changed heritage documentation, with modern workflows augmented by advanced technology (Wong, 2021). The following reflections are based on recent issues raised by Yamamoto et al., showing progress in digital documentation procedures. Very high precision: 0.1 mm point cloud generation through 3D laser scanning and photogrammetry (YAMAMOTO, 2024). These systems enable automated measurement extraction, detailed digital twins for monitoring, and multi-temporal analysis. Implementation of 3D laser scanning and photogrammetry, including point cloud generation, achieved 0.1 mm accuracy. These systems generate digital twins, ensure automated measurements, and support multi-temporal analysis.

Modern mobile apps and cloud tools have improved data collection and management. Data can now be collected in real-time and shared across platforms, easing collaboration. Incorporating IoT sensors allows continuous monitoring of historical structures. On the imaging front, new technologies such as hyperspectral imaging enable detailed material analysis. (HUANG, 2021)

Image-based rendering and 3D modeling have become crucial in computer vision, especially for robotics. New cameras offer real-time environmental views, improving interaction. Challenges remain in capturing and storing precise scene geometry (ZHANG et al., 2022).

Photogrammetry, or Structure-from-Motion (SfM), converts 2D images into 3D models using photo overlap from different angles. This process reconstructs 3D shapes by projecting them onto the sensor's 2D plane. (FLORES-FUENTES, 2023)

Laser scanners produce 3D data for surface descriptions, but identifying fractures, worn edges, and reliefs remains difficult due to low resolution despite millions of points. (HATIR, 2021)

Digital photogrammetry uses overlapping images to determine 3D dimensions, location, and shape, based on the principle that a point's dimensions appear in at least two images. (JIANG, 2022)

HBIM, a geometric digital representation, provides insights into materials and deterioration, making it more effective for restoration than traditional 3D models. (MAROUN, 2022)

Laser scanning and photogrammetric products struggle with complex surface reconstruction when integrated with HBIM models, as extrapolation overlooks constructive logic and geometry. (DONGXU, 2023)

Digital image pre-processing enhances accuracy by removing noise, while spatial filters improve visual clarity by blocking specific frequencies per pixel, depending on filter kernel type and size. (MAROUN, 2022)

Picture-based crack detection offers more reliable results using image recognition than manual processes (LAVADIYA, 2023). High-resolution digital cameras enhance fracture detection by capturing detailed cement images in one shot, allowing precise crack identification across concrete types (WON, 2024). Computer science macro studies involve mapping inputs, understanding mechanisms, and producing substitute outputs. (HOLBROOK, 2020)

1.3. CHALLENGES AND CONSIDERATIONS

Despite technological advances, several challenges persist in workflow implementation. Brown et al. identify key considerations (BROWN, 2022), which are further expanded upon by Mitchell and Wang. Technical challenges remain significant, including the complexity of data integration and software compatibility issues. Heritage settings often present unique hardware limitations while data storage and management demands grow

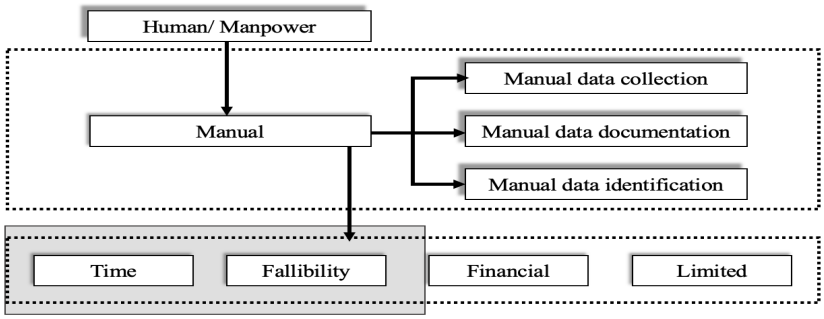


Figure 1. Manual data collection problems (by author, 2025)

exponentially. System scalability, technology obsolescence, network connectivity, and security concerns require ongoing attention and resources. (MITCHELL, 2024)

Conservation challenges add another layer of complexity to workflow implementation. Material compatibility issues must be carefully considered, while intervention ethics guide decision-making processes. Heritage value

restoration remains paramount, requiring careful balance with technological integration. Environmental impact considerations, sustainability concerns, cultural sensitivity, and stakeholder engagement all influence the design and implementation of the workflow.

2. Methodology

This study brings together relevant data within a theoretical framework aimed at understanding AI and its generation, thus making it more accessible. We examined current tools for site surveying, generative technical drawings, and digital data related to data restoration. It also analyzes the factors influencing the appearance of cracks in historical buildings and the need to develop links with SQL databases (Figure 2). In addition, it examines the method for creating detailed, image-based building models and the overall diversity of AI applications. This objective includes the technical and qualitative limitations that these tools may impose. In other words, the building model must be faithful to the existing conditions on site, and the dense area of the restored structure must be recorded from supporting images.

The study will examine the unique artificial intelligence model (AIM) for

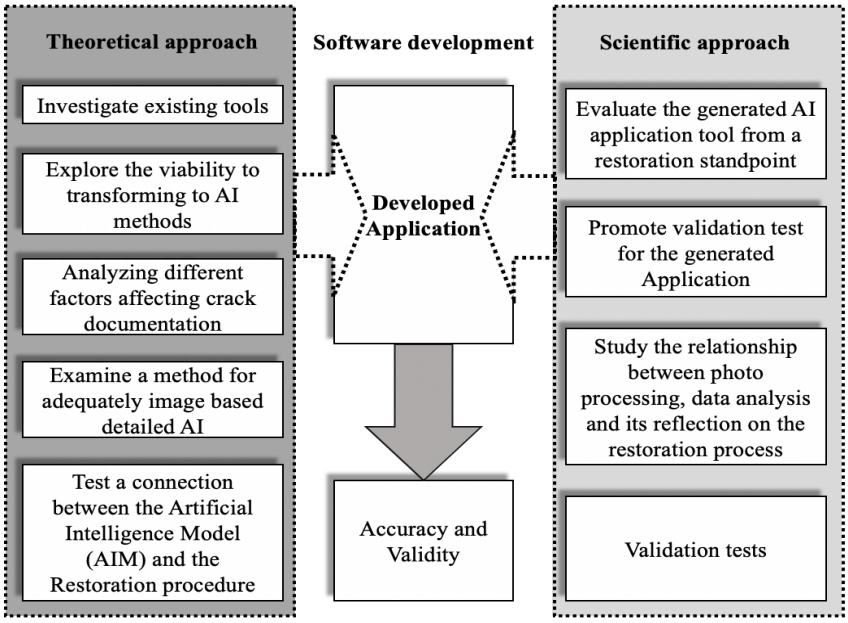


Figure 2. Development of the application Database (by author, 2025)

restoration, using representations of historic buildings. Heritage data and AI are now integrated to document, understand, and manage historical archives.

A complementary library that includes all geometric and non-geometric collections and connections. At this stage, the data acquires self-awareness and seeks solutions to common problems. (MAROUN, 2022)

The study also explores the relationships between information and data analysis in the context of strategy. The focus is on providing a framework for reconstructing integrated models and integrated symbolic information. Furthermore, the study of AI-generated data from a restoration perspective, following a globally recognized approach, identifies the best activities addressing crack issues in the fields of historical research, supervision, and detailed documentation, aiming to develop a recognized model and integrate restoration techniques and specifications. Ultimately, a quantitative approach to SQL database validation is proposed.

2.1. RESEARCH DESIGN

This study employs a multi-method approach, combining qualitative and quantitative methodologies to address historic building restoration and crack detection (Figure 3). Our technique is based on quantitative analysis of digital imaging data obtained through systematic collection and study of high-resolution images. This involves statistical analysis of fracture patterns and propagation rates, and validation of measurements using imaging

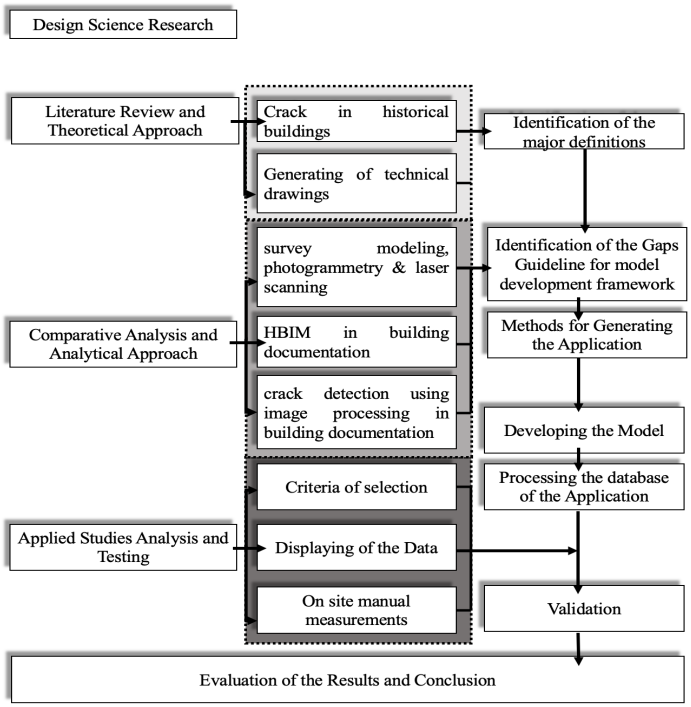


Figure 3. Design scientific research workflow for crack documentation Application (by author, 2025)

techniques and standardized image processing protocols to quantify crack size.

The experimental component focuses on testing and validating machine learning techniques, representing a leap in automated crack detection. We evaluated deep learning models, including comparisons of neural network designs, to discover optimal solutions for historical buildings. These models are tested using datasets from historical structures, with findings cross-validated against expert evaluations to ensure reliability and accuracy.

To meet restoration demands, we developed data retrieval procedures for rapid access to critical structural data. The qualitative component includes interaction with conservation experts through structured restoration techniques and assessments of practical studies. This method enables documentation and integration of ancient procedures with current technologies, bridging historical and digital approaches. Combining qualitative insights with quantitative data yields a nuanced understanding of conservation challenges and solutions.

Validation involves multiple layers of verification, including cross-referencing automatic detection with expert findings. We utilize performance measures to assess accuracy and conduct temporal investigations of crack data to validate the technique over time. This approach balances technical innovation and historical authenticity, addressing practical issues in documenting and maintaining historical structures.

2.2. DATA COLLECTION

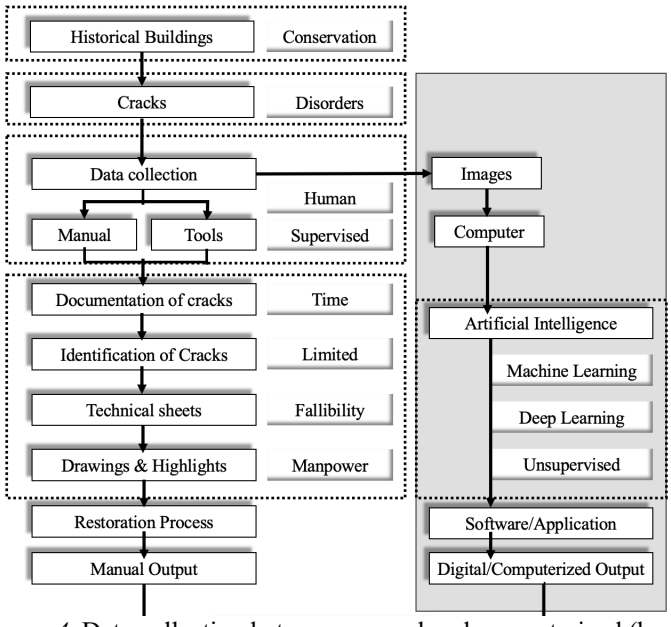


Figure 4. Data collection between manual and computerized (by author, 2025)

The data-collecting process employs a thorough approach combining traditional documentation methods with current technology database design. The technique begins with high-resolution digital photography using modern imaging technology to capture minuscule fracture details. These photographs serve as the foundation for our structured AI tool, which will be transferred and will be the primary focus of SQL database development (Figure 4).

With each image methodically cataloged, crucial metadata includes the crack's spatial coordinates, size, identification, and environmental conditions at the time of collection. The database schema is intended to meet both historical and current documentation requirements, with a strong relational structure linking visual data to thorough structural evaluations.

We created a bespoke SQL database architecture with specific tables for crack characteristics (dimensions, patterns, propagation history), building structural aspects (materials, age, historical relevance), and maintenance records. The SQL connects to the data retrieved from the images; this organized method facilitates quick querying for temporal analysis, pattern detection, and predictive maintenance planning. Visual documentation and analytical data are stored in a format enabling extensive analysis while adhering to historical restoration standards, thanks to integrated data collection techniques. The database structure meets urgent documenting requirements while laying the groundwork for future machine learning applications and automatic crack detection systems.

2.3. TECHNICAL IMPLEMENTATION

The technological implementation framework is a fusion of machine learning technologies and database management systems, designed for the restoration of historical buildings. Our technique utilizes convolutional neural networks (CNNs) trained on historical datasets of construction materials, enabling the identification and categorization of crack forms, from hairline fissures to structural deformations. These ML models adapt to various architectural styles and materials while maintaining efficiency across historical settings.

The core implementation features an analytical platform and repository, a central SQL database serving as the backbone. The system is designed with primary tables featuring relationships, housing the hierarchy of building components, crack attributes, and enabling monitoring over time. The schema includes tables for structural elements and cracks, with relationship tables documenting crack progression (Figure 5).

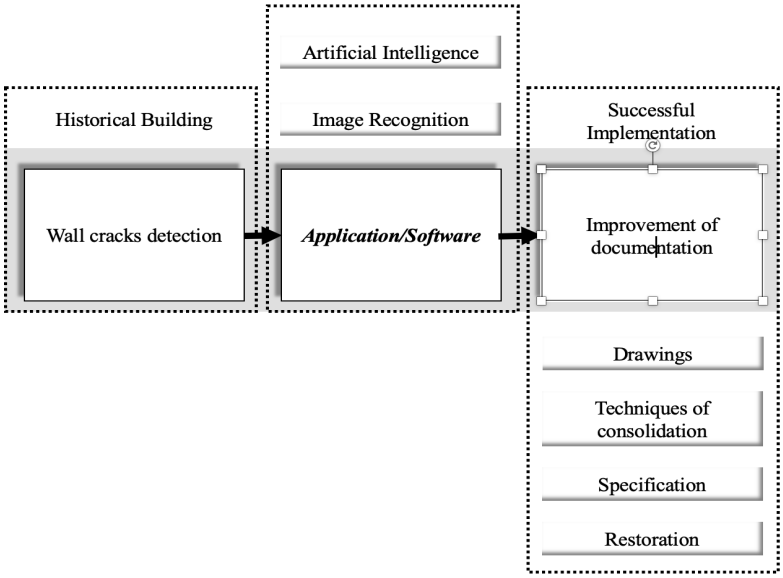


Figure 5. Implementation of AI in data accuracy and documentation of Cracks (by author, 2025)

Incorporating historical records, the database includes contextual and environmental metadata. This architecture encompasses sensor data and automated monitoring, providing an advanced analysis framework. The system uses validation tools to ensure data accuracy within historical documentation inputs and source types, including engineering information, maintenance logs, photos, sketches, and blueprints.

Using integration protocols, sensor networks interact and interoperate with digital imaging systems and multidisciplinary interfaces, enabling collaborative work across domains and access to archived materials (Figure 6).

We incorporate processes for validating and verifying data quality within a restoration monitoring system. To perform systematic upkeep in heritage conservation, a strategy for documenting and governing the building is essential. Standardized surveying methods have been used over the last decade to capture photographs. The next step is to create an instrument that gathers pertinent structural data and allows comparison with previous records, integrating advanced data on future restoration or maintenance using AI technology. (MURPHY et al., 2011)

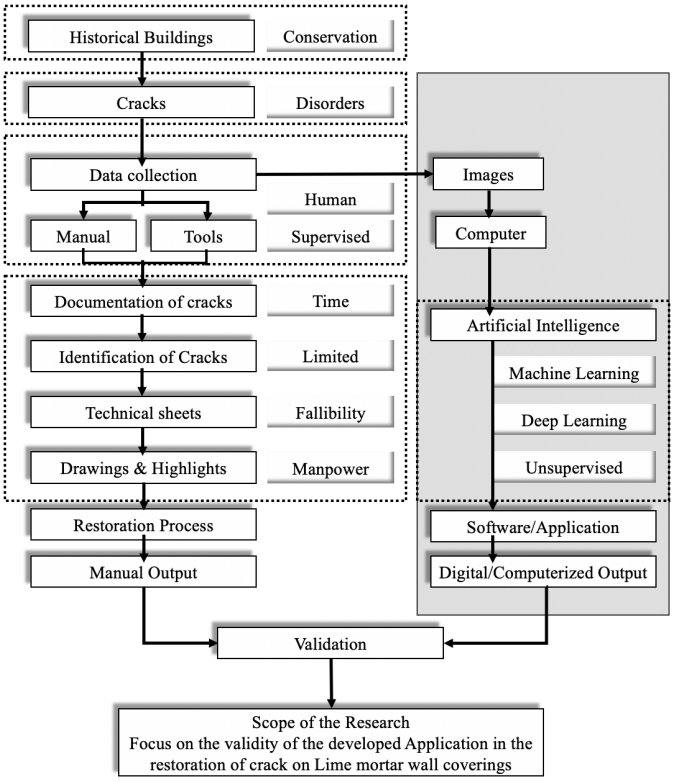


Figure 6. validation process of data collection (by author, 2025)

3. Displaying the Database for Crack Restoration

The AI Crack Detector supports forecasting objective functions, including material components, compressive strength, performance requirements, restoration materials, quantities, and techniques. The ML and DL algorithms help meet these constraints and optimize combinations of specifications and restoration methods to achieve optimal performance indicators. Recognizing and detecting cracks is one advantage of the AI image base.

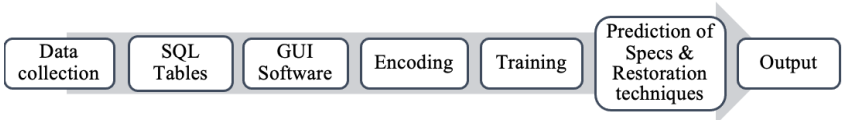


Figure 7. Graph showing the sequence workflow from data collection of historical building restoration techniques to the final output of specification and bill of quantities (by author, 2025)

These methods serve as optimization tools, adjusting criteria to achieve specific goals. Key decision factors include constraints such as client expectations, building conditions, and construction norms.

Once restoration material is selected, AI assists with data evaluation and design output. Analytic methods or heuristic coding serve as frameworks for implementing restoration techniques or numerical modeling.

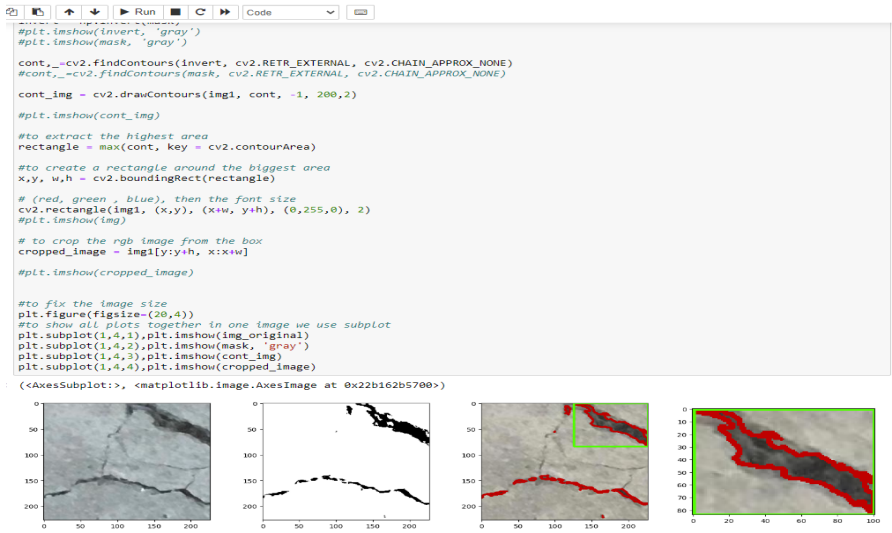


Figure 8. Algorithm and Crack detection (by author, 2025)

Generating restoration files from specifications and BOQs is a rigorous data collection task. Relevant information, site measurements, material samples, photographs, and evidence must be systematically collected and documented. Without a strong dataset, analysis risks being incomplete or inaccurate. Figure 8 shows how such data is mapped within a restoration plan.

The developed Application marks an advancement in crack restoration. A comprehensive database of crack restoration is extracted from diverse sources. SQL tables organize datasets, supporting storage and retrieval. The architecture enables scalability and streamlines workflow.

Scale and depth define the training regimen for machine learning. Large volumes of annotated data help algorithms discern crack patterns. Over time, the software minimizes human oversight through automation, improving data-driven restoration with precision and reliability.

The graphical user interface (GUI) addresses the practical needs of architects, restorers, and researchers. Designed for accessibility and ease, it helps users navigate datasets, analyze trends, and access best-practice recommendations.

An innovative aspect is the workflow's integration of ML techniques. A feedback loop enables automated identification and analysis of cracks by

connecting SQL databases, a GUI, and the ML module. This reduces the time and cost of manual inspection, allowing practitioners to make evidence-based decisions quickly.

3.1. COLLECTION OF RESTORATION DATA

Restoration projects depend on several crucial documents, including images, labels, description, cause of disorder, side effects, restoration techniques, materials, specifications, bills of quantities (BOQs), and methodologies (Figure 9). These form the framework guiding the process of returning a structure to its original condition. The process begins with data collection, involving information about the building's history, architectural features, and current state of deterioration. Without this data, developing an effective restoration specification is impossible.

RESTORATION AND CONSOLIDATION TECHNICS								
Disorder Type	Type Name	Group	Description	Causes of the disorder	Side effects of the disorder	Consolidation Treatment	Consolidation Material	Technique of Consolidation	Monitoring
COP01	Hair Crack	Crack & Deformation	Minor crack with a width dimension between 0.1 um & 1mm, mostly the hair crack occupies the joints between the stone and could crosses the stone itself from inside of the wall to the surface	Tension, pressure on the stone, weak ground conditions, movement in ground due to subsidence or changes in the water table within the ground. Cracks will often follow the line of least resistance. These cracks are created due to a pressure on the stone from above from the settlement of the floor.	Crack initiation and propagation in sharp microscopic cracks in case these cracks width changed it can lead to a changing in shape, bending, buckling or twisting of a stone block. The hair crack could be a minor issue but should be monitored in case it grew in width.	The crack should be filled with lime mortar	Fine grade Lime mortar with granulate particles less than 0.1um	1- The cracks should be cleaned with a soft brush, with removing any large loose particles. Not more than one-third of the depth of the mortar should be removed. An air blower could be used to eliminate the fine debris. 2- The stone and the kept parts of the mortar should be wet in order that the new material will hold. 3- The mortar granulate should be equivalent to 0.1um to unable penetration. 1:2 (Lime:Water) 4- The mortar should be liquified with water. 5- Using a pointed injection to fill the areas with lime mortar patched stained with some colored pigments that could be added to match the stone masonry. The mortar should be tightly packed into the joints in order to eliminate any air pockets. The excess should be scraped away and cleaned with the brush. 6- Allow to dry	1- The cracks and the filled joints should be monitored for a year at least passing a winter and a summer to check material loss or growing cracks. 2- For the most critical cracks as a sheap way of monitoring a jauges saugnac ruler should be fixed on. 3- An electrical micro crack meter or fissurometer instruments could be used in the most critical places.
COP02	Medium Crack	Crack & Deformation	Medium Crack with width dimension between 1 mm / 3mm, most of the medium cracks started as a hair crack, until it went deep inside the stone and cracked open the stone from the inside of the wall to the surface.	Tension, pressure on the stone, traction, weak ground conditions, movement in ground due to subsidence or changes in the water table within the ground. Due to traction effect the cracks will often cut the stone in the least resistance area.	Crack initiation and propagation in sharp microscopic cracks in case these cracks width changed it can lead to a changing in shape, bending, buckling or twisting of a stone block. The hair crack could be a minor issue but should be monitored in case it grew in width.	The crack should be filled with a mixture of lime/sand mortar	1- Fine grade Lime mortar with granulate particles less than 0.1um 2- Fine grade sand with particles less than 2mm	1- The cracks should be cleaned with a soft brush, with removing any large loose particles. Not more than one-third of the depth of the mortar should be removed. An air blower could be used to eliminate the fine debris. 2- The stone and the kept parts of the mortar should be wet in order that the new material will hold. 3- Preparing a mixster of fine granulate particles lime with fine grade sand with granulate particles less than 2mm. 1:3 (lime:Sand) 4- The mixture should be mildly wet. 5- Using a pointed trowel or injection to fill the areas with lime/sand mortar mixture patched stained with some colored pigments that could be added to match the stone masonry. the mortar should be tightly packed into the joints in order to eliminate any air pockets. The excess should be scraped away and cleaned with the brush. 6- Allow to dry	1- The cracks and the filled joints should be monitored for a year at least passing a winter and a summer to check material loss or growing cracks. 2- For the most critical cracks as a sheap way of monitoring a jauges saugnac ruler should be fixed on. 3- An electrical micro crack meter or fissurometer instruments could be used in the most critical places.

Figure 9. Table showing the essential database collected used in the development of the Application Software (by author, 2025)

Restoration specifications serve as detailed plans, specifying appropriate materials, defining project scope, and outlining procedures. To ensure the project follows standards and proceeds in an organized manner, such documentation provides direction. The BOQ ensures required materials are available when needed and helps keep the project within budget, preventing delays or shortages. Based on the data, specialists determine suitable repair materials and methods, critical for drafting specifications that reflect the project's requirements.

In the Application workflow, data collection was conducted using current technologies and established standards, notably by UNESCO. The focus was on authenticity, respect for original materials and values, and sustainability. The information gathered was divided into two categories. The first addressed types of structural cracks, offering classifications, descriptions, causes, effects, and suitable repair methods and materials. This category is crucial for developing software to address a wide range of structural issues (see Corpus, 2019).

The second category covered restoration treatments, consolidation materials, and techniques tailored to crack types under different conditions,

including location and severity. This enabled a comprehensive analysis of problems and potential solutions, which could be modified to meet user needs.

The analyzed data informed a training program for users of the Application. To ensure architectural restorers understand the software, the curriculum is designed for real-world restoration settings.

Successful restoration projects require rigorous data collection, detailed planning, and adherence to established standards. These practices are fundamental to preserving the historical and cultural significance of built heritage.

.3.2 GENERATION OF THE GUI APPLICATION

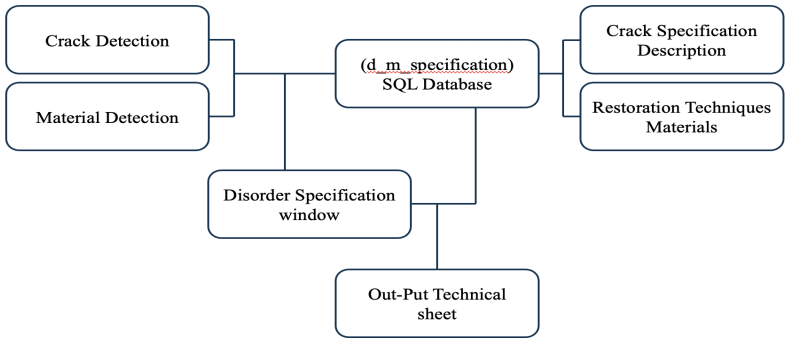


Figure 10. The connections between the Crack detection, database, the disorder specification to generate a final out-put with technical sheets (by author, 2025)

For the application's front end, PyQt was selected, with Qt Designer playing a central role in the interface construction. To significantly expedite the layout process and facilitate the efficient organization of interface elements, a drag-and-drop functionality in Qt Designer was utilized. A subsequent interface, focused on Disorder Specification and Restoration technical sheets (Figure 10), serves as a foundational component of the system. Its development followed the approach established during the main window's creation in PyQt Designer, supporting straightforward integration, data connectivity, and effective management of restoration information. This interface integrates multiple essential data sources:

- Outputs from machine learning models, including image-based crack detection, identification of construction materials, and quantitative analysis of disorder dimensions.

- A supporting SQL table responsible for organizing data stemming from crack identification, as well as maintaining databases on restoration techniques, materials, and treatment processes.

- Additional data contributed directly by the restorer.

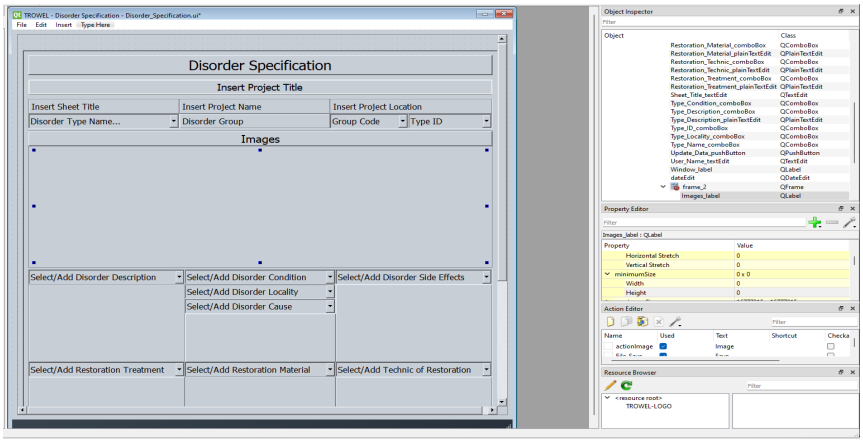


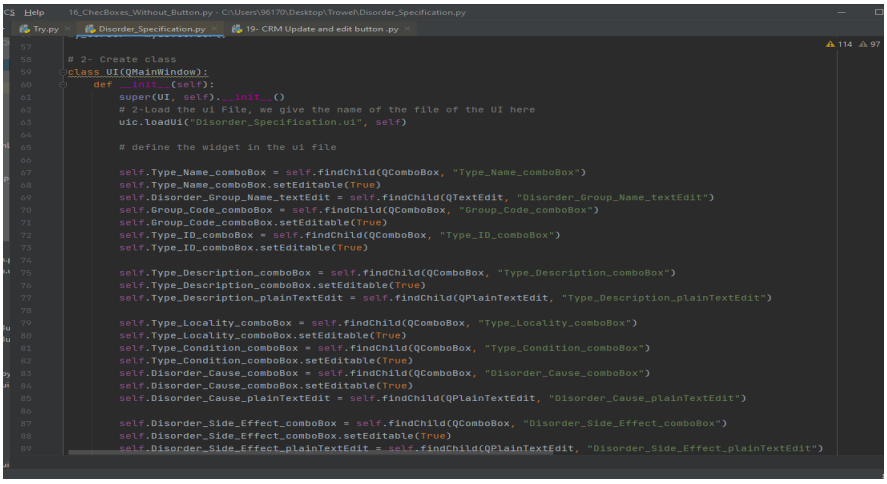
Figure 10. Development of the Crack specifications and Restoration sheets front-end (by author, 2025)

- Functionality for real-time updates to the SQL database.
- Automated generation of comprehensive technical sheets as final documentation.

Each widget, whether a button, dropdown menu, combo box, or text label, was systematically assigned a unique identifier, ensuring clear identification and structured interconnection across the interface (Figure 11).

3.3. ENCODING OF THE RESTORATION DATA

MySQL was selected as the core database to manage information on crack types and restoration methods. The process began with creating the d_m_specification table, a standard operation in relational database design. In such a structure, columns define data categories, and each row holds a record tied to those categories.



```
# 2- Create class
class UI(QMainWindow):
    def __init__(self):
        super(UI, self).__init__()
        # 2-Load the ui File, we give the name of the file of the UI here
        uic.loadUi("Disorder_Specification.ui", self)

        # define the widget in the ui file

        self.Type_Name_comboBox = self.findChild(QComboBox, "Type_Name_comboBox")
        self.Type_Name_comboBox.setEditable(True)
        self.Disorder_Group_Name_textEdit = self.findChild(QTextEdit, "Disorder_Group_Name_textEdit")
        self.Group_Code_comboBox = self.findChild(QComboBox, "Group_Code_comboBox")
        self.Group_Code_comboBox.setEditable(True)
        self.Type_ID_comboBox = self.findChild(QComboBox, "Type_ID_comboBox")
        self.Type_ID_comboBox.setEditable(True)

        self.Type_Description_comboBox = self.findChild(QComboBox, "Type_Description_comboBox")
        self.Type_Description_comboBox.setEditable(True)
        self.Type_Description_plainTextEdit = self.findChild(QPlainTextEdit, "Type_Description_plainTextEdit")

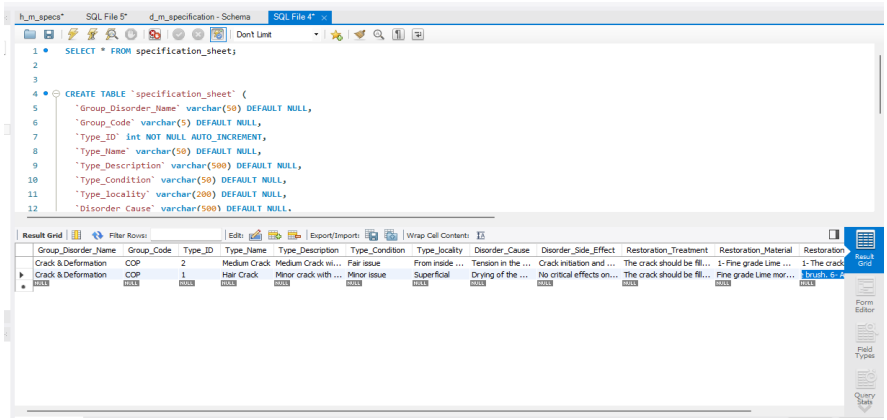
        self.Type_Locality_comboBox = self.findChild(QComboBox, "Type_Locality_comboBox")
        self.Type_Locality_comboBox.setEditable(True)
        self.Type_Condition_comboBox = self.findChild(QComboBox, "Type_Condition_comboBox")
        self.Type_Condition_comboBox.setEditable(True)
        self.Disorder_Cause_comboBox = self.findChild(QComboBox, "Disorder_Cause_comboBox")
        self.Disorder_Cause_comboBox.setEditable(True)
        self.Disorder_Cause_plainTextEdit = self.findChild(QPlainTextEdit, "Disorder_Cause_plainTextEdit")

        self.Disorder_Side_Effect_comboBox = self.findChild(QComboBox, "Disorder_Side_Effect_comboBox")
        self.Disorder_Side_Effect_comboBox.setEditable(True)
        self.Disorder_Side_Effect_plainTextEdit = self.findChild(QPlainTextEdit, "Disorder_Side_Effect_plainTextEdit")
```

Figure 11. Connecting code to the generated window (by author, 2025)

Before running SQL commands, careful planning of the table's architecture was crucial. This stage involved selecting a table name, determining the number of columns, and specifying data types. The primary key, essential for uniquely identifying each record, was set as Disorder_ID and configured to auto-increment. This approach streamlines identification and tracking across crack types and related data.

To link the database with the user interface and machine learning modules, Python scripts were developed. These scripts connected interface



```
SELECT * FROM specification_sheet;

CREATE TABLE `specification_sheet` (
    `Group_Disorder_Name` varchar(50) DEFAULT NULL,
    `Group_Code` varchar(5) DEFAULT NULL,
    `Type_ID` int NOT NULL AUTO_INCREMENT,
    `Type_Name` varchar(50) DEFAULT NULL,
    `Type_Description` varchar(500) DEFAULT NULL,
    `Type_Condition` varchar(50) DEFAULT NULL,
    `Type_locality` varchar(200) DEFAULT NULL,
    `Disorder_Cause` varchar(500) DEFAULT NULL.
```

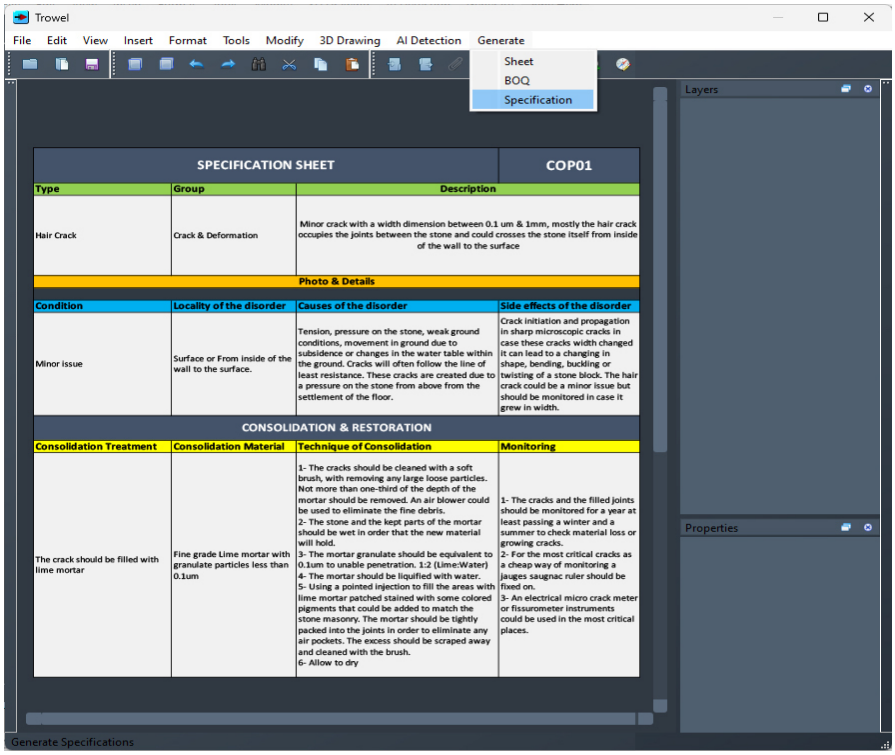
Group_Disorder_Name	Group_Code	Type_ID	Type_Name	Type_Description	Type_Condition	Type_locality	Disorder_Cause	Disorder_Side_Effect	Restoration_Treatment	Restoration_Material	Restoration
Crack & Deformation	COP	2	Medium Crack	Medium Crack wi…	Fair issue	From inside …	Tension in the …	Crack initiation and …	The crack should be fill…	1- Fine grade Lime …	1- The crack
Crack & Deformation	COP	1	Hair Crack	Minor crack with …	Minor issue	Superficial	Drying of the …	No critical effects on…	The crack should be fill…	Fine grade Lime mor…	Fourth 6- A

Figure 12. Crack documentation process (by author, 2023)

components, combo boxes, text fields, and labels, to the user interface and front-end application, facilitating smooth data exchange. Additional code integrated the SQL backend with machine learning algorithms, enabling efficient and accurate analysis and classification of crack images.

The software supports generating analytical reports and recommendations based on image analysis. The architect-restorer can update or modify data at any phase, with all adjustments recorded for future training cycles. This flexibility ensures ongoing relevance and robustness. In summary, the Application's framework integrates its graphical interface, database, SQL backend, and machine learning modules into a unified, adaptive system.

3.4. GENERATION OF CRACK SPECIFICATIONS



SPECIFICATION SHEET			COP01
Type	**Group**	**Description**	
Hair Crack	Crack & Deformation	Minor crack with a width dimension between 0.1 um & 1mm, mostly the hair crack occupies the joints between the stone and could crosses the stone itself from inside of the wall to the surface	
Photo & Details			
Condition	**Locality of the disorder**	**Causes of the disorder**	**Side effects of the disorder**
Minor issue	Surface or From inside of the wall to the surface.	Tension, pressure on the stone, weak ground conditions, movement in ground due to subsidence or changes in the water table within the ground. Cracks will often follow the line of least resistance. These cracks are created due to a pressure on the stone from above from the settlement of the floor.	Crack initiation and propagation in sharp microscopic cracks in case these cracks width changed it can lead to a changing in shape, bending, buckling or twisting of a stone block. The hair crack could be a minor issue but should be monitored in case it grew in width.
CONSOLIDATION & RESTORATION			
Consolidation Treatment	**Consolidation Material**	**Technique of Consolidation**	**Monitoring**
The crack should be filled with lime mortar	Fine grade Lime mortar with granulate particles less than 0.1um	1- The cracks should be cleaned with a soft brush, with removing any large loose particles. Not more than one-third of the depth of the mortar should be removed. An air blower could be used to eliminate the fine debris. 2- The stone and the kept parts of the mortar should be wet in order that the new material will hold. 3- The mortar granulate should be equivalent to 0.1um to unable penetration. 1:2 (Lime:Water) 4- The mortar should be liquified with water. 5- Using a pointed injection to fill the areas with lime mortar patched stained with some colored pigments that could be added to match the stone masonry. The mortar should be tightly packed into the joints in order to eliminate any air pockets. The excess should be scraped away and cleaned with the brush. 6- Allow to dry	1- The cracks and the filled joints should be monitored for a year at least passing a winter and a summer to check material loss or growing cracks. 2- For the most critical cracks as a cheap way of monitoring a jauges saugnac ruler should be fixed on. 3- An electrical micro crack meter or fissurometer instruments could be used in the most critical places.

Figure 13. Generated specification sheet (by author, 2025)

Cracks present a significant challenge due to their irregular and unpredictable nature, often leading segmentation and detection algorithms to overfit. In the initial phases of model training, both training and validation errors decrease, suggesting effective learning. But, after a certain threshold, the training error continues to decline while the validation error rises, indicating the onset of overfitting. Various crack detection methods, strategies for assessing damage severity in existing structures, and relevant considerations for restoration are explored, along with innovative design elements to enhance structural strategies, potentially offering more effective alternatives to traditional restoration techniques.

Crack detection isn't straightforward due to the chaotic, unpredictable nature of cracks. These irregular features often trip up segmentation and detection models, causing overfitting (Figure 14). Typically, both training and validation errors drop initially, which seems promising. However, as training continues, training error decreases while validation error rises, a classic sign of overfitting. There is also exploration of how generative design can support restoration, offering broader solutions than traditional approaches. The software was tested on specific hairline cracks, yielding satisfactory results.

When applied to hairline crack detection, the software showed promising performance. While the confusion matrix isn't the only metric for evaluating accuracy, it remains valuable. Due to the lack of a dedicated dataset for critical damage detection, a binary classification approach was used to train the neural network for image feature recognition, specifically for hair cracks (small, medium, large, and splitting). After establishing the neural network framework, the binary training data facilitated determining parameter values that characterize variances.

While the confusion matrix is standard for accuracy evaluation, it's not the only option. In this case, since no dedicated dataset existed for identifying critical damage, researchers used binary classification to train the neural network for image feature recognition. Once the classification framework was established, binary data helped pinpoint parameters distinguishing between crack types.

4. Results and Analysis

4.1. DOCUMENTATION EFFICIENCY

The integration of advanced database systems and automated crack detection workflows in the generated Application has reshaped documentation practices for historic buildings. Streamlined and efficient digital procedures replaced traditional approaches, often reliant on disparate records and manual data entry. Time spent on documentation has been reduced, and the repetitive workload faced by restoration professionals is alleviated, thanks to simplified data entry interfaces and automated classification tools.

The machine learning algorithms used in crack detection have demonstrated accuracy surpassing conventional manual inspections. Where early identification of structural vulnerabilities can inform timely interventions and support sustainable maintenance strategies, precision is vital in heritage conservation. The system's ability to monitor and document crack progression over time enables enhanced predictive maintenance planning, resulting in more informed and proactive restoration efforts.

The adoption of a structured SQL database has improved organization and accessibility of documentation. Restoration teams benefit from standardized data storage and reliable retrieval processes, which facilitate collaboration and support decision-making across projects and timeframes. The database remains flexible to accommodate unique characteristics of different historic structures while enforcing uniform documentation standards, ensuring reliability and quality of collected data. Altogether, these advancements strengthened adaptability and effectiveness of restoration initiatives, supporting ongoing stewardship of cultural heritage assets.

4.2. MACHINE LEARNING PERFORMANCE

The introduction of our SQL database system represents a significant step in enhancing documentation, working closely with machine learning algorithms. Our models have attained high accuracy in identifying cracks, supported by the robust database architecture. This infrastructure enables comprehensive data storage and efficient data analysis. The schema was designed to record essential crack features and capture relationships among structural elements, environmental conditions, and crack evolution.

Database development began with a review of historical building documentation, informing the advanced relational structure. Primary tables store crack data, measurements, coordinates, and timestamps. Relationship tables track crack progression, enabling temporal analysis. Advanced indexing and optimized querying reduced false positives compared to conventional methods. This improvement stems from data validation protocols and integrated cross-referencing mechanisms.

The schema's flexibility accommodates varied features while maintaining data consistency, aided by pattern recognition across crack types. For standardization, the SQL database uses stored procedures and triggers to validate and categorize data. Custom APIs support seamless integration between machine learning and the database, enabling real-time updates and automated documentation, thereby reducing the need for manual intervention.

Database integration supports complex queries and analysis. Advanced SQL functions enable specialists to analyze temporal trends, identify patterns, and plan maintenance effectively. Optimized for reading and writing, the system ensures rapid access to historical data. It meets current documentation needs and provides a scalable platform for future advancements in detection and analysis.

4.3. DATABASE IMPLEMENTATION & RESULTS

The implementation of our SQL database system has enhanced the documentation of historical building restoration and crack detection. The

robust architecture features a hierarchical schema that organizes crack elements, attributes, and relationships. Each component, crack dimension, group, type, and description is methodically cataloged. Data integrity is maintained through careful management of foreign key relationships, ensuring no crucial information is lost. Generated causes of disorder, consolidation treatments, materials, and restoration techniques showed improved consistency in data connection.

A significant improvement is the accelerated retrieval of data. Advanced indexing and materialized views have reduced query times, enabling quick access to essential information. Caching and query optimization further expedite access to frequently used datasets. Retrieval and management have shifted from a slow process to efficient, near-instantaneous access, enabling real-time analysis and decision-making, an improvement over prior systems.

The database is adaptable in handling diverse data formats, which is essential for restoration documentation. It supports the integration of high-resolution images, measurements, textual records, and temporal data. Handlers and conversion protocols preserve data integrity and detail, ensuring standardization and richness in documentation. Collaborative features have redefined workflows for restorers. A permission management framework enables secure, flexible multi-user access, allowing data updates and Application upgrades using AI.

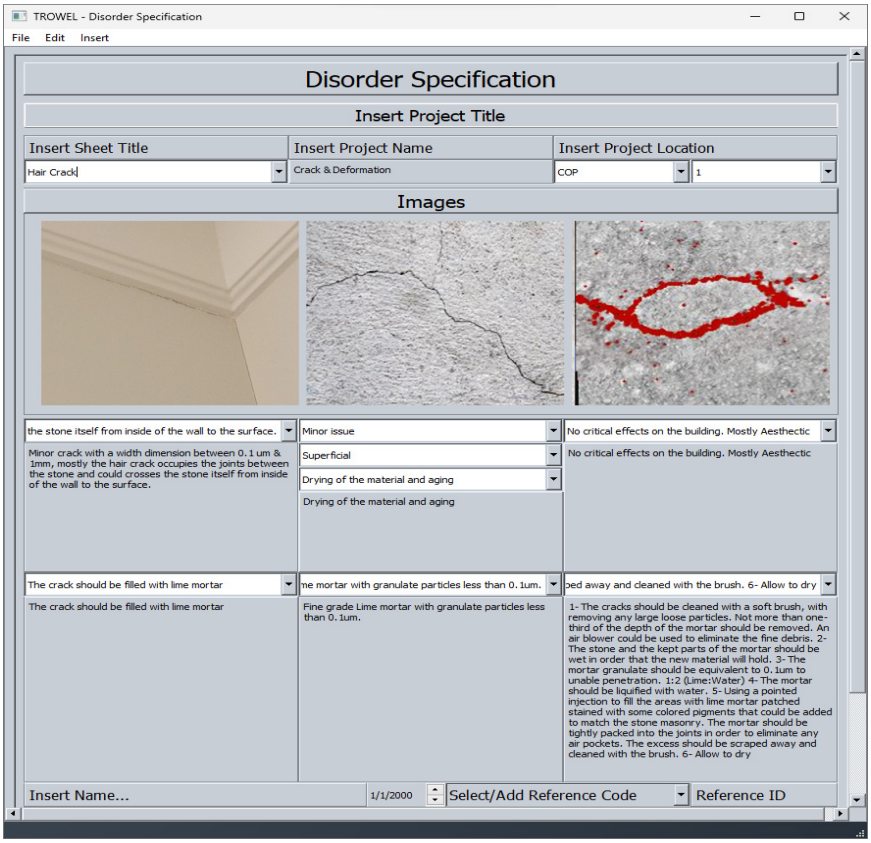


Figure 14. Generated Cracks data and Restoration Specification (by author, 2024)

In summary, the generated results, the workflow Application produced the following results:

Regarding disorder identification:

Type of disorder, Grouping of the disorder, description.

For disorder analysis:

Severity of the disorder, Locality of the disorder, Causes of the disorder, Side effects of the disorder.

Regarding restoration and consolidation treatment:

Consolidation treatment, Consolidation material, Consolidation technique.

Conclusion

Our research into SQL database implementation for preserving historical buildings yielded key findings, practical strategies, and areas for further exploration. Integrating machine learning with established documentation methods, supported by a comprehensive SQL database, proved feasible and effective. Historical walls and deploying our database improved crack detection and documentation accuracy. While automated systems and SQL architectures increase efficiency, human expertise remains essential for interpreting complex structural patterns and making informed decisions about restoration. Standardizing database schemas and documentation methods is crucial for consistent data collection and analysis across projects.

Our approach addresses a gap in previous solutions by offering a unified, end-to-end restoration workflow. Rather than focusing on isolated procedures, our Application supports the entire process, including generating technical documentation, building crack models of historical walls, identifying and measuring cracks, creating groups, and proposing consolidation techniques, along with bills of quantities and specifications. This methodology reduces fieldwork and streamlines project management.

The workflow developed through our database bridges advanced technology and manual data entry. It integrates accurate digital tools with the creativity and intuition of restoration professionals. Centering the human perspective in artificial intelligence encourages environmentally responsible practices and enables tailored solutions. As the software evolves to use AI, its user-oriented design is expected to enhance usability and service delivery, while reducing cost and human error.

We recommend this approach, allowing teams to adopt new practices without disrupting existing workflows. Comprehensive training in SQL database management and restoration techniques is essential for successful implementation. Systems should be regularly updated to incorporate new technologies and methods. Human oversight must remain central, especially for validating automated analyses and ensuring contextual accuracy.

Looking ahead, future work on machine learning should focus on tighter integration with SQL systems, particularly for real-time processing and pattern recognition. Database functionality can be enhanced through sophisticated queries and improved visualization tools.

SQL databases play a pivotal role, serving as the infrastructure linking all system components. Further research should investigate advanced architectures to handle complex restoration data while maintaining performance and accessibility. Strategies for partitioning include query optimization and redundancy management, tailored to heritage documentation needs. The development of distributed databases across institutions is also a compelling area, offering broader analyses of restoration trends across historical sites.

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II. DIGITAL FABRICATION & CONSTRUCTION TECHNOLOGY

3D PRINTING APPLICATIONS IN THE GCC HOUSING MARKET

Challenges and Opportunities

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Abstract. The last decade has witnessed a notable growth in Additive Manufacturing (AM) technologies. commonly called 3D printing, this expansion is driven by evolving machines, materials, and techniques designed to explore geometric possibilities and structural applications, suggesting a new production landscape for the building industry. Concrete, a globally dominant construction material and notably abundant in the GCC region, has garnered significant attention in applications involving 3D printing for construction purposes. This paper highlights diverse applications of large-scale 3DCP, focusing on applications in the GCC. The paper pursues the following objectives: firstly, to analyze different approaches that effectively establish synergy between design, materials, and machines, towards developing contextual residential structures. Secondly, to study the distinctions between continuous and segmented production of building components, concentrating on processes and machines. Thirdly, to highlight various practices learned from projects realized in the GCC region. The outcome is to suggest alternatives for materials and processes to drive a contextually oriented approach to 3D printing residential structures.

Keywords: *Architecture, Housing, Additive Manufacturing, 3D Concrete Printing.*

1. Introduction

The utilization of computers and digital technologies in architecture boasts a rich history. It began with recognizing their potential in design and planning, coinciding with the emergence of computers as powerful arithmetic and logical tools, and the inception of Artificial Intelligence in the early 1970s. The integration of Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) technologies, demonstrated by the pioneering work of Frank Gehry in 1992, marked a significant milestone in this progression (Kalay, 2005). Over the past two decades, this trend in design and production has advanced significantly. CAD/CAM applications have become standard practice in the Architecture, Engineering, and Construction (AEC) industry, encouraging a transformative shift in building methodologies.

One of the CAM techniques that has been growing remarkably in the last decade is Additive Manufacturing (AM). Also referred to as 3D printing, the scalability of such a method, based on the development of various machines, materials, and techniques, has been proposed to explore possibilities and applications to rethink building production. Rael and San Fratello (2018) summarized methods and materials of 3D printing as follows:

- Binder jetting, developed by MIT in 1993, is an additive manufacturing process where a liquid binder is selectively deposited onto thin layers of powder. The binder bonds each layer, and new powder layers are successively added and bonded similarly. This process continues for hundreds or even thousands of layers. The surrounding loose powder supports the part during printing, allowing for the creation of complex geometries, including overhangs and undercuts. Once printing is complete, the object is carefully removed and cleaned to remove excess powder.
- Fused Deposition Modeling (FDM) emerged in the late 1980s and was commercialized in 1990. FDM is commonly employed for prototyping purposes rather than for producing final products. This process operates on the additive principle by laying plastic filament down a predetermined path. The filament, melted from the heated metal nozzle, is then deposited accordingly.
- Paste Extrusion has emerged as one of the most accessible methods of 3D printing, particularly for large-scale production, owing to its use of diverse machines and materials. The process revolves around the extrusion of a paste, stored in a tube, which is then pushed through a nozzle onto a built platform. Compressed air, a syringe, or a ram press facilitates this extrusion. The process closely resembles traditional FDM methods, as objects are constructed layer by layer from the bottom up, with the distinction that the material is not heated within the nozzle. This method has been trialed with various materials, including cement/concrete, clay, silicone resin, and UV paste.

Over the past decade, 3D printing using concrete, also named as 3D Concrete Printing (3DCP), has attracted growing interest due to its promise in constructing large-scale structures. This surge is reflected in a substantial body of research and a growing number of projects worldwide adopting the technique (Khoshnevis, 2004; Bos et al., 2016; De Schutter et al., 2018; Ma, Li, and Wang, 2018). Among various architectural applications, housing has emerged as a key area of focus, offering a fertile ground for experimentation. Its relevance stems from the pressing demand for innovative solutions that

enhance quality, reduce costs, promote sustainability, and allow for greater customization.

This paper examines the diverse applications of 3DCP in housing, focusing on how various material strategies and construction techniques can be integrated to optimize building processes. It discovers on-site printing and segmented production, emphasizing the design constraints, performance variations, and emerging opportunities associated with each approach. While international case studies are briefly addressed, the primary emphasis is on completed projects within the GCC region, offering insights into their unique challenges and contextual relevance.

The paper is organized into four main sections: first, a concise overview of the origins and technological evolution of 3DCP. Second, a summary of selected global applications, focusing on the machinery, materials, and methods employed. Third, an in-depth analysis of key 3DCP housing projects in the Gulf Cooperation Council **(**GCC), assessing their impact and implications. Finally, the paper concludes by outlining alternative strategies for housing delivery that align with regional conditions and priorities.

2. Background

The origins of 3DCP can be traced back to the mid-1990s in California, where early research focused on addressing key limitations in conventional concrete construction. These included formwork's high cost and complexity, material procurement inefficiencies, logistical challenges, safety risks, and significant environmental impacts. From its inception, 3DCP was envisioned as a method to enable the construction of customized structures with minimal labor and waste. However, despite its promise, 3DCP remains a complex process that requires the seamless coordination of multiple variables, including machine dimensions, material rheology, data transfer protocols, and integration with other construction systems (Tay et al., 2017; El-Sayegh et al., 2020).

A foundational contribution to the field came from Khoshnevis and Dutton (1998), who introduced the concept of Contour Crafting (CC). In this gantry-based system, fluid concrete is deposited layer by layer using a precision-controlled nozzle. A defining innovation was using attached trowels that shaped and smoothed the extruded material in real time, producing clean surface finishes and reducing the need for post-processing (Khoshnevis, 2004). This system set the stage for further experimentation and continues to inform many of today’s large-scale additive manufacturing systems.

The years following saw a rapid expansion in research, experimentation, and deployment of 3D printing technologies. Langenberg (2015) documented this progression in his visual timeline, Mapping 20 Years of 3D Printing in Architecture, highlighting key projects and the evolution of materials from plaster and polymers to high-performance concrete mixes.

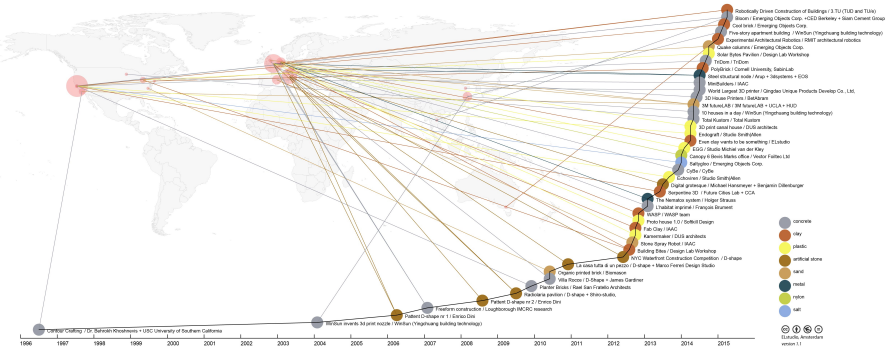


Figure 1. Twenty Years of 3D Printing in Architecture (source: Langenberg, 2015).

Tay et al. (2017) comprehensively categorized emerging 3DCP methods by scale, machinery, and material types. Their analysis highlighted a growing academic and industry focus on printing full-scale structural components. One of the critical technical challenges they identified was the difficulty in synchronizing material properties—such as viscosity and setting time—with the printing system's operational speed and mechanical precision. Failures in this synchronization often result in deformation or collapse of layers during printing.

Building on earlier reviews, El-Sayegh et al. (2020) offered a more recent evaluation of 3DCP technologies and applications. Their study examined the benefits and limitations of different printing approaches, focusing on performance, cost, and implementation risks. However, as the authors noted, their review did not deeply engage with the architectural implications of 3DCP, particularly the integration of printing systems with structural, mechanical, and spatial design strategies. This gap continues to limit the adoption of 3DCP in mainstream construction practice, where interdisciplinary coordination is essential.

More recently, Perrot et al. (2022) and Tu et al. (2023) have emphasized the importance of structural integration, material adaptability, and digital workflow alignment. Their work illustrates a shift toward more holistic approaches that consider how structures are printed and how these elements are designed, engineered, and inhabited in context.

2.1 3DCP APPLICATIONS IN THE BUILDING INDUSTRY

In 2016, the Chinese company Winsun completed one of the earliest large-scale 3D printed buildings, the Office of the Future, in Dubai, United Arab Emirates (UAE). The project comprised a 36 × 12 × 6 meter structure from modular components produced using 3DCP. The printing system employed a proprietary cement-based mixture and featured an automated robotic arm mounted on a Cartesian-type gantry crane. These volumetric components were fabricated off-site in China, then shipped to Dubai and assembled on a granular foundation, allowing for potential relocation. Designed with an open interior layout, the printed office modules offered flexibility for integrating mechanical, electrical, and plumbing systems tailored to different uses. While not a residential project, this initiative is

often a pioneering milestone in applying 3DCP in architecture (Ghaffar, Corker, and Fan, 2018).

ICON, an American construction-tech company, has pioneered large-scale 3DCP using a bespoke gantry system guided by an in-house developed intuitive software. Their proprietary cementitious mix is engineered to resist slumping, enhance layer bonding, and accelerate set times. In March 2018, ICON unveiled its first 3D printed house prototype in Austin, Texas, printed with the Vulcan system, to address homelessness and housing insecurity. The following year, in 2019, ICON collaborated with New Story in Tabasco, Mexico, producing 50 modular homes, each printed in just 24 hours using the Vulcan II printer for low-income communities (Bauguess, 2020). Recently, ICON has revealed a series of innovative projects and concepts focused on scalability, flexibility, and customization. This includes the latest multi-story robotic construction system that can print an entire building enclosure, encompassing foundations and roof structures. Also, a digital home design catalogue (CODEX) with predesigned housing prototypes, and a Beta version for an AI (Artificial Intelligence) driven design tool (Vitruvius.AI) that could streamline the process from design to construction (ICON Technology, Inc., n.d.)

In 2021, the world saw the completion of the first 3D printed residential building in Beckum, Germany (Figure 2). This modern three-bedroom, three-bathroom home spans 1,722 square feet and features a sleek interior with advanced smart home systems. Built using extrusion-based additive manufacturing, the process involved extruding fresh cement mortar layer by layer, eliminating the need for formwork. PERI 3D used the BOD2 printer, developed by Danish firm COBOD, featuring a modular gantry system adaptable to various construction sites. Materials were fed through a silo and mixing pump from m-tec. A Building Information Model (BIM) supported early-stage planning and coordination across design and engineering teams (Weger et al., 2022). While Beckum's project is widely recognized as a milestone in 3D printing of housing given its design, and volume, some researchers consider the Tecla house in Italy, completed earlier in 2021 using local clay by WASP and architect Mario Cucinella, the first fully 3D printed sustainable residence despite not being built out of concrete, which is the focus of this research (Youssef and Abbas, 2023). Nevertheless, the Beckum house is a still considered a milestone in the field.



Figure 2. 3D printed house in Beckum, Germany (source: Weger, et al., 2021).

Nowadays, 3D printed housing projects are gaining momentum across the globe. These include the 100-home *Wolf Ranch* community in Texas by ICON and Lennar (ICON Technology, Inc., n.d.), Europe's first standardized social housing in the UK using COBOD's BOD2 printer (COBOD, 2023), and fast, affordable prototypes in Portugal and New Zealand (COBOD, 2024; CyBe, 2023). Australia has also introduced its first multistorey 3D printed residence, signaling a broader shift toward scalable and regionally adapted construction models (Shaikhnag, 2025).

3 Adoption of 3DCP in the GCC Region

Concrete is one of the most widely used construction materials worldwide and is particularly dominant in the Middle East and North Africa (MENA) region. In recent years, it has become a focal point for innovation in 3D printing within the built environment, fueling a surge of interest in 3DCP across the GCC countries. Nations such as Kingdom of Saudi Arabia (KSA), UAE, Kuwait, and Oman are actively exploring 3DCP to tackle pressing challenges in the construction sector, aiming to reduce labor costs, shorten construction timelines and minimize construction waste. Moreover, GCC's enthusiasm for 3DCP is driven by a strong commitment to innovation, and sustainability. This progress is supported by a collaborative ecosystem of government agencies, academic institutions, and private sector partners, all working together to research, develop, and implement advanced techniques and materials specifically tailored for 3D printed construction (Omrania, 2022).

In 2016, the UAE launched the *Dubai 3D Printing Strategy*, an initiative to leverage 3D printing technologies to benefit society and position Dubai as a global hub for AM by 2030. The strategy targets three key sectors: Construction, medical products, and consumer goods, with a central objective of ensuring that 25% of Dubai's buildings incorporate 3D printing technology (Dubai Future Foundation, 2023). To this date, the ambition has already materialized in landmark projects including the aforementioned Office of the Future and the 3D printed Dubai Municipality building, completed in 2019 and recognized as the world's largest (Meisenzahl, 2019). Shown in Figure, the structure was printed on-site without climate control to showcase the technology's adaptability to local context. Apis Cor used a crane to maneuver its vehicle-sized printer, which was equipped with proprietary software. The walls were fabricated using a mix of locally sourced materials such as cement and gypsum, combined with the company's custom-developed compounds (DC Hub, 2020).



Figure 3. 3D printed municipality building in Dubai, by Asis Cor (source: Apis Cor, n.d.)

Alongside industry-led initiatives, academic research in the UAE has increasingly focused on assessing the potential of 3D printing technologies within the construction sector. Rajan et al. (2018) examined successful 3D printed building projects in the UAE, identifying the key factors that contributed to their outcomes, both successful and otherwise. Using qualitative data from literature reviews and stakeholder interviews, the study aimed to prioritize these factors to inform future projects and guide decision-making in the field. Ibrahim et al. (2022) conducted a comprehensive review of literature related to 3DCP, focusing on the UAE as a case study from an environmental perspective. Their findings indicated that 3DCP could reduce environmental impact by up to 49% and improve cost-efficiency by as much as 78% compared to conventional construction methods. The study also emphasized the potential of 3DCP to support sustainable practices and deliver personalized design solutions.

In a broader regional context, Almahamid et al. (2023) explored the determinants of 3D printing adoption in the GCC, highlighting key enablers such as government support, perceived usefulness, organizational readiness, and innovation culture. The study found that successful adoption is primarily driven by strategic policy alignment, access to technical expertise, and a clear understanding of the economic and sustainability benefits of 3D printing within the construction sector.

3.1 3D PRINTED HOUSING STRUCTURES IN THE GCC

The methodology employed in this section is grounded in a visual and qualitative review of pioneering 3DCP projects across the GCC. Given the scarcity of peer-reviewed technical data, the study systematically gathers and examines visual records such as photographs, renderings, and construction documentation, alongside qualitative insights from companies' reports, press releases, and academic case studies. Key project parameters, including construction techniques, material compositions, environmental settings, and collaborative structures, were identified and organized to reveal prevailing trends, innovations, and challenges. This method enables a comparative understanding of the region's most significant 3D printed housing projects while highlighting the need for greater transparency and scholarly engagement in future research.

Within the UAE, two notable attempts at 3DCP of housing structures exist. The first initiative was launched in 2019 in Sharjah, marking a significant milestone in the region's adoption of 3D printing for residential construction. Dutch firm CyBe Construction (CyBe Construction, n.d.) was awarded the contract to build a 90-square-meter house within the Sharjah Research, Technology, and Innovation Park (SRTI Park). The American University of Sharjah (AUS) played a central role in supporting the project through technological oversight and offering students hands-on training opportunities. AUS also collaborated with faculty, researchers, and several industry partners, including Middle East Engineering Technologies (MEET), a company specializing in 3D printed construction. Additionally, Ginco Contracting Co. (Ginco Contracting Co. LLC, n.d.) contributed to the physical construction of the house, further reinforcing the interdisciplinary and collaborative nature of the initiative (Keane, 2023).

The house was printed using an on-site mobile robotic arm printer, CyBe RC (Robot Crawler), which offered greater flexibility than traditional gantry-type systems, primarily due to its enhanced degrees of freedom. To

accommodate the limited reach of the robotic arm, the building design was divided into wall segments, as illustrated in Figure 4. The robot's versatility also allowed for the use of interchangeable nozzles to produce varying paste layer widths. However, as per CyBe, a 30 mm nozzle was used throughout the project. In order to maintain a controlled environment, which is a critical issue when working with concrete, the printing process was conducted inside a temporary shed, which offered a maintained material temperature. Although the fragmentation of walls was necessary due to the arm's spatial and x/y/z reach constraints, the robotic system is believed to allow for the fabrication of complex geometries that would typically be unfeasible with gantry-based printers. Moreover, the decision to conduct on-site printing inside a shed raises the question of whether off-site prefabrication could have been a more practical approach, involving prefabricating the elements in a factory, and followed by on-site assembly.



Figure 4. 3D printed house in Sharjah, UAE (source: Keane, 2023).

In KSA, the National Housing Company of Saudi Arabia enlisted the expertise of Consolidated Contractors Company (CCC) and CyBe Construction, based on their previous experience in the region, to take part in Saudi Arabia's inaugural 3D printed house on land allocated by the Ministry of Housing, situated west of King Khalid International Airport in Riyadh. This milestone was achieved in 2018 and was part of a broader initiative aimed at revolutionizing the public housing sector within the kingdom. Local Saudi suppliers provided the finishing materials for the project (Omrania, n.d.). The house, spanning 80 square meters and featuring a single bedroom, comprised 27 walls and 21 parapets, all printed within a week. Similar to UAE/ Sharjah's project, the house, shown in Figure 5, was printed in fragments using CyBe RC (Robot Crawler). The entire project was completed within five weeks, marking a significant advancement in construction methodologies (Omrania, n.d.).

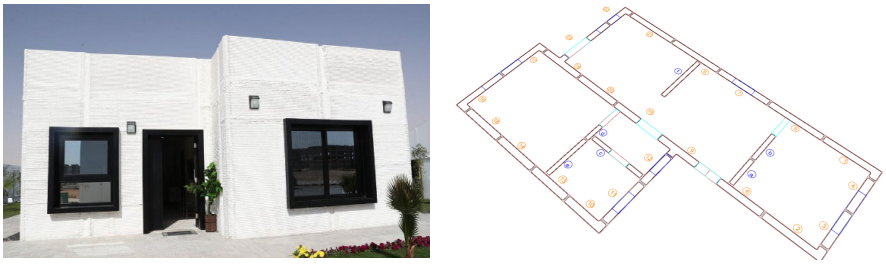


Figure 5. Exterior view of the 3D printed villa in Riyadh, and layout showing wall fragments by CyBe (source: CyBe Construction, n.d.)

In 2023, Emaar, one of the UAE's leading developers, inaugurated its first 3D printed villa within one of its residential communities, thus reflecting the company's commitment to innovation, and forward-thinking housing solutions. The printing process was carried out in 2019 through a collaboration with COBOD, using the BOD2 gantry-based 3D printer, and designed by the (U+A, n.d.; COBOD, n.d.).

Designed by Dubai-based architectural firm U+A as a single-story structure, and covering an area of 202 square meters, the villa comprises three bedrooms, four bathrooms, a fully equipped kitchen connected to a dining area, and a dedicated study space. The architectural layout features smooth, curved geometries, demonstrating the design flexibility made possible by 3DCP while creating a stronger visual connection with the natural surroundings. Technically, the printing process used a cementitious mixture of cement powder, binders, and fine aggregates. The BOD2 printer, operated on-site, was maneuvered using a crane and required minimal recalibration throughout the process. The construction was conducted in a tented environment to maintain controlled temperature and humidity, similar to the Sharjah 3D printed house approach. The total printing time for the villa was approximately 96 hours (COBOD, n.d.). Worth mentioning that Emaar printed only one villa and has not used the technique in other developments. Figure 6 illustrates the villa's original rendering and the printing equipment used during the construction.



Figure 6. 3D printed villa by Emaar in Dubai (source: U+A, n.d., and COBOD, n.d.).

In a notable advancement, Dar Al Arkan, a leading real estate developer based in Riyadh, KSA, launched its first 3D printed villa using state-of-the-art technology from COBOD International. Located in Shams Al Riyadh, a rapidly developing district northwest of the capital, the villa is part of a 12 million square meters development. It aligns with the goals of Saudi Arabia's Vision 2030 (Omrania, n.d.).

The villa spans 345 square meters across three levels, with a total height of 9.9 meters, as shown in Figure 7. The ground floor covers 130 square meters and includes a spacious hall with multiple living areas, a kitchen, and two bathrooms. The second floor extends 140 square meters, featuring three bedrooms, a main suite, two bathrooms, a living room, and a balcony. The third level, referred to locally as an "annex" due to its smaller footprint, houses a staff room with a bathroom, a multipurpose hall, and a laundry area. In KSA, such configurations are typically classified as two stories plus annex (Omrania, n.d.).

The construction utilized COBOD's BOD2 modular truss gantry system, combined with local concrete mixture and the D.fab solution co-developed by Cemex and COBOD, which enables customers to use 99% locally sourced concrete with only 1% of proprietary additives. Impressively, the printed materials for the villa cost less than €10,000. A notable achievement was that the structure was printed outdoors in desert conditions during the high-heat months of August and September, when temperatures exceeded 40°C, without using a protective tent (COBOD, n.d.).



Figure 7. 3D printed villa in Riyadh by COBOD (source: COBOD, n.d.)

Recently, 3DXB Group set a Guinness World Record by completing the world's largest 3D printed villa in Al Awir 1, Dubai, with a built-up area of 303.4 square meters. The structure was printed in a single continuous session using the MaxiPrinter technology, reaching a height of 4 meters without segmental assembly. A locally sourced concrete mix optimized through additive manufacturing minimizes material waste and reduces carbon footprint. This project, developed in collaboration with Dubai Municipality and the Mohammed Bin Rashid Housing Establishment, aligns with Dubai's 3D Printing Strategy, aiming for 25% of new buildings to be 3D printed by 2030 (3DXB Group LLC, n.d.).

The analyzed projects in this section refer to pioneering attempts across the GCC, thus illustrating the region's interest in adopting 3DCP in residential construction. From the early pilot in Sharjah to the record-setting villa in Dubai and multi-story developments in Riyadh, each initiative showcases diverse applications of robotic printing technologies, construction strategies, and material formulations. However, despite the significance of these efforts, there remains a notable lack of detailed technical documentation and peer-reviewed publications. Most of the available

information is from company websites, press releases, or construction news outlets, with little to no critical analysis or independent evaluations made publicly available. Moreover, while the projects offer a potential model for employing 3DCP to deliver housing, there is no adequate cost or structural viability information. This limits the ability of researchers and practitioners to assess the actual performance, scalability, and sustainability of these emerging construction methods. As the region continues to position itself as a leader in 3D printed architecture, greater transparency and academic engagement will be essential to fully understanding and optimizing these technologies' potential. Table 1 below summarizes the key features of these projects, including the machines and materials used, based on the available data.

TABLE 1. Summary of 3DCP of housing projects in the GCC, focusing on the UAE and KSA.

Project	Printer / Machine	Material / Mix	Location	Printing Approach
Sharjah Pilot House (2019)	CyBe RC (Robot Crawler)	Proprietary CyBe concrete mix (printed in tent)	SRTI Park, Sharjah, UAE	Printed on wall fragments
Riyadh Pilot House (2018)	CyBe RC (Robot Crawler)	CyBe mix, local finishing materials	Riyadh, Saudi Arabia	Printed on wall fragments
Emaar 3D Printed Villa (2023)	COBOD BOD2 (Gantry system)	Cement, binders, aggregates (printed in tent)	Dubai, UAE	Printed as a continuous whole
Dar Al Arkan Villa (2023)	COBOD BOD2 + Cemex D.fab	99% local concrete, 1% proprietary additive	Shams Al Riyadh, KSA	Printed as a continuous whole
3DXB Record Villa (2023)	MaxiPrinter (3DXB)	Local concrete mix optimized for additive printing	Al Awir 1, Dubai, UAE	Printed as a continuous whole

4. Reimagining Alternatives

While advancements in 3D concrete printing are being propelled by sustained research and development, it is equally critical to acknowledge parallel investigations into alternative materials and construction methodologies aimed at delivering environmentally sustainable and user-responsive housing solutions. This section highlights two parallels for future exploration.

The first involves utilizing natural materials, such as local soils and clays, to fabricate residential walls and architectural elements. Recent research has focused on the emerging field of earthen 3D printing, which demonstrates significant promise as a sustainable and economically viable construction technique. The strategic use of earth as a primary construction material leverages its inherent abundance, renewability, and local accessibility, thereby substantially mitigating the environmental impacts typically associated with material transportation and conventional building practices (Benyoucef and Razin, 2021). Ongoing studies are dedicated to the formulation of 3D printable earth-based composites, such as alkali-activated

slag-fly ash concretes, which are frequently modified with clay to optimize rheological properties and minimize inter-particle friction—parameters that are critical for enhancing both printability and structural integrity (Sahoo and Gupta, 2023). While it is understandable that such material might not be the most suited for the GCC, it is worth exploring similar models given that some areas in the region are rich in soil composition.

The second research trajectory, which is well-suited to the region, focuses on collaborative fabrication, defined as the integration of diverse construction modalities, including precast concrete assemblies, advanced 3D concrete printing for façade and interior components, and prefabricated utility modules. This approach advocates for a flexible, hybridized construction paradigm that synthesizes digital fabrication techniques with established building systems, especially in the GCC region, to tackle efficiency, scalability, and design customization. As outlined in "Design and Delivery of National Housing in the UAE: An Alternative Approach" (Mohamed et al., 2023), collaborative fabrication facilitates a more adaptive and coordinated housing delivery process, fostering innovation while remaining sensitive to local infrastructural and contextual constraints. Such an approach responds to current challenges facing the 3DCP model, such as horizontal planar enclosures (floors, slabs/ roofs) and structural elements. Figure 8 illustrates a diagrammatic explanation of such a model.

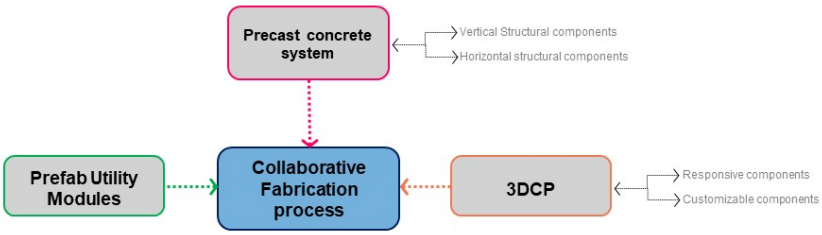


*Figure 7. C*ollaborative Fabrication Framework: Integrating Precast Concrete Systems, Prefabricated Utility Modules, and 3D Concrete Printing (3DCP) to Deliver a Hybrid Construction Process Combining Structural Integrity, Utility Efficiency, and Customization.

These alternative strategies collectively signify a new progressive perspective toward housing models that prioritize ecological stewardship and responsiveness to the dynamic requirements of end users and communities. Incorporating natural materials and hybridized construction systems presents new opportunities for realizing sustainable, resilient, and contextually attuned housing designs.

5. Conclusions

The adoption of 3DCP in construction has received sustained attention from academia and industry, and this has been reflected in a growing number of experimental projects and pilot studies across the globe. In addition to the projects highlighted in research, the growing body of research confirms that 3D concrete printing is no longer a fringe innovation but a central topic in construction technology discourse. A recent comprehensive review by Mohamed, Mishra, and Isam (2025) analyzed over 140 publications focused

on 3DCP for building structures, highlighting the significant academic and industrial interest in the field. The study provides a detailed overview of material properties, sustainability potential, and the ongoing challenges related to large-scale implementation, and it underscores the need for further exploration in areas such as structural integration, design optimization, and environmental impact.

Recent developments have focused on overcoming key challenges such as limited vertical capacity, integration of structural systems, and constrained design flexibility. Companies are advancing the field by introducing novel machinery and computational design workflows. For instance, ICON's recent innovations include a next-generation robotic system with extended reach, a digital housing catalog, and an AI-driven design platform to streamline the process from concept to construction.

Currently, two main categories of printing systems dominate the field. First, whether fixed or mobile, multi-axis robotic arms enable the production of complex forms but are limited in printable area and often require segmenting wall components. Second, gantry-based systems, operating on x–y–z axes, support greater vertical and horizontal reach but restrict design flexibility. Despite ongoing refinement, both systems face limitations in printing complete structural elements such as floors and roofs, which are typically realized through prefabrication and assembled post-printing.

While 3D printed housing continues to be promoted as a scalable solution for affordable, sustainable, and customizable construction, the extent to which built projects meet these objectives lacks practicality. In the GCC region, most initiatives remain at a pilot or demonstration stage. Low labor costs, strict building codes, and entrenched conventional practices have slowed the transition toward broader implementation. Nonetheless, the region's strategic vision and continued investment in innovation signal the potential for future expansion.

Future research will expand on two topics. First, a deeper look into GCC applications, with a better understanding of machines, materiality, and the reasons for not expanding such an initiative. Second, elaborating on the notion of collaborative fabrication as a logical alternative takes advantage of existing prefabricated systems, while advocating for purpose-driven 3DCP. The main objective will consistently deliver environmentally and socially sustainable, customizable housing structures.

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CURA SALADA

Robotic Heated Spatial 3D Printing of Salt-Clay Composites for Health-Oriented Vernacular Architecture

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Abstract. This research presents the development of a novel spatial 3D printing methodology for salt-clay composites, aimed at enabling sustainable and self-sanitizing architectural applications. Grounded in a material exploration process, the project investigates how the naturally antimicrobial and abundant properties of salt can be translated into a viable construction technique, especially for contexts with limited access to conventional building materials and healthcare infrastructure. The study draws inspiration from Speleotherapy, a treatment involving the inhalation of aerosols from natural salt-rich environments to treat pulmonary respiratory diseases, and the traditional topical use of salt in treating skin diseases. These therapeutic precedents inform the speculation that salt could passively contribute to air purification and infection control within built environments, particularly healthcare settings. Siwa Oasis in Egypt, with its abundance of salt lakes and historical use of Karshif (a salt-clay-sand mixture) in the construction of the 12th-century fortress of Shali, serves as a contextual anchor for the investigation.

Building on prior studies involving Liquid Deposition Modelling (LDM) extrusion of salt-based composites, the research introduces a novel robotic spatial 3D printing methodology developed through an iterative experimental process. The final system employs a custom-designed heat-assisted extrusion end effector, that enables free-form material deposition. Critical parameters such as tool orientation,

applied air pressure, printing speed, and localized heat application are fine-tuned to improve scalability and geometric complexity. The methodology culminated in the successful fabrication of self-supporting 3D lattices composed of half-arched units, which serve as the basis for proposed architectural applications such as window lattices and wind catchers. While further refinement is needed to address challenges related to structural stability and extrusion consistency, the study offers a compelling proof of concept. It establishes new avenues to connect materiality and human health through the implementation of architectural elements that, based on their material characteristics, can passively enhance overall well-being. Ultimately, this research positions salt-clay heated spatial 3D printing as a foundation for further exploration of antimicrobial, sustainable materials, fostering healthier built environments through the integration of robotic fabrication and material innovation.

Keywords: *Heated spatial 3D printing, Robotic extrusion, Salt-clay composites, Antimicrobial materials, Sustainable Architecture*

1. Introduction

Following the COVID-19 pandemic, the World Health Organization (WHO) (2022) released its first global report on infection prevention and control, stating that 7 percent of patients in high-income countries and 15 percent in low- and middle-income countries are likely to suffer from at least one infection during their hospital stay.

Salt, a naturally abundant material, occurs in rock salt deposits formed by evaporated seawater, in salt domes due to geological pressure, and in brine from salt lakes or seawater. Industrial brine waste from desalination is a newer salt source but poses environmental risks to marine ecosystems due to increased salinity and temperature changes (Ralston et al., 2025). There has always been a negative correlation between salt and the construction industry, as salt can cause cracking in porous building materials like concrete and bricks and can leave undesirable efflorescence on wall surfaces. Nonetheless, salt has an untapped architectural potential, evident in the precedent use of Karshif in Siwa Oasis for the construction of the 12th century Shali fortress. Due to the abundance of salt lakes in the region, salt was used as a building material where irregular salt blocks (composed of salt crystals, sand, and clay) were cut from the crust of the lakes and left to sun-dry. These blocks were then used as bricks and were bound with a salt-rich mud mortar. Salt crystallization during drying, along with repeated humidity cycles, reinforced the structure's water-resistant, monolithic form (Rovero et al., 2009). In 2007, the Architecture agency of Laetitia Delubac and

Christian Félix revived the use of traditional Karshif technique through their modern ecolodge design in Siwa Oasis (Félix Delubac Architectes, 2007).

Beyond architecture, salt's role in Speleotherapy began in the 19th century where Dr. Feliks Boczkowski established the first health resort in the Wieliczka Salt Mine after observing the health benefits for miners. After which various professionals further explored the therapeutic effects of salt rich environments to treat several medical conditions, especially respiratory and skin-related (Salt Therapy Association, 2018; Lăzărescu et al., 2014). Salt's desirable properties such as heat retention, fire resistance, hygiene, reflectivity, diffusibility, affordability, and availability, make it ideal as a building material, especially in health-related environments.

2. State of the Art

Additive manufacturing continues to evolve from simply offering rapid prototyping to utilizing high-performance materials that prioritize sustainability with academia driving innovation and industry applying it to enhance efficiency, reduce waste, and create advanced structures. Over a decade has passed since the introduction of salt-starch composites in additive manufacturing by Ganter which later expanded to dissolvable scaffolds by Japanese researchers (Pungercar et al., 2023). The Saltygloo, a pavilion inspired by the Inuit Igloo, was developed by the 3D printing design studio Emerging Objects in 2013. More than 300 panels were 3D printed from locally harvested salt from the San Francisco Bay combined with maltodextrin and assembled into a translucent lightweight pavilion (Emerging objects, 2013). Another example is the SaltBlock, a 3D-printed block developed by Egyptian universities, which aimed at reviving Karshif of Siwa Oasis. The block is made from a mixture of salt, sand, and Ethylene-vinyl acetate (EVA) polymer, and exhibited desirable compression strength and thermal performance (El-Mahdy et al., 2021).

While the previously stated case studies focused on LDM extrusion of salt-based composites using only 3-Degree of Freedom (DoF) printers, this research aims to investigate innovative techniques that leverage the capabilities of 6-DoF robotic arms in order to develop an improved process. For instance, Soliquid's 2018 suspension printing method extrudes material into a gel medium, allowing free-form extrusion of 3D structures with minimal waste (Carlota V., 2019). Despite its structural advantages, it faces challenges like long drying times and the need for lower-density materials than the support medium. Additionally, a study from the Harvard GSD presented Spatial Print Trajectory (SPT) method which employed non-layered, spatial robotic motion and a heat gun-equipped end effector to create porous, self-supporting structures. The vertical return-loop tool path

formulated as a NURBS curve, divided into anchor and drag segments, with varying speeds ensures material accumulation in anchor segments, stabilizing the structure (Claire Im et al., 2018). Lastly, a study at RWTH Aachen University introduced Spot Deposition Modelling (SDM), a method that deposits discrete amounts of material at fixed points rather than continuous extrusion. This allows for greater control over geometry and porosity. The research explored several deposition strategies, including vertical spot deposition, which uses descending extrusion values (Ebase > Etop) to create tapered vertical strands. These strands are then bent to form arched geometries, enabling the construction of porous 3D lattice structures. A key limitation was the use of a 3-DoF Delta WASP 40100 printer. The study suggests that employing a 6-DoF robotic arm could improve adhesion control and precision by enabling tool rotation along the bending axis (Tabakova et al., 2023).

3. Methodology

The research methodology begins with formulating a salt-based composite by optimizing a mix of salt, binders, and natural additives. Next, an advanced robotic fabrication process is inspired by state-of-the-art approaches discussed previously. The exploration begins with developing a suspension 3D printing approach using a clay powder medium, instead of a fluid medium to avoid dissolution of salt molecules. Subsequently, the process transitions to a heated spatial 3D printing technique, utilizing a customized end-effector equipped with dual heat guns for free-form printing. This methodological evolution aims to optimize the fabrication of intricate lattice structures from salt-based composites. Finally, the study proposes architectural applications, specifically designing components for alternative healthcare facilities in hot, arid climates, addressing affordability, sustainability, and thermal comfort for low-income settlements.

The robotic arm used in this research is the ABB IRB 140, a compact 6-axis industrial robotic arm with a long reach of 810 mm which can be floor-mounted, wall-mounted or suspended from the ceiling. In order to operate the robotic arm, a g-code is developed by the visual programming of a script created though the Robots plug-in in Grasshopper3D within Rhinoceros. This g-code controls various parameters, including print speed, tool orientation, and extrusion timing and positioning.

3.1. MATERIAL EXPLORATION

This research builds on a recent study evaluating salt-based composites with binders such as clay, gypsum, cement, and starch. Among the tested

mixtures, the clay-salt-starch composite with a (40:60) clay-to-salt ratio and starch added at one-third the salt's mass, proved the most viable (Pungercar et al., 2023).

This section presents material findings based on the most successful mixtures previously mentioned, the experiments were divided into two binder groups; clay and gypsum. Mixtures were manually extruded using a silicone extrusion gun on acrylic sheets, and pumpability was assessed by noting the number of layers extruded under minimal resistance using two 3D printed nozzles with inner diameters, 6mm and 10 mm (Figure 1). To evaluate the effect of salt, a control mixture without salt was tested for comparison. Table (1) summarizes the recipes while Table (2) provides detailed observations regarding extrusion performance of each recipe.

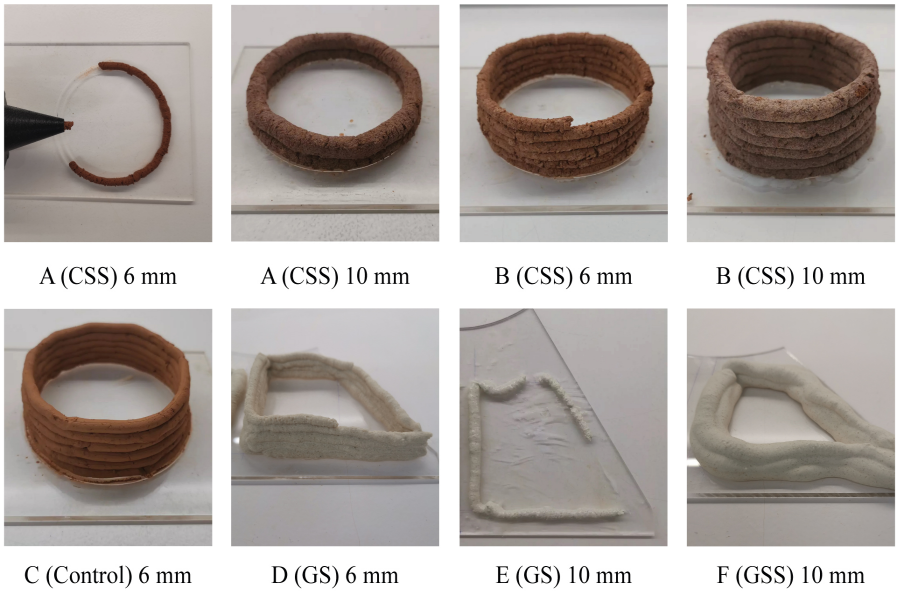


Figure 1. Catalogue of salt–clay and salt–gypsum composite specimens (A–F) extruded with 6 mm and 10 mm nozzles to assess pumpability. Specimens include two clay–salt–starch mixtures (A, B), a clay control without salt (C), two gypsum–salt mixtures (D, E), and one gypsum–salt–starch mixture (F).

TABLE 1. Mixture recipes for salt–clay and salt–gypsum composites, showing binder–salt ratios, material quantities, and pumpability results using 6 mm and 10 mm nozzles.

Group	Recipe	Pumpability (Number of layers 0-6)		Ratio (Binder: Salt)	Mass				
		6 mm Nozzle	10 mm Nozzle		Salt (g)	Clay (g)	Gypsum (g)	Starch (g)	Water (g)
Clay	A (CSS)	0	2	40:60	240	160	-	60	70
	B (CSS)	4	6	40:60	240	160	-	95	85
	C (Control)	6	-	100:0	0	500	-	95	85
Gypsum	D (GS)	4	6	65:35	160	-	290	-	100
	E (GS)	0	0	60:40	160	-	280	-	90
	F (GSS)	0	3	70:30	160	-	350	90	160

CSS: Clay-Salt-Starch, GS: Gypsum-Salt, GSS: Gypsum-Salt-Starch

TABLE 2. Extrusion performance and drying observations for salt–clay and salt–gypsum composite recipes using 6 mm and 10 mm nozzles.

Group	Recipe	Observations	
		6 mm Nozzle	10 mm Nozzle
Clay	A (CSS)	Extrusion failed. Shear thickening occurred due to starch reducing pumpability of mixture. As force applied increases resistance increases.	Improved pumpability but only up to 2 layers. No noticeable shrinkage occurred. Salt efflorescence visible after drying.
	B (CSS)	Good pumpability of up to 4 layers. No noticeable shrinkage occurred. Less salt efflorescence and rougher drier texture compared to specimen extruded using 10 mm nozzle.	Improved pumpability, no problem extruding up to 6 layers. No noticeable shrinkage occurred. Salt efflorescence appeared more on the acrylic base.
	C (Control)	Pumpability was better compared to recipes A & B, up to 6 layers. Smoother, cleaner surface finish. Noticeable shrinkage occurred. Dried faster due to absence of salt.	-
Gypsum	D (GS)	Pumpability was acceptable up to 4 layers. 5th layer was difficult to extrude. Smoother finish than	-

	clay group. Efflorescence is not as visible due to its light color. Mixture consistency was a little runny.	
E (GS)	Extrusion failed.	Extrusion failed.
F (GSS)	-	Pumpability lower than recipe A, up to 3 layers only. Water content needs to be lowered as consistency is very runny. Smooth surface finish. Salt efflorescence is not visible. No noticeable shrinkage occurred.

As shown in Table 2, recipe B (CSS), containing clay, salt and starch, performed best, successfully extruding a 4-layer cylinder even with the 6 mm nozzle. Table 1 indicates that this recipe contained 60% of the main extrusion material as salt. Meanwhile in the gypsum group, recipe D (GS), with 35% salt and adjusted water content, allowed satisfactory extrusion of up to 4 layers using the 6 mm nozzle. Beyond this, extrusion became difficult due to premature drying and nozzle clogging, although prints retained smooth finishes and minimal efflorescence compared to recipe B of the clay group. Further experiments using slow-setting gypsum may be required to better assess its viability as a binder. Interestingly, the control clay specimen exhibited shrinkage, whereas the recipes containing salt did not, suggesting that salt may reduce shrinkage by retaining water within the mixture.

3.2. SUSPENSION 3D PRINTING APPROACH

In the suspension 3D printing method, the procedure relies on using air pressure supplied to the cylindrical container of the Lutum piston end effector, pushing a rubber piston down the plastic container within, forcing the extrusion material to come out of the nozzle. This ø 8 mm nozzle is extended up to 200 mm in length in order to be longer than the depth of the powdered clay available within the transparent container. This parameter also constrains the maximum height of the printed sample, which should not be higher than 150 mm. Figure (2) demonstrates the robotic setup for this process.

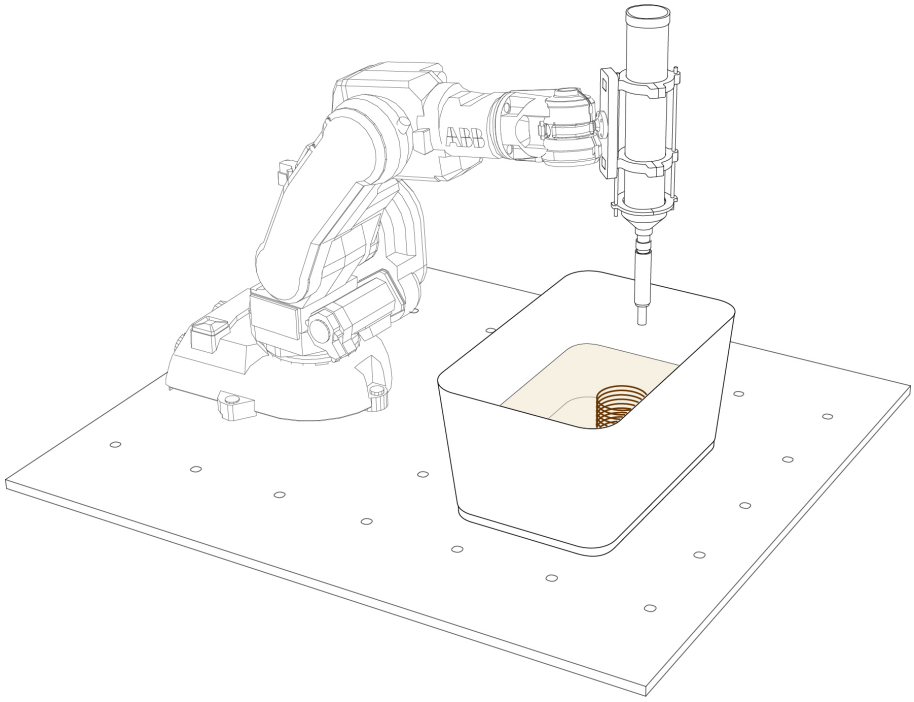


Figure 2. Robotic suspension 3D printing setup using a Lutum piston end effector with ø 8 mm nozzle for extruding clay-based composites.

3.3. HEATED SPATIAL 3D PRINTING APPROACH

Another approach is utilizing heat to simultaneously dry the material while extruding it. Manual extrusion experiments were conducted first to test the viability of this approach, as shown in Figure (3). It involved the use of a silicone extrusion gun with a 10 mm diameter 3D printed nozzle attached to it, sliding horizontally and vertically while extruding the material, with a hand-held heat gun directing heat onto the printed specimen. The first horizontal print achieved 47 mm of cantilever, eventually reaching 60 mm after several attempts. Vertical extrusion began with 30 mm, reaching a maximum of 85-90 mm. However, these lengths were limited by the operator's physical stamina, as muscle fatigue reduced performance over time. The experimentation confirmed that spatial printing with heat is feasible, prompting the next step: designing the tool for the robotic arm. The Lutum piston tool was modified so that a 3D printed holder is placed right above the extrusion nozzle, housing two opposing heat guns. The heat guns

were angled initially at 45° from the nozzle and later revised to 30° to prevent collision during complex toolpaths. Wooden supports were cut and bolted to the tool's fixation brackets, to mount electronic components directly on the tool head. These components were controlled using an Arduino Uno programmed via the Arduino IDE (Integrated Development Environment). An optocoupler isolation board was used to safely transmit signals between the robot's 24V system and the Arduino's 5V circuit. A 5V relay allowed the Arduino to switch the heat guns on and off, with an independent 110/220V power supply mounted on the robotic arm away from the tool. Figure (4) shows the modified Lutum piston tool attached to the robotic arm.

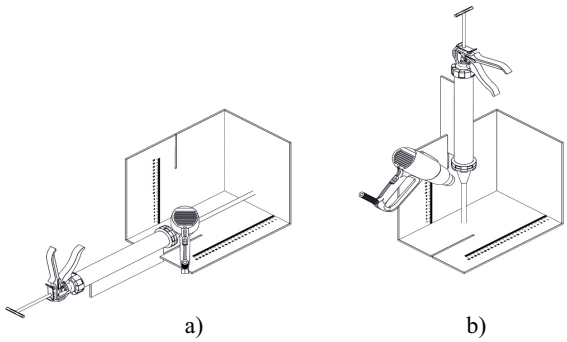


Figure 3. Manual heated spatial 3D printing tests using a silicone extrusion gun with ø 10 mm nozzle and a hand-held heat gun: (a) horizontal extrusion, (b) vertical extrusion, showing cantilever and vertical strand capabilities.

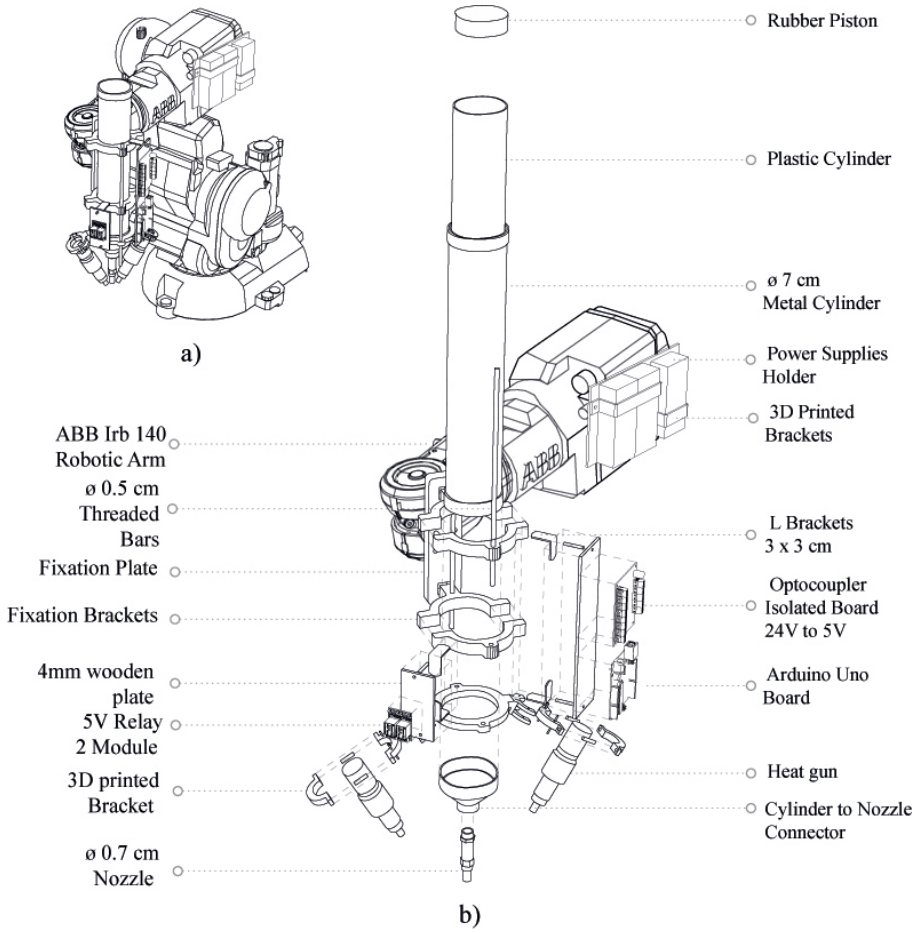
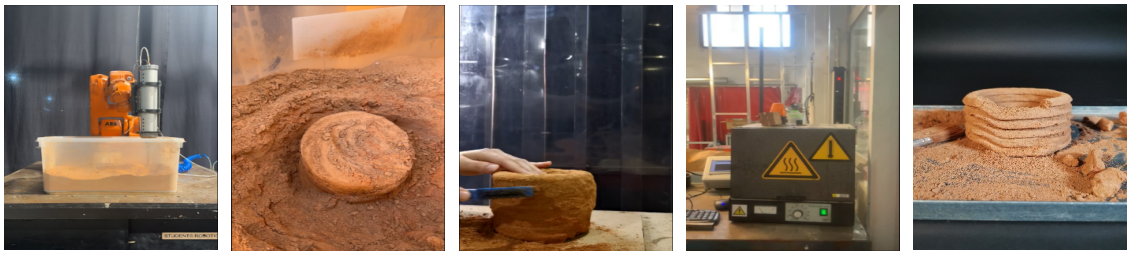


Figure 4. Heated spatial 3D printing robotic setup using the modified Lutum piston end effector: (a) overall view of the ABB IRB 140 robotic arm with mounted extrusion and heat system, (b) close-up of the end effector showing dual heat guns and extrusion nozzle.

4. Results and Discussion

A spiral geometry was printed by the suspension 3D printing approach and dried over several days. The final specimen was brittle and disintegrated under compressive force, with an unpleasant finish due to residual powder compacting between the spiral layers. A firing attempt of the specimen to remove the excess powder and enhance bonding in a kiln was halted at a low temperature between 200-250°C, due to smoke formation caused by the organic starch content. Figure (5) documents the entire process starting with the suspension 3D printing and ending with the resulting specimen.



a) b) c) d) e)

Figure 5. Suspension 3D printing workflow for spiral specimens: (a) extrusion of the spiral geometry using the suspension setup, (b) excavation of the dried specimen from the powder medium, (c) removal of residual clay powder by brushing, (d) kiln firing attempt to enhance material bonding (halted at 200–250 °C due to starch content), (e) final brittle specimen after drying and partial firing.

After suspension 3D printing proved unsuccessful, the focus shifted to heated spatial 3D printing. Several vertical printing attempts were made, reaching a maximum height of 300 mm, but failed to remain upright once disconnected from the printing nozzle. To address this issue, various wire-frame geometries with multiple curves were tested; however, all except for the final cube geometry, consisting only of vertical curves, were challenging due to collisions (Figure 6). Furthermore, inclined cylindrical geometries with bigger cross-sections were tested, revealing that heat-assisted extrusion proved effective for stabilizing overhangs, allowing for inclinations of less than 45° without the need for printing supports, something typically required in standard Fused Deposition Modelling (FDM) printing. A two-directional deviation with a 30° angle was achieved, resulting in a double twisted cylinder (Figure 7). These results highlighted the technique's potential and warranted further exploration of its capabilities necessary to achieve the geometric intricacy desired by this research.

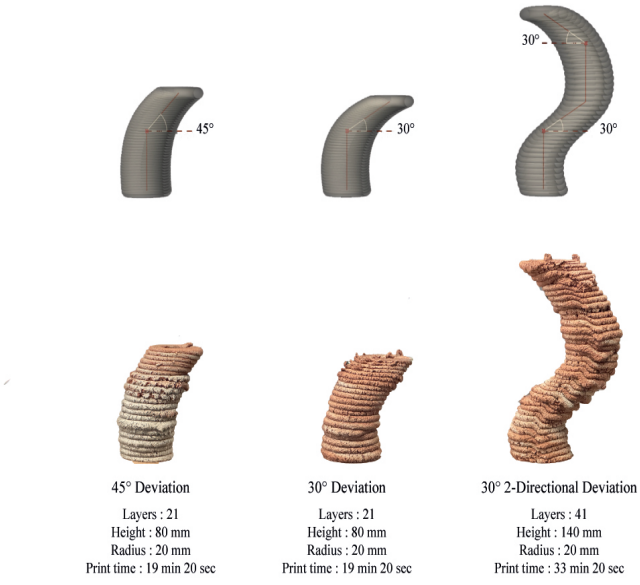
Reflecting on the state-of-the-art projects previously discussed, SPT and SDM stand out as having significant potential for integration with the heated spatial 3D printing technique. Upon applying the methodology behind the SPT with the salt-clay composite, it was observed that frequent collisions were a major issue during heated spatial 3D printing due to the initial 45° heat gun holder angle and model's dimensions (100 mm length, 20 mm loop spacing), limiting maneuverability and interfering with structures. Achieving a satisfactory result remained challenging even after changing the heat gun holder angle to 30° and the model's dimensions to (200 mm length, 25 mm loop spacing), due to collisions caused by using two heat guns and the close proximity of the loops. After further trials, it became obvious that this technique works best when multiple single curves have wide spacing

between one another and only one heat gun is attached to the tool, which led to the exploration of the second methodology, SDM.



Figure 6. Catalog of wire-frame geometries tested for heated spatial 3D printing. Multiple curves were evaluated to address instability of individual vertical strands, with most designs encountering collisions except for the final cube geometry consisting solely of multiple vertical strands.

Figure 7. Catalog of inclined cylindrical geometries tested for heated spatial 3D printing. Heat-assisted extrusion stabilized overhangs, enabling inclinations below 45° without support and achieving a two-directional deviation of 30°, resulting in a doubled twisted cylinder.



However, in order to adapt this methodology for the heated spatial 3D printing exploration, several additional considerations had to be addressed. One major issue was the logic of achieving the conical shape of the vertical strand; in this case the vertical path was segmented into various planes, with

the tool's speed progressively increasing as it ascended to the top while extruding continuously instead of depositing discrete spots. This was done to achieve a smoother texture compared to the segmented texture of the original SDM technique. Another adjustment stemmed from the cubic form selected for the 3D lattice structure, where each face comprises a pair of opposing half-arches. To prevent undesirable collisions at their junction, it was necessary to offset the meeting point of the tips of the two arches while accounting for the strand thickness. This strategic offset ensured that the arches complemented rather than conflicted with each other during the printing process, resulting in smoother strand transitions and enhancing the overall stability of the printed structure.

As illustrated in Figure (8a) the printing path begins at point 1 and ascends toward point 2. From there, the tool bends the vertical strand diagonally to point 3, forming a half-arch. Critical parameters such as air pressure, printing speed, and heat application were essential. Through multiple trials, an optimal combination of parameters was found, leading to a more refined printing process that created stable structural forms, as seen in Figure (8b). Initially, the heat guns operated at too high a temperature 430°C, causing the material to dry prematurely and preventing proper strand bending. Lowering the temperature to 250°C while keeping air pressure below 1 bar improved flexibility and enabled successful shaping. However, this introduced a new issue: the strand tips became too narrow and structurally weak. Increasing air pressure to 2 bars helped deposit more material, reinforcing the tips. However, the bent tip still struggled to align with the specified plane due to the material's inherent flexibility. This revealed that reducing the bending angle in future experiments would improve alignment and enhance structural stability. Another challenge arose with collisions at the corners, where inadequate spacing between vertical strands led to interference between new and existing strands. This highlighted the importance of refined spacing and path planning. Despite this, the methodology proved successful in the creation of intricate 3D lattice structures, showcasing its potential for more complex and stable structural designs.

a) b)

CURA SALADA

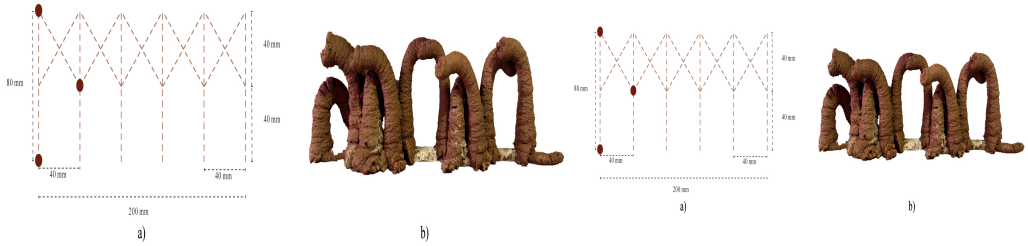
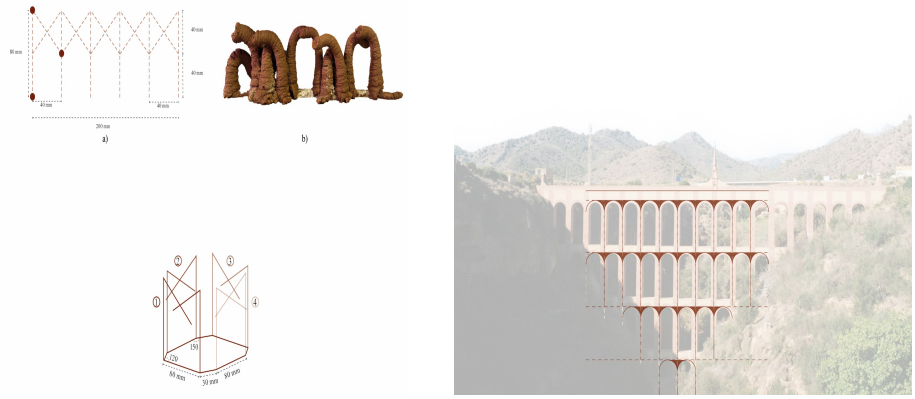


Figure 8. Extrusion of half-arches using heated spatial 3D printing: a) diagram illustrating the printing path from the base to the bent strand forming a half-arch.; b) successful attempt with optimal parameters: 2 bars air pressure, 9 mm/s printing speed and 250°C applied heat.

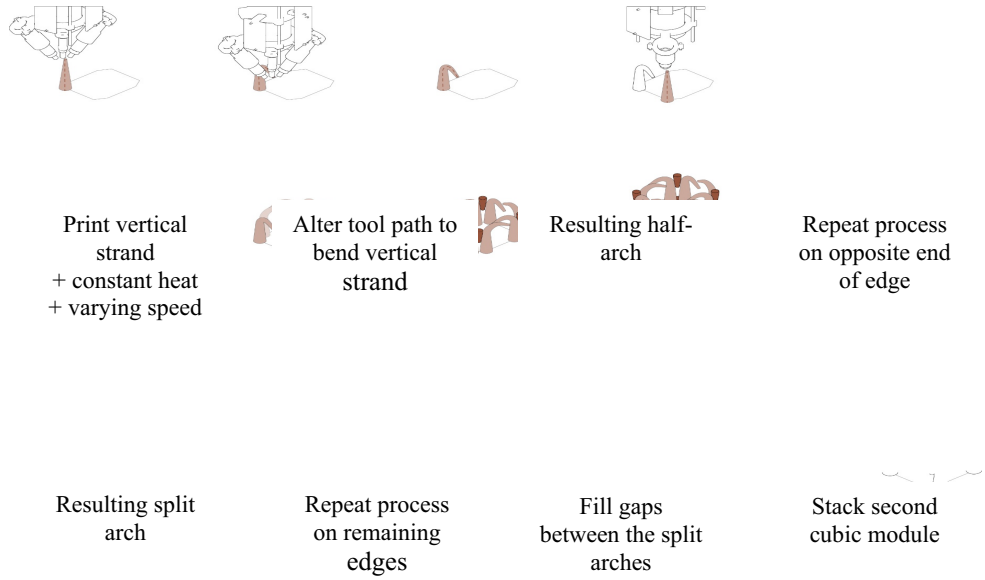
In order to achieve the proposed cubic building unit, both strands of the first edge are printed, followed by the remaining edges in a clock-wise direction. To avoid collisions at corners where strands meet, a 30 mm offset at a 60° angle is applied. This offset is repeated for subsequent edges, forming a chamfered cubic module measuring 110 mm (80 mm + 15 mm +15 mm) by 132 mm (80 mm + 26 mm + 26 mm), as shown in Figure (9a). This printing methodology allows modular extension along the X and Y axes, with vertical growth requiring additional infill for support. A parallel can be drawn to the construction of aqueducts, where gaps between arches are filled with the same building material to support upper levels as shown in Figure (9b).



a) b)

Figure 9. Modular extrusion methodology for cubic building units: (a) sequence showing the extrusion of a chamfered cubic module with 30 mm offsets at corners to prevent collisions; (b) analogy to Aqueducto Del Águila, Nerja, Spain, illustrating the use of infill to support vertical growth.

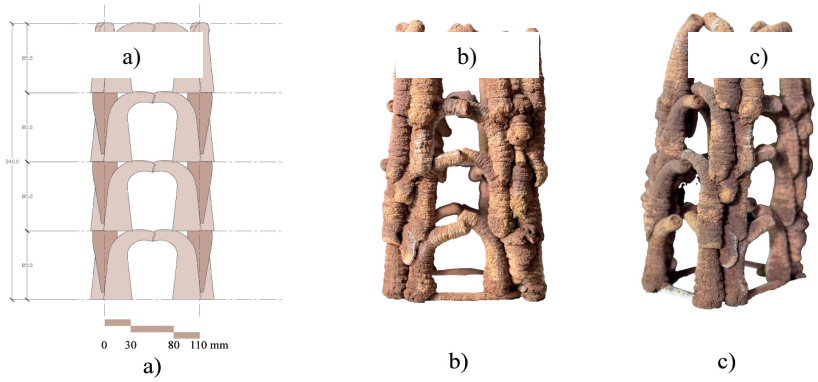
This approach ensures structural stability as the lattice is built vertically, offering a strategy for incorporating traditional construction logic into advanced 3D-printed designs. During fabrication, after all four edges of the



cubic module are printed, the tool moves to each corner's midpoint at a height of 40 mm, equivalent to four-tenths of the total height of a vertical strand before it is bent. Extrusion incorporates a timed-delay of 10 seconds to fill the triangular gaps between bent strands. Then the tool ascends up at a varying speed, ranging from 3 mm/s to 9 mm/s, until it reaches a plane situated 90 mm high, or at nine-tenths of the strand's original height. This process is repeated at all corners, enabling stable vertical layering and allowing a second module to be printed atop the first as shown in Figure (10).

Figure 10. Heated suspension 3D printing procedure for half-arched cubic units. Shows vertical layering by filling triangular gaps at each corner with a 10-second delay and controlled ascent, enabling stable stacking of a second module atop the first.

Following the success of this approach, it was possible to stack four cubic modules with a total height greater than 300 mm as illustrated in Figure (11). However, a slight inclination was observed in the print due to manual intervention needed for adjusting the gap-filling supports. This issue, caused by minor sliding to ensure correct alignment with corners, highlights the need for refinements in the Grasshopper3D script. Automating these adjustments will improve future designs by enhancing precision, reducing human intervention, and increasing the efficiency of the robotic fabrication process. Moreover, it was observed that while the corners of the cubic modules were successfully bound and acted as unified elements, the split-open half-arches did not bind properly, which led to instability. This mismatch in structural behavior resulted in the corners remaining intact while the structure began to dismantle at the open half-arches, creating weak points in the overall print. The greater the height, the more pronounced the instability at the split arches, compromising the overall integrity of the structure. An alternative stacking strategy was explored to address this issue,



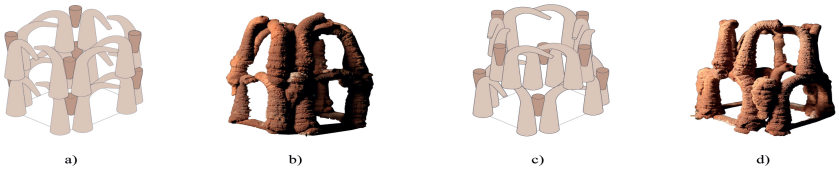
a) b) c)

where the second cubic module was rotated 45°, creating a diamond-shaped configuration from a top-plan view. This rotation caused the vertical strands to be positioned directly over the tips of the half-arches from the first cubic module. This method served as a countermeasure, allowing for better binding between the half-arches and resulting in a stronger cubic module that might be more stable for vertical stacking. However due to the complexity and time-consuming nature of the rotated stacking strategy, the initial vertical stacking strategy was retained for further testing (Figure 12).

Figure 11. 4-tiered prototype of stacked cubic modules: a) digital model showing arrangement, b) front view of physical prototype, c) diagonal view of physical prototype.

Figure 12. Vertical stacking strategies for cubic modules: a) digital model of orthogonal stacking, b) physical 2-tier prototype of orthogonal stacking, c) digital model of rotated (45°) a) *ʒ, d) physical 2-tier prototype of rotated* b) .

For the final prototype, a hybrid stacking configuration combining horizontal and vertical stacking was tested to enhance stability and overcome the weakness observed in the split-open half-arches especially as the print height increased. A pyramidal configuration emerged as the most promising due to its inherent geometric stability. The cubic module dimensions were 110 mm by 130 mm, with the initial height of the vertical strand set at 90 mm. Additionally, the plane where the tool bends the strand was positioned at two-thirds of the strand height, at 60 mm, ensuring proper alignment in front of its neighboring pair. The pyramid was constructed with five cubic modules at its base, reducing by two modules as it ascended, culminating in a single cubic module at the top, with a final crowning module completing the four-tiered structure. No significant inclination was observed this time, as manual intervention was not required, and the gap-filling supports were accurately defined in the script. However, the process faced occasional interruptions due to the need to refill the emptied cartridge. This caused pressure fluctuations, leading to material accumulation in areas where thinner cross-sections of the strands were required, resulting in strand breaks and instability. These faulty strands had to be removed and reprinted before the process could continue, highlighting a need for adjustments to avoid time-wasting interruptions and discrepancies in material application. Figure (13) showcases the final prototype, achieved through the robotic fabrication process. The final result demonstrates the effectiveness of the pyramidal configuration, which provided enhanced stability and resolved previous



structural weaknesses, particularly in the open arches.

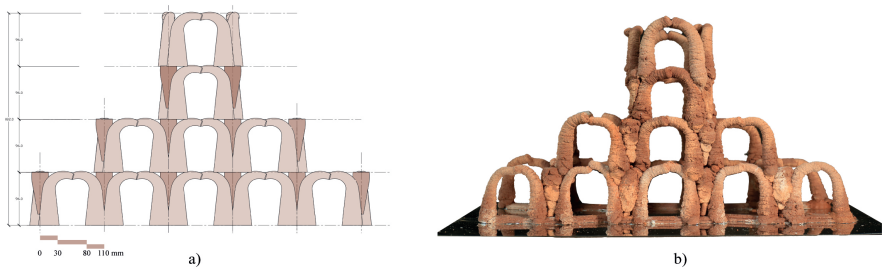


Figure 13. Final 4-tiered pyramidal prototype: a) digital model showing the stacking configuration with decreasing number of cubic modules per tier; b) physical prototype demonstrating improved stability and resolved weaknesses in split-open half-arches.

5. Case Study

With the success of spatially printing 3D lattice structures using the salt-clay mixture, the research shifts toward exploring architectural applications that leverage both the geometric potential and material properties of the composite. A suitable site context with an abundance of salt lakes and limited healthcare infrastructure is Siwa Oasis, a natural desert reserve, situated in Marsa Matrouh Governate in Egypt. Known for its strong connection to traditional practices and reliance on local resources like date palms and salt, Siwa's salt lakes not only support eco-tourism due to their therapeutic properties but also contribute to construction materials.

However, Siwa's geographic isolation presents challenges in healthcare delivery. The oasis has a few local clinics and a small hospital, which lack specialized staff and equipment. For advanced treatment, residents often travel 300 kilometers to Marsa Matrouh, a time-consuming and difficult journey, especially with seasonal tourism straining local resources. To improve access, the research suggests enhancing local clinics and deploying mobile health units, ideally constructed from the salt-clay composite to meet healthcare needs in a way that respects the region's cultural heritage.

Proposed architectural applications include utilizing the cubic lattice modules as lattice windows, particularly suited for hot, arid climates. These lattices promote natural ventilation and air purification by increasing the surface area exposed to the air, and offer shading and privacy. A second application involves the use of wind catchers, traditional vertical shafts designed to capture and direct wind for indoor cooling. Constructing a wind catcher using the salt-clay modules developed in this research could significantly enhance its functionality by leveraging the unique antimicrobial properties of the material enabling the structure to act as a natural air filter as well. Moreover, salt's inherent thermal conductivity, which allows it to absorb and release heat gradually, contributes to maintaining a more comfortable indoor environment without relying on energy-intensive cooling



systems. This integration of traditional architecture and innovative material science offers a culturally responsive, sustainable solution for improving indoor air quality and comfort in remote or underserved healthcare settings like Siwa Oasis.



a) b)

Figure 14. Proposed architectural applications of salt–clay cubic lattice modules: a) lattice window enhancing shading, ventilation, and air purification; b) wind catcher improving indoor cooling and air quality in hot, arid climates.

6. Conclusion

This research successfully established a novel methodology for heated spatial robotic 3D printing using a salt-clay mixture, enabling the fabrication of intricate, self-supporting lattice geometries. Despite this progress, several challenges remain. A primary issue was the inconsistency in material behavior during extrusion, the pressure build-up within the cartridge caused water droplets to drip over the printed strands amplifying the salt efflorescence. Although salt crystallization is typically seen as a structural risk, it may also improve bonding between printed elements in this context, potentially strengthening the overall structure. This dual aspect of salt efflorescence, both a potential weakness and a speculative benefit, requires further investigation to fully understand its effects, particularly over long periods and in humid environments. Additionally, fluctuations in extrusion pressure caused inconsistent material flow, leading to inconsistent strand formation and necessitating time-intensive reprinting. Irregular extrusion flow and frequent manual interventions, including cartridge refills and gap corrections, reduced process efficiency. Solutions such as additive-enhanced material mixes and automated refilling systems could improve consistency and enable continuous printing. Scaling up also revealed structural weaknesses in half-arched elements, emphasizing the need for reinforced designs and vertical stacking strategies to enhance multi-level stability.

To validate the material's theoretical advantages, further assessments including air purification, thermal conductivity, and compressive strength assessments are crucial. Design optimizations like varying nozzle diameters to explore more intricate lattice designs, and implementing real-time adaptive control systems could improve precision and sustainability. Applications such as lattice windows and wind catchers could extend to modular walls or furniture, maximizing the material's antimicrobial and insulating properties.

In conclusion, the adaptation of the Lutum piston extruder for heated spatial 3D printing demonstrated the potential of combining traditional materials with robotic innovation. This work lays the foundation for sustainable, health-driven architectural solutions grounded in cultural context and material intelligence.

Acknowledgements

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SIMULATION-INFORMED DESIGN OF KINETIC FURNITURE

A Case Study of an Interactive Table for Social Engagement

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Abstract. This study presents a simulation-based approach for designing kinetic furniture that fosters spontaneous social interaction. While kinetic furniture has the potential to dynamically reshape interpersonal distances, existing research lacks tools to evaluate its effects without costly physical prototyping. We developed an agent-based simulator that models conversational behavior in informal settings. The simulator was calibrated using data from a real-world experiment, in which participants' positions and group dynamics were observed and analyzed through computer vision techniques. Using the validated simulator, we tested multiple kinetic behaviour algorithms for the table and found that while some promoted conversational merging, they also increased the likelihood of conversation splitting. The ability to simulate such behavioural outcomes highlight the value of simulation, which reduces fabrication costs and enables the exploration of adaptive interaction strategies. We further discuss future directions in which AI-enhanced kinetic furniture could dynamically respond to and influence human interaction, contributing to culturally contextual and socially intelligent spatial environments.

Keywords: *Kinetic Furniture, Cyber-Physical Systems, Social Engagement, Agent-Based Simulation*

SIMULATION-INFORMED DESIGN OF KINETIC FURNITURE: A CASE STUDY OF AN INTERACTIVE TABLE FOR SOCIAL ENGAGEMENT

1. Introduction

In architecture and urbanism, fostering social interaction is a central goal in the design of public spaces. UN-HABITAT (2024) highlights that successful public spaces enable people to meet and interact. Such environments unite communities and shape local identity and social ties.

A range of approaches have been developed to support this goal. Notably, Hillier and Hanson (1984) introduced Space Syntax, a framework for analyzing spatial configurations in architecture and urban design. Notably, it was applied in the redesign of Trafalgar Square by Norman Foster, where the introduction of large steps invited people to linger, transforming the space into a vibrant public arena (Dursun, 2007).

While efforts to create sociable public spaces have been a consistent focus in architecture and urbanism, it seems meaningful to revisit a fundamental question: why is facilitating social interaction in public space so important. Urban observations by Mehta (2019) show that diverse interactions and co-presence in public spaces foster social cohesion and help shape cultural norms. According to Granovetter (1973), social interaction holds significant benefits at both micro and macro levels. “Weak ties”—casual connections formed through incidental encounters in social settings—can have a positive impact on individuals’ career development. At a broader social level, such ties enhance the circulation of information and ideas, thereby contributing to social and economic dynamism.

However, it is important to recognize that not all individuals find it easy to engage socially. McCroskey (1977) said a certain number of people experience anxiety or apprehension when having conversations with unfamiliar others in social contexts. These psychological barriers can limit the potential for inclusive and diverse interactions in public spaces.

To address this issue, designers and researchers in the field of Human–Computer Interaction (HCI) have developed a variety of Kinetic Furniture systems. By movement and spatial reconfiguration, such furniture aims to create social affordances that make it easier for people to interact naturally.

1.1. STATE OF THE ART

Sadka et al. (2022) developed a kinetic stool that subtly rotates, orienting users’ bodies to encourage spontaneous conversations between unfamiliar individuals. In an experiment with 18 participants, the intervention was shown to increase communication, particularly in socially awkward first encounters. One limitation of the study was that the timing of the seat’s rotation was manually controlled by the researchers, meaning that researcher

intervention remained a confounding factor. The lack of autonomy in the system highlights a challenge for future development.

Grönvall et al. (2014) developed a bench dynamically changing its surface gradient by altering seat heights and conducted field experiments in public settings. The bench's shape-shifting often prompted users to interpret the movement's meaning, sparking commentary, observation, and shared speculation—leading to social interaction. However, the dramatic transformations sometimes made interactions feel unnatural and hindered the bench's basic function as seating.

Grønbæk et al. (2017) proposed a framework for designing interactive tables that dynamically alter spatial configurations to mediate social interaction. He identified three key considerations: transition speed, stepwise reconfiguration, and radical shifts. While radical shifts can adapt to various group sizes and activities, they also risk startling users, which may inhibit interaction.

1.2. BACKGROUND

As these studies demonstrate, there exists extensive research that seeks to promote social interaction through the physical prototyping of furniture. However, building mock-ups and conducting empirical studies with participants can be costly and time-consuming (Takeuchi and You, 2014). This has led to a growing need for simulation environments that can predict how people would interact with such furniture, without requiring physical fabrication or real-world trials.

While simulation techniques for modeling crowd dynamics are relatively well established, there remains a notable gap in research focused on simulating interactive social behavior—particularly the kinds of interpersonal exchanges that occur in one-on-one or small-group settings. In other words, few studies have addressed the challenge of predicting how individuals might engage with one another in response to the dynamic affordances of kinetic furniture.

Takeuchi and You (2014) developed a simulator to tune the seat rotation algorithm in a kinetic furniture system aimed at encouraging conversation among strangers. The simulation was used to examine whether the algorithm could consistently generate interaction across a variety of stool quantities and spatial arrangements.

However, since the system has not yet been tested in real-world scenarios, two fundamental questions remain unanswered: first, whether the stools will indeed function as predicted in actual use; and second, whether the simulator itself is producing valid and reliable behavioral predictions. These limitations highlight the need for more rigorous validation of simulation-based approaches in the context of socially interactive design.

2. Research Objectives

This paper's goal is to design and realize furniture that fosters interpersonal interaction—particularly among strangers—in public or semi-public spaces. To achieve this, the primary research objective is the development of a validated simulation method that can predict human social behavior in response to the spatial and kinetic properties of interactive furniture.

A reliable and behaviorally grounded simulator would enable designers to assess the potential effectiveness of interaction-promoting furniture without the need to fabricate and test physical prototypes. This not only reduces time and material costs but also allows for rapid, iterative exploration of design alternatives.

3. Methodology

To achieve the objectives outlined above, this research proceeds through the following three phases:

1.Simulation Construction

A simulation environment was constructed to model human behavior in informal social settings, allowing for the prediction of movement patterns, interaction tendencies, and spatial clustering among individuals.

2.Simulator Validation through Real-World Experimentation

The accuracy and reliability of the simulator was assessed by conducting controlled experiments with actual participants. Observational data was collected and compared to the simulator's output. This process informed the calibration of behavioral parameters and improved the predictive fidelity of the model.

3.Design and Evaluation of an Interactive Table

The validated simulator was used as a design tool to develop kinetic behaviour algorithms, allowing us to examine which of them most effectively facilitate spontaneous social interaction. In order to examine how the geometry of the kinetic table influences user behaviours, the mock-up was tested with the rotation function set to manual operation, during a symposium at the University of Tokyo (Figure 1).



Figure 1. The mock-up was tested during a symposium at the University of Tokyo, with manual rotation, to examine how the table's geometry influences user behaviour.

3.1. DEVELOPMENT OF THE SIMULATOR

Previous studies have explored the simulation of pedestrian dynamics in crowd settings (Helbing and Molnar, 1995), as well as agent-based models for simulating social interactions and conversational behavior (Stehlé, Barrat and Bianconi, 2010).

The latter describes how conversation groups form and evolve over time, based on individual agents' state transitions, pairing of isolated agents, group splitting, and the inclusion of new members into ongoing conversations. However, this model neglects spatial factors and treats agents as homogeneous entities.

Building on this prior work, we introduced a simulator which has a phase-based interaction model. Crucially, it also incorporates two major aspects not addressed in prior models: (1) Spatial decision-making, including table and position selection around the table, and (2) Agent heterogeneity, with each agent assigned an extraversion score and each pair of agents assigned a mutual familiarity score.

The simulator is implemented in Unreal Engine, a real-time 3D game engine, allowing for dynamic visualization and rule-based agent behavior (Epic Games, 2025). The simulation process follows the structure illustrated in Figure 2, 3, 4.

In constructing the simulator, certain parameter values cannot be determined and must be initially set arbitrarily. If the simulation output deviates substantially from the behavioral patterns observed in real-world experiments, the corresponding parameters will be adjusted to improve realism and reliability.

The simulator operates through the following behavioral phases:

1.Table Selection

Agents select a table based on a weighted combination of (a) average familiarity with others at the table, (b) table availability, and (c) extraversion level. The relative weights of these factors are subject to tuning.

2. Standing Position Selection

If the table is empty, a position is chosen randomly. If others are present, agents prefer to stand near those with high familiarity (above a threshold); otherwise, the position is selected randomly. The threshold is tunable parameter.

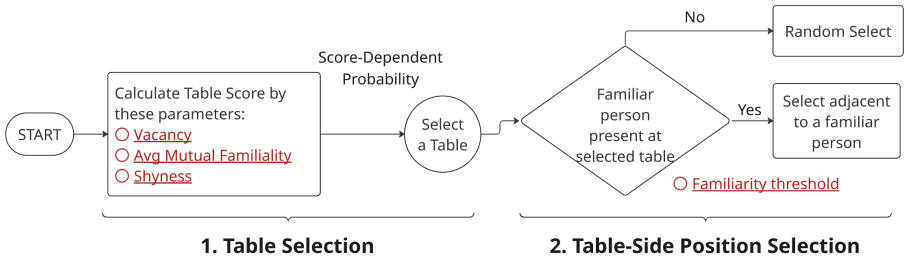


*Figure 2. F*lowchart of the simulator's (1) Table Selection and (2) Standing Position Selection phases. Parameters requiring tuning are indicated in red.

3.Conversation Initiation

Conversations occur between two agents when they are within a specified distance and facing angle. Specifically, the distance threshold is set at 1000 mm based on the analysis in Section 3.3, and the facing angle at 120 degrees, following prior studies on human visual fields (Stidwill and Fletcher, 2017).

4. Joining a Conversation

The same spatial and orientation criteria are used to allow isolated agents to join existing conversations.

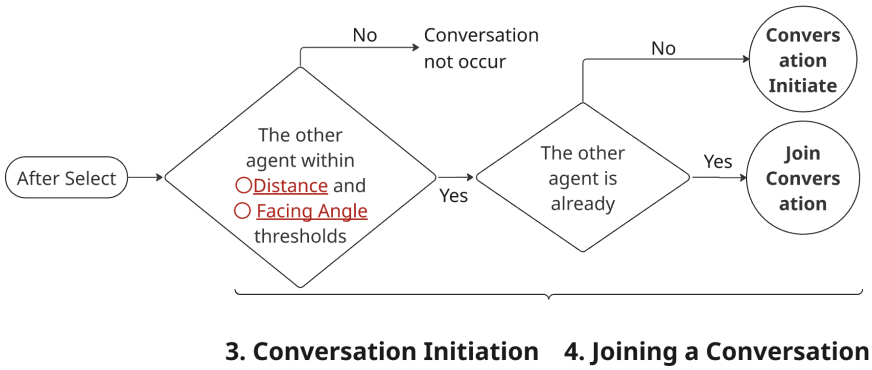


*Figure 3. Flow*chart of the simulator's (3) Conversation Initiation and (2) Joining a Conversation phases.

5–6. Merging and Splitting of Conversation Groups

Dynamic combination or division of ongoing conversations will be further explained in Section 3.3, along with the experimental basis for their inclusion.

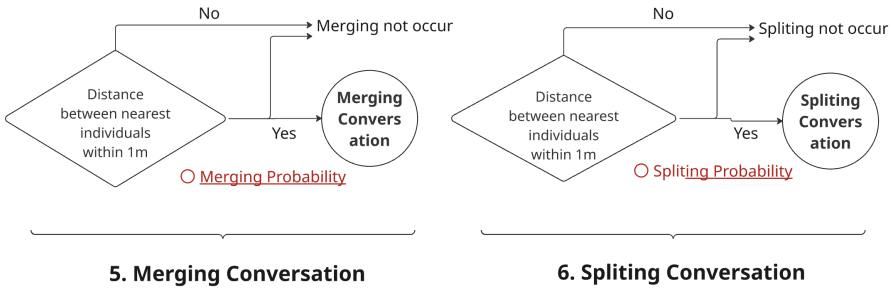


*Figure 4. Flow*chart of the simulator's (5) Merging Conversation and (6) Spliting Conversation phases.

The simulator outputs five key metrics: (1) total conversations, (2) merges, (3) splits, (4) average group size, and (5) average mutual familiarity. These outputs are used in Section 3.3 to tune the parameters and in Section 4.3 for evaluating the kinetic behaviour algorithms.

3.2. PRELIMINARY EXPERIMENT

To support simulator development, we conducted a preliminary experiment to examine human behaviour in informal social settings. Seventeen university students in their twenties (mixed gender) participated, divided into two groups of 8 and 9 to reduce linguistic burden during communication.

Each group was instructed to imagine a networking or social event and to engage in free conversation for two five-minute sessions while holding drinks.

To simulate natural arrival flow, participants entered the room in pairs at 20-second intervals. The experiment was conducted indoors in a spacious room within inside the department building. A 4.5 m × 7.2 m area was secured using partitions, and two tables—one round and one rectangular—were placed within space. The session was recorded using a single fixed-position video camera.

Afterward, participants completed a questionnaire on (1) their prior familiarity with others and (2) self-rated extraversion on a 10-point scale. All participants took part on a voluntary basis and provided informed consent prior to participation.

3.3. ANALYSIS OF EXPERIMENT AND TUNING SIMULATOR

The goal of the tuning process is to compare the simulation results against those obtained from the preliminary experiment, and to adjust the initially arbitrary parameters accordingly to improve the reliability of the simulator. The analysis of the preliminary experiment was conducted through two approaches:

(1) manual annotation to extract the same metrics as the simulator output; and

(2) quantitative analysis, involving the estimation of participants' positions based on video data and subsequent measurement of interpersonal distances.

3.3.1. Manual Annotation

Based on observational data, we discovered a phenomenon not considered in the initial simulation model: merging of separate conversation groups. Accordingly, we added this interaction state to the conversation model, in addition to the phases described in prior research.

3.3.2. Quantitative Spatial Analysis

To extract spatial interaction data, we applied the YOLO11 object detection algorithm (Jocher and Qiu, 2024) with a pretrained model to the video recordings to detect individuals and estimate their poses (Figure 5). Specifically, we extracted the 2D image coordinates of the participants' ankles and used homography transformation to convert these into real-world coordinates projected onto the floor plane.

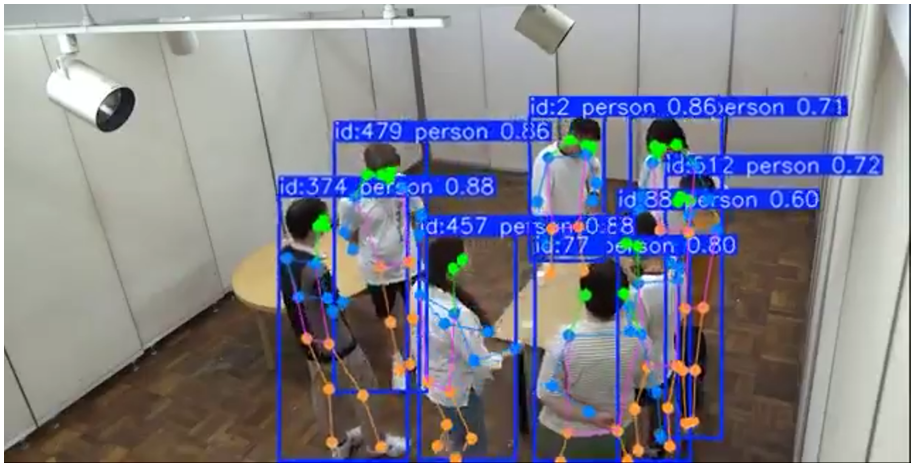


Figure 5. Detecting individuals and estimating their poses through YOLO11 object detection algorithm

From the data, we inferred that conversation merging is triggered by the minimum distance between individuals in separate groups. Three merges were observed, with distances of 557 mm, 1017 mm, and 809 mm. Based on this, a threshold of 1000 mm was set, below which merging may occur. The probability of merging under this threshold is a tunable parameter.
Conversely, splitting is inferred to be associated with the maximum distance between individuals within a group. Four splits were observed, with distances of 1405 mm, 2685 mm, 2206 mm, and 2044 mm. A threshold of 1400 mm was defined, above which splitting becomes likely. The corresponding probability is likewise tuned by comparing simulation results with empirical data.

3.3.3. Data Selection for Tuning

In the first trial with English-speaking participants, most individuals did not stand beside tables. As the interaction with tables was minimal, this data was excluded from tuning. Likewise, in the second trial with Japanese-speaking participants, the awareness of the experimental setting appeared to influence behavior, as all nine participants conversed as a single group—a scenario unlikely to occur naturally. Therefore, this case was also excluded. The tuning process used data from: (1) Trial 1: Japanese-speaking participants, (2) Trial 2: English-speaking participants

3.3.4. Tuning Methodology

Due to limitations of our simulator, automated large-scale parameter sweeps could not be implemented. Therefore, we manually conducted 100 simulation runs, recorded the output as CSV data, and used the results to

train a Gaussian Process Regression (GPR) model to approximate the simulation behavior. We adopted GPR because it provides calibrated predictive means and variances under small-sample, noisy observations and is a widely validated surrogate for computer experiments and Bayesian optimization (Rasmussen & Williams, 2005). Using the GPR model, we conducted multi-objective optimization with the objectives being the 5 outputs mentioned in Section 3.1 corresponding to the results of the Preliminary Experiment.

Initially, the simulator was designed to apply universally across both English- and Japanese-speaking participants, aiming for a shared behavioral model. As shown result 1 (Table 1), this approach produced outcomes that averaged the behaviors of both groups rather than representing either accurately.

This overgeneralization highlights a limitation: tuning the simulator simultaneously for different cultural contexts reduced behavioral fidelity. In response, we conducted a second round of tuning focused solely on the Japanese-speaking group. As shown in result 2, this yielded outputs more closely aligned with observed behaviors.

TABLE 1. Five outputs from Experiments and Simulation.

		Result from Experiments			Result from Simulations		
		Japanese	English	Avg	Non-Tuning	result1	result2
Five outputs	Number of Conversation	7	6	6.5	5	6.4	6.2
	Avg Number of People	4.94	2.74	3.84	3.94	3.53	5.56
	Number of Merge Conversation	3	0	1.5	1	1.2	0.8
	Number of Split Conversation	0	2	1	0	0.4	0
	Avg of Familiarities	1.98	5.56	3.77	2.48	3.51	2.74

These results indicate that culture-specific tuning is more effective for developing accurate behavioral models and suggest that cross-cultural generalization may require fundamentally different strategies.

Thus, an optimized parameter set was obtained for Japanese speakers. Validation against the pre-tuning baseline confirmed improvements across most metrics, except for the number of merged conversations. Increasing the number of simulation runs is expected to further improve GPR model accuracy and parameter optimization.

With a validated simulator, we were now equipped to apply it as a design tool. In the following chapter, we use this simulator to evaluate different kinetic behaviour algorithms and inform the development of an interactive table aimed at fostering social interaction.

4. Design and Evaluation of the Interactive Table

Based on the simulator developed and calibrated in Section 3, this chapter focuses on designing an interactive table to promote social interaction. The simulator serves as a predictive tool to evaluate how specific design choices —particularly regarding movement—affect interpersonal behavior.

Kinetic furniture allows for countless combinations of geometry and movement. To constrain the scope, we fixed the table's geometry and focused on kinetic algorithms as the variable of interest. Our key question is: How does movement change in interpersonal distance influence the likelihood or quality of interaction?

Even when limiting the design space to kinetic algorithms, identifying an effective algorithm through intuition alone is challenging due to the vast number of possibilities. Here, simulation becomes essential.

By evaluating interaction outcomes under different rotation patterns, the simulator enables objective comparison and helps identify strategies that best facilitate conversation. This shifts design from intuition-based to evidence-based.

4.1. DESIGN CONSIDERATIONS

In prior research on kinetic furniture, design approaches have often been polarized—either creating objects that dramatically attract attention and sometimes disrupt social settings, or conversely, blending seamlessly into everyday environments without drawing notice. This study aims to balance these extremes by integrating benefits from both.

The interactive table is designed with three semi-circular rotating tabletops, which move at a speed that does not startle users. The table is intended for standing use by groups of up to approximately nine people. Its comma-shaped form, inspired by *ISOLA.S* by Setsu & Shinobu Ito (2004), balances visual appeal with ergonomic function.

A distinctive feature of the design is its emphasis on conversation merging as a strategy to promote interaction. Merging expands the number of participants in a conversation, potentially leading to broader exchange. This work uniquely explores how rotational movement can intentionally reshape interpersonal distance to facilitate such merging.

The design of the interactive table therefore carries two primary intentions: (1) To attract users through a visually engaging form that invites proximity and initiates interaction (i.e., "creating interaction"), and (2) To promote interaction by encouraging the physical merging of conversation groups via table rotation (i.e., "growing interaction").

4.2. MOCK-UP FABRICATION AND IN-SITU OBSERVATION

To evaluate how the interactive table might be used in real-world settings, we fabricated a full-scale mock-up using digital fabrication. The structure and mechanical assembly are illustrated in the accompanying axonometric drawing (Figure 6). The table was designed to allow disassembly and reassembly without damaging components, enabling flexible deployment.

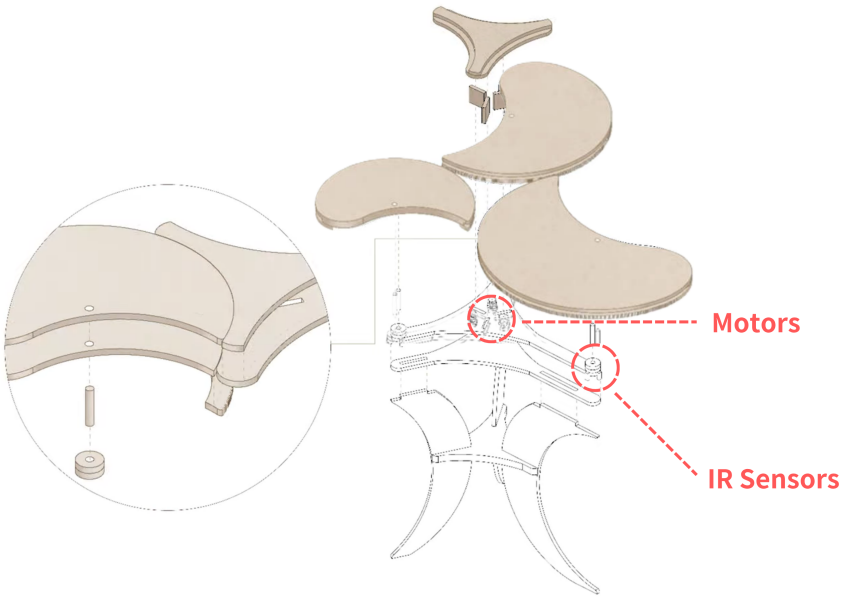


Figure 6. Infrared sensors were installed to detect the presence of people, and a microcontroller was used to control the motor-driven rotation of the tabletop.

The mock-up was tested during a symposium at the University of Tokyo, placed in a public area for free interaction (Figure 1). The motorized rotation was disabled; instead, users could manually rotate the tabletop segments. This setup aimed to identify rotation configurations that felt natural or conducive to interaction, informing later algorithm design.

We found that the table's distinctive comma-shaped form successfully attracted user interest, with several participants approaching it out of curiosity.

Observations showed that the rotation angle of each semi-circular segment affected user positioning, producing varied spatial arrangements. The concave–convex geometry led to two main patterns:

(1) In small groups (2–3 people), users clustered around the convex edge of a single tabletop, sometimes forming separate conversations at different segments.
(2) In larger groups (4+), users spanned multiple segments, positioning themselves in the concave belly of the shape or between adjoining segments.

These behavioral patterns provide valuable insight into how the physical geometry and configurations of the table influence spatial grouping and conversation dynamics. Based on these observations, we proceed to the next stage: exploring a rotation algorithm that enhances naturally occurring patterns of interaction.

4.3. EVALUATION OF ROTATION ALGORITHMS

Using the updated simulator developed in Section 3.3, we conducted a series of simulations to test variations of table rotation algorithms. The goal was to identify which rotation behaviors most effectively facilitate social interaction. To isolate rotation effects, simulations were conducted in a controlled environment with a single table (Figure 7).

We classified the tested rotation algorithms into four main categories, each with multiple versions:

(1) No Rotation
This served as the baseline for comparison.

(2) Time-Based Rotation
The tabletop rotates continuously or periodically based on time, independent of user behavior.

(3) Sensing-Based Simple Rotation
The table rotates triggered by user detection, following simple rules.

(4) Behaviorally Informed Rotation (Observation-Based)
This category incorporates insights from the behavioral observations described in Section 4.2:

(a) Merge-Oriented Rotation: adjusts segment angles to bring separate conversations closer for promoting conversations merging.
(b) Full Occupancy Retraction: retracts to a compact configuration to encourage merging and spatial cohesion.

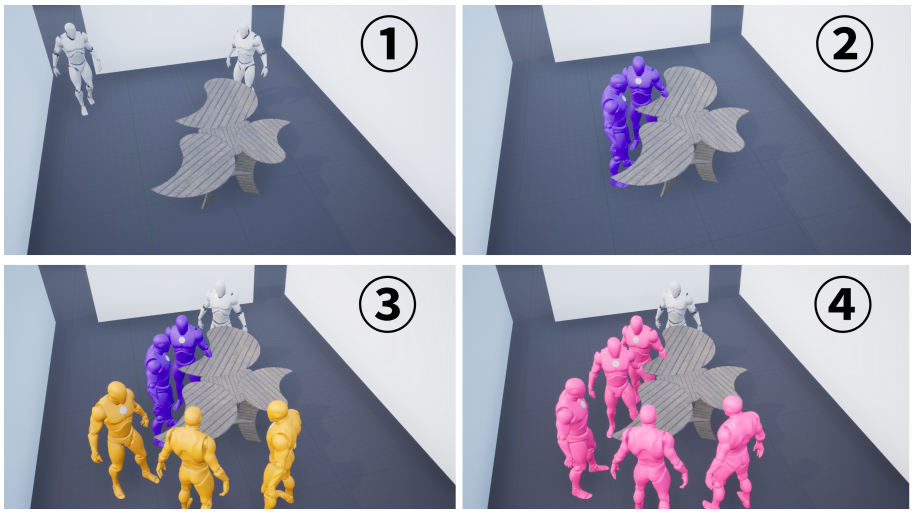


Figure 7. Sequence of simulation steps: (1) table and position selection, (2) conversation initiation, (3) joining a conversation, and (4) conversation merging. Agents engaged in conversations are color-coded by group.

We ran three trials per pattern under varied initial conditions. In total, Algorithm (1) was tested 48 times, (2) 30 times, (3) 24 times, and (4) 48 times, with either 4 or 6 agents per 2-minute simulation. Averaged outputs are shown in Table 2.

TABLE 2. Averaged outputs from the simulation for each rotation algorithm. As merged conversations are counted separately from the original two conversations, the number of conversations is influenced by the number of merge conversation.

Number of all Agents	Algorithm	Number of Conversation	Number of People	Number of Merge Conversation	Number of Split Conversation
4	(1)	2.708333	3.370923	0.5	0
	(2)	3	3.519222	0.6	0
	(3)	2.583333	3.2425	0.166667	0
	(4)	3.083333	3.335764	0.541667	0.125
6	(1)	4.208333	4.178958	0.708333	0.041667
	(2)	5.4	4.585333	1.2	0.2
	(3)	4.666667	4.399167	0.916667	0.083333
	(4)	4.375	4.389385	0.666667	0.041667

The results show that Algorithm (2), which rotates continuously at fixed intervals, produced the highest number of conversation merges for both group sizes. However, with 6 agents, it also showed a notably higher number of conversation splits. This may be because Algorithms (1), (3), and (4) tend

to stop rotating as more users arrive, while Algorithm (2) maintains consistent movement regardless of context.

5. Conclusion and Discussion

Kinetic furniture offers a unique potential to dynamically reshape spatial environments by physically altering the user's position. Focusing on this characteristic, this study developed a simulator capable of evaluating such furniture in terms of its ability to foster social interaction.

An agent-based model of conversational behaviours was constructed and validated using data from a preliminary experiment. This iterative, data-driven tuning process is rarely seen in prior work and represents a key contribution of this study.

The validated simulator can reliably predict behavioural outcomes without requiring full-scale prototyping, reducing design costs and enabling the exploration of diverse kinetic strategies. Using this tool, we tested multiple table rotation algorithms. The results demonstrate that while continuous rotation algorithm facilitates merging and wider interaction, it also increases the risk of disrupting ongoing conversations. These findings suggest that a hybrid approach— strategic combination of multiple algorithms —may offer better balance between interaction and stability.

To make a stronger claim about the real-world effectiveness of the simulator as a tool for kinetic furniture design, a future step is to conduct a user study using the actual interactive table. This is an essential next phase in confirming the simulation's predictive validity.

In the preliminary experiment, we also intentionally involved participants from different linguistic and cultural backgrounds (Japanese- and English-speaking groups). While the simulator was initially intended to apply a universal behavioural model, our analysis revealed that such generalization is challenging. Therefore, the current version has been adapted to reflect culture-specific behaviour. Previous studies have shown that preferred interpersonal distances during social interaction vary across cultures (Hall, 1966; Sorokowska et al., 2017). A localized simulator that reflects regional differences could help generate culturally resonant kinetic behaviors, producing context-sensitive interaction spaces and architectural environments rich in social meaning.

As seen in Cedric Price's vision of the Fun Palace—an adaptive and interactive cultural facility—cyber-physical systems can transform their architectural or furniture functions by altering embedded algorithms (Price, 1984). This makes it possible for kinetic systems to adapt dynamically to different situations and communities. Importantly, the software that governs

behavior does not need to be fixed at the time of design, but can evolve and update over time.

In the future, if sensors or cameras embedded in the furniture can estimate conversational engagement, the system could dynamically alter its kinetic algorithm in real time. Moreover, if machine learning is employed to learn which configurations lead to more engaging conversations, AI-driven kinetic furniture could proactively choose movement strategies to promote social interaction. This evolution suggests a future in which kinetic furniture not only responds passively but also acts actively—continuously shaping spatial and social experience through intelligent behavior.

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A STREAMLINED DECENTRALISED WORKFLOW FOR OBTAINING SPECIFIC MECHANICAL PERFORMANCE AND GRADE OF 3DCP

Towards the Standardization and Industrialization of 3DCP

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Abstract. This work presents findings of ongoing experimental research on 3D Concrete Printing, aiming at rationalising the production parameters in favour of the final mechanical performance – the grade – and at the same time proposing a decentralised approach for the rapid definition of production standards and their reliable and tamper-proof distribution to streamline the obtaining of a specific 3D-Printed Concrete grade. Moving from preliminary considerations about the fragmentation of current research, we suggest approaching the standardisation problem from the basic principle of the structural requirements rather than the development of hyper-specialised materials. We propose a 2-step experiment with the creation of a Distributed Ledger Technology-based decentralised framework acting as a repository of experimental data from different production laboratories, each with its specific setup and production settings. In the first stage, the decentralised framework collects and analyses the production data, detecting different production settings and mechanical performance relations and patterns. In the second stage, the system suggests optimised production settings for obtaining the required grade. The decentralised framework constitutes the infrastructure for the definition of production standards based not only on construction requirements but also considering the variable production setups, laying the foundation for a smoother adoption of the standards.

Keywords: *3D Concrete Printing, concrete grade, industrialization, standardization, decentralized ledger technology.*

1. Introduction

Nearly a century after its invention, 3D Concrete Printing (3DCP) remains impractical for industrial use. The system, patented in 1944, already included key features of today's technology, such as embedding metallic mesh as the shear-resistant material within concrete. Today, despite advancements in Computer Numerical Control (CNC) machines, robotics, material science, Internet of Things (IoT), and Artificial Intelligence (AI), the lack of standardised regulations prevents 3DCP's industrial application. Additionally, hyper-specialised research aims to solve numerous 3DCP-related challenges, but it has so far failed to promote a real and systematic industrialisation of such technology, as it generally fails to address the standardisation problem. Hence, our focus is on rationalising the process so as to provide a robust workflow that could lead to more coherent and standards-compliant applications.

Through a schematization of the traditional concrete construction pipeline, we propose an equivalent scheme for 3DCP-based construction, enhanced by the adoption of Decentralised Ledger Technologies (DLT) and capable of creating a tamper-proof verification and validation system. As a multi-step and multi-disciplinary process, 3DCP entails several technical and non-technical dimensions, all subject to standardisation. However, the design-to-construction process attributes a central role to the adoption of the right concrete grade, as this property defines the mechanical performance of the material and, therefore, of the structural element, entailing structural and safety consequences.

In the design-to-construction workflow, the designer and the constructor define the structural design, giving a precise indication of the required concrete mechanical performance. The 3DCP provider, or the 3DCP-capable constructor, oversees the production of the structural elements using 3D-Printed Concrete (3DPC) with the required concrete grade. Therefore, from an industrial point of view, the first unresolved challenge of 3DCP structural applications is about being able to obtain a certain concrete grade given specific production settings and environmental conditions and its related validation based on an agreed construction code. While representing common knowledge and standard practice in the case of traditional cast-in-place concrete, the grade remains a crucial parameter to be controlled and verified in the case of 3DPC.

For standard concrete applications, the grade is determined via compression test of specimens after 28 days of curing, and it corresponds to the compressive strength expressed in megapascals (MPa). For example, M20 concrete has a compressive strength of at least 20MPa. Depending on the grade, concrete is classified as normal, standard, or high strength (Table 1). A minimum grade of M20 is recommended for reinforced concrete applications.

TABLE 1. Traditional cast-in-place concrete grade.

Mix ratio	Compressive strength	Concrete grade	
1:5:10	5 Mpa	M5	Normal
1:3:6	10 Mpa	M10	
1:2:4	15 Mpa	M15	
1:1.5:3	20 Mpa	M20	
1:1:2	25 Mpa	M25	Standard
Design mix	> 25 Mpa	> M25	Standard or High Strength

In the case of 3DCP, current national and international regulatory bodies do not provide clear and agreed-upon guidelines for such verification and standards, hence leaving a legal void that prevents adopting 3DCP as a standard building technology. In today's interconnected society, and with the body of knowledge produced by researchers all over the world, 3DCP represents more than a local approach, but rather the outcome of a global effort, and as such, its shortcomings should be addressed (Ahmed, 2023). In this context, it appears necessary to rely on common, shared and secure workflows and technologies allowing multiple and multi-located scientists to contribute in a standardised manner. With this assumption, we propose a decentralised experimental framework which relies on the adoption of Blockchain Technologies (BTs) for the management and recording of materials preparation, specimens' production, onsite testing, and performance validation. BCTs can support such kind of experimentations in light of their transparent nature, tamper-proof capability and potential to embed automated processes via smart contracts (Hunhevicz et al., 2022).

The choice of adopting a decentralised experimental framework is also motivated by the considerable number of tests required to obtain a representative sample of production: a single fabrication laboratory would inevitably present time, technology, environmental and materials limitations, thus being representative of a unique production scenario without scalable and universal value. With scalability being a primary goal, the involvement of other labs in different geographic locations has two requirements: 1) adopting decentralised ledger technologies (DLT); 2) following strict production guidelines for executing and monitoring all production stages, from materials preparation to 3D printing, curing, and testing.

2. Research Background and Literature Review

The industrialisation of 3DCP and its introduction into the market as an alternative to onsite concrete casting have not yet reached their expected expansion due to the insufficient development of technologies and materials,

and the lack of validated and shared standards (Diks, 2019; El-Sayegh et al., 2020; Van Der Putten et al., 2022).

Attempts at standardising some of the dimensions having an impact on 3DCP processes are being made, for example the industrial application of Additive Manufacturing (AM) technology ("ISO/ASTM 52939," 2023), or the geometric properties and testing of 3DPC specimens (Cai et al., 2024).

Considering the top five high-frequency keywords from the scientific publications on 3DCP between 2014 and 2023 (Wang et al., 2024), a prevalent interest in the mechanical performance of 3DPC seems to emerge, but as already observed, the research tends to focus on very specific aspects, such as the use of admixtures, the integration of shear-resisting materials, etc.

The mechanical performance of 3DPC is affected by ink properties, concrete mixture preparation, and environmental conditions, while the hardened material is characterised by anisotropic behaviour due to the deposition of material filaments and the layered structure (Şahin and Mardani, 2023). Additionally, scholars agree on the relevance of the water-to-binder ratio (*w/b*, sometimes indicated as *w/c*, water-to-concrete) in the determination of the final concrete grade (Yu et al., 2021).

The use of Artificial Intelligence (AI) and Machine Learning (ML) for large datasets analysis and AI-inference can suggest optimised production parameters or provide indications and instructions for maintaining process quality (AlKhader et al., 2023). Large Language Models (LLM) and Multimodal Large Language Models (mLLM) can enable *adaptive 3DCP* (Di Marco and Cheung, 2025) with real-time automatic adjustments of production settings and 3D printing hardware.

The multi-disciplinarity of the process, together with the scattered research and the proposed decentralised setting, generates a concrete risk of misalignment of research topics, nomenclature, materials, and technologies, and mismatch problems in the communication and exchange of information and data, making it necessary to standardise the way such information is conveyed among the involved stakeholders. This circumstance becomes even more important in the presence of 3DCP service providers (Monroy et al., 2023); therefore, the definition of an ontology for the effective and reliable transmission of information is necessary (Han and Schaefer, 2019).

The construction industry's digital transformation is being reshaped by blockchain technology, which offers more than just incremental improvements to existing processes by enabling entirely new paradigms of decentralised governance and economic coordination (Davidson et al., 2018; Dounas et al., 2021; Hunhevicz et al., 2022). At the heart of this transformation lies blockchain's unique capacity to create trust-minimised systems that align stakeholder incentives through crypto-economic mechanisms, automate verification processes via smart contracts, and

facilitate collaborative innovation across organisational boundaries. Recent advancements in blockchain technology have prompted significant interest in its potential applications within the construction sector, particularly concerning governance and standardisation challenges. Scholarly investigations have explored how blockchain's inherent features — decentralisation, immutability, and smart contract automation — could address systemic inefficiencies in construction processes. Within this broader discourse, emerging research has begun examining the intersection of blockchain and additive manufacturing, specifically 3DCP, where standardisation remains a critical barrier to widespread adoption.

Existing literature highlights the fragmented nature of 3DCP development, with research institutions, material suppliers, and construction firms operating under disparate methodologies and quality benchmarks. This lack of cohesion has led to inconsistencies in material performance, structural reliability, and process optimisation, hindering scalability. Traditional approaches to standardisation — typically centralised and slow-moving — struggle to accommodate the rapid innovation cycles characteristic of additive manufacturing. Consequently, decentralised technologies emerged as a potential solution, investigating whether blockchain's governance models could provide a more adaptive framework for knowledge sharing and compliance.

Several studies have documented blockchain's role in enhancing traceability and accountability in construction supply chains, with applications ranging from material provenance tracking to automated contract enforcement. Research by Hunhevicz et al. (2022) demonstrates how crypto-economic incentives can improve data quality in construction projects, while others have explored blockchain-based systems for real-time quality assurance in industrial applications (Zhong et al., 2020). These findings suggest that similar mechanisms could be applied to 3DCP.

Further academic inquiry has focused on decentralised autonomous organisations (DAOs) as a governance model for collaborative industries. Theoretical frameworks propose that DAOs could facilitate distributed decision-making in technical standardisation, allowing stakeholders to vote on protocol updates without centralised oversight (Hassan and De Filippi, 2021; Lombardi and Dounas, 2022; Wang et al., 2019). However, the practical implementation of such models in construction — particularly in a technology as nascent as 3DCP — has yet to be thoroughly examined.

A parallel strand of research investigates the integration of blockchain with IoT and digital twins in construction (Lee et al., 2021), emphasising automated data verification and machine learning-driven optimisation. These studies provide foundational insights into how smart contracts could validate 3DCP

parameters in real time, though concrete applications remain largely conceptual.

3. Research Gaps and Research Questions

The lack of shared and validated standards entails a considerable number of research and practical challenges, resulting in an endeavour that requires a coordinated multi-stakeholder approach. Moving from the main requirement of a design-to-construction process, that is, the mechanical performance of concrete, we focus on how to standardise the production process to obtain a specific concrete grade.

After identifying the elements of the 3DCP process that are necessary to obtain a specific concrete grade, we propose a method for streamlining the adjustment of the production of 3DPC specimens according to the required concrete grade.

The hypothesis is that a decentralised framework can significantly help the definition of standards by allowing the collection of a large amount of experimental data, at the same time acting as a tamper-proof repository and distributor of standards.

This paper aims to address the following research questions:

- What properties allow for standardising the 3DCP process and obtaining a specific concrete grade?
- How can a decentralised system handle such information in favour of the definition of shared and validated standards?

4. Methodology

The methodology involves a two-phase experimental approach conducted in a dedicated robotic 3DCP fabrication lab equipped with a KUKA KR300 R2700-2 and hydraulic press for testing. In the first phase, a series of 3DPC samples is produced following international concrete standards, with key production parameters (e.g., layer deposition speed, material composition, curing conditions) precisely monitored and recorded. These samples then undergo compression testing to determine their mechanical resistance and performance grade. The resulting data — linking production parameters to the experimentally validated concrete grade — is compiled into a structured dataset and securely stored on a private blockchain to ensure traceability and immutability.

The second phase, outlined but not covered by this work, focuses on industrial application, where a target concrete grade is specified, and the corresponding optimal production parameters are retrieved from the

blockchain. This phase simulates real-world construction workflows, leveraging AI-driven analysis of the dataset to recommend lab-specific printing parameters for achieving the desired 3DPC performance.

Figure 1 shows the 2-step experiment (Di Marco et al., 2025), where such parameters are monitored during the production process, and their values are stored, together with the corresponding grade, in a production package.

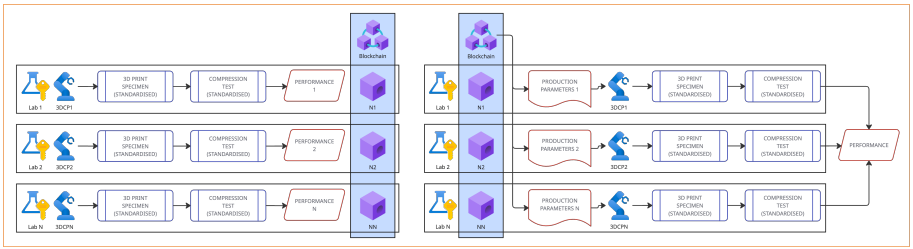


Figure 1. 2-step experiment for grade standardisation - Image created by the first author.

5. 3DCP parameters

Understanding the relation between production parameters and mechanical performance is essential to establish an efficient 3DCP process based on optimised and standardised dimensions. A benchmarking of materials and performance has been conducted, based on the 3D printing and compression testing of 3DPC specimens, and a thorough tracking of relevant parameters has been maintained, subdividing such parameters into three categories: design, environmental, and production parameters.

5.1 DESIGN PARAMETERS – SPECIMEN DESIGN

The most common cubic specimen sizes for the compression test of 3DPC are 30, 40, and 50mm (Cai et al., 2024). Depending on the nozzle diameter, these specimens consist of a single-line wall, thus showing no intralayer discontinuity.

Adopting the traditional specimen dimensions, we propose a cubic specimen with a side length of 150mm, allowing for multi-filament layers with the possibility of using a cross-ply pattern (Figure 2), in favour of a more homogeneous lateral mechanical performance (Şahin and Mardani, 2023).



Figure 2. Cubic 3DPC specimen with cross-ply pattern.

The 3D-printed cubic specimens are cut to dimensions (Figure 3) after the printing job has finished, removing the irregular superficial texture derived from the cross-ply pattern: this allows for improving the contact between the face of the specimen and the plate of the press, ensuring the best execution of the compression test.



Figure 3. 3DPC specimens cut to dimensions.

5.2 ENVIRONMENTAL PARAMETERS – INDOOR CONDITIONS

Humidity and temperature affect the evaporation of water and the workability and rheology of the concrete mix, and ultimately the mechanical performance of 3DPC. Our study is limited to indoor applications, typically for prefabrication in a controlled environment. However, the methodology is scalable and applicable to outdoor applications by adding other environmental parameters, such as wind speed and direction or others.

5.3 PRODUCTION PARAMETERS – MATERIALS, SOFTWARE, HARDWARE

The ink used in our tests presents the following components: Ordinary Portland Cement (OPC), Sulphoaluminate Cement (CSA), Sand, Water Reducer (PCE Superplasticiser), Cellulose Ether (HPMC), Thixotropic Agent, and Polypropylene Fibre.

Concrete mix composition and preparation are monitored, and all parameters are annotated together with software and hardware settings (slicing parameters, robotic arm parameters, and nozzle dimensions) as summarised in Table 2, which also served as the template used for tracking 3DCP parameters.

TABLE 2. 3DCP parameters tracking

Design parameters	- Specimen shape - Specimen dimensions - Slicing
Environmental parameters	- Temperature - Humidity
Production parameters	- Ink formulation - Concrete mix - Mixer settings - Pump settings - 3D printer type - 3D printer model - 3D printer settings - Extruder settings - Nozzle size

The observation throughout the preparation of the first set of 3DPC samples shows that the parameters having the most relevant effect on the final 3DPC grade are the infill pattern and the water-to-ink ratio (hereafter w/i) in the concrete mix. The adoption of the standard cubic specimen with 150mm side and the subsequent multi-filament layer and cross-ply pattern allows for considering the anisotropic behaviour of 3DPC, and at the same time offering a solution to the varying compression strength depending on the orientation of the applied load. The mechanical strength of 3DPC is maximum for lateral load along the X direction (along the filament), minimum for lateral load along the Y direction (perpendicular to the filament) and intermediate for vertical load along the Z direction (perpendicular to the layer) (Cai et al., 2024). By alternating the filament orientation, swapping the X and Y directions in every new layer, the cross-ply pattern makes it possible to consider only two load

orientations during the compression tests: vertical (perpendicular to the layers) and lateral (coplanar to the layers).

Regarding the w/i ratio, we have found that it substantially affects the 3DPC grade: a little variation of this parameter, in fact, determines a sensible increase or reduction of the grade. The optimal w/i ratio is, in turn, highly dependent on the ink composition and on the 3D printing setup.

6. 3DPC grade

The compression tests have been conducted on the first set of 60 3DPC produced specimens, alternating vertical and lateral loads (Figure 4).



Figure 4. Compression test with lateral load.

We observed a high variability of the grade depending on the w/i ratio, with the optimal value being 0.15 (15%): with this value, the 3DPC grade has been consistently M25 for both vertical and lateral loads. A w/i of 17% corresponded to a significant decrease in the grade, measured both vertically and laterally, with no specimen reaching grade M20 and with vertical grade being consistently higher than lateral grade, thus revealing an increased anisotropic behaviour despite the presence of the cross-ply pattern (Table 3).

TABLE 3. 3DPC grade with 17% w/i ratio

Specimen ID	w/i	Load orientation	Strength (MPa)
20230912-003	0.17	Vertical	17.9
20230912-004	0.17	Vertical	15.5
20230912-005	0.17	Vertical	18.0
20230912-006	0.17	Vertical	15.8

20230912-007	0.17	Lateral	5.4
20230912-008	0.17	Lateral	4.4
20230912-009	0.17	Vertical	17.9

In the latest tests, we have used a batch of expired ink and set the w/i ratio precisely to 15% to study the mechanical performance in suboptimal conditions due to ink expiration. We discovered that the lateral grade decreases significantly, never reaching M20 and with an average strength of 13.5MPa, while the vertical grade increases to an average of M35, with a minimum of M30 and a maximum of M40.

7. Production package preparation and distribution

We envision the standardisation of 3DPC as a process relying on the systematic aggregation of manufacturing and performance data into a unified digital record — the *production package*. This comprehensive file serves as the foundational element for traceability, quality assurance, and knowledge sharing among researchers and within the construction industry. By integrating the production package into a blockchain network, stakeholders gain access to an immutable, decentralised repository of verified 3DPC parameters, enabling reproducibility, compliance, and data-driven optimisation.

The production package is a structured digital file that encapsulates all critical data generated during the lifecycle of a 3DPC specimen — from design and fabrication to curing and mechanical testing. Each package contains seven core components, ensuring full transparency and replicability:

1. Design Parameters define the specimen's digital blueprint, including layer resolution and geometric tolerances.
2. Environmental Conditions document ambient factors such as temperature and humidity during printing.
3. Production Parameters record real-time operational data, including materials properties and preparation, software and hardware settings.
4. Visual Documentation provides high-resolution images of the specimen at key stages, facilitating visual quality control.
5. Curing Regimes specify time, temperature, and humidity profiles during the hardening phase.
6. Testing Results compile compressive strength measurements and failure modes from standardised lab tests.
7. Assigned grade links the specimen's performance to conventional concrete classifications.

These components are formatted into a standardised schema (Table 4) to ensure interoperability across blockchain nodes and downstream applications.

TABLE 4. Production package data scheme

Data category	Format	Use case
Design parameters	Cad/bim + json metadata	Digital replication of geometric models
Environmental data	Time series csv	Anomaly detection
Production settings	Machine logs (xml)	Process optimisation
Visual records	Jpeg/png + timestamps	Defect auditing
Curing parameters	Structured logs + time series csv	Compliance alignment
Test results	Lab reports (pdf)	Grade certification
Grade classification	Standardized tag	Regulatory alignment / benchmarking

The transition of the production package from a standalone digital file to a blockchain-anchored asset fundamentally redefines how 3DCP data is managed, shared, and utilised across the construction ecosystem. Upon completion of specimen testing, the package undergoes a structured integration process with a permissioned blockchain network, designed to address the construction industry's need for traceability, auditability, and collaborative innovation.

7.1 IMMUTABLE DATA ANCHORING AND VERIFICATION

Each production package is processed through a cryptographic hashing algorithm, generating a unique digital fingerprint that permanently links the dataset to the blockchain. This hash is embedded into a transaction block alongside metadata, such as timestamps and contributor credentials, creating an immutable audit trail. This mechanism ensures provable data integrity, critical for compliance scenarios where regulators or clients demand evidence of unaltered production records.

7.2 DECENTRALISED ACCESS AND SMART CONTRACT AUTOMATION

Unlike traditional centralised databases, the blockchain distributes copies of production packages across a network of authorised nodes (e.g., manufacturers, testing labs, and regulatory bodies). Access is governed by smart contracts — self-executing protocols encoded with predefined rules, providing stakeholders with enhanced control and hence design capabilities.

A contractor seeking to verify the grade of a 3DPC element submits a query via a smart contract, which retrieves the corresponding production package from the blockchain and cross-checks its testing results against project specifications.

A materials scientist might request all packages tagged with a specific curing regime to analyse performance trends, with the smart contract filtering and aggregating data without exposing proprietary information.

This automation reduces reliance on intermediaries while enabling real-time compliance checks and peer-to-peer data sharing.

7.3 INTEROPERABILITY FOR PREDICTIVE ANALYTICS

Standardised schemas within production packages allow AI tools to parse historical data at scale.

For instance, a machine learning model could correlate extrusion speed and ambient humidity with compressive strength outcomes, identifying optimal parameters for a target grade; flag anomalies in real-time production data by comparing live sensor feeds against blockchain-stored benchmarks, triggering corrective adjustments.

8. Discussion and Future Developments

According to the tests conducted and the results obtained, it emerges that the design parameter corresponding to the infill strategy plays an important role in the definition of 3DPC. Existing attempts at standardising the specimens for determining 3DPC grade refer to single-filament constructs that might be representative of specific applications of 3DPC, such as hollow walls or formworks. However, when considering a broader range of applications, such as bespoke free-form structural elements, the slicing method becomes paramount. Our choice of adopting the cross-ply pattern made it possible to achieve a uniform M25 grade for vertical and lateral loads, allowing for complex production scenarios and the horizontal 3D printing of layers that will be oriented vertically once the element is assembled. This, in turn, opens up the possibility of laying complex rebar layouts within the horizontal 3D-printed layers, knowing that such rebars will be working on a vertical plane, and this circumstance might contribute to the embedding of shear-resistant elements inside 3DPC constructs, one of the challenges of current 3DCP production.

The w/i ratio shows a direct effect on the 3DPC grade: in our production setting, the optimal value of 15% maximises the grade and minimises the anisotropic behaviour of the specimen. However, this parameter is strictly

related to the ink composition, the 3D printing hardware and the production tools (mixer and pump); therefore, more testing is required to define whether our findings are generalisable and scalable or remain confined within our production setting. The involvement of other 3DCP labs, as per the above description, will help clarify this aspect.

One relevant finding regards the consistent good performance and grade of 3DPC for vertical load, which is maintained in sub-optimal conditions such as wrong w/i values or expired ink. This further strengthens our studies on stress-informed non-planar slicing, aiming at capitalising on the anisotropic behaviour of 3DPC for better structural performance.

This study conceptualises a blockchain as a stigmergic information layer (Dounas et al., 2022), utilising smart contracts and tokenisation to enable collective digital factories in construction. The proposed framework focuses on orchestrating a network of research labs, material scientists, and digital tools for building design, though its application can be extended to the entire AEC lifecycle. Our research specifically leverages this model of stigmergic coordination to accelerate international research in 3D Printed Construction (3DPC). The intrinsic global and collaborative nature of this endeavour makes it an ideal use case for a decentralised framework. A key goal is to facilitate the foundational work for establishing standardised codes and practices for building with the 3DPC technology. We posit that this model of coordination, powered by cryptoeconomics, is better suited to the construction industry's fragmented nature than current organisational modes, and it better supports the expansion of the concept of Decentralised Science.

As planned in the 2-step experiment, the future developments will focus on:

- Studying the correlation between w/i and ink composition.
- Uploading production packages and creating the production dataset, deploying the whole BTs-based process.
- Analysing the production dataset with AI.

9. Conclusions

In this work, we implemented the first part of our 2-step experiment for the streamlining and standardisation of 3DPC grade. Based on the experimental data from compression tests on 3DPC specimens, we verified the importance of the w/i ratio during the preparation of the concrete mix to maximise the mechanical performance, and we proposed the adoption of the cross-ply infill strategy for the slicing to reduce the anisotropic behaviour of the construct. We then described the encoding of the production package, in preparation for the intermediate phases of the experiment, which will consist of using BCTs

for creating the production dataset and AI for the analysis and optimisation of parameters and grade.

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FROM MOLD TO MODULE

A Scalable and Customizable Metal Formwork Generation Approach to Affordable Rammed Earth Housing

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Abstract. This study presents a generative design strategy—referred to as the 3M approach (Metal, Modular, and Mobile)—for developing reusable and scalable metal formwork systems tailored to rammed earth construction. Although rammed earth offers significant environmental benefits, its widespread adoption remains limited due to labor-intensive techniques and the lack of standardized, affordable molds. To address these challenges, a parametric model was developed using Rhino–Grasshopper and Python, enabling the rapid generation and optimization of formwork components. The proposed system employs lightweight 3 mm metal modules that can be assembled by small teams without heavy machinery, accommodating both standard and non-linear geometries. Demonstrated through three case studies of varying scales, the system supports flexible, efficient, and repeatable deployment.

Keywords: *Generative design, computational model, modular formwork, design for manufacture and assembly (DfMA), rammed earth.*

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1. Introduction

Rammed earth has reemerged as a sustainable and context-sensitive alternative for affordable housing, particularly in post-disaster and low-resource settings. Despite its ecological benefits and low embodied energy, its widespread adoption remains constrained by labor-intensive construction methods, skilled labor requirements, and the absence of adaptable formwork systems. This study introduces a generative 3M approach—Metal, Modular, and Mobile—to address these challenges through the development of a scalable and customizable metal formwork system tailored for rammed earth construction. The approach is designed to accelerate the delivery of durable, low-cost structures in emergency and resource-constrained contexts.

The 3M approach is the result of interdisciplinary collaboration among architects, civil engineers, and metal formwork manufacturers, emphasizing adaptability, human-scale deployment, and operational efficiency. While previous studies have investigated mold geometry and materials (Abdelaal et al., 2024; Werkhaizer et al., 2021), this research specifically employs 3 mm hot-rolled metal plates as the base material. The design follows widely acknowledged principles in formwork development—such as modularity, lightweight construction, and ease of handling without heavy machinery—as emphasized by Pan (2012). The resulting molds are robust yet lightweight, enabling assembly and disassembly by small teams without specialized equipment. Standardized components—such as 50 × 100 cm and 40 × 150 cm units—can be flexibly combined to construct structures ranging from 30 m² to 300 m². The system also accommodates non-standard applications, including curved walls and sloped geometries, enhancing versatility for diverse housing types and site conditions.

The proposed model was developed in Rhino 8.0 and Grasshopper, with custom Python 3.0 scripts. It processes wall layouts as curves and openings as input points, generating optimized formwork configurations. Three case studies—a compact 40–80 m² dwelling, a 300 m² community space, and a curved-wall prototype—demonstrate the system's adaptability, structural efficiency, and reduction in construction time. By minimizing unique components and streamlining workflows, the model offers scalable applications across varied project types while aligning with sustainable and circular design principles.

2. Theoretical Background

The growing interest in rammed earth construction is largely driven by its ecological benefits, including low embodied energy and reliance on locally available materials (Arar et al., 2024; Gulmus et al., 2024). However,

widespread implementation remains constrained by challenges such as limited scalability, the absence of standardized formwork systems, and high labor requirements. In response, this study proposes a generative design framework grounded in three core principles: durable and reusable materials, modular organization, and mobility. In the proposed approach, durability and reusability are achieved through the use of metal-based components, which offer structural strength, precision, and extended service life.

Rather than treating formwork as a temporary scaffold (Azambuja et al., 2025), the proposed approach reconceptualizes it as a reusable and adaptable construction element. The theoretical foundation builds upon three interconnected themes: the role of modularity in formwork design, the structural and lifecycle advantages of using metal, and the spatial as well as logistical flexibility enabled by portable systems. Collectively, these principles aim to enhance construction efficiency, reduce costs, and facilitate the broader adoption of earthen building techniques, particularly in post-disaster recovery efforts and resource-constrained environments.

2.1. MODULARITY

Modular and prefabricated formwork systems are increasingly adopted for their ability to reduce construction time, improve quality, and lower labor demands—especially in mass and affordable housing projects (Yang et al., 2023; Mandala & Nayaka, 2023; Bakale, 2024). Tunnel formworks, for example, have proven effective in accelerating project delivery in reinforced concrete construction.

Despite advancements in compaction techniques, rammed earth building still relies heavily on traditional, labor-intensive molds, which limits scalability (Gomaa et al., 2023). A major barrier remains the high cost of professional-grade molds, restricting broader application. Standardizing formwork components enables the prefabrication of rammed earth modules, enhancing efficiency and ensuring consistent quality. As Pan (2012) notes, large-scale production of standardized units reduces costs and supports flexible, repeatable systems.

Although rammed earth is not yet widely adopted in mainstream construction, its environmental advantages, adaptability to varied design needs, and formal flexibility position it as a promising alternative—particularly when supported by modular and scalable construction approaches.

2.2. METAL FORMWORK

Metal formwork systems offer superior durability, precision, and reusability compared to traditional materials such as timber or plastic. While timber

may have lower initial costs, it degrades quickly, whereas metal retains its shape over many use cycles, improving wall quality and reducing maintenance needs. Although the upfront investment is higher, repeated use makes metal significantly more cost-effective.

Aguilar Huerta et al. (2023) report that after approximately 20 cycles, metal formworks are 66% more efficient in terms of cost and performance. Contrary to common assumptions, metal systems can be relatively lightweight and easy to disassemble, enabling transport and assembly by small teams without heavy machinery—making them ideal in contexts with limited skilled labor or resources. Moreover, their extended reuse potential offsets their environmental footprint (Nilimaa et al., 2023; Li et al., 2022). By combining structural reliability with modular flexibility, metal formworks present a sustainable and scalable solution for rammed earth construction, particularly in projects prioritizing standardization and adaptability.

2.3. MOBILITY AND REUSE

Mobility and reuse are essential for creating sustainable and adaptable construction systems. Mobility allows components to be transported and reassembled across different sites, while reuse extends their service life. Together, these qualities reduce material production needs, simplify logistics, and improve economic efficiency.

In a sector responsible for approximately 40% of global resource consumption and waste, the selection of reusable formwork materials is crucial (Ness & Xing, 2017). Steel and plastic systems can be reused significantly more times than wood-based alternatives, substantially lowering waste generation and material demand (Li et al., 2022). Reuse also reduces structural costs, which can account for up to 25% of a project's total budget (Prajapati et al., 2014).

A circular economy perspective—emphasizing reduction, reuse, and recycling—further supports mobile systems as scalable infrastructure (Gregson et al., 2015; Goyal et al., 2018; Senem et al., 2025). The 3M approach aligns with this logic, proposing a lightweight, reconfigurable, and modular formwork system designed for repeated deployment across diverse construction contexts.

3. Methodology

Building on the theoretical foundations of modularity, material performance, and mobility, this section outlines the generative design approach adopted in the study. A parametric model was developed to generate, evaluate, and

optimize the proposed formwork system for rammed earth construction. The generative design approach refers to an iterative process in which rules, relationships, and algorithms define the output (Koh, 2014; Liu et al., 2018; Arar et al., 2024). Rather than starting from a fixed form, the design outcome emerges through rule-based logic, material behavior, and continuous feedback between digital and physical domains (Koh, 2014). The following subsections describe the structure and logic of the parametric model developed within this framework.

3.1. VARIABLES AND CONSTANTS

The parametric model was implemented using the Python Script component within the Rhino–Grasshopper environment. Table 1 presents the model's inputs, data types, and corresponding descriptions.

TABLE 1. Variables, Constants, and Data Types Used in the Parametric Model.

Name of the Item	Data Type	Description
wall	Polyline	Defines the outer boundary of the wall as a closed polyline
offsett_dist	int	Offset distance representing wall thickness
Window_xy	PointList	Center point of the window placement
Door_xy	PointList	Center point of the door placement
Window_radius	domain	Domain defining min and max values for window radius
Door_radius	domain (Grassshopper)	Domain defining min and max values for door radius using Rhino.Interval
wall_length	int (Python)	Overall length of the wall
wall_thickness	int (Python)	Wall thickness, cast as integer if not already
module_length_min	float	Minimum length of a single formwork module (between 1 and 100 cm)
module_length_max	float	Minimum length of a single formwork module (between 1 and 100 cm)

The algorithm takes the inner and outer boundaries of a structure—both represented as closed polylines of equal thickness in plan view—as inputs. It operates along the inner edge of the outer wall and performs several tasks: defining door and window openings as parametric intervals, optimizing the number of required formwork modules, and calculating the need for additional modules by applying an outward offset to the polyline.

3.2. RULES AND OPERATIONS

Rammed earth construction practices vary internationally, influenced by national standards and regulatory frameworks. For this study, the design and implementation of the formwork system were informed by established practices in the literature, adapting key operational guidelines for practical application.

Rammed earth walls are ideally constructed as continuous, monolithic elements; however, field conditions and variations in workmanship can result in joints or discontinuities (Alibeyoğlu, 2023). Door and window openings must comply with seismic code requirements for placement and size. Structural studies confirm that both 'L'- and 'T'-shaped wall intersections are feasible and safe in load-bearing earthen buildings (Bui, 2019). The rules embedded in the parametric model are as follows:

- The width of openings must not exceed 1.2 m and should remain below one-third of the total length of the corresponding wall (Minke, 2006).
- Continuous wall sections located between openings should measure at least one-third of the wall's height, with a minimum required length of 1 m (Minke, 2006).

All doors must be designed to open outward, and a large window or an additional outward-opening door should be positioned opposite the main entrance (Minke, 2006). The algorithm takes the inner and outer boundaries of a structure—both represented as closed polylines of equal thickness in plan view—as inputs. It operates along the inner edge of the outer wall and performs several tasks: defining door and window openings as parametric intervals, optimizing the number of required formwork modules, and calculating the need for additional modules by applying an outward offset to the polyline.

3.3. RELATIONS AND INTERDEPENDENCIES

The generative model incorporates a series of interrelated design constraints that reflect construction logic and practical assembly requirements. These dependencies are encoded into the algorithm to guide module placement, reduce complexity, and enhance on-site efficiency:

- Formwork alignment: Tie-rod holes and panel connections on inner and outer modules must be precisely aligned to maintain surface continuity.

- Module hierarchy and efficiency: The algorithm prioritizes standard modules, filling remaining gaps with secondary modules to minimize joint count and expedite installation.
- Opening integration: Window and door placements dynamically alter module sequences, potentially requiring custom units or omission of standard ones.
- Wall length adaptation: Wall lengths are rounded to the nearest 10 cm, when necessary, to match available module sizes and enable flexible yet practical construction.
- Integer handling and output validity: All length values are cast as integers to avoid rounding errors. If no valid configuration is found, the model returns an empty output, preventing unusable results.
- Deviation allowance: A ±10 cm tolerance in wall lengths allows the algorithm to generate buildable solutions when exact dimensions cannot be met.

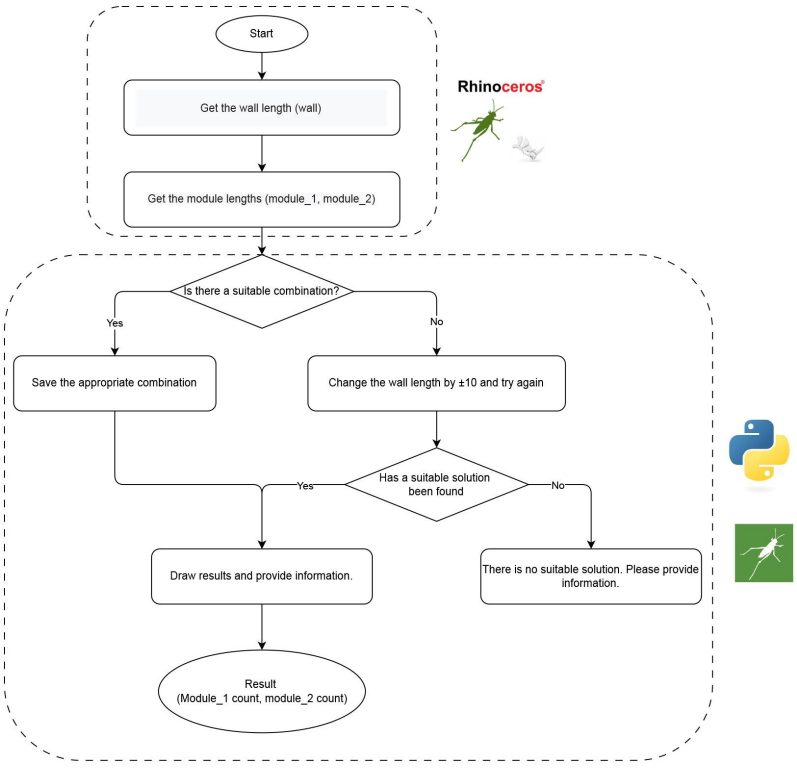


Figure 1. Algorithmic workflow for generating modular metal formwork configurations.

3.4. INPUT-OUTPUT AND FLOW

The computational model operates through a sequence of parametric rules that transform initial design inputs into optimized modular formwork configurations. As illustrated in Figure 1, the workflow begins with two primary inputs:

- The polyline representing wall geometry.
- A list of point coordinates defining door and window locations.

These inputs are processed through conditional checks and geometric operations. The model evaluates wall lengths, filters invalid values, and determines module combinations (module_1 and module_2) based on remaining wall segments. Boolean triggers control conditions such as wall-length tolerances, reuse priorities, and opening adjustments.

The algorithm seeks configurations that satisfy all constraints while minimizing the number of distinct module types. If no valid output is found, the system halts and returns an empty result to prevent infeasible solutions. The flowchart in Figure 1 summarizes this process, highlighting the interdependence of geometric logic and decision parameters in producing constructible and efficient outcomes.

4. Case Study

To evaluate the practical applicability of the proposed modular metal formwork system, three case studies of varying scale and geometry were selected.

4.1. SAMPLE SELECTION

The selected projects represent diverse spatial, functional, and formal characteristics, enabling the assessment of the system's adaptability (Figure 2).

- Case 1 (Arar et al., 2024): A compact single-family dwelling of approximately 70 m², characterized by rectilinear walls and orthogonal geometry. This case serves as a testbed for rapid deployment and efficient formwork placement.
- Case 2 (Url_01): A mid-sized public building of approximately 300 m², designed for communal use. This case evaluates the system's scalability, particularly in planning large wall spans with repetitive modules.
- Case 3 (Url_02): A curved-wall prototype incorporating non-linear geometries. This case examines the flexibility of the system in adapting to complex shapes and optimizing module usage for bespoke designs.

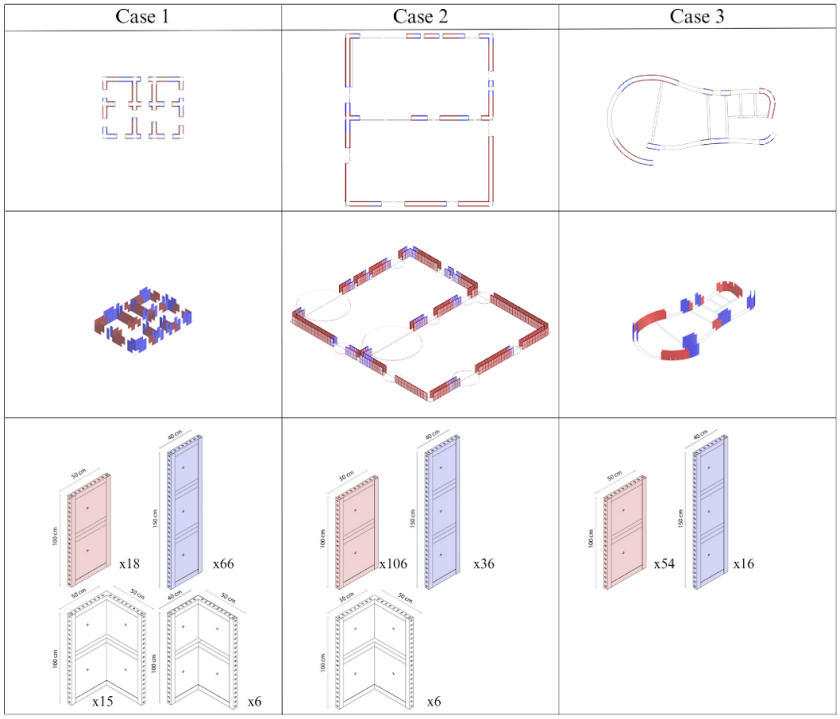


Figure 2. Diagrammatic wall layouts used in the case study (adopted by authors).

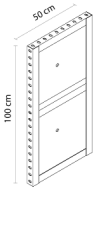
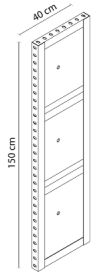
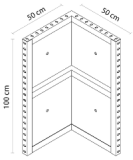
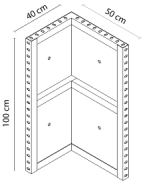
	module_1	module_2	corner module_1	corner module_2
module				
usage	edge/outer corner	edge/outer corner	inner corner	inner corner
placement	vertical/horizontal	vertical	vertical	vertical

Figure 3. Module typologies showing dimensions, edge/corner usage, and placement direction.

4.2. IMPLEMENTATION

- Case 1 – In this project, the construction planning and phases were predetermined. The wall lengths corresponding to each construction stage were provided to the system as discrete inputs. The system generated optimized module configurations, which were then integrated into Grasshopper commands to enable precise formwork placement.
- Case 2 – A sample project with an unknown construction schedule was selected. The required quantities of *module_1* and *module_2* were determined under the assumption that the building would be constructed in sequential phases, following the methodology of Case 1. For formwork placement, the external walls were parametrically defined as polygons in Grasshopper. Points were positioned at the centers of each opening, from which circles—having diameters equal to the lengths of the corresponding openings—were generated and subtracted from the polygon. The resulting linear elements were used as input data for the system, and the outputs were integrated back into Grasshopper to complete the computational workflow for formwork placement.
- Case 3 – Designated as a curved-wall prototype, this case used the lengths of individual wall segments between openings as discrete input parameters. The system generated output configurations, which were subsequently integrated into Grasshopper commands to parametrically position the formwork along the curves defining the wall geometry.

4.3. FINDINGS AND OUTCOMES

The Python script, executed within the Grasshopper environment, calculates the minimum number of formwork modules required to construct a given wall length using two predefined module widths (module_1 and module_2). This enables construction planning with the least possible amount of new fabrication. Wall lengths can be provided to the system in two ways:

- Polygon-based extraction – by subtracting door and window openings from a closed polygon representing the building's walls,
- Line-based input – by supplying each wall as an individual line segment.

This flexibility allows the algorithm to adapt to both straightforward and more complex project geometries. The system is compatible with phased construction workflows, meaning that walls can be built in stages based on available resources or scheduling needs. For sloped wall surfaces, however, the algorithm—currently designed to generate outer face modules as mirrored offsets of the inner face modules—would require the development of an additional connection detail to ensure proper alignment.

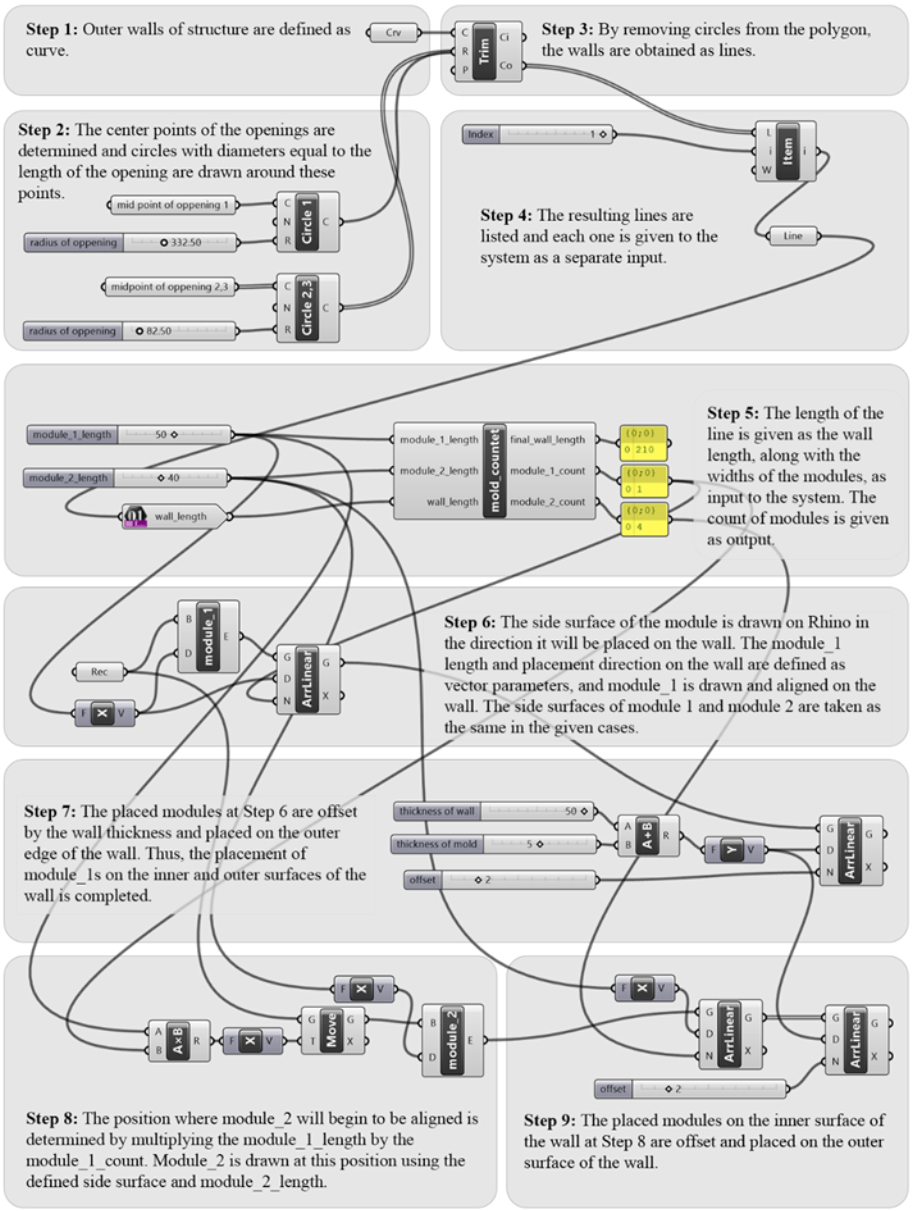


Figure 4. Grasshopper script used for Case 2.

In Case 2, for example, after subtracting 14 door and window openings from the building's outer polygon and one interior wall, the remaining polyline segments were split into individual lines, producing a total of 20 discrete wall segments. These were then entered into the model as separate input

lengths for formwork placement optimization. Quantitative results from the three case studies are as follows:

Case 1 – Compact 70 m² dwelling:

- Output: 66 × module_1 and 18 × module_2.
- All modules arranged vertically, fitting the rectilinear layout with minimal waste.

Case 2 – 300 m² communal space:

- Output: 156 × module_1 and 36 × module_2.
- Algorithm prioritized repetitive usage to maximize efficiency across longer wall spans.

Case 3 – Curved-wall prototype:

- Output: 54 × module_1 and 16 × module_2.
- Curvature caused challenges during boundary offsetting, occasionally producing invalid or overlapping segments. Despite this, the system adapted module placement to follow local curvature while maintaining construction feasibility.

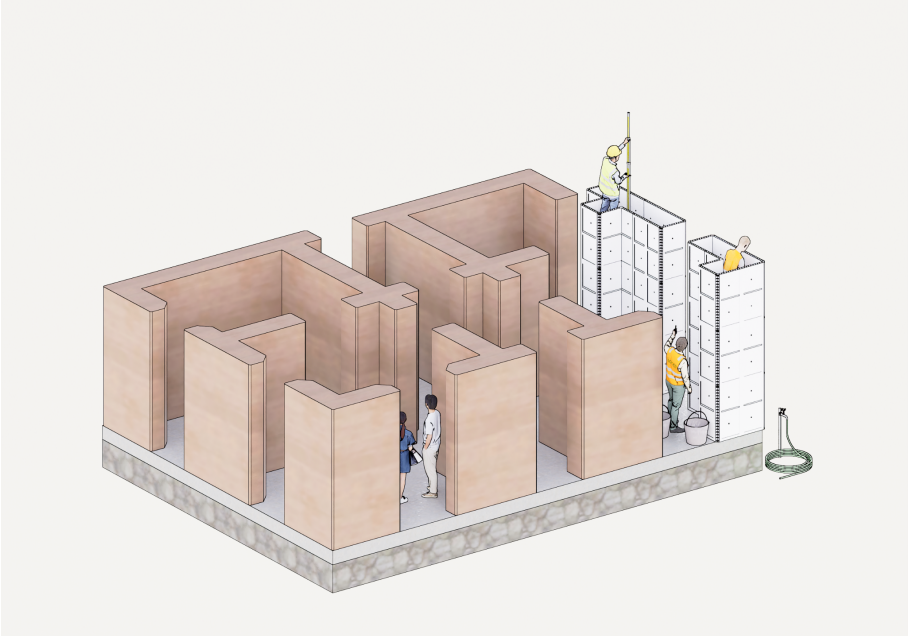


Figure 5. Visualization of construction.

Across all scenarios, the model complied with the predefined construction rules, minimized the number of unique module types, and avoided invalid configurations. The outputs demonstrate high adaptability, logical module distribution, and construction efficiency in varying spatial contexts.

5. Conclusion

This study introduced a generative, modular metal formwork system specifically designed for rammed earth construction, addressing the combined challenges of scalability, cost-efficiency, and adaptability. By embedding construction rules, material constraints, and assembly logic into a parametric framework, the algorithm was able to produce effective, repeatable configurations across diverse building typologies—from compact dwellings to large communal facilities and complex curvilinear prototypes.

Beyond its computational advantages, the proposed approach integrates principles of local fabrication, durability, and reusability, making it particularly relevant in low-resource or post-disaster contexts. The reliance on lightweight, standardized metal components enables rapid deployment by small teams without the need for heavy machinery, while the modular design ensures flexibility for both standard and non-standard geometries. This combination of adaptability and reusability aligns with circular economy principles, contributing to waste reduction and extended lifecycle performance.

With further refinement—particularly in handling complex geometries, integrating sloped or irregular surfaces, and field-testing the connection details—the system holds strong potential to scale sustainable construction practices. Ultimately, this work contributes to bridging traditional earthen building techniques with modern generative workflows, offering a replicable framework for affordable, community-driven, and environmentally responsible housing solutions.

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DEPLOYABLE RESILIENCE

Computationally Designed Scissor-Structures for Culturally Responsive Disaster Camps

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Abstract. Natural disasters such as floods, earthquakes, hurricanes, and conflict-driven displacement create large-scale humanitarian crises, leaving millions without adequate housing. Current emergency shelters often provide only temporary relief, failing to account for the long-term realities of displacement, with refugees residing in provisional camps for an average of 17 years (UNHCR, 2019). This research introduces a hybrid deployable system based on scissor-like kinematics, which enables rapid deployment, compact transport, and structural reusability. Textile-reinforced concrete (TRC) is employed as a secondary phase material to transition lightweight, collapsible shelters into durable long-term dwellings. The architectural inspiration derives from the Iranian Chahartaqi typology, offering spatial efficiency, cultural resonance, and symbolic grounding. The study adopts a research-through-design methodology, combining parametric modeling (Grasshopper3D), motion simulation (Kangaroo Physics), and iterative prototyping. The design emphasizes standardized pin-joint connections, facilitating ease of assembly, maintenance, and scalability. A transportation study demonstrates that collapsed modules, each measuring 1.2 × 0.6 × 1.4 m, allow up to 360 units to fit within a standard trailer, ensuring cost-effective logistics. Material selection prioritizes strength-to-weight efficiency and sustainability: aluminum alloy (6061-T6) for scissor members and PTFE-coated fiberglass for tensile membranes. Results confirm reliable deployability, strong correlation between digital simulations and physical behavior, and system reusability across multiple deployment cycles. By situating the proposed system within the broader discourse on hybrid structural skins (Liew, Popescu & Block, 2019) and textile-integrated construction (Popescu & Block, 2020), the paper advances a framework for shelters that bridge immediacy and permanence. The

findings contribute to resilient, culturally grounded, and computationally optimized design strategies for post-disaster housing.

Keywords: *disaster camp, temporary shelter, permanent shelter, post-disaster camp, natural disasters, deployable structures, retractable structures, scissors structures*

1. Introduction

The increasing frequency and intensity of natural disasters and conflicts worldwide have created an urgent need for shelter solutions that are both rapidly deployable and capable of transitioning into long-term housing. Existing emergency shelter systems often prioritize speed and logistics over cultural, social, and environmental considerations, resulting in inadequate living conditions and a lack of local identity. These shortcomings are particularly evident in Global South contexts, where imported design paradigms often clash with traditional spatial values and climatic needs. (Bendito, F. and Bris, P. (2019).

This research addresses the intersection of cultural heritage, computational design, and emergency architecture by proposing a transformable shelter system inspired by the Chahartaqi, an iconic element of Iranian vernacular architecture. The Chahartaqi typology—characterized by a domed structure supported on four piers—provides not only spatial efficiency and cross-ventilation but also embodies symbolic, historical, and climatic significance.

The proposed design integrates a scissor-like deployable mechanism for rapid assembly, coupled with textile-reinforced concrete (TRC) formwork to enable structural permanence. This dual-phase system allows for immediate shelter provision and subsequent transformation into dignified, durable dwellings—bridging the gap between the ephemeral and the permanent in humanitarian shelter design.

To realize this vision, the study employs parametric design tools (Grasshopper3D and Kangaroo Physics), structural simulation, and iterative prototyping to explore geometric, mechanical, and material configurations. Special attention is given to the material behavior of TRC under curvature constraints and its interaction with the scissor system. The research further reflects on the challenges of curing, performance testing, and cultural adaptation of such hybrid systems.

By synthesizing principles from deployable architecture, digital fabrication, and vernacular heritage, this paper contributes a culturally grounded, structurally resilient, and computationally optimized framework for post-disaster housing. It argues for a shift from generalized, Western-

centric approaches to localized, adaptive solutions capable of restoring both shelter and identity in the aftermath of crisis.

2. Literature Review

2.1. DEPLOYABLE SCISSOR STRUCTURES IN ARCHITECTURE

Scissor structures are composed of repetitive linear members joined by hinged connections, allowing synchronized folding and unfolding. Their geometric adaptability, modularity, and compactness make them highly suitable for emergency contexts where portability and rapid deployment are critical. De Temmerman (2007) and Roovers & De Temmerman (2015) introduced computational design strategies using circle-packing to generate efficient scissor grids, while Hoberman's patents (1991) demonstrated large-scale transformable applications in architecture. More recent applications confirm their relevance in post-disaster contexts, where they provide adaptable and lightweight frameworks without complex mechanical systems.

2.2 TEXTILE-REINFORCED CONCRETE (TRC)

TRC merges fine-grained concrete with high-performance textiles, producing thin, durable, and lightweight shells. Studies confirm its potential for creating doubly curved geometries with minimal formwork (Goldfeld et al., 2016; Moazzen, 2022). Popescu & Block's KnitCandela (2020) exemplifies how knitted and cable-net formworks can translate into structurally efficient freeform shells. These approaches align with this research's dual-phase concept, where deployable scissor frameworks are stabilized into permanent dwellings through TRC casting.

2.3 HYBRID STRUCTURAL SKINS

The integration of flexible and rigid materials has been explored in hybrid structural skin research. Liew, Popescu, & Block (2019) presented a prototype combining a glass-fiber-reinforced polymer (GFRP) elastic gridshell with a fiber-reinforced concrete envelope, demonstrating how elastic formwork systems can be braced by rigid materials. This principle informs the present study's vision of pairing scissor-based deployable systems with TRC shells to achieve both adaptability and permanence.

2.4 CULTURAL REFERENCING THROUGH THE CHAHARTAQI

The Iranian Chahartaqi typology—a domed square supported by four arches—remains a resilient architectural archetype with historical, spiritual, and climatic significance. Its square-to-dome transition lends itself to modular reconstruction while embodying cultural symbolism. Incorporating this typology provides displaced communities with a sense of continuity and rootedness, addressing critiques of Western-centric humanitarian design (Kamali, 2024).

2.5 PARAMETRIC DESIGN AND SIMULATION-BASED OPTIMIZATION

Parametric tools such as Grasshopper3D and Kangaroo Physics enable responsive modeling and real-time simulation of scissor kinematics and TRC behavior. Radziszewski (2015) and others have illustrated how optimization techniques balance structural constraints with architectural expression, ensuring feasible and context-sensitive outcomes.

2.6 TRANSFORMABLE ARCHITECTURE IN DISASTER RELIEF CONTEXTS

Emergency architecture has progressed beyond tents and prefabricated containers. Chamma & Mendoza (2016) and Friedman (2011) emphasize resilient design strategies that evolve from immediate relief to long-term habitation. This paper contributes to this discourse by hybridizing deployable scissor frameworks with TRC shells, culturally anchored in the Chahartaqi typology, to provide adaptable and dignified housing solutions.

3. Conceptual Framework

The conceptual foundation of this project is rooted in the Chahartaqi (Figure 1), a typology defined by four load-bearing pillars supporting a central dome. Historically, the Chahartaqi symbolizes cosmological order and spatial clarity in Persian architecture. Its square-to-circle transition lends itself well to modular decomposition and parametric reconstruction.
To enable deployability, the Chahartaqi's dome geometry was translated into a hyperbolic paraboloid grid, which could be articulated using scissors mechanisms. This transformation maintains the spatial language of the original structure while introducing kinetic adaptability.

The parametric model was developed using Grasshopper, incorporating constraints on member lengths, joint angles, and deployable radius. Force simulations via Kangaroo ensured that the structural form could expand and

collapse efficiently. A secondary layer, conceived as a concrete textile shell, provides weatherproofing and permanence once deployed.



Figure 1. Chahartagi [https://www.mizanonline.ir, https://www.iranview.ir]

4. Methodology

This study adopts a research-through-design methodology that combines computational modeling, historical typological analysis, and physical prototyping to explore an innovative approach to transitional architecture. The workflow follows five interrelated phases: contextual research, parametric design development, joint and connection detailing, transportation logistics, material prototyping, and sequential deployment strategies.

4.1. CONTEXTUAL AND TYPOLOGICAL RESEARCH

The design process began with a cultural and historical study of the Chahartaqi typology, a domed square supported by four arches prominent in Iranian heritage. Diagrams and spatial mappings were generated to analyze geometric proportions, vault articulation, and spatial organization. This step provided a symbolic and spatial framework to ground the technical development in local architectural logic. Archival references and Persian-language dissertations were reviewed to establish parameters for cultural resonance and structural compatibility.

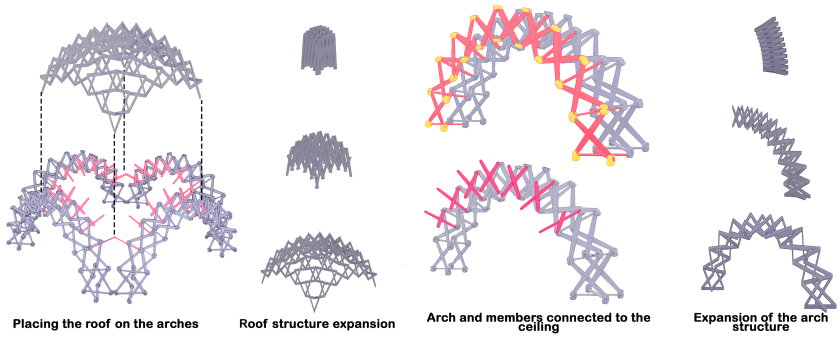


Figure 2. The model of placing the structure, arch members, and expansion of the arch structure, demonstrating the collapse state and fully deployed.

4.2. USER-CENTERED ASSEMBLY AND TRAINING PROTOCOL

The proposed shelter system was developed with an emphasis on accessibility for end-users, many of whom may have limited construction experience. To reduce dependency on specialized labor, the scissor modules employ standardized pin joints and snap-fit connectors that allow intuitive assembly with minimal tools. Components are color-coded and numerically labeled to guide sequence and orientation, thereby preventing assembly errors. Training is envisioned as an integral part of the deployment strategy: illustrated manuals and step-by-step diagrams would accompany each module, while local workshops or demonstrations conducted by aid workers can familiarize communities with the system before full-scale construction begins. Where digital infrastructure permits, augmented reality (AR) applications could further enhance user comprehension by overlaying assembly instructions directly onto components. By embedding these training mechanisms into the design process, the system promotes efficiency, reduces the risk of misuse, and empowers displaced populations to actively participate in building their own shelters. This participatory approach not only accelerates deployment but also fosters community ownership and resilience in post-disaster recovery.

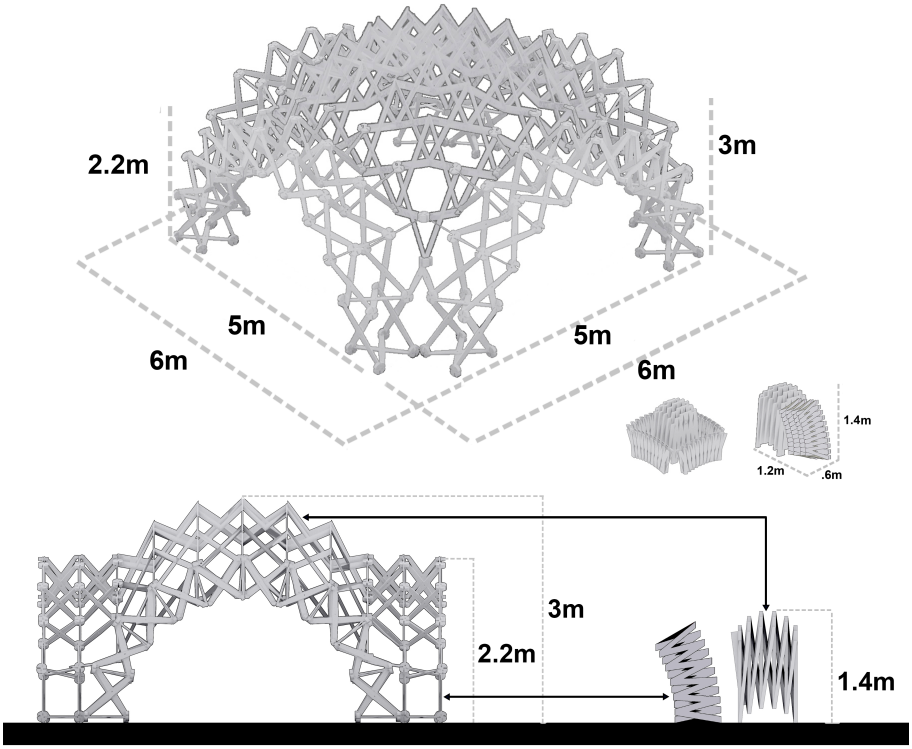


Figure 3: Measured dimensions of the scissor-structure-based dome in its fully deployed and collapsed states, demonstrating the compact-to-expanded transformation range

4.3. JOINTS AND CONNECTIONS

All scissor members were designed with standardized pin joints, minimizing fabrication complexity and enabling rapid on-site assembly. Using a single type of hinge improved scalability, reduced manufacturing costs, and ensured reliability during repeated folding and unfolding cycles. This connection logic also supports long-term durability and simplifies maintenance in resource-limited contexts.

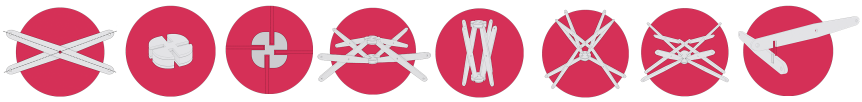


Figure 4. Connection details of the scissor structure. The diagram illustrates the standardized pin-joint system used across all members, highlighting its role in enabling synchronized deployment, structural stability, and simplified fabrication

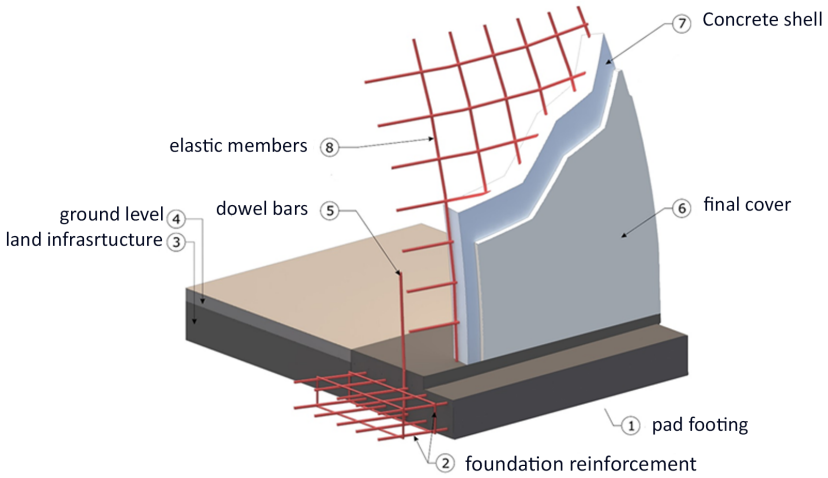
4.4. TRANSPORTATION LOGISTICS

Collapsed modules measure 1.2 × 0.6 × 1.4 m. A standard 13.6 × 2.5 × 2.7 m trailer can accommodate approximately 360 modules, underscoring the system's transport efficiency. This compactness significantly reduces logistical costs and accelerates deployment in post-disaster contexts, where rapid mobility is critical.

Figure 5. Transportation logistics of collapsed modules. The image shows a worker using a lifting machine to load modular units into a standard trailer, emphasizing compactness and efficiency in post-disaster deployment.

4.5. MATERIAL AND CONSTRUCTION PROTOTYPING

The scissor members were specified as aluminum alloy (6061-T6), chosen for its lightweight strength, corrosion resistance, and recyclability. PTFE-coated fiberglass served as the tensile membrane, valued for its UV resistance, translucency, and durability. Textile-Reinforced Concrete (TRC) was cast over deployed textile meshes to stabilize the geometry, drawing on techniques outlined by Popescu & Block (2020). Prototype testing assessed pourability, curing behavior, and long-term structural stability.



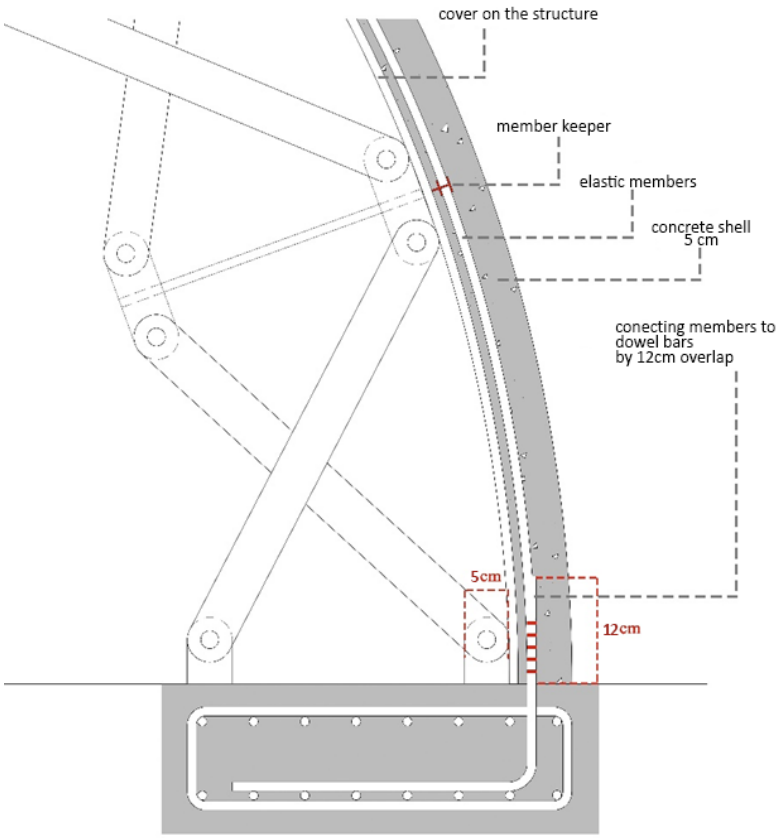


Figure 6. Foundation and anchoring detail. The drawing illustrates pad footings, foundation reinforcement, dowel bars, elastic members, and the concrete shell, showing how the system integrates with ground-level infrastructure to ensure stability.

Figure 7. Sectional assembly detail. This diagram demonstrates the connection between members and dowel bars, the layered construction of elastic members and concrete shell, the role of member keepers, and the protective cover.

4.6. REUSABILITY AND SEQUENTIAL DEPLOYMENT

A defining feature of the system is reusability. Each scissor module can be deployed, collapsed, and redeployed multiple times, extending its lifecycle. Critically, modules can serve as sequential formworks: once a TRC shell is cast and stabilized, the scissor structure can be collapsed and reused to form another unit. This iterative process reduces overall material demand, enabling scalable production of permanent shelters with minimal resources.

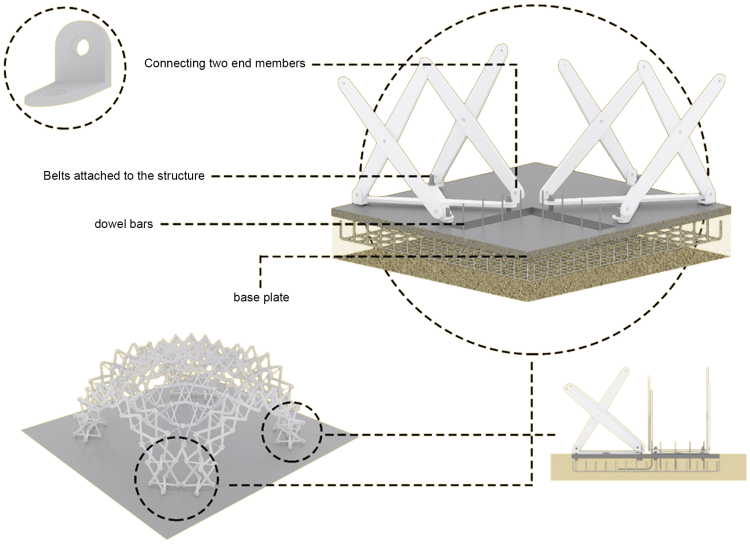


Figure 8. Ground connection detail, depicting how scissor members are anchored to the site and connected to each other, ensuring both structural rigidity and modular reusability.

4.7. REUSABILITY AND SEQUENTIAL DEPLOYMENT

The computational design process was developed within the Grasshopper environment, where parametric definitions controlled the scissor modules through constraints on rotational angles and member lengths. These parameters established a flexible yet rule-based system capable of generating multiple geometric iterations. Kangaroo Physics was employed to simulate the kinematic behavior of the assemblies in real time, enabling the evaluation of deployment sequences, equilibrium states, and geometric stability during transformation. Through iterative exploration, variations in dome height, span, and the number of radial scissor arms were systematically tested, allowing the identification of configurations that balanced structural efficiency with spatial performance.

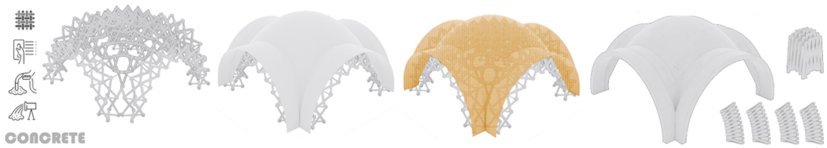


Figure 9: Fully deployed prototype of the scissor-structure dome covered with a textile-reinforced concrete (TRC) shell, demonstrating the transition from a flexible kinetic system to a stabilized permanent shelter.

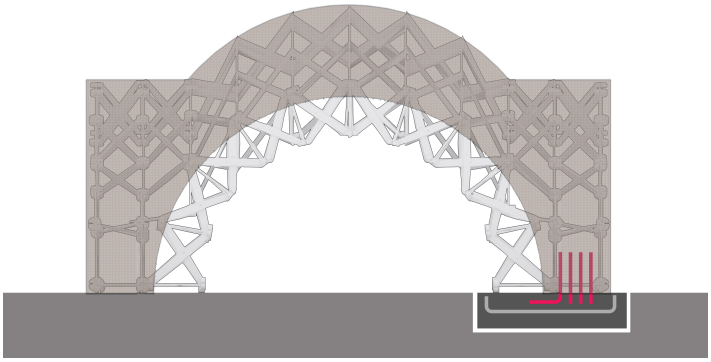


Figure 10. Service elevation of a single unit. The elevation drawing shows the integration of wires and pipes into the structure, illustrating how utilities are incorporated into the modular system for long-term habitability.

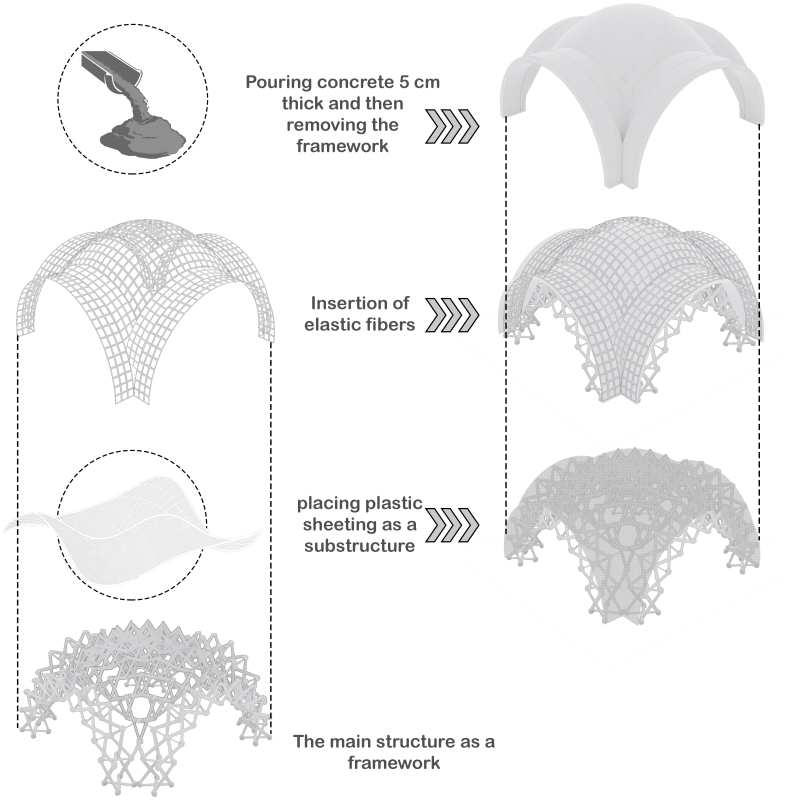


Figure 11. Step-by-step process of forming the textile-reinforced concrete (TRC) shell over the deployed scissor structure. (a) Pouring a 5 cm thick TRC layer; Removing the temporary mold and framework; (b) Inserting elastic fibers to enhance flexibility and crack resistance; (c) Placing fiber-reinforced sheets as a substructure to support and (d) shape the final shell form.

4.8. WALL CONSTRUCTION DETAILS AND MATERIAL HIERARCHY

In the development of the deployable shelter transitioning to a permanent structure, detailed wall sections were designed to reflect both structural logic and cultural appropriateness. These sections aim to balance local construction practices with thermal and material efficiency.

The first wall section begins with a row of traditional bricks at the top, followed by diagonal brick patterns that serve both structural and aesthetic purposes. Beneath these is a composite concrete block acting as a structural core, with polystyrene insulation forming the inner layer for thermal performance. This composition blends vernacular techniques with lightweight insulating systems to support comfort in diverse climates.

The second wall section adopts a more infrastructural approach. It starts with Robbit mesh, which is coated with cement-sand mortar to create a durable surface. This is followed by a side wall post, functioning as a vertical support element, braced by a strap for lateral stability. At the base, a central stone anchors the wall, providing foundational solidity.

Together, these sections illustrate a spectrum of strategies—from ornamental masonry to structural pragmatism—highlighting how material layering contributes to the architectural, cultural, and environmental resilience of the shelter system.

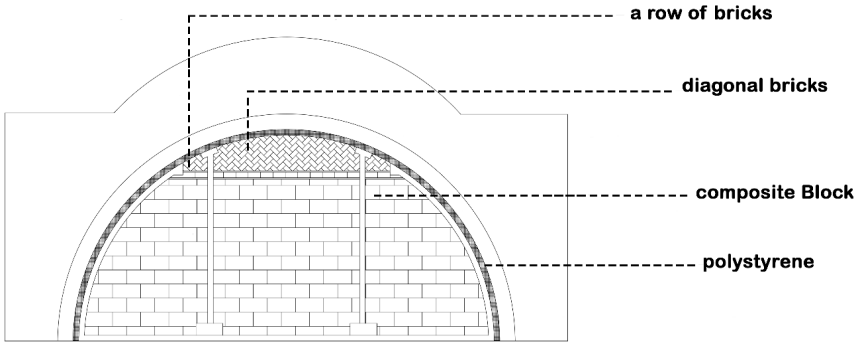


Figure 12. Wall section 1 illustrating layered materials from top to bottom: (1) traditional brick course, (2) diagonal brick bond for visual patterning and distribution of forces, (3) composite concrete block for primary structure, and (4) polystyrene insulation for thermal performance

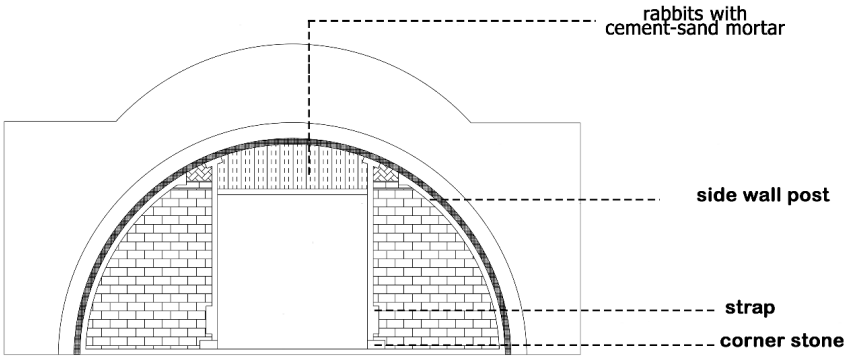


Figure 13. Wall section 2 showing the structural layering: (1) Robbit mesh coated with cement-sand mortar, (2) vertical side wall post for load transfer, (3) horizontal strap element for bracing, and (4) central stone footing for anchorage

4.9. PHYSICAL MODELING AND VALIDATION

To bridge the gap between digital design and real-world feasibility, a scaled physical model of a hyperbolic paraboloid scissor structure was fabricated. The form was selected based on its inherent structural efficiency and deployability, aligning with principles discussed in De Temmerman's and Roovers' work on circle packing and scissor-grid logic. The physical prototype was constructed using lightweight rods connected by pivot joints, allowing for controlled expansion and retraction. The hyperbolic surface was tested for deployability, spatial rigidity, and visual impact.

This hands-on experiment not only validated the computational simulations developed in Grasshopper and Kangaroo but also offered insight into joint behavior, spatial tolerances, and load transfer. Observations from the model were instrumental in refining the scale and form of the deployable shelter's final proposal.

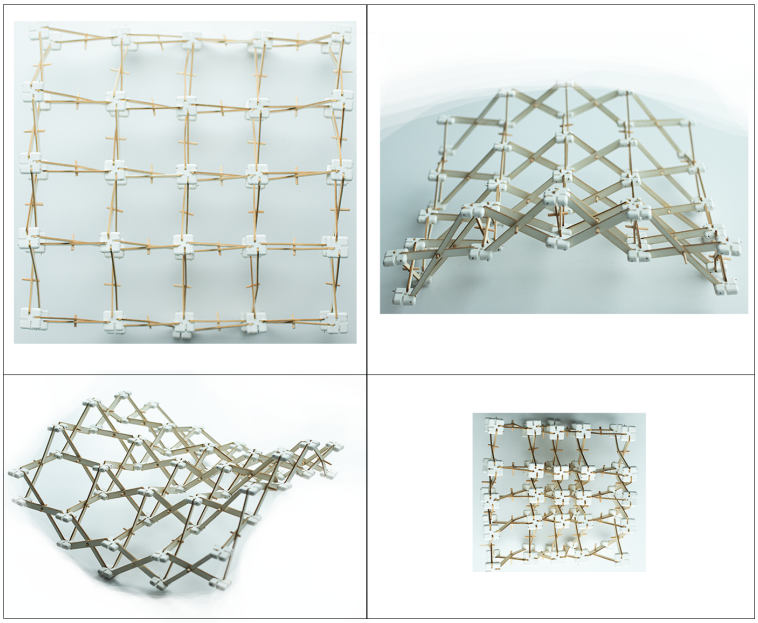


Figure 14. Physical model of the hyperbolic scissors structure demonstrating deployability and curvature.

4.10. DEPLOYMENT MECHANISM AND FINAL PROTOTYPE DEMONSTRATION

To evaluate the feasibility of the scissor-based deployable dome, a full physical prototype was developed illustrating both its collapsed and fully deployed states. This model represents the culmination of the geometric studies, material experimentation, and simulation iterations discussed in the previous sections. The collapsed form confirms the compactness and portability of the shelter, making it suitable for rapid deployment in emergency contexts. Meanwhile, the deployed configuration validates the spatial efficiency and structural stability anticipated in digital simulations.

This hands-on exploration provided key insights into the behavior of hinge connections, the interaction of components under real-world constraints, and the effects of tolerances and material flexibility.

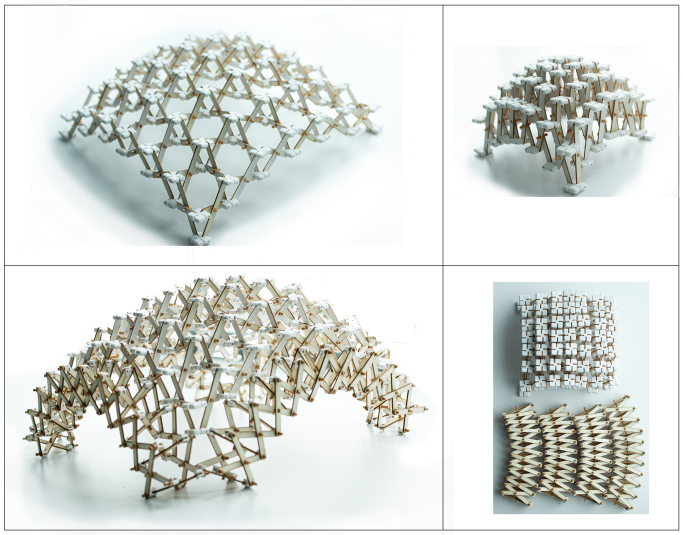


Figure 15. Physical model of the final structure demonstrating the collapse state and fully deployed state of the final dome and curvature.

5. Results and Discussion

5.1. STRUCTURAL BEHAVIOR AND DEPLOYABILITY

The deployable scissor-like structure demonstrated high efficiency in its transformation between compact and expanded states. The modular system, developed through parametric modeling, exhibited kinematic stability and geometric flexibility during simulation. By utilizing rotational joints and uniform-length members, the structure could be folded into a minimal volume for transportation and then deployed into a full-scale spatial system. These findings validate the effectiveness of geometric control through circle packing strategies, enhancing predictability and design precision.

5.2. SPATIAL PERFORMANCE AND CULTURAL SYMBOLISM

The reinterpretation of the Chahartaqi typology played a central role in establishing spatial identity and psychological comfort. The cross-in-square layout with a central vaulted space, common in Persian heritage, was preserved in the scissor-based configuration. This formal continuity allowed the structure to evoke a sense of belonging and rootedness, even in the context of displacement. The open central core offered natural ventilation and lighting, while also serving as a gathering space—an element essential for post-disaster community cohesion.

5.2. TRANSITION TO PERMANENT STRUCTURE

The transition from a temporary shelter to a permanent housing solution was made possible through the integration of textile-reinforced concrete (TRC). Once deployed, the scissor framework was stabilized with textile mesh and subsequently sprayed or cast with TRC, creating a lightweight yet durable shell. This duality of function—mobility and permanence—ensures both rapid deployment and long-term usability. The use of TRC addressed challenges of material scarcity, structural efficiency, and construction time in post-crisis scenarios.

5.3. ASSEMBLY AND CONNECTION STRATEGY

The modular nature of the system facilitated fast and intuitive assembly, emphasizing user-centered deployment. Each unit was designed to be erected with minimal tools and by unskilled laborers, relying on standardized pin joints, color-coded elements, and snap-fit connections to guide correct placement. This reduced dependency on specialized workers while empowering communities to participate directly in the construction process.

Specific attention was given to foundation anchoring, ceiling closures, and wall junctions, with modular details simplified into repeatable sequences. Training integration was envisioned through illustrated manuals, pre-deployment workshops, and, where possible, augmented-reality (AR) guidance to minimize error in unfamiliar contexts. These strategies collectively aimed to minimize construction time while ensuring stability, safety, and environmental protection under variable site conditions. By embedding training into the deployment process, the system not only accelerates shelter provision but also strengthens community resilience and long-term adaptability.

5.4. LIMITATIONS AND CONSIDERATION

Despite the promising results, certain limitations emerged. The environmental performance of textile-reinforced concrete (TRC) under varying climatic conditions remains insufficiently studied. Fluctuations in humidity can affect the bond between textile reinforcement and the cementitious matrix, potentially leading to microcracking or reduced durability, while high temperature variations may accelerate shrinkage, creep, and long-term fatigue. In hot–humid contexts, such as tropical or subtropical regions, TRC shells may require protective coatings or admixtures to improve resistance to moisture ingress and thermal expansion.

Conversely, in arid climates, rapid moisture loss during curing could compromise shell integrity without proper curing protocols.

Additionally, the transformation process from deployable to rigid state requires coordination and precision that may challenge inexperienced users. Finally, while the scissor system supports deployability, its compatibility with the structural behavior of hardened TRC shells warrants further testing, particularly in relation to joint stress concentrations and long-term serviceability.

6. Conclusion

This study proposes a hybrid shelter system that bridges the gap between emergency deployability and long-term permanence by synthesizing computational design techniques, vernacular architectural typologies, and innovative material systems. By reimagining the Iranian Chahartaqi as a modular, scissor-like deployable framework stabilized through textile-reinforced concrete, the project offers a culturally rooted, structurally efficient, and socially responsive solution for post-disaster housing.

The research demonstrates that parametric modeling and circle-packing algorithms can be used to optimize scissor structures not only for compact deployment but also for meaningful spatial articulation. The integration of TRC as a permanent material allows these lightweight, transformable geometries to transition into durable architectural shells. This dual-state adaptability directly addresses the temporal and logistical challenges of emergency shelter, while promoting a more dignified and culturally resonant architectural language.

While the system's potential is significant, it also introduces new technical and social considerations. Further investigation is required into the curing conditions, environmental performance, and material behavior of TRC in diverse climatic contexts. Moreover, user-centered prototyping and feedback loops are essential to ensure the structure's feasibility in real-world humanitarian deployment scenarios.

Ultimately, this research contributes to the broader discourse on decolonizing shelter design by prioritizing local architectural heritage, participatory construction methods, and sustainable material use. It opens up a critical pathway for the development of shelter systems that are not only fast and flexible but also meaningful and enduring**.**

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THE IMPACT OF ROBOTIC 3D PRINTING AND ARTIFICIAL INTELLIGENCE ON FACADE REVITALIZATION

A Case Study: The Old City of Sana'a

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Abstract. The Fourth Industrial Revolution is significantly altering the Architecture, Engineering, and Construction (AEC) industry, as Artificial Intelligence (AI) and robotics have become essential to design and execution. These technologies provide dynamic design frameworks, anticipatory analytics, and intelligent robotic execution capabilities. This article examines the crucial function of AI and robotics, particularly AI-assisted Robotic 3D Printing (R3DP), in improving efficiency, facilitating architectural innovation, and promoting design sustainability in the upkeep and reinterpretation of building facades. The ancient Al -Qasimi House's facade renovation is the main subject of the research. It blends cutting-edge digital technology with conventional design logic, which is distinguished by intricate geometric designs and environmentally friendly material usage. Machine learning algorithms are used to extract artificial intelligence-based patterns from existing facade elements, enabling accurate digital capture and precise analysis of the complex traditional motifs. Generative design modeling, based on the extracted patterns and structural analyses, explores innovative, context-sensitive, and reinterpretable design solutions. Finally, robotic 3D printing (R3DP) simulations are applied to these generative models, demonstrating the feasibility of customized additive manufacturing for the facade. This integration markedly enhances productivity by automating the analysis and design iteration processes, hence diminishing manual work. Architectural innovation is facilitated by equipping designers with instruments to investigate a wide spectrum of design options grounded in classical aesthetics while challenging modern limits. This method improves sustainability by enabling accurate material deposition in R3DP, resulting in substantial waste

reduction and optimum resource utilization. The capacity to produce custom components on-site enhances the longevity of ancient structures by facilitating precise and resilient repairs, hence reducing the necessity for total replacement. The study illustrates the appropriateness of machine learning, computer vision, and robotic manufacturing for safeguarding cultural heritage while facilitating creative architectural solutions. The approach created provides a generalizable framework and a reproducible procedure for incorporating AI and robotics in heritage preservation across many architectural settings, making it more than just a demonstration application. We anticipate a substantial decrease in material waste, a measurable speedup of design iterations, and the development of a new paradigm for sustainable heritage conservation that strikes a balance between tradition and technology.

Keywords: *Artificial Intelligence, Robotic 3D Printing, Architectural facades, Additive Manufacturing, Old City of Sana'a.*

1. Introduction

One of a building's most intricate features is its facade. In addition to shaping a building's architectural expression, they serve as a barrier between the interior and outside environments, regulating the movement of matter and energy from the latter into the former. As a result, they significantly affect the comfort of the user, the environmental conditions of indoor spaces, and the energy efficiency of the structures (Leschok, M., Cheibas, I., Piccioni, V., Seshadri, B., Schlüter, A., Gramazio, F., Kohler, M. and Dillenburger, B., 2023).

Research on the impact of robotic 3D printing and artificial intelligence (AI) on façade revitalization has emerged as a critical area of inquiry due to its potential to transform architectural design, enhance structural integrity, and foster material innovation in heritage contexts (Milano, F., Gamote, R.P., Olivo, N.E., Piccioni, V., Chen, P.Y., Gallagher, C., Schlueter, A., Dillenburger, B., Luible, A., Gramazio, F. and Kohler, M., 2024., Guamán-Rivera, R., Martínez-Rocamora, A., García-Alvarado, R., Muñoz-Sanguinetti, C., González-Böhme, L.F. and Auat-Cheein, F., 2022).

The advancement of additive manufacturing in building has transitioned from initial material and procedural investigations to advanced integrations of robots and artificial intelligence, allowing customized, large-scale façade elements with enhanced performance (Naboni & Jakica, 2022).

As technology advances and societal demands change, so does architectural design and production. Architecture must adjust to new design

and fabrication techniques in the mass production and robotics-driven environment of today (Yabanigül, Meryem N., Derya Gulec Ozer. 2025).

The industry's ability to adjust to these technological breakthroughs and continuous research efforts make this adaptability possible (Lowke, D., Anton, A., Buswell, R., Jenny, S.E., Flatt, R.J., Fritschi, E.L., Hack, N., Mai, I., Popescu, M. and Kloft, H., 2024). Construction robot-assisted 3D printing speeds up the production of intricate geometric structures while lowering labor costs and material waste, all of which support the construction industry's sustainable and environmentally friendly growth (Xu, Z., Song, T., Guo, S., Peng, J., Zeng, L. and Zhu, M., 2022). Automation, like other engineering fields, is progressively becoming a crucial part of architecture as breakthroughs in Artificial Intelligence (AI) optimize numerous processes and augment design skills (Živković, Milijana, Maša Žujović, and Jelena Milošević., 2023).

Notwithstanding swift progress in robots, their utilization in building continues to be a nascent field of research. The use of robots in building processes increases efficiency by facilitating uninterrupted operations and substituting human labor in dangerous settings (Barjuei, E.S., Capitanelli, A., Bertolucci, R., Courteille, E., Mastrogiovanni, F. and Maratea, M., 2024).

Manipulators for construction 3D printers, as seen in Fig. 1, exhibit the robotic platforms utilized in the additive manufacturing sector (Mycroft, W., Katzman, M., Tammas-Williams, S., Hernandez-Nava, E., Panoutsos, G., Todd, I. and Kadirkamanathan, V., 2020).

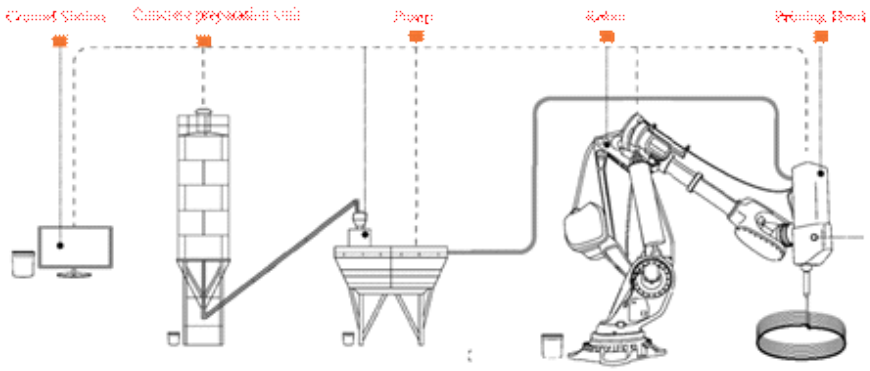


Figure 1. An example of a robotic arm 3D printer with some main components. Adaptive form (Roux, C., Kuzmenko, K., Roussel, N., Mesnil, R. and Feraille, A., 2023.

The printing procedure for each object is a distinct endeavor (Mycroft, W., Katzman, M., Tammas-Williams, S., Hernandez-Nava, E., Panoutsos, G., Todd, I. and Kadirkamanathan, V., 2020). making it difficult to anticipate

every event that occurs throughout the 3D printing process and to pre-program the robot appropriately. As a result, the robotic platform's ability to instantly adapt to the dynamic process condition is a difficult task (Delgado, J.M.D., Oyedele, L., Ajayi, A., Akanbi, L., Akinade, O., Bilal, M. and Owolabi, H., 2019). By preventing mistakes and saving time, AI applications in the additive manufacturing sector may greatly enhance process performance. By working independently and assessing the results of past acts, AI systems are able to modify their behavior to a certain degree (Mohammadpour, A., Karan, E. and Asadi, S., 2019).

Historical urban centers worldwide stand as testaments to human ingenuity, cultural evolution, and architectural prowess. Their facades, often intricate and laden with historical narratives, are particularly vulnerable to the ravages of time, environmental factors, and, increasingly, conflict. The preservation and revitalization of these facades are not merely aesthetic endeavors but crucial acts of safeguarding collective memory and cultural identity. However, traditional restoration methods are often labor- intensive, time-consuming, and can struggle to replicate complex historical details with precision and cost-effectiveness (P. K. Singh 2023). This challenge is acutely felt in regions like the Old City of Sana'a, a UNESCO World Heritage site, where centuries of unique mud-brick architecture face existential threats from neglect, natural decay, and ongoing geopolitical instability (Sana'a Center 2021). The advent of advanced technologies, particularly robotic 3D printing and artificial intelligence (AI), presents unprecedented opportunities to revolutionize the field of heritage preservation and facade revitalization. Robotic 3D printing, with its ability to fabricate complex geometries with high accuracy and efficiency, offers a promising avenue for the precise reproduction of damaged or missing architectural elements (V. S. Kumar 2025). This technology can significantly reduce material waste and construction time, making restoration projects more sustainable and economically viable (Arthur 2025).

The emergence of new technology, notably robotic 3D-printing and artificial intelligence (AI), offers unparalleled prospects to transform heritage preservation and facade rehabilitation.

1.1. ROBOTIC 3D PRINTING IN CONSTRUCTION

Applications of robotic 3D printing in architecture are expanding swiftly, facilitating the incorporation of novel materials and customized shapes (Nicholas, P., Rossi, G., Williams, E., Bennett, M. and Schork, T., 2020). Robotic 3D - printing has many advantages over conventional construction, as it reduces human error, is relatively inexpensive, and opens the door to

creative, complex designs while reducing the amount of expertise required to complete the process of construction (Cabibihan, J.J., Gaballa, A., Fadli, F., Irshidat, M., Mahdi, E., Biloria, N., Mansour, Z. and Abdulrazak, H., 2023).

Architectural design and manufacturing are ever advancing in response to technical innovations and societal demands. In the contemporary age marked by mass manufacturing and automation, architecture must adjust to innovative design and fabrication techniques (Khalili-Araghi, S. and Kolarevic, B., 2020). In the contemporary age defined by mass manufacturing and automation, architecture must adjust to novel design and fabrication techniques (Yabanigül, M.N. and Gulec Ozer, D., 2024). Although 3DCP has evolved for over two decades, it is currently more accessible than ever for both industrial and research sectors (Gamage, K., Fawzia, S., Zahra, T., Teixeira, M.B.F., and Ramli Sulong, N.H., 2024).

A primary benefit is the capacity to fabricate complex designs without molds, rendering it especially appealing for bespoke building (Perrot, A., Jacquet, Y., Rangeard, D., Courteille, E. and Sonebi, M., 2020). The possible application of 3DCP in the structure sector is becoming increasingly apparent as research in this area proliferates. With 3DCP technology's growing potential for manufacturing in numerous sizes, the industry is adopting it at an increasing rate (Sanjayan, J.G. and Nematollahi, B., 2019).

These facades need to be preserved and revitalized in order to protect cultural identity and communal memory, which goes beyond simple aesthetics. But conventional restoration techniques are sometimes time-consuming, labor-intensive, and may not be able to accurately and economically reproduce intricate historical features (Singh, 2023). Regions such as the Old City of Sana'a, a UNESCO World Heritage site, whose centuries of distinctive mud-brick architecture confront existential threats from neglect, natural disintegration, and persistent geopolitical turmoil (Sana'a Center for Strategic Studies, 2021).

Artificial intelligence (AI) and robotic 3D printing in particular offer previously unheard-of potential to transform the fields of façade restoration and heritage protection. A possible method for accurately replicating missing or damaged architectural features is robotic 3D printing, which can create complicated geometries with great efficiency and accuracy (Kumar, 2025).

While various studies have focused on large-scale 3D construction capability (3DCP) structures, this paper presents a new approach. This paper explores the transformative potential of integrating robotic 3D printing and artificial intelligence (AI) in facade restoration, with a particular focus on historic facades. The study focuses specifically on the Old City of Sana'a, a UNESCO World Heritage Site. Sana'a's unique architectural heritage faces significant challenges due to conflict, environmental degradation, and the complexities of traditional restoration methods. AI has the potential to

analyze and evaluate facades, with the potential to improve materials and design alternatives. These innovations and technologies demonstrate their potential not only for analysis and evaluation but also for ensuring sustainability and combining research with technological evaluation.

This study seeks to demonstrate how these advanced technologies can offer innovative and sustainable solutions for facade restoration. The paper will examine the status of robotic 3D printing and AI applications in construction and heritage, propose a conceptual methodology for their combined deployment in Sana'a, and discuss the implications, challenges, and potential future directions of this integrated approach. Ultimately, this research contributes to the broader debate about leveraging technology to preserve cultural heritage, providing a model for similar initiatives at other endangered historic sites around the world.

2. Methodology

The different architectural characteristics in the given façade image were highlighted and delineated in this study using AI-based image refining techniques. Visually separating recurring motifs and distinctive design features for more research is the goal of this technique. It was conducted in a specific sequence: a preliminary analysis of a historic façade of the Old City of Sana'a, through which the focus was on extracting architectural patterns, decorative elements, and structural motifs. The process aims to pave the way for artificial intelligence-based pattern extraction, generative design modelling, and robotic manufacturing simulation. Fig. 2.

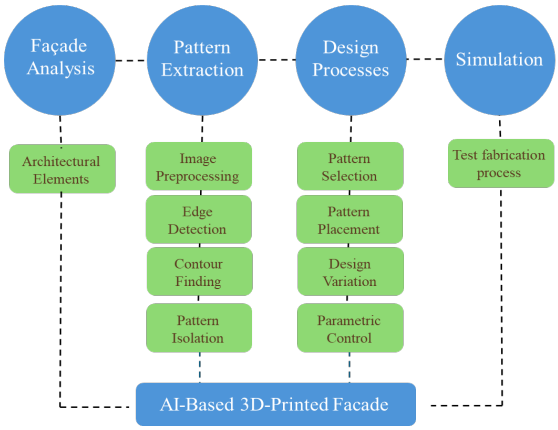


Figure 2. *Methodology used to show the impact of artificial intelligence and 3D printing in architecture.*

2. Research and Analysis of Sana'a Architecture

2.1. KEY ARCHITECTURAL FEATURES

The Old City of Sana'a features distinctive architectural elements that have been preserved for centuries Fig. 3,4:

Multi-storied Tower Houses: These structures, which offer roomy living spaces behind defendable city walls, are a novel approach to defensive requirements. They are frequently made of baked brick and rammed earth (pise).

Exceptional Craftsmanship: The buildings showcase remarkable craftsmanship in the use of local materials and traditional building techniques.

Homogeneous Islamic Settlement: The city presents a cohesive architectural ensemble, with designs and details reflecting an organization of space characteristic of early Islamic periods, preserved over time.



Figure 3. The Sana'a tower house and its vertical components.

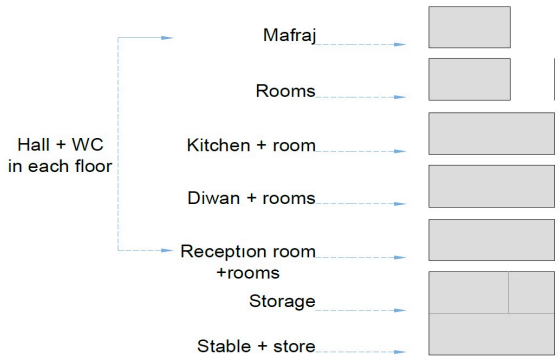


Figure 4. Shows the distinctive architectural elements of the old city of Sana'a.

3. Facade Pattern Analysis

A diverse array of traditional Yemeni architectural features may be seen on the facade Fig. 5. Analysis of various facade images revealed several recurring patterns and motifs. Key patterns and motifs identified include:

Geometric Patterns: A prominent feature is the extensive use of geometric patterns, including squares, triangles, diamonds, and zig-zags. These are often arranged in repetitive sequences to create visually rich textures.

Intricate Window Designs: Windows are frequently adorned with elaborate gypsum tracery, forming complex floral or geometric grilles. Arched windows are common, often topped with decorative elements.

Horizontal Bands and Friezes: Facades are often segmented by horizontal bands of white gypsum, which serve both as decorative elements and to emphasize the multi-story nature of the buildings. These bands frequently incorporate repetitive patterns.

Color Contrast: The striking contrast between the reddish-brown tones of the mud-brick or stone walls and the white gypsum decorations is a defining characteristic, highlighting the intricate patterns.

Stained Glass/Jali Work: Several windows, especially those in the arched parts, have stained glass or ornamental screens (qamariya- in Yemeni architecture). These components frequently have intricate geometric patterns that are radial or floral in nature, letting light through in ornamental ways.



Figure 5. A diverse array of traditional Yemeni architectural features on the facades

The patterns exhibit significant repetition, indicating a modular or uniform design approach, advantageous for AI-driven pattern extraction and generative modeling.

4. AI-based Pattern Extraction Methodology

4.1. APPROACH

For this project, we employed traditional computer vision techniques for pattern extraction, focusing on edge detection and contour finding to identify recurring elements in the facade image Fig. 6.

4.2. IMPLEMENTATION

The pattern extraction process involved: 1. Image Pre-processing: The original façade picture (jpg) was imported and transformed into grayscale. Grayscale conversion streamlines the image by eliminating color data, facilitating the use of intensity-based processing methods. Converting the image to grayscale and applying Gaussian blur to reduce noise. 2. Edge Detection: Using the Canny edge detector to identify edges in the image.
3. Contour Finding: Detecting contours based on the identified edges. By detecting contours, the distinct shapes and outlines of the architectural patterns (e.g., triangular friezes, window frames, and decorative motifs) were identified. The -RETR_EXTERNAL- mode was used to retrieve only the extreme outer contours, and -CHAIN_APPROX_SIMPLE- was used to compress horizontal, vertical, and diagonal segments. 4. Pattern Isolation: Filtering contours based on area and aspect ratio to isolate potential patterns.

4.3. RESULTS

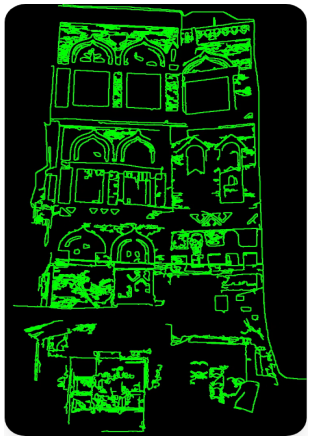
Through the pattern extraction process, the main decorative elements were identified from the facade image provided to the AI, including geometric patterns, window frames, and horizontal stripes. These extracted patterns formed the basis for the next stage, the generative design phase.



Original Image



Extracted Edges



Extracted Patterns



Original Image Extracted Edges

Figure 6. Processed image showing workflow extracted architectural patterns.

5. Generative Design Modeling

5.1 APPROACH

Utilizing the identified architectural patterns, generative design models were developed to investigate novel facade ideas influenced by the Old City of Sana'a. This approach utilizes AI to create variants and original compositions while conforming to the aesthetic criteria established in the historical facade. The methodology concentrated on reconfiguring and amalgamating these motifs in diverse manners to produce numerous design variants.

The generative models were informed by the following concepts, extracted from the facade analysis:

- Geometric Repetition: Focus on the recurrence of triangular friezes, as well as circular and semi-circular patterns.

Material Contrast: Preserving the distinctive contrast between the white gypsum plastering and the reddish-brown brick textures.

-Window Typologies: Using arched windows and patterns resembling qamariya as focal points.

Modularity and Variation: Examining the ways in which these components might be mixed and matched to produce facade compositions that are varied but historically relevant.

5.2 IMPLEMENTATION

The steps in the generative design process were: 1. Pattern Selection: Patterns from the extracted collection are chosen at random. 2. Pattern Placement: Arranging the chosen patterns at random points on a fresh canvas. 3. Design Variation: Creating several versions by altering the pattern arrangement and selection.

5.3 RESULTS

Three distinct generative design models were produced. The extracted patterns were arranged differently in each of the three facade design variants that were produced. These variants show how classic aesthetics may be connected to modern architectural expressions through the reinterpretation of historical design aspects Fig. 7.

Design Model 1: Classic Style with Delicate Modifications

While adding small, AI-driven modifications in the pattern arrangement and details, this model seeks to closely resemble the Sana'a facade's traditional look. It illustrates the possibilities for accurate architectural replication and restoration by showing how generative design may create new ideas that are almost identical to historical examples.

Design Model 2: Parametric Variations in Modern Interpretation

A more modern interpretation of the Sana'a architectural language is investigated by this model. It suggests how classical shapes might be modified for contemporary building by emphasizing the extracted patterns' parametric variability and modularity. The versatility of generative design in producing innovative but culturally aware architectural solutions is demonstrated by this design, which highlights various configurations of arched openings, ornamental plasterwork, and brick textures.

Design Model 3: Abstract Generative Artwork

The spirit of Sana'a facade patterns is captured in this abstract generative art model. It transforms the architectural themes into a modern creative expression by highlighting the interaction of light and shadow on textured surfaces. This model demonstrates how AI may be used to produce abstract representations that capture the essence of old buildings, paving the way for conceptual designs and creative displays.

These produced models show how AI may be used to both artistically synthesis new ideas with a strong foundation in historical architectural traditions and to evaluate and extract patterns. For architects and

preservationists, the capacity to quickly produce a large number of variants may greatly speed up the design process.

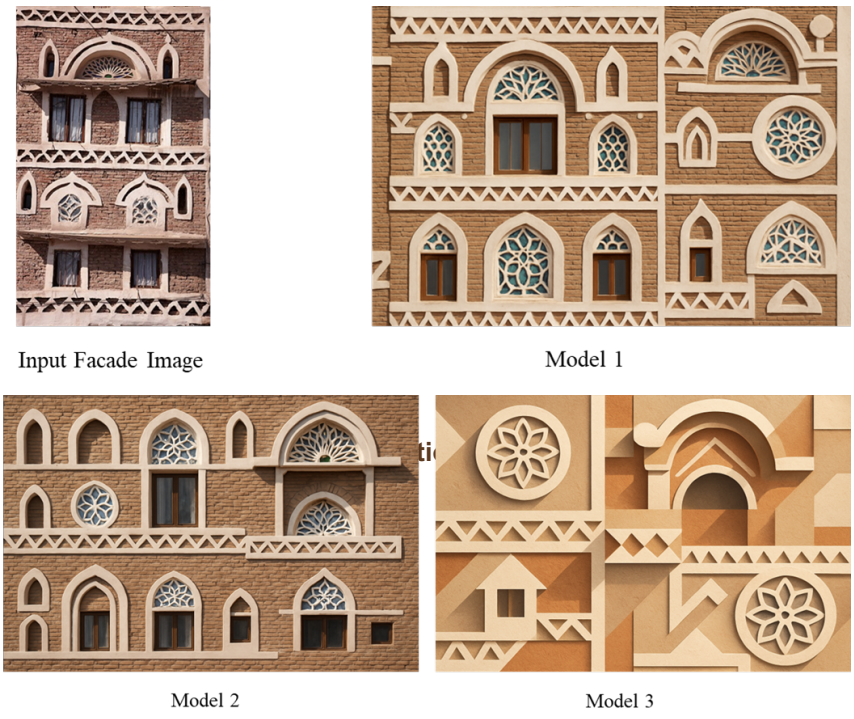


Figure 7. Shows the different models that have been produced.

6. Robotic Fabrication Simulation

6.1 APPROACH

With an emphasis on toolpath creation for a simplified pattern, a conceptual framework for robotic fabrication simulation was created. This framework describes the possible automated manufacturing techniques that might be used to implement generative designs.

6.2 PROPOSED WORKFLOW

The process for robotic manufacturing that has been suggested includes converting 2D patterns into accurate 3D models, which is known as 3D modeling. 2. Toolpath Generation: establishing robotic toolpaths to fabricate the components of the facade. 3. Simulation: Modeling the mechanical. fabrication process to identify and resolve potential issues. 4. Code Generation: Generating robot-specific code for actual fabrication.

6.3 SIMULATION RESULTS

To illustrate the basic ideas of how to build a robotic system for these patterns, a simple tool path simulation for a typical pattern is performed. The simulation provides practical evidence of the correctness of the manufacturing strategy by considering tool movements and path generation.

6.4 INTEGRATED WORKFLOW

The complete workflow integrates all three components (pattern extraction, generative design, and fabrication simulation) into a cohesive process:
1. Input facade image → Pattern extraction → Extracted patterns.
2. Extracted patterns → Generative design → New facade designs.
3. New facade designs → Fabrication simulation → Fabrication toolpaths.

6.5 RESULTS

The process effectively illustrated the viability of the suggested method, from examining a historic facade to creating new ideas and modeling their production, according to the recommendation. This whole procedure demonstrates the possibilities of integrating robotic manufacture, generative design, and artificial intelligence in architectural applications.

8. Conclusions and Future Work

8.1. CONCLUSIONS

According to research, robotic 3D printing and artificial intelligence have the potential to completely transform building façade refurbishment by providing accurate, eco-friendly, and creative design options. The possibility of using computational methods to analyze architectural history, applied partly to Sana'a's Old City, has been illustrated by this study. The suggested approach provides a strong foundation for putting these cutting-edge technologies into practice. It includes data collection and digitization, AI-driven analysis, AI-assisted design and material optimization, and robotic 3D printing. Even though there are still many obstacles to overcome, the potential advantages, material compatibility, and robotic 3D printing capabilities much exceed these difficulties. Robotic 3D printing and AI are essential instruments for preserving the world's cultural legacy because of their capacity to precisely replicate intricate shapes, expedite restoration procedures, and intelligently manage the preservation lifecycle.

Future research should concentrate on a few important topics. First, empirical research and pilot projects are required to test the suggested technique in the particular context of Sana'a, taking into account the logistical challenges of operating in a conflict-affected area as well as the

special material characteristics of its mud-brick building. Creating and evaluating 3D printed materials that closely resemble the thermal, structural, and aesthetic properties of conventional Sana'ani construction materials is part of this. Second, further study into sophisticated AI models for hyper-realistic generative design that can create intricate and culturally subtle architectural motifs will greatly improve the authenticity of features that are duplicated. Thirdly, in order to ensure that Sana'a craftsmen and local communities have the knowledge and abilities to use these technologies for long-term preservation, efforts should be focused on knowledge transfer and capacity building.

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III. DECOLONIZING ARCHITECTURE & LOCALIZED DESIGN

INK MEETS STONE MEETS AI

Integrating Traditional Ink Painting and Artificial Intelligence into Architectural Pedagogy

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Abstract. This research proposes a decolonized pedagogical model that integrates traditional Chinese ink painting with accessible artificial intelligence (AI) tools in architectural education. The method rebalances digital innovation with cultural rootedness, challenging Western-centric design paradigms by using ink aesthetics —such as voids/solids, gradients, and the atmospheric concept of yijing (意境)—as a foundation for spatial thinking. A series of three beginner-friendly, project-based exercises form the core of this approach. In the first, AI as a Digital Ink Brush, students use tools like AutoDraw to transform hand-drawn ink sketches into digital compositions, sparking discussion on the balance between artistic control and computational precision. The second exercise, Generating Patterns from Ink, employs platforms like PatternedAI to convert ink washes and motifs into repeatable digital patterns for architectural surfaces like façades and tiles, directly linking heritage symbolism to contemporary materiality. Finally, Space Planning with AI Collage uses intuitive tools like Canva's Magic Studio to blend translucent ink art with building photographs, exploring how ink's fluid transitions can soften rigid architectural forms and reconfigure spatial hierarchies. These technical exercises translate into meaningful design applications. Students create cultural narratives by using AI to visualize spaces where shadows mimic brushstrokes or spatial sequences follow the rhythm of an ink landscape. The process bridges digital and physical realms when laser-cutters materialize AI-generated patterns into architectural models. A crucial component of critical reflection encourages students to compare their AI-assisted outcomes with works like I.M. Pei's Suzhou Museum, fostering discussions on authenticity, reinterpretation, and the ethical use of technology. This pedagogical framework makes advanced technology accessible while centering cultural heritage. It builds cultural

confidence by demonstrating how local traditions can shape global design, counters technological intimidation through low-barrier tools, and positions AI not as a replacement for tradition, but as a powerful medium for cultural continuity and creative experimentation in architectural education.

Keywords: *hands-on AI, ink painting, architectural pedagogy, cultural design, beginner-friendly tech*

1. Introduction

Artificial intelligence (AI) is rapidly reshaping architectural education and practice. From generative design algorithms to AI-supported visualization, computational tools promise efficiency, expanded creativity, and new ways of engaging with complex problems. Yet, their complexity often creates barriers for students, particularly those without coding backgrounds. As many educators have noted, the rapid pace of technological change has left gaps in architectural pedagogy, with some students excelling in digital fluency while others feel marginalized or excluded (Oxman 2017; Kolodner 2002).

Globally, AI has become a contested subject in higher education. On the one hand, it is celebrated for its capacity to automate routine tasks, democratize access to information, and expand the boundaries of human creativity (Mersch 2020). On the other hand, scholars warn of the risks of overreliance on algorithmic processes that may obscure authorship, reinforce existing inequities, or propagate biases embedded in training data (Crawford 2021). Within architecture, these tensions manifest in the studio environment, where traditional skills like sketching and model-making coexist uneasily with advanced computational design methods (Do and Gross 2001). Many programs struggle to strike a balance between analog and digital design training, often defaulting to a technologically deterministic narrative that privileges software proficiency over reflective practice.

A parallel debate concerns the cultural dimension of architectural pedagogy. For decades, architectural education has been critiqued for privileging Western-centric models, sometimes at the expense of local cultural traditions (Anthony 2002; Stevens 2003). The globalization of curricula, accreditation standards, and design media has tended to homogenize architectural education, with students from diverse contexts frequently learning from case studies, precedents, and theories rooted in Euro-American traditions. This phenomenon has led to calls for more culturally responsive, context-sensitive pedagogical frameworks (Gay 2018).

This paper explores an alternative path by introducing traditional Chinese ink painting into architectural education, augmented with beginner-friendly AI tools. Ink painting, with its centuries-old lineage, embodies principles of void and solid, rhythm and flow, and atmospheric conception (yijing, 意境) that are directly translatable to architectural thinking. By integrating this practice into an AI-supported workshop, the project aims to foster cultural grounding, reduce technological intimidation, and encourage reflective experimentation.

Rather than presenting a fully developed "decolonized approach," this study proposes a pedagogical experiment: a set of exercises and workshops that integrate ink painting as a cultural foundation with AI as a supportive design medium. The experiment, conducted at Xi'an Jiaotong-Liverpool University (XJTLU) in collaboration with ink master Xia Xiaobin, aims to provide students with an accessible entry point into AI, while simultaneously engaging them in discussions about heritage, identity, and innovation. Through hands-on engagement, students blend analog ink painting, digital manipulation, and AI-supported design to explore architectural narratives. The paper argues that such hybrid exercises not only enhance creative learning but also contribute to broader debates on cultural responsiveness in AI pedagogy.

2. Literature Review

The role of AI in architectural pedagogy has received increasing attention in recent years. Generative tools, data-driven design methods, and machine learning have been shown to expand design exploration and creative opportunities (Mitchell 2019; Carpo, 2021). Within architectural curricula, AI is often introduced as part of advanced computational studios, relying on scripting, algorithmic design, and parametric modeling. However, these approaches can demand substantial technical proficiency, creating a digital divide between students with and without prior computational training (Oxman 2017). The challenge of inclusivity is not unique to architecture—research in computer science education similarly highlights the risk of marginalizing students who lack a coding background (Lye and Koh 2014). Integrating AI requires careful consideration of accessibility, transparency, and pedagogy that scaffolds rather than intimidates (Kolodner 2002).

Recent scholarship emphasizes that AI should be framed as a supportive tool rather than an autonomous agent. Mersch (2020) argues that AI can democratize creativity when presented as a co-creative partner, but risks becoming an opaque "black box" when students are not invited to interrogate its processes. Crawford (2021) similarly warns of the political and cultural biases embedded in AI systems, highlighting the need for critical AI literacy.

For architectural education, this implies that pedagogy must include not only technical instruction but also reflective practice that questions how AI mediates cultural representation.

Analog traditions remain foundational in architectural education. Sketching, hand drawing, and physical modeling foster spatial reasoning, intuition, and embodied cognition (Lawson 2005; Schön 1983). Theories of reflective practice stress that design learning emerges from cycles of doing, observing, and reflecting (Schön 1987). Analog media, rather than standing in opposition to digital technologies, can serve as complementary practices that ground students' sensorial and critical engagement with design. In fact, Do and Gross (2001) argue that diagrams and hand sketches remain central to architectural reasoning precisely because they capture ambiguity and provisionality—qualities that can become obscured in digital environments.

The intersection of analog and digital practices has generated a growing body of literature on hybrid pedagogy. Burry (2011) suggests that digital craft extends rather than erases traditions of making, while Celani (2012) explores how digital fabrication reconfigures relationships between hand, tool, and material. AI, as the latest addition to this lineage, offers opportunities for synthesis if integrated thoughtfully with traditional artistic practices.

Cultural grounding in design pedagogy has also received attention as a corrective to the homogenization of global curricula. Altomonte (2012) critiques the standardization of sustainable design education, pointing to the need for context-sensitive frameworks. In China, ink painting embodies spatial and compositional principles directly translatable to architecture: void and solid, rhythm and flow, atmospheric conception (yijing, 意境). Wang (2015) observes that architectural education in China has long grappled with the tension between international modernist paradigms and local traditions, often leaving students uncertain about how to integrate cultural references meaningfully. Louie (2019) and Chang (2014) highlight that heritage-informed creativity can empower students to build cultural confidence, provided traditions are treated as adaptive and evolving rather than static.

Comparative cases further illustrate the potential of heritage-based pedagogy. In Japan, sumi-e painting has been linked to spatial thinking in architectural education (Fujii 2016). In Islamic contexts, geometric design traditions provide fertile ground for exploring pattern, proportion, and ornament in dialogue with digital tools (Necipoğlu 1995; Dabbour 2012). Indigenous design pedagogy in North America has drawn from storytelling and craft traditions to foster relational and ecological approaches to architecture (Nelson 2018). These cases underscore that embedding cultural traditions into design education is not about nostalgia, but about expanding the epistemological diversity of architectural thinking.

At the same time, critical voices caution against romanticizing cultural traditions or essentializing them. Smith (2006) stresses that traditions must be understood as living practices open to reinterpretation. Dutta and Robinson (2019) warn that global design education can reproduce colonial hierarchies if heritage is treated superficially or tokenistically. Pedagogical strategies that genuinely integrate tradition with innovation must therefore embrace reflexivity, allowing students to question, adapt, and reinvent cultural references in contemporary contexts.

Taken together, the literature highlights three gaps this paper addresses: the accessibility challenge of AI in education, the pedagogical value of balancing analog and digital design practices, and the potential of cultural heritage to provide meaningful grounding for technological exploration. The following sections present a workshop experiment that responds to these gaps by combining Chinese ink painting with beginner-friendly AI tools in architectural pedagogy.

3. Methodology

This research employs a qualitative, practice-based approach, situating the workshop as a case study for educational innovation. The aim was not only to test specific exercises but also to explore how integrating cultural heritage with AI could reshape students' perceptions of design and technology. The methodology was guided by principles of action research, in which teaching interventions generate both educational outcomes and research insights (Reason and Bradbury, 2001).

The workshop was designed as a one-week intensive elective at Xi'an Jiaotong-Liverpool University (XJTLU). Participants included undergraduate architecture students from different years of study, with a mix of Chinese nationals and international students. No prior experience with AI tools was required. The diversity of student backgrounds provided an opportunity to observe how participants with different cultural and technical competencies engaged with the exercises.

The structure of the workshop was framed around three phases: (1) traditional foundations, (2) AI exploration, and (3) reflective practice. In the first phase, students were introduced to ink painting principles such as voids, ink diffusion (pòmò 破墨), and compositional hierarchy. Instruction was provided by the author in collaboration with ink master Xia Xiaobin, whose demonstrations emphasized both technique and philosophy. Students practiced brushwork and experimented with different textures, washes, and gradients, producing a portfolio of initial sketches.

In the second phase, these sketches became the basis for digital reinterpretation. Students were guided in digitizing their work and

experimenting with beginner-friendly AI platforms, including AutoDraw, Brush Ninja, and PatternedAI. The rationale for choosing these platforms was their low entry barrier: they require minimal technical expertise and provide immediate feedback, enabling students to focus on creative exploration rather than complex software learning curves.

The third phase involved structured reflection and group critique. Students presented their analog and digital outputs, comparing them with architectural precedents such as I.M. Pei's Suzhou Museum and Wang Shu's Ningbo Museum. Group discussions encouraged participants to articulate how their cultural assumptions and design sensibilities were challenged or reinforced through the process. This reflective dimension aligns with Schön's (1983) model of the reflective practitioner, emphasizing cycles of action and reflection.

Data collection for this study included observational notes, photographic documentation of student work, and informal feedback gathered during discussions. While not intended as a formal evaluation, these materials provided qualitative insights into the pedagogical value of the approach. Ethical considerations were addressed by anonymizing student contributions and framing the workshop as an educational experiment rather than an assessment exercise.

The methodology acknowledges limitations. The small sample size and short duration limit the generalizability of findings. Additionally, the lack of systematic assessment instruments means outcomes are interpreted qualitatively rather than quantitatively. Nevertheless, the study contributes valuable insights into how cultural heritage and AI might be meaningfully combined in design pedagogy, offering a foundation for future research and curricular development.

4. Workshop Structure and Exercises

The XJTLU workshop was structured as a one-week intensive, alternating between analog ink painting sessions, digital experimentation, and reflective discussion. Its design emphasized accessibility, cultural grounding, and iterative learning. Each exercise built on the previous one, guiding students from foundational practice to AI-augmented experimentation.

EXERCISE 1: AI AS A DIGITAL INK BRUSH

In this exercise, students created ink sketches inspired by traditional landscape and architectural motifs (see figure 1). These sketches were digitized through scanning or photographing and then imported into beginner-friendly AI platforms such as AutoDraw and Brush Ninja. Students

explored AI-assisted refinement, experimenting with line smoothing, shape suggestion, and stylized replication. The key pedagogical goal was to highlight the interplay between spontaneity and algorithmic augmentation. Students observed how AI could enhance precision without erasing the expressive qualities of ink, sparking discussions about authorship, creative control, and the boundaries of digital assistance. This exercise also encouraged experimentation with layering techniques—combining multiple AI iterations with hand-painted textures to produce hybrid compositions.



Figure 1. Students explore traditional ink painting techniques

EXERCISE 2: GENERATING PATTERNS FROM INK

Participants transformed their ink washes into digital patterns using tools like PatternedAI. They manipulated symmetry, repetition, and scale, translating fluid, organic brushwork into motifs suitable for architectural applications such as facades, wall screens, or tiling. This exercise underscored how traditional aesthetics could inform contemporary design elements, demonstrating continuity between cultural heritage and modern architectural practice. Students were encouraged to reflect on the adaptability of ink motifs: how an ink blot could evolve into a dynamic wall pattern or a rhythmic façade element. In doing so, the workshop bridged material culture with computational design, highlighting AI as a mediator rather than a replacement for human creativity.

EXERCISE 3: FROM INK TO ARCHITECTURAL NARRATIVES

The final exercise challenged students to integrate analog and AI outputs into conceptual architectural proposals. Using digital sketches, AI-generated patterns, and hand-painted imagery, students developed narrative compositions that explored spatial flow, atmosphere, and cultural resonance. This phase emphasized reflective practice: students compared their projects with architectural precedents such as I.M. Pei's Suzhou Museum and Wang Shu's Ningbo Museum, identifying how these works reframe traditional motifs within contemporary contexts. Critiques encouraged students to articulate the conceptual and aesthetic decisions underlying their designs, highlighting how ink and AI could collaboratively inform architectural storytelling.

Pedagogical Approach and Student Interaction

Throughout the workshop, the instructor and ink master Xia Xiaobin facilitated iterative guidance, emphasizing experimentation over perfection. Students worked both individually and collaboratively, allowing for peer learning, cross-cultural dialogue, and critique-based reflection.

Structured reflection sessions after each exercise prompted students to consider multiple dimensions:

- Technical: How did AI alter or enhance brushwork, texture, or composition?
- Cultural: How did the integration of ink painting influence design decisions or interpretations of heritage?
- Creative: How did analog and digital methods interplay to expand ideas or challenge assumptions?

By alternating between hands-on analog work and digital exploration, the workshop provided students with a low-barrier, iterative path into AI-supported design. This structure ensured that technology did not overshadow creativity, while cultural grounding maintained relevance and engagement for both Chinese and international students.

The phased approach—analog foundations, AI augmentation, and reflective synthesis—allowed students to experience AI as a co-creative tool rather than a replacement for traditional skills. Students reported heightened confidence in engaging with AI, increased appreciation for the nuances of ink painting, and a stronger sense of cultural identity in their design thinking. The structure also fostered critical dialogue about the ethical, aesthetic, and cultural implications of integrating AI into architectural pedagogy.

Together, these exercises provided a foundation for observing how students interacted with hybrid analog–digital workflows. The following section examines student engagement, highlighting accessibility, cultural resonance, and creative exploration.

5. Case Study: Student Engagement at XJTLU

Observations and informal feedback collected during the workshop highlighted several important themes related to accessibility, cultural resonance, creativity, and critical engagement. These insights illuminate how students interacted with the hybrid analog–digital pedagogy and provide qualitative evidence of the workshop's educational impact.

A key outcome was the accessibility of beginner-friendly AI tools. Students with little or no prior AI or coding experience were able to engage meaningfully with the platforms, producing sophisticated visual outputs with minimal technical frustration. Many participants reported that the immediacy of the tools—offering near-instant feedback and intuitive controls—enabled them to experiment freely, without fear of "making mistakes." One student noted, "I never thought I could use AI in design without learning complex software, but these tools made it fun and approachable."

This finding underscores the importance of carefully selecting digital platforms in pedagogical design. By lowering technical barriers, the workshop allowed students to focus on creative exploration and conceptual thinking rather than struggling with software mechanics.

Cultural grounding emerged as another significant theme. Chinese students particularly valued the opportunity to engage with ink painting as a core component of the design process, seeing their heritage represented as a starting point for innovation rather than an ornamental addition. International students, meanwhile, expressed curiosity and appreciation for the principles of void and solid, rhythm, and atmospheric conception (yijing, 意境), which they had not encountered in previous architectural training.

These experiences reinforced the pedagogical potential of heritage-informed design education. Embedding cultural traditions within the workshop provided students with a shared visual and conceptual language, fostering cross-cultural dialogue and encouraging reflection on how local context can enrich design thinking.

The combination of analog and AI-mediated practices significantly expanded students' creative approaches. The juxtaposition of freehand brushwork with algorithmically enhanced outputs encouraged iterative exploration. Students experimented with layering, pattern transformation, and spatial composition, resulting in a diverse range of outcomes—from highly abstracted digital landscapes to patterns directly applicable to architectural surfaces.

During critiques, students articulated how ink painting inspired new ways of thinking about architectural form. One participant remarked, "The blurred transitions in ink made me rethink how walls can dissolve into light," reflecting an emergent sensitivity to spatial fluidity and atmospheric nuance.

Such observations indicate that analog techniques can catalyze novel design perspectives when combined with computational tools.

Group discussions provided an essential reflective component. Students were prompted to consider issues of authorship, authenticity, and the cultural implications of AI-mediated outputs. Some students noted the tension between embracing AI assistance and maintaining individual creative control, revealing emerging awareness of the ethical and philosophical dimensions of computational design.

Comparisons with architectural precedents, such as I.M. Pei's Suzhou Museum and Wang Shu's Ningbo Museum, enabled students to situate their experiments within broader design narratives. These dialogues highlighted the role of tradition as a living practice—one that can be reinterpreted, adapted, and innovatively integrated rather than merely preserved.

Despite the overall success, several challenges were observed. Some students initially relied too heavily on AI-generated outputs, treating the technology as a shortcut rather than a co-creative partner. In these cases, facilitators intervened to reorient focus toward iterative exploration and reflective practice. Additionally, time constraints limited the depth of experimentation for certain students, particularly those who were still developing confidence with brush techniques or AI interactions.

Overall, the workshop demonstrated that integrating ink painting with beginner-friendly AI tools can simultaneously lower technical barriers, foster cultural awareness, and stimulate creative and critical thinking. Student engagement was enhanced by the iterative structure, supportive facilitation, and balance between analog and digital methods. These findings suggest that culturally grounded, accessible pedagogical interventions can provide meaningful entry points into AI-enhanced architectural design while fostering reflective and contextually informed design thinking.

6. Findings and Reflections

The workshop combining traditional Chinese ink painting with beginner-friendly AI tools yielded several key findings with implications for architectural pedagogy, creative practice, and cultural engagement. These findings are organized around accessibility, cultural grounding, creative exploration, and critical reflection.

A primary outcome of the workshop was the successful reduction of barriers to AI engagement. By using low-threshold platforms like AutoDraw, Brush Ninja, and PatternedAI, students with minimal technical background were able to produce meaningful design outputs. This aligns with Oxman (2017), who emphasizes the importance of inclusive computational pedagogy to prevent marginalization of students lacking prior coding experience. The

immediacy of feedback allowed learners to focus on experimentation rather than technical mastery, effectively democratizing access to computational tools (Mersch, 2020). This suggests that carefully curated, beginner-friendly AI applications can serve as scaffolds for creative exploration, enabling students to gain confidence and agency in computational design without the intimidation often associated with professional software or coding-intensive platforms.

Embedding Chinese ink painting as a foundational practice strengthened students' cultural awareness and design identity. Chinese participants reported a heightened sense of continuity with their heritage, while international students gained exposure to alternative spatial and compositional logics. This reflects Louie (2019) and Chang (2014), who highlight that heritage-informed pedagogy can empower students to engage creatively with cultural traditions while fostering confidence and context-sensitive design thinking. Principles of void and solid, rhythm, and atmospheric conception (yijing, 意境) were internalized not as static cultural artifacts but as generative tools informing creative decision-making. The workshop demonstrates that heritage-informed pedagogy can enrich design thinking by offering students culturally resonant starting points for innovation. By framing traditional practices as living and adaptable rather than fixed, the exercises encouraged students to reinterpret cultural references in contemporary architectural contexts.

The iterative interplay between analog ink painting and AI-mediated digital transformation fostered hybrid thinking. Students explored layering, abstraction, and pattern generation, often producing outputs that neither analog nor digital methods alone could achieve. These findings support Do and Gross (2001), who argue that analog sketches and diagrams capture ambiguity and provisionality critical to architectural reasoning, while Burry (2011) suggests that digital tools can extend rather than erase traditional making practices. This combination expanded the creative repertoire, highlighting how traditional skills and computational tools can be mutually reinforcing. Student reflections indicated that the tactile experience of ink painting informed spatial sensitivity, while AI facilitated rapid iteration and experimentation with form, composition, and surface treatment. Such findings align with research emphasizing the complementary relationship between hand and digital practice in architectural reasoning (Do and Gross 2001; Burry 2011).

The workshop's reflective component was essential in fostering critical awareness of authorship, authenticity, and the role of AI in design. Students discussed the balance between human creativity and algorithmic assistance, considering both the opportunities and limitations of AI-generated outputs. This aligns with Crawford (2021), who warns that opaque AI processes can

propagate biases, and with Schön (1983), who emphasizes reflection as central to professional learning in design. Engagement with architectural precedents, including I.M. Pei's Suzhou Museum and Wang Shu's Ningbo Museum, helped students contextualize their work and explore how cultural motifs can be meaningfully adapted in contemporary practice. These discussions cultivated not only design literacy but also ethical and philosophical understanding of the interplay between heritage and technology.

Despite positive outcomes, challenges were noted. Some students initially over-relied on AI, highlighting the need for clear pedagogical guidance to position AI as a co-creative partner rather than an autonomous agent. Time constraints limited the depth of exploration for certain participants, and the small sample size constrains generalizability. Nonetheless, these limitations offer opportunities for future refinement. Extending workshop duration, introducing comparative cultural case studies, or incorporating structured assessment could strengthen the pedagogical impact and provide measurable evidence of learning outcomes.

The findings indicate that integrating ink painting with AI supports multiple educational objectives: it enhances accessibility, fosters culturally grounded creativity, and cultivates critical, reflective practice. By situating AI as an enabling rather than dominant force, the approach encourages students to maintain agency over design while engaging with contemporary computational tools. Overall, the workshop illustrates a model of pedagogy that bridges analog and digital practices, leverages cultural heritage as a design resource, and emphasizes reflection as a core component of learning. These outcomes suggest broader applicability for architectural education, particularly in contexts seeking to balance technological fluency with cultural literacy and creative agency.

7. Discussion

The workshop combining traditional Chinese ink painting with beginner-friendly AI tools offers several insights into contemporary architectural pedagogy, highlighting the interplay between culture, creativity, and technology. The findings suggest that such hybrid approaches can address longstanding challenges in design education while opening new avenues for student engagement.

A central theme is the positioning of AI as a supportive, rather than substitutive, design tool. Students engaged most meaningfully when AI outputs were framed as prompts, extensions, or collaborators rather than finished solutions. This aligns with Mersch (2020), who emphasizes that AI

can democratize creativity if treated as a co-creative partner rather than a black-box authority. In architectural pedagogy, this distinction is critical. AI offers rapid iteration, pattern generation, and visualization capabilities, yet its overuse can risk superficiality or a loss of authorship. The workshop demonstrated that integrating AI within a structured reflective framework enables students to retain creative control while benefiting from computational augmentation.

The iterative combination of hand-painted ink and AI-mediated outputs illustrates the pedagogical potential of hybrid analog–digital workflows. Analog techniques such as brushwork and ink washes cultivate tactile sensitivity, spatial reasoning, and observational skills (Lawson 2005; Schön 1983). Digital tools, in turn, expand possibilities for abstraction, pattern manipulation, and rapid iteration. This duality underscores the argument that traditional and computational methods are not mutually exclusive; rather, they can be synergistic. Students' work revealed that digital augmentation can enhance rather than replace analog sensibilities, producing hybrid outputs that reflect both human intuition and algorithmic experimentation. Such practices support reflective learning, enabling students to iteratively test, observe, and refine their designs.

The integration of Chinese ink painting provided a culturally resonant foundation for creative exploration. By rooting design activities in heritage-informed practices, students developed a stronger sense of cultural identity and confidence. Both Chinese and international students reported that exposure to ink painting influenced their perception of space, composition, and atmospheric qualities, demonstrating the pedagogical value of culturally grounded approaches (Gay 2018; Louie 2019). The workshop also fostered reflective practice, a hallmark of Schön's (1983) model of the reflective practitioner. Structured discussions and critiques prompted students to articulate their design choices, evaluate the influence of AI, and consider the ethical and aesthetic implications of blending tradition with technology. This reflective dimension ensured that technological experimentation was coupled with critical thinking rather than treated as a purely technical exercise.

The workshop illuminated broader ethical and philosophical questions surrounding AI in design. Students grappled with issues of authorship, authenticity, and cultural appropriation. By situating AI outputs within cultural and historical contexts, the exercises prompted critical interrogation of how algorithmic processes mediate heritage. These discussions align with Crawford's (2021) concerns regarding biases and opaque processes embedded in AI systems. Pedagogy that foregrounds reflexivity enables students to question not only the creative affordances of AI but also the social, cultural, and political implications of its application.

The findings reinforce the potential of culturally grounded, low-barrier AI interventions to foster inclusivity in architectural education. By combining analog heritage practices with accessible technology, the workshop mitigated the digital divide and empowered students from diverse backgrounds to participate meaningfully in computational design exercises. This approach challenges the Euro-American-centric assumptions prevalent in global architectural curricula (Dutta and Robinson 2019) and demonstrates that heritage can serve as a generative resource rather than a static relic. It suggests a pedagogical model in which students' cultural contexts are treated as assets, fostering both technical competence and culturally informed creative agency.

While the workshop yielded promising insights, its scale and scope were limited. Future research could expand the model across larger cohorts, extend the duration of workshops, or incorporate comparative cultural studies—such as Japanese sumi-e, Islamic geometric patterns, or Indigenous craft traditions—to evaluate the adaptability of this pedagogical framework. Additionally, structured assessment metrics could complement qualitative observations, providing a more systematic evaluation of learning outcomes, AI literacy, and cultural engagement. Such developments would strengthen the evidentiary basis for broader adoption of heritage-informed AI pedagogy in architecture.

8. Conclusion

This study explored the integration of traditional Chinese ink painting with beginner-friendly AI tools in architectural pedagogy, presenting a workshop-based experiment at Xi'an Jiaotong-Liverpool University. The research demonstrates that culturally grounded, accessible approaches can simultaneously foster creativity, technical confidence, and critical reflection in design education.

Key Contributions

1. Accessibility and Confidence with AI: By employing low-barrier AI platforms, the workshop allowed students with minimal technical experience to engage meaningfully with computational design. This highlights the potential for beginner-friendly tools to democratize access to AI, reducing intimidation and enabling experimentation.
2. Cultural Grounding as a Design Resource: Ink painting served as a culturally resonant foundation for creative exploration. Both Chinese and international students reported enhanced appreciation for spatial composition, atmosphere, and rhythm, illustrating how heritage-informed pedagogy can enrich design thinking and foster cultural awareness.

3. Hybrid Analog–Digital Creativity: The iterative combination of analog brushwork and AI-mediated outputs encouraged hybrid workflows that expanded students' creative possibilities. Analog practices cultivated tactile and observational skills, while AI enabled rapid iteration, abstraction, and pattern generation, producing outcomes unattainable through either method alone.
4. Reflective and Ethical Engagement: Structured reflection and critique prompted students to consider issues of authorship, authenticity, and the role of technology in mediating cultural expression. These discussions fostered critical literacy alongside technical skill, aligning with contemporary models of reflective and culturally responsive pedagogy.

The experiment demonstrates that AI can be framed as a supportive tool rather than a replacement for traditional design practices. Integrating cultural heritage with computational tools offers a pathway for inclusive, contextually sensitive pedagogy that values students' diverse backgrounds as assets. By emphasizing process over final product and reflection over automation, such approaches cultivate adaptive, critically engaged designers capable of negotiating the interplay between tradition, technology, and innovation.

While limited in scale, the workshop provides a foundation for broader experimentation. Expanding the model to larger cohorts, incorporating diverse cultural traditions, and introducing systematic assessment frameworks could enhance its pedagogical impact and generalizability. Comparative studies across different design contexts could further explore the adaptability and universality of heritage-informed AI pedagogy.

Ultimately, this study underscores the potential of hybrid, culturally grounded pedagogies to reshape architectural education in an era of rapid technological change. By integrating analog heritage practices with accessible AI tools, educators can foster creativity, cultural awareness, and reflective practice, empowering students to navigate the evolving landscape of architectural design with confidence, agency, and critical insight.

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FROM TECHNICAL AUTOMATION TO CULTURAL MEDIATION

AI-Powered Translation of Local Narratives into Heritage-Informed Design Knowledge

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Abstract. The growing use of AI in the architecture, engineering, and construction (AEC) industry holds great promise for augmenting design processes, but most existing applications remain limited to operational or workflow-level applications. This study suggests a change of course: investigating how AI-powered natural language processing (NLP) functionality —specifically, large language models (LLMs) can be reconfigured to support culturally situated design practice in cross-cultural design settings. Current advances in generative AI (GenAI) demonstrate the ways it is able to translate unstructured inputs (e.g., stakeholder narratives, community views, or local knowledge) into structured design intelligence and hence bridge the qualitative-technical divide. This conceptual exploration places AI not as a tool to automate processes but as a dynamic mediator of cultural and contextual knowledge, capable of capturing spatial, material, and social values embedded in local narratives. We examine some Saudi Arabian heritage architecture case study to test how LLMs can identify recurring design patterns or preferences from qualitative inputs and generate structured outputs to support decision-making in early stages. Drawing from prompt engineering and domain knowledge integration methods, we highlight approaches to align AI outputs with culturally resonant design priorities while addressing challenges such as "hallucinations" (inaccurate generations) and bias mitigation. Our approach challenges dominant top-down digital workflows by integrating AI as a collaborative partner supporting foreign architects working in culturally rich contexts. Leveraging the power of AI to parse complex narratives and codify implicit design logic, this research aims to advance architecture that is more responsive to identity, culture, and context. We also discuss ethical considerations—including data sovereignty and accountability—and propose a human-in-the-loop strategy to ensure AI augments, rather than replaces, cultural expertise in design. This study contributes a foundation for future research on AI as a tool for equitable and contextually adaptive design innovation in the AEC industry.

Keywords: *Large Language Models (LLMs), Cultural Heritage, Cross-cultural Design, Natural Language Processing (NLP), Participatory Design.*

1. Introduction

The integration of artificial intelligence (AI) into the architecture, engineering, and construction (AEC) industry has increased over recent years, offering new dimensions for automating tasks, optimising workflows, and enhancing performance analysis (Abioye et al., 2021; Saka et al., 2024). However, most current AI applications remain rooted in technical operations level —including parametric modelling, construction sequencing, and energy optimisation—while not directly dealing with the cultural and contextual dimensions of design (Akinosho et al., 2020; Moscatelli, 2022). This ignoring is surprising, as architecture is inherently a socio-spatial discipline where design quality depends not only on technical efficiency but also on the translation of local narratives, traditions, and material practices into meaningful built forms (Al-Hathloul & Mughal, 1999; Marques et al., 2018)

In this context, we are separating culturally grounded design practices—observable patterns in spatial organisation, material use, and construction methods—and culturally resonant design priorities—community values, social needs, and identity aspirations that may not always align with existing practices. Our point of view recognises that traditional practices may evolve with history, while core cultural priorities persist, shaping how society interacts with the environment.

With the global design practices increasingly involving cross-cultural engagements, the limitations of current AI tools become more evident. Foreign designers working in culturally rich regions such as Islamic Saudi Arabia in many cases struggle to interpret local socio-spatial logics, resulting in built environments that lack cultural resonance or identity (Fabbri, 2020). Traditional urban patterns in the Gulf Cooperation Council countries –GCC– are rooted in religious and social principles that shape privacy, material selection, and neighbourhood clustering (Al-Hathloul & Mughal, 1999). The ability to integrate such knowledge into design outputs—spatial configurations, typological guidelines, or material palettes—remains a critical unsatisfied need in AI-AEC workflows.

Recent advances in generative AI (GenAI), especially large language models (LLMs), provide an innovative channel for bridging this divide. LLMs can parse and synthesise unstructured qualitative inputs such as community interviews, oral histories, and vernacular descriptions into structured design intelligence (Gozalo-Brizuela & Garrido-Merchan, 2023; Zheng & Fischer, 2023). Under this framework, AI works not as a technical aid but as an intermediary between cultural and contextual understanding, able to derive embedded spatial reasoning, material preference, and social values from narrative sources. That is what this research specifically addresses, namely, natural language processing (NLP) functions in LLMs for cultural narrative interpretation, as an additional counterpart to current technical AI deployments in parametric design and construction optimisation and not as a replacement. By virtue of this functionality, LLMs have the ability to bridge between local knowledge bearers and outside design teams, facilitating early-stage identity-sensitive decisions.

This research proposes a conceptual and methodological shift: leveraging the natural language understanding capabilities of LLMs to facilitate culturally grounded design reasoning in AEC. Through a simulated case study situated in a Saudi Arabian context, we explore how AI can translate community-derived narrative into usable design information outputs, producing structured materials such as spatial briefs, vernacular

typologies, and material recommendations for architects unfamiliar with local cultural codes. At the core of this strategy lies an insistence that AI supplements and does not usurp cultural knowledge, leaving community agency intact with respect to interpreting and applying their respective cultural expertise. By doing so, AI is framed as an interpreter in mutual engagement, reconciling proposals in architecture with cultural agendas at a human-in-the-loop level to avoid hallucinations, bias, and over-automation (Du et al., 2024; Wang et al., 2023).

Our contributions are in two manin points. First, we frame LLMs as mediators of socio-cultural logic in design, extending their role beyond workflow optimisation to actively support culturally grounded reasoning in early-stage architectural processes. Second, we introduce a simulation-based approach for translating qualitative narratives—such as community feedback and vernacular descriptions—into structured design outputs including spatial briefs, typological guidelines, and material recommendations. By grounding this exploration in a culturally specific context, this work contributes to the emerging discourse on AI for equitable, adaptive, and culturally responsive design innovation in the AEC sector.

2. Background: From Technical AI to Cultural Mediation in Design

The convergence between AI and design in the architecture, engineering, and construction (AEC) industry has largely been guided by optimisation and automation, with performance, efficiency, and risk mitigation being given prominence at the cost of cultural and contextual sensibility (Abioye et al., 2021; Saka et al., 2023). Recent research, however, suggests interpretive, context-aware applications of AI, particularly large language models (LLMs) that are capable of retrieving latent design logic from qualitative narratives. Related work from four converging fronts is discussed here: (1) AI in AEC, (2) generative AI for spatial and cultural reasoning, (3) natural language processing (NLP) for vernacular and participatory knowledge integration, and (4) critical perspectives on decolonising and ethical AI in cross-cultural design.

2.1 AI IN AEC: FROM OPTIMISATION TO INTERPRETATION

AI in AEC has been used for parametric modelling, clash detection, generative design, and construction monitoring for several decades, working mostly with structured data and deterministic digital workflows (Akinosho et al., 2020). These technologies work excellently for performance-driven design but almost always overlook the socio-cultural aspects of design, especially in non-Western or culturally significant sites (Moscatelli, 2022).

Recent studies show a gradual move toward interpretive AI. For example, Bu et al. (2025) conduct a comprehensive investigation into value misalignment in LLM-generated text for cultural heritage purposes and conclude that over 65% of generated text exhibits cultural misalignments along multiple dimensions of heritage knowledge. Their study highlights the significant requirement to link automated AI tools with professional evaluation from the cultural heritage sector to deliver culturally suitable interpretations—

a process critical in safeguarding heritage and in culturally responsive projects. This trend suggests AI in AEC is progressing from automating alone to knowledge flow brokering, with conceptual underpinnings for adaptively responsive design processes.

2.2 GENERATIVE AI AND CULTURAL REASONING

Generative AI (GenAI), as demonstrated by GPT-4 and other LLMs, has been exceptionally able to convert unstructured narratives into structured design intelligence (Gozalo-Brizuela & Garrido-Merchan, 2023; Zheng & Fischer, 2023). In an architectural setting, it makes it possible to extract implicit design rules, vernacular types, and building material patterns from community commentary, past records, or oral histories. Nevertheless, recent research indicates important challenges in said application: Bu et al. (2025) illustrate how more than 65% of LLM-created text for cultural heritage activities present cultural value misalignments, citing the essential requirement for professional verification in culturally situated design outputs.

However, generative approaches in culture-informed environments pose significant epistemic challenges, including hallucination, overgeneralization, and embedded bias. Mitigative approaches include training corpora that have been curated with extreme caution, prompt engineering, fine-tuning, and multi-phase expert validation loops (Du et al., 2024; Wang et al., 2024). These research methodology results have direct implications in our research, where LLMs have been utilised for Saudi cultural narrative analysis and generating design-relevant outputs under human review.

2.3 NLP, VERNACULAR KNOWLEDGE, AND PARTICIPATORY DESIGN

Participatory and community-engaged design has long struggled to translate narrative, informal, and locally embedded knowledge into actionable design directives. Traditional workflows often fail to capture oral histories, stakeholder interviews, and community feedback in a form usable by architects or engineers (Campays & Said, 2025). NLP-driven approaches offer a new mechanism for codifying vernacular logic, allowing AI to surface patterns, preferences, and spatial principles embedded in local language.

LLMs have been applied in heritage research to reconstitute typologies and spatial sequences from dispersed textual and oral evidence, as with demonstrations of privacy gradients in Islamic housing or symbolic orientation of spiritual spaces (Al-Hathloul & Mughal, 1999). Extended to the field of participatory design, such translation of community narratives into structured design briefs enables cross-cultural or foreign design teams to interact with local identity respectfully and in contextual terms. Such a methodology-based perspective forms the background to our study, where LLMs are framed as intermediaries between local narratives and formal architectural decision-making.

2.4 CRITICAL PERSPECTIVES: DECOLONISING AND ETHICAL AI IN CROSS-CULTURAL DESIGN

A rising line of research calls for any AI application in design—particularly in cross-cultural contexts—to consider power asymmetries, epistemic privilege, and the extractive legacy inherent in technology development. Unreflexive deployment of AI systems risks reinstalling digital forms of colonialism, where data and cultural knowledge are

abstracted, interpreted, and turned into operational knowledge in ways that reinforce dominant epistemologies and silence local voices (Lewis et al., 2024; Roberts & Montoya, 2023). This dynamic is heightened in cross-cultural design settings, as in the case of foreign-led architectural projects in areas such as the Gulf, where outside designs —if left unmediated—have the effect of "flattening" or "overwriting" native socio-spatial cadences and exacerbating top-down knowledge transfer at the expense of actual cultural exchange (Al-Hathloul & Mughal, 1999). The concept of AIgemony (Bahrami, 2025) highlights how prevailing narratives and infrastructures grant disproportionate power to certain actors, constituting what counts as "valid" design knowledge and whose values are built into smart systems.

Linked to these concerns is a critical interrogation of the ethical framing of AI itself. Attard-Frost, De los Ríos, and Walters (2022) show that prevailing AI ethics guidelines are often narrow in scope—focusing on algorithmic fairness or transparency—while eliding the broader political economy and business practices that govern how AI is resourced, legitimised, and scaled. Without this contextualization, well-intentioned technical safeguards can become a veneer of "ethics washing," masking deeper structural inequities in whose knowledge is solicited, who benefits, and who is surveilled or excluded. Decolonial perspectives argue for expanding ontology and methods in AI ethics to interrogate not just what systems do, but who builds them, under what agendas, and with which cultural assumptions.

A counter-literature for Indigenous data sovereignty and participatory AI points toward forms of governance in which community agency is paramount, relational epistemologies are primary, and knowledge-holders retain rights to control how their cultural data is used, interpreted, and distributed (Roberts & Montoya, 2023). Prototypes such as CARE (Collective benefit, Authority to control, Responsibility, Ethics) encapsulate the requirement for data-intensive AI deployment by consent and control from the community, offsetting extractive cultural information mining that would otherwise continue to reinforce forms of colonial knowledge appropriation. In parallel, human-in-the-loop and participatory approaches situate cultural experts as dynamic co-designers, embedding recursive validation, contextual refinement, and accountability into AI-augmented inferences (Attard-Frost et al., 2022).

In architectural applications, this occurs when foreign design teams use AI to process place-based narratives without recognising the power imbalance inherent in who gets to control the interpretation and application of cultural knowledge. Together, these critical views both problematize nonreflective deployments of AI in highly cultural design environments and provide normative guardrails adopted by this research. Casting LLMs as intermediaries instead of extractors, and combining their outputs with highly structured, culture-aware human review, is an explicit effort to counter digital colonialism, bring to light underlying socio-spatial values, and maintain community agency in translating narrative knowledge into design intelligence.

2.5 RESEARCH GAP AND POSITIONING

Despite these technical capabilities, existing work reveals substantial gaps in cultural accuracy and ethical application. Bu et al. (2025) show that current LLMs struggle with

cultural heritage interpretation, exhibiting misalignments including cultural misunderstanding, historical bias, and contextual irrelevance—issues that become particularly problematic in cross-cultural design contexts. Furthermore, limited attention has been paid to the ethical implications of AI-mediated cross-cultural design, particularly regarding power dynamics between foreign designers and local communities. While technical frameworks for LLM application in built environment contexts have been established, their extension to living cultural mediation—where community narratives inform ongoing design decisions—remains underexplored and fraught with cultural sensitivity challenges.

This research addresses these gaps by developing a framework for AI-mediated cultural translation in contemporary architectural practice, grounded in decolonial ethics and participatory methodologies. Building from those critical frameworks, our methodology significantly embeds community agency utilizing structured validation processes and elevates cultural experts as co-interpreters rather than information sources, extending technical as well as ethical dimensions of AI use in culture-aware design settings.

3. Methodology

This study explores how a large language model (LLM) can be configured as a domain-specific cultural design assistant without custom training, by leveraging prompt engineering and curated domain knowledge. The aim is to support foreign architects working in Saudi Arabia by enabling the AI to interpret unstructured local cultural and technical commentary and convert it into structured, actionable architectural guidance grounded in heritage principles.

3.1 DOMAIN KNOWLEDGE SOURCE

The *Heritage Architecture of Saudi Arabia: History of Ancestors – Manual Guidelines for Restoration Projects* (Heritage Manual) serves as the model's primary reference. It contains detailed documentation on:

- Traditional materials and sourcing (e.g., coral limestone, mud binders)
- Historical construction techniques
- Regional architectural typologies (Najdi, Hijazi, Ahsa'i, Haili, Asiri)
- Cultural values embedded in spatial design
- Restoration protocols for heritage buildings

The manual is segmented into thematic sections (e.g., "Masonry Materials," "Structural Systems," "Decorative Elements") for efficient cross-referencing and retrieval.

3.2 AGENT CONFIGURATION

Instead of fine-tuning, we configure a custom GPT agent through iterative knowledge integration:

Stage 1: Baseline Configuration

- System prompt defining role as culturally aware Saudi heritage architecture assistant
- Core instruction constraints (no speculation, preserve Arabic terms, verify against Heritage Manual)

Stage 2: Heritage Manual Integration

- Segmented manual content uploaded by thematic sections
- Cross-referencing capabilities between related topics (materials, typologies, cultural practices)

Stage 3: Validation and Refinement

- Test with sample local commentary using structured prompt queries
- Refine prompt structure based on output quality and cultural accuracy
- Optimise retrieval accuracy for manual sections

3.3 INPUT DATA AND TESTING PROTOCOL

The agent processes authentic local architectural commentary sourced from published documentary and journalistic sources (detailed in Section 4.1), including documentary transcripts, news articles, and cultural magazine features that document heritage practitioners' perspectives. Sources include detailed descriptions of traditional materials (e.g., coral limestone extraction practices), culturally-embedded functional elements (e.g., rawasheen balconies), and climate adaptation strategies.

Processing Pipeline:

- Translation Protocol: Arabic-English with cultural term preservation (e.g., حجر الكاشور → kashur stone)
- Context Classification: Automatic categorisation into materials, methods, or cultural significance
- Reference Mapping: Link input concepts to relevant Heritage Manual sections

Structured Query Framework: The agent's performance is evaluated using five standardised prompt categories:

1. Material & Construction Query "Based on the local commentary provided, what traditional building materials and construction techniques should be prioritised for this project, and why are they culturally or climatically appropriate?"
2. Spatial Organisation Query "From the narrative described, what are the key spatial requirements and circulation patterns that need to be incorporated into the design to respect local cultural practices?"
3. Climate Adaptation Query "What climate-responsive design features are mentioned or implied in this local input, and how should they be integrated into contemporary architectural solutions?"
4. Cultural Elements Query: "Which specific cultural or heritage elements from this narrative should be preserved or reinterpreted in the design, and what is their significance?"
5. Technical Compliance Query: "Based on this local feedback, what restoration or construction protocols from traditional Saudi architecture should guide the technical implementation of this project?"

3.4 EVALUATION FRAMEWORK

The configured agent undergoes validation with diverse local commentary samples representing different architectural domains (materials, construction methods, cultural elements) to ensure robust performance.

Output Structure: Each response generates:

- Technical Brief: Material properties, sourcing, construction methods
- Heritage Context: Cultural significance and traditional applications
- Design Guidelines: Actionable recommendations with climate considerations
- Source Attribution: Specific Heritage Manual references

Evaluation Criteria:

- Factual Grounding: Accuracy against Heritage Manual content
- Cultural Accuracy: Preservation of cultural context and Arabic terminology
- Design Utility: Actionability for architectural practice by foreign designers
- Consistency: Stable responses across repeated queries and paraphrased inputs

This methodology enables systematic assessment of the agent's ability to mediate between local cultural narratives and structured architectural guidance while maintaining cultural authenticity and technical rigour.

4. Agent Testing and Validation

Following the methodology outlined in Section 3.3, the NARA (Narrative-to-Architecture AI) agent was validated using five thematic narrative excerpts extracted from three published sources documenting living heritage practices across different Saudi Arabian regions. The selected sources were:

1. **National Geographic Documentary** – "Enchanted Soudah: Traditions in the clouds" (Effendi, 2024), featuring highland Asiri building traditions
2. **Arab News Article** – "How Jeddah residents are reviving old Ramadan traditions" (Radwan, 2023), documenting urban Hijazi coastal heritage
3. **Al Arabiya Magazine Article** – "Dalia Al-Abdali: A Saudi woman who loves heritage and furnishing old houses" (Al-Halabi, 2016), focusing on domestic heritage practices

From these sources, narrative data was extracted from three heritage practitioners representing distinct regional contexts and heritage relationships:

- **Ibrahim Al Fathy** (Rijal Almaa, Aseer) – Highland Asiri heritage practitioner with expertise in mountain construction techniques, stone masonry, and climate-responsive building strategies documented in the National Geographic feature (Effendi, 2024)
- **Abu Abdulaziz Diyab** (Jeddah Al-Balad) – Urban Hijazi heritage practitioner with deep knowledge of coastal architectural traditions, material sourcing, and social customs in historic Jeddah neighborhoods documented in Arab News coverage (Radwan, 2023)
- **Dalia Alabdali** (Jeddah) – Heritage professional specializing in domestic traditions, interior spatial arrangements, and the revival of household cultural practices in traditional Hijazi architecture documented in Al Arabiya Magazine (Al-Halabi, 2016)

Each practitioner's documented commentary was analyzed to extract thematic narratives focusing on different aspects of heritage practice including material use, spatial organization, cultural customs, climate adaptation, and construction methods. This process yielded five distinct test narratives ranging from 180 to 380 words each, representing diverse architectural domains and regional contexts.

4.1 SAMPLE NARRATIVE INPUTS

To demonstrate the nature and quality of input data processed by NARA, narrative excerpts were extracted verbatim from published sources and formatted as plain text inputs for agent processing. Arabic passages were preserved in original script with English translations added for documentation purposes. three representative narrative excerpts are presented below:

Narrative Example 1: Traditional Construction Methods (Asiri Highland Context) From Ibrahim Al Fathy's documented commentary on restoring his ancestral home in Rijal Almaa:

> *"In the basement, Ibrahim pointed out that his home was built on a solid rock foundation. 'It must be very strong. If you don't find a good location for the foundation, facing the right direction of the wind, the house will collapse,' he said, placing his hands on the original walls that are rendered with a mixture of mud and manure... Ibrahim restored his house using traditional materials and centuries-old methods he learned from the elderly village masons. He pressed the mud with his own feet and inserted ragaff, flat-shaped sharp rocks, into the exterior walls to protect them from the rainfall"*
> *(Effendi, 2024).*

This narrative exemplifies technical construction knowledge embedded in practitioner descriptions, including foundation requirements, material composition, and weatherproofing techniques specific to highland Asiri architecture. Narrative Example 2: Social Customs and Spatial Practices (Urban Hijazi Context). From Abu Abdulaziz Diyab's account of life in historic Jeddah:

> *"Growing up, I would always find extra plates on a table at every iftar meal. My mother and our neighbors would exchange plates almost every day, a tradition still practiced till this day. I grew up in these neighborhoods and I can never leave. It's alive and busy with people from all walks of life. It's a humble place, always welcoming, and a melting pot of cultures and traditions"*
> *(Radwan, 2023).*

This narrative demonstrates implicit spatial and social requirements—the cultural practice of plate exchange implies specific circulation patterns, community access points, and spatial relationships between neighboring homes that must be considered in heritage-informed design. Narrative Example 3: Gender Roles in Heritage Architecture (Jeddah Domestic Context) From Dalia Alabdali's description of women's traditional roles:

> *"المرأة بشكل عام كانت هي صانعة منزلها، وأنها في الحجاز قديماً عرفت بتصميم وتأثيث منزلها، فكانت تحيك، وتصنع جهاز زواجها بنفسها"*
> *(Al-Halabi, 2016).*

> *[Translation: Women in general were the makers of their homes, and in the Hijaz, women were traditionally known for designing and furnishing their homes, weaving and making their wedding furniture themselves.]*

This narrative reveals the often-overlooked role of women in heritage architecture, providing insight into domestic spatial requirements, craftsmanship traditions, and gender-specific design considerations.

4.2 TESTING PROTOCOL

These five narratives were systematically evaluated using the five standardized query categories described in Section 3.3 (Material & Construction, Spatial Organisation, Climate Adaptation, Cultural Elements, and Technical Compliance), producing 25 total agent responses for comprehensive performance analysis. The test cases were selected because they authentically represent spatial customs, material priorities, and cultural values embedded in Saudi building traditions, while also providing sufficient descriptive richness to test the agent's interpretive capabilities across technical, cultural, and contextual dimensions.

4.3 GPT AGENT RESPONSE ANALYSIS

NARA's performance evaluation demonstrated promising capabilities alongside important limitations in cultural interpretation and architectural guidance generation. Agent outputs were demonstrated to derive implicit knowledge from narrative descriptions of cultures, consistently organising into Materials, Structural Systems, and Decorative Elements categories compatible with typical architectural practice. This structured framework showed potential for enabling foreign architects to integrate heritage considerations into design workflows, though performance varied considerably across different types of queries as well as cultural contexts.

Analysis of agent replies revealed reasonable performance at recognising culture-specific spatial needs that tended to be implicit, as opposed to explicit, in narratives. Processing descriptions of customs associated with traditional hospitality, for instance, permitted inferring the need for separate circulation and gender-separated spaces without direct reference to these cultural expectations, though such inferences sometimes needed further validation to avoid error. Integration of the system with the Heritage Manual demonstrated potential for cross-referencing narrative information with documented heritage practice, helping to minimise speculation while preserving cultural integrity in technical advice. Integration was optimal for clearly defined technical aspects and struggled with abstract or symbolic cultural notions, however. Testing across varying Saudi architectural regions (Hijazi coast, Asiri highlands) indicated that the agent could differentiate between regional building traditions and apply climatically responsive strategies based on geographical settings, though depth and accuracy in these differences tended to vary and sometimes needed professional correction to prevent oversimplifying complex cultural inter-relationships.

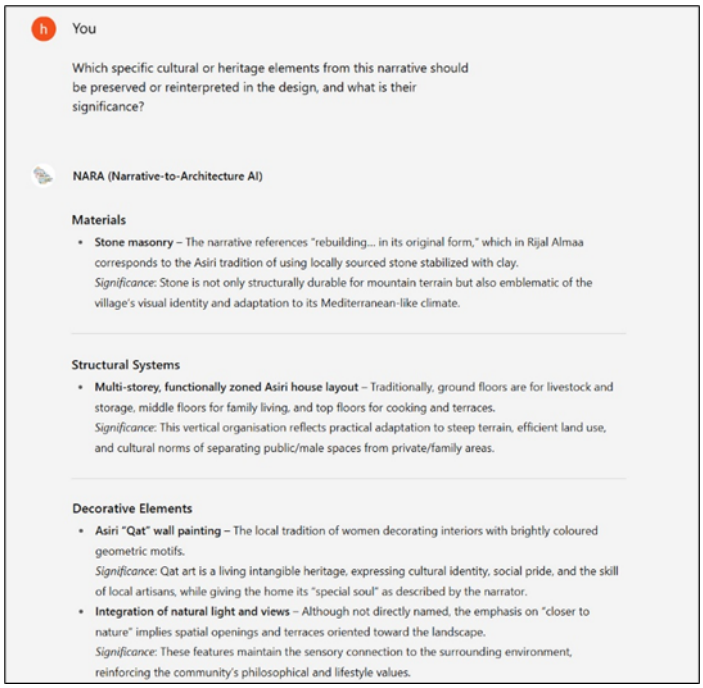


Figure 1: GPT Agent Response for the fourth prompt

For example, when processing Abu Abdulaziz Diyab's narrative about traditional hospitality and plate exchange between neighbors (Radwan, 2023), the agent correctly inferred the need for accessible circulation between homes and community gathering spaces. However, it initially failed to recognize the Hijazi-specific requirement for separate guest entrances (diwan) and screened rawasheen (wooden balconies) that enable women to participate in social observation while maintaining privacy—a critical cultural-spatial relationship that required manual clarification and cross-referencing with Heritage Manual sections on Hijazi domestic architecture before the agent could generate culturally appropriate spatial guidance.

4.4 EVALUATION RESULTS AND VALIDATION AGAINST HERITAGE MANUAL

Comprehensive assessment of the agent responses revealed promising performance across various query types and regional scenarios, with verification using the Heritage Manual confirming that the vast majority of construction methods and material details properly matched documented heritage practice. The system exhibited excellent ability to retain Arabic terms whilst offering suitable cultural reference, facilitating foreign architects in comprehending technical detailing as well as their cultural meaning.

Cultural interpretations were consistently accurate and contextually appropriate as verified through systematic cross-referencing against the Heritage Manual (Ali & Fahmy, 2024). Verification process included: (1) factual validation of material and construction technique descriptions against documented heritage practices, (2) assessment of cultural sensitivity in interpreting social and spatial customs, (3) evaluation of regional specificity in recommendations, and (4) review of Arabic terminology preservation and contextual

usage. Most responses required only minimal refinement in emphasis or term usage rather than fundamental correction.

Performance analysis across the five types of queries revealed that Material & Construction queries had consistently accurate response performance by taking advantage of extensive technical documentation from the Heritage Manual. Cultural Elements and Climate Adaptation queries had generally excellent performance, but at times required additional detail for highly symbolic concepts or complex interdisciplinary relationships. The system demonstrated strong consistency in core recommendations when tested using paraphrased forms of the same narratives, demonstrating stable underlying reasoning with appropriate flexibility for nuances in cultural content.

However, implementation challenges were uncovered during evaluation. Central among these is the limited availability of structured knowledge about heritage suitable for AI training, as comprehensive digitised resources for Saudi building traditions remain limited despite encouraging initiatives. That the extensive Heritage Manual currently exists as one repository of cultural knowledge further illustrates that the system at times performs poorly for highly metaphorical language or abstract cultural concepts without clear documentation. These implementation challenges indicate that, whereas current methods have significant promise, broader implementation would benefit from additional digitised heritage resources and more systematic methods for cultural knowledge representation in AI training algorithms.

5. Conclusion

This study explored the potential of large language models (LLMs) to serve as mediators of cultural and contextual knowledge in the architecture, engineering, and construction (AEC) sector, focusing on Saudi Arabian heritage architecture. Through the development of the NARA (Narrative-to-Architecture AI) agent via prompt engineering and domain-specific knowledge integration, we demonstrated how AI can function as a bridge between unstructured cultural narratives and structured architectural guidance. The agent successfully translated qualitative inputs—such as local commentaries, oral histories, and vernacular descriptions—into actionable design outputs, including material recommendations, spatial briefs, and climate-responsive strategies, while preserving cultural authenticity and technical accuracy.

In this work, we tried to position LLMs not only as workflow automation tools but as dynamic intermediaries with the capability to interpret socio-spatial logic embedded in cultural narratives. By this approach, we tried to be part of the wave of challenges to the dominant technical focus of AI in AEC, offering a framework for culturally resonant design practice. Additionally, the methodology emphasised ethical and decolonial principles, ensuring that AI augments rather than replaces cultural expertise. Through the integration of human-in-the-loop validation and prioritisation of community agency, we addressed critical concerns of bias, hallucination, and power asymmetries in cross-cultural design settings.

However, the study also revealed many limitations. The agent's performance varied depending on the complexity of cultural concepts, with abstract or symbolic elements

requiring additional refinement. The rarity of digitised heritage reliable resources further constrained the system's ability to handle nuanced or undocumented cultural knowledge. These challenges underscore the need for expanded datasets and more robust methods for cultural context representation in AI training, hoping the ongoing work on the Saudi Architecture Characters Map would help in this regard.

In conclusion, this research establishes the groundwork for AI as a collaborative partner in culturally situated design, advocating for technology that respects and elevates local knowledge. As the AEC industry increasingly engages with cross-cultural contexts, our framework offers a pathway to harmonise technical innovation with cultural integrity, ensuring that the built environment reflects the values and aspirations of the communities it serves.

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COLLECTIVE ACTION AND MATERIAL AWARENESS AS AGENTS OF SOCIAL IMPACT IN POST-DISASTER HOUSING

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Abstract. This study investigates the social and educational impacts of a hands-on building workshop conducted after the 2023 earthquakes in Türkiye. The project involved the construction of a stabilized rammed earth structure with timber elements through a participatory process engaging over 100 volunteers. The research focuses on participants' perceptions of collaborative construction and material awareness, emphasizing how such experiences foster civic empowerment and ecological literacy. Employing a mixed-methods approach, the study combines qualitative insights from 16 semi-structured interviews with a quantitative survey conducted with 35 participants, using a 5-point Likert scale to evaluate changes in ecological consciousness, construction confidence, and collective agency. The findings contribute to broader discussions on grassroots resilience and sustainable reconstruction, highlighting the pedagogical value of building by hand.

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1. Introduction

Post-disaster contexts are often marked by an intensified culture of solidarity, where time-sensitive and resource-limited conditions demand the most efficient use of available means. These periods disrupt the routines of everyday life and frequently interrupt logistics chains due to factors such as damaged transportation infrastructure, harsh climatic conditions, or limited access to heavy machinery. Under such constraints, addressing immediate and long-term shelter needs becomes a complex challenge, especially across large geographic areas and populations.

This study examines social and educational dynamics that emerged in response to the devastating earthquakes that struck Türkiye on February 6, 2023, with epicenters in Kahramanmaraş, affecting 11 provinces and nearly 14 million people (Url-01; Arar et al., 2024). According to the official statement released by AFAD on March 20, 2023, the Kahramanmaraş earthquake resulted in 50,096 fatalities and 115,000 injuries, while 528,146 individuals were evacuated from the affected region (Salık Ata, 2023; Url-1). As part of a grassroots recovery effort, a pilot rammed-earth structure was built through a participatory workshop based on the traditional 'imece' model. The hands-on workshop combined participatory design principles with on-site learning to realize a full-scale, functional building, using stabilized rammed earth and timber components. The hands-on building process brought together over 100 volunteers from diverse backgrounds, including architects, engineers, students, and local residents, fostering a collective construction experience.

The research investigates the impacts of this workshop, particularly in terms of participants' perceptions of collaboration and material awareness. Beyond producing a functional prototype, the initiative aimed to promote civic empowerment and ecological literacy. The study contributes to broader discussions on grassroots resilience and sustainable reconstruction, emphasizing the pedagogical value of building by hand in post-disaster contexts. The findings offer insights into how participatory architecture can support psychological recovery, strengthen community agency, and encourage the adoption of sustainable practices at the local level.

2. Collective Modes of Production

The term 'imece' refers to a traditional form of collective labor, defined as "many people coming together to complete a task cooperatively for an individual or a community, thereby accomplishing tasks in succession," and "the equal sharing of labor among villagers to carry out both essential and voluntary work in rural communities" (Url-02). In the context of traditional adobe construction, the 'imece' method has been widely practiced. Local residents and experienced adobe masters typically come together to organize the construction of a house for someone in need (Yeşilyurt & Köse Doğan 2022). The group collectively determines how many adobe blocks will be needed, taking into account the weather conditions and the scale of the building. Once the blocks are produced and sun-dried, the construction of the structure proceeds through a shared effort. In this process, traditional adobe construction functioned not only as a means of shelter production, but also as a socio-cultural ritual that emphasized building together (Gülmüş et al., 2024). It simultaneously enabled the transmission of embodied knowledge through direct, hands-on interaction with the material. However, contemporary construction techniques increasingly rely on specialization and mechanization, thereby marginalizing craftsmanship and collective modes of production.

2.1. COLLECTIVE ACTION

Collective action plays a crucial role in enhancing post-disaster resilience. Community-driven construction practices, such as participatory shelter initiatives, provide timely and context-sensitive housing solutions while simultaneously fostering empowerment, experiential learning, and social cohesion. Rooted in traditions of building together, these collaborative models embody cultural values such as solidarity, cooperation, and mutual responsibility. As Davis (2011) emphasizes, such approaches strengthen local ownership and support networks, reinforcing community bonds throughout the recovery process. Similarly, Cretney (2016) underlines how community-led responses not only address immediate needs but also contribute to long-term resilience by fostering local agency and reinforcing a sense of collective identity.

As Sennett (2012) observes, cooperation is not merely a spontaneous human instinct but a form of craftsmanship that can be cultivated and refined through practice, especially in shared acts of making. Post-disaster building processes create precisely such opportunities, where people working side by side cultivate trust and mutual understanding. Unlike externally driven recovery efforts, these forms of collective making restore not only physical

structures but also social relations, offering a space for rebuilding communities through the act of building itself.

This perspective is further supported by Dabaieh and Sakr (2015), who argue that sustainable construction processes should be seen as socially situated and participatory endeavors rather than purely technical acts. In their work with earth-based construction, they brought together professionals, students, local builders, and policy actors in shared workshop environments. Dabaieh and Sakr's (2015) findings suggest that the most meaningful architectural outcomes often emerge when diverse knowledge systems intersect in the field, allowing all participants to learn through doing while contributing to a common goal.

The psychological significance of participation is illustrated in the work of Norton et al. (2012), who introduced the concept of the IKEA effect. This concept refers to the tendency of individuals to place greater value on objects they have had a hand in creating. Their research demonstrates that the labor invested in a task enhances one's emotional connection to its outcome, even when the end product may be objectively modest. In post-disaster scenarios, where feelings of helplessness and loss are common, the opportunity to take part in rebuilding efforts can help restore a sense of control, dignity, and competence. Rather than remaining dependent on external aid, individuals become active contributors to their own recovery process.

In line with Davis (2011), the experimented bottom-up workshop approach stands in contrast to externally imposed recovery models that often overlook local knowledge and agency. Krimgold's metaphor, cited in Davis, captures this ethos aptly: the soft human community must survive and secrete its own shell. This image emphasizes the importance of enabling communities to craft their own environments through processes of care, cooperation, and collective authorship. Moreover, Participatory Rural Appraisal (PRA) techniques, as demonstrated by Harisankar et al. (2024), facilitate mutual learning between researchers and local communities and support collective decision-making in the co-design of resilient housing strategies.

2.2. MATERIAL AWARENESS

Material awareness in participatory building processes is not merely shaped by the functional or structural performance of materials but also by the tactile, sensory, and emotional relationships individuals develop through direct engagement. As Miranda-Santos et al. (2023) emphasize, involvement in the making process enhances sensory intimacy with materials—such as the feel, smell, and texture of earth—contributing to a deeper sense of

comfort, familiarity, and attachment. Participants who physically handle and manipulate materials often report a heightened sense of belonging and emotional investment in the built environment.

In self-build practices, especially those rooted in earth construction, this awareness is closely linked to embodied knowledge and local tradition. The study by Kebaili et al. (2022) highlights how craftsmanship and material handling skills are transmitted through experience and repetition, making the material not only a technical component but also a medium for knowledge exchange and cultural continuity. Similarly, Morel et al. (2021) stress the importance of respecting vernacular techniques when working with earthen materials, as these techniques are often finely attuned to environmental conditions and social contexts.

The case of Sonsuz Şükran Village in Türkiye indicates how such material awareness is cultivated within a broader cultural and artistic agenda. As shown in the work of Yeşilyurt and Köse-Doğan (2022), the revival of adobe construction in this artistic rural community has enabled a reconnection with traditional material knowledge, while also promoting creative reinterpretation. The villagers' engagement in hands-on construction reinforces collective memory and environmental stewardship, demonstrating that the use of local, natural materials can foster both technical and cultural sustainability. Furthermore, material awareness extends beyond the immediate act of construction (Senem et al., 2025). It becomes a way of seeing, evaluating, and caring for the environment. This resonates with Norton's (2012) notion of the *IKEA effect*, which describes the increased valuation people assign to things they have had a hand in creating. Applied to architecture, this implies that people's emotional and aesthetic appreciation of a space is amplified when they participate in its making.

3. Methodology

This study employs a mixed-methods approach to investigate the social and educational impact of a participatory rammed earth construction workshop organized in a post-disaster rural setting. Mixed-methods research has been effectively applied in architectural and construction studies that prioritize user experiences and perceptions. Chau, Tse, and Chung (2010) utilized a similar design to examine preferences and willingness-to-pay for green building attributes, while Strazzeri and Karrech (2023) applied both qualitative and quantitative techniques to assess perceptions of rammed earth construction technology in Western Australia.

The research design follows an exploratory sequence, beginning with qualitative data collection through semi-structured interviews. The resulting

codes and themes informed the development of a quantitative survey aimed at measuring participants' attitudes and perceptions. This integration allowed for both in-depth exploration and broader validation of findings. The overall methodological framework is illustrated in Figure 1.

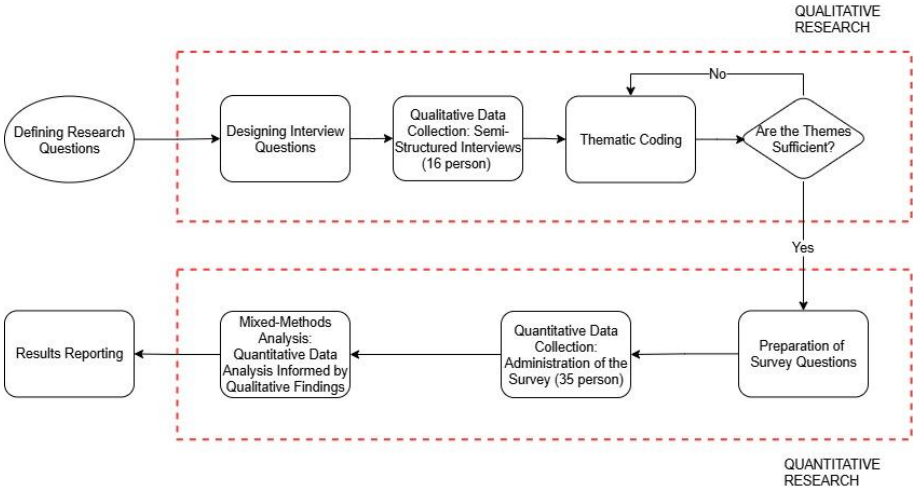


Figure 1. Sequential mixed-methods framework integrating qualitative theme development and quantitative validation.

As a part of the second phase, the survey included a series of Likert-scale items commonly applied in social science research to systematically capture and interpret subjective perceptions, as outlined by Joshi et al. (2015). The five-point Likert-scale questions were designed to measure participants' attitudes toward earthen construction materials, their perceptions of skill acquisition during the workshop, and their sense of agency within collaborative building processes. The data collection aimed to capture both immediate reflections and sustained perceptions of participants regarding the material processes, group dynamics, and the emotional and cognitive value of the experience.

4. Case Study

The primary aim of this study is to evaluate the social impact of a participatory, hands-on rammed earth construction workshop on participants, specifically regarding their awareness, attitudes, and sense of empowerment related to earthen building practices.

4.1. WORKSHOP CONTENT

The workshop was conducted in [omitted for blind review], Türkiye, which was among the regions most severely impacted by the earthquakes that occurred on February 6, 2023. It aimed to explore the contemporary relevance of earthen construction by combining traditional techniques with hands-on experimentation in spatial design. Framed as a participatory recovery initiative, the program sought to demonstrate the potential of rammed earth as a sustainable and inclusive building method in post-disaster settings.

The workshop brought together over 100 volunteers who contributed at different stages of the hands-on construction process between August 5 and October 27, 2024. Participants were selected through an open call launched in June 2024 and joined the project for varying durations, representing a broad spectrum of ages and professional experiences. Upon arrival, participants received an orientation introducing the site layout, construction techniques, and material composition. They were then integrated into ongoing tasks, including earth sieving, ramming, foundation work, and timber roofing. Through these activities, they directly contributed to the making of a full-scale stabilized rammed earth structure.

Accommodation was provided in temporary post-earthquake housing units situated in a nearby schoolyard, with access to hygiene and recreation facilities. Transportation was organized through walking or vehicle shuttles, and meals were prepared collectively with occasional support from the local host. Informal interactions extended to local markets and restaurants, enabling participants to engage with the surrounding community. Reflections and observations were recorded in a shared workshop diary, encouraging critical awareness of the process.

4.2. PARTICIPANTS

From the pool of over 100 workshop participants, 16 individuals took part in in-depth interviews, while 24 responded to the follow-up survey; some participants contributed to both. The survey sample reflected demographic diversity. Thirteen participants were aged between 18–25, ten between 26–40, and one was over 40. The gender breakdown included 18 women and 6 men. Professionally, the group comprised 14 architects, 2 engineers (civil and mechanical), 7 undergraduate students, and 1 practicing sculptor and

digital artist. Regarding educational attainment, 22 participants held a bachelor's degree, 1 held an associate degree, and 1 held a master's degree.

4.3. DATA COLLECTION

The data collection process consisted of two complementary phases: qualitative and quantitative. In the qualitative phase, semi-structured interviews were conducted online and audio-visually recorded. Each participant responded to a standardized set of 14 questions. The recorded video sessions, ranging from 11 to 25 minutes in length, were transcribed verbatim for analysis. Using frequency-based methods, the transcripts were systematically coded, leading to the identification of thematic categories and related sub-themes. These insights directly informed the structure and content of the subsequent quantitative survey.

4.4. SEGMENTATION/CODING

The transcribed interview data were analyzed using a frequency-based thematic coding approach. Participant responses were systematically reviewed and organized under six overarching themes derived from the workshop experience. These themes focused on aspects such as learning by doing, peer-to-peer knowledge exchange, and shifts in perception before and after participation in the construction process. Unlike approaches that emphasize emotional or value-based interpretation of narratives (Kebaili et al., 2022), this study prioritized tracking experiential learning outcomes and perceptual changes over time. The coding process aimed to capture how participants internalized hands-on knowledge and engaged with collaborative construction methods in a post-disaster context.

Special attention was paid to instances where direct engagement with materials influenced learning outcomes, group dynamics, and participants' evolving understanding of earth-based construction. The coding process emphasized collective agency, resilience, and embodied knowledge gained through participation. In total, six main themes and twenty-four subcodes (Figure 2) were identified, encompassing motivations for participation, collaborative production, technical learning, perceptual shifts, challenges encountered, and future intentions.

Informed by participatory evaluation principles (Harisankar et al., 2024), the thematic framework was grounded in the lived realities of participants and emphasized community-specific insights. These coded themes directly informed the structure and content of the subsequent quantitative survey, enabling the integration of qualitative and quantitative findings through a

cross-referential logic. Figure 2 presents the complete structure of thematic categories and subcodes.

Theme	Code Nbr	Codes
Volunteering and Participation Motivation	01.01	Social responsibility
	01.02	Personal curiosity
	01.03	Social network
	01.04	Collective belonging
Collective Production and Task Distribution	02.01	Rotational work
	02.02	Emotional connection
	02.03	Sense of fairness
	02.04	Collective decision-making and spontaneous problem-solving
Learning in Earthen Construction	03.01	Technical processes
	03.02	Material performance
	03.03	Breaking prejudices
	03.04	Practical applicability
Shifting Perceptions and Trust in the Structure	04.01	Initial doubts
	04.02	Perceptions transformed through experience
	04.03	Comparison with traditional knowledge
	04.04	Trust and ownership
Challenges, Adaptation, and Personal Growth	05.01	Climatic conditions
	05.02	Physical fatigue
	05.03	Accommodation
	05.04	Conflict resolution
Future Perspective	06.01	Personal implementation
	06.02	Willingness to rejoin
	06.03	Social benefit
	06.04	Suggestions for improvement

Figure 2. Themes and codes derived from semi-structured interviews

4.5. ANALYSIS AND FINDINGS

This section presents the main findings of the study, drawing on qualitative themes and their quantitative validation.

4.5.1. Qualitative Research

The qualitative findings highlight the transformative role of collective, hands-on engagement with materials in fostering both technical learning and strong social bonds. High frequencies of "emotional connection" (84) and "collective belonging" (42) codes indicate that the act of building together forged deeper relationships than those formed through prior social networks (39). This dynamic aligns with the traditional notion of collective action, a

communal labor practice based on solidarity and mutual aid, showing how shared physical effort can generate new forms of social cohesion. The data also reveal a cognitive shift throughout the process. Initial skepticism (12) gave way to altered perceptions through direct experience (28), eventually leading to trust and a sense of ownership (23). Participants placed more value on the process (57) than on the technical performance of the material (26), suggesting that participatory making reshapes understanding through embodied action. While challenges such as physical fatigue (20) and climate conditions (14) were present, they were often reframed as shared accomplishments. The strong willingness to rejoin (24) further indicates the long-term resonance of the experience. Taken together, these insights position collective action and material awareness not only as tools for construction, but as active agents of social impact in post-disaster housing. The building process created opportunities for agency, empathy, and transformation through cooperation grounded in physical making.

	Code Nbr	frequency	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
	01.01	14	1	1	1	0	0	1	0	1	2	1	2	0	3	1	0	0
	01.02	18	0	3	0	1	0	0	0	0	0	0	1	3	4	1	4	1
	01.03	39	2	1	1	3	3	1	2	4	6	1	0	4	5	3	2	1
	01.04	42	2	3	0	2	2	0	5	1	8	2	2	1	3	4	6	1
	02.01	23	2	0	1	3	2	1	1	1	3	1	2	1	1	1	1	2
	02.02	84	4	7	4	12	5	6	5	5	11	4	1	3	7	5	4	1
	02.03	16	0	1	1	2	1	0	1	1	1	0	0	1	3	2	1	1
	02.04	17	0	3	0	2	2	2	0	0	2	0	1	1	1	1	1	1
	03.01	57	0	4	5	6	3	1	2	2	1	0	2	9	4	11	5	2
	03.02	26	0	1	2	3	0	2	2	1	0	2	2	3	1	4	3	0
	03.03	12	2	1	1	0	1	1	0	1	2	1	0	1	0	1	0	0
	03.04	17	0	2	1	1	2	1	1	1	0	0	1	1	0	4	1	1
	04.01	12	2	2	0	0	0	0	2	0	0	0	2	1	1	0	0	2
	04.02	28	1	2	3	3	2	1	1	1	0	1	4	4	0	1	3	1
	04.03	19	3	0	2	2	2	0	0	0	2	0	1	1	0	0	2	4
	04.04	23	2	3	1	5	1	1	0	0	1	1	1	0	1	0	1	5
	05.01	14	0	0	1	3	2	0	1	1	1	0	0	1	0	1	2	1
	05.02	20	0	1	2	2	1	1	1	1	2	0	0	3	1	3	1	1
	05.03	13	1	0	0	2	1	0	1	0	0	0	0	2	1	2	2	1
	05.04	4	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	1
	06.01	20	1	1	1	1	1	1	1	1	1	1	2	2	0	2	2	2
	06.02	24	1	1	1	2	2	1	1	1	1	2	2	2	2	2	2	1
	06.03	7	1	0	0	2	0	1	0	1	1	0	0	0	1	0	0	0
	06.04	20	1	3	2	1	1	0	1	0	1	1	2	2	1	3	1	0

Figure 3. Frequency distribution of themes and codes across interview participants in the qualitative analysis.

4.5.2. Quantitative Research

The quantitative survey aimed to assess how the participatory experience influenced participants' perceptions of earth-based construction, ecological awareness, and sense of agency.

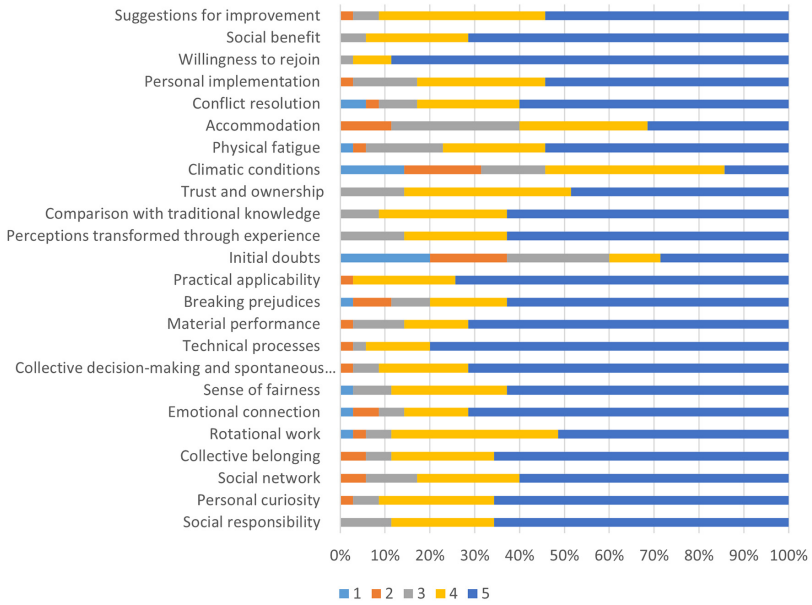


Figure 4. Survey findings aligned with qualitative themes.

These findings (Figure 4) are consistent with the thematic codes developed in the qualitative phase. For instance, codes such as *perceptual shift*, *collaborative production*, and *technical learning* were directly validated by survey results, suggesting alignment between observed narratives and self-reported attitudes. The visual design of the survey output further facilitated the interpretation of data and highlighted correlations between hands-on participation and long-term attitudinal change.

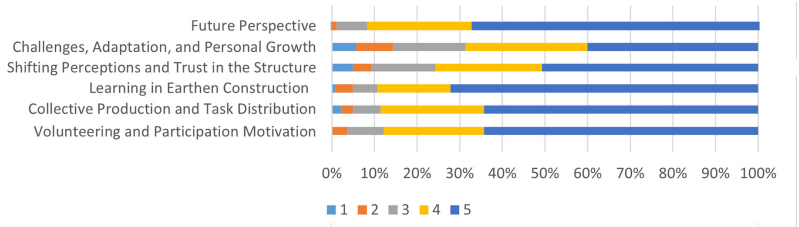


Figure 5 Likert-scale distribution of participant responses across six thematic categories derived from the qualitative phase.

5. **Results and Discussion**

This study investigated the educational, perceptual, and social impacts of a participatory earth-building workshop conducted after the 2023 earthquakes

in Türkiye. Drawing on a two-phased mixed-methods methodology, the research combined qualitative data from semi-structured interviews with quantitative survey results to develop an integrated understanding of how collaborative construction can influence learning, perception, and agency.

The analysis of interview transcripts resulted in the identification of six major themes: motivations for participation, collaborative production, technical learning, shifting perceptions, challenges encountered, and future intentions. Participants described the workshop as a transformative learning environment where knowledge was gained through direct action, observation, and peer interaction. These findings echo the arguments made by Harisankar et al. (2024), who emphasize that participatory engagement with earthen construction provides not only technical training but also fosters context-specific awareness and collective empowerment in disaster-prone regions.

Initial skepticism regarding earthen materials evolved into appreciation as participants engaged in tasks such as soil preparation, formwork assembly, ramming, and timber framing. This shift echoes Miranda-Santos et al. (2023), who highlight how raw-earth architecture contributes to emotional well-being and spatial comfort through its textured, organic materiality. Morel and Charef (2019) similarly emphasize the atmospheric and aesthetic qualities of rammed earth, noting its role in creating warmer and more natural environments.

This perceptual transformation corresponds with literature that links mistrust to limited knowledge. Gelirli (2022) identifies lack of information as a key reason for negative attitudes toward earthen materials, while Ben-Alon (2020) notes that earth is often perceived as a "low-tech" or "poor man’s material." In this study, several participants expressed concerns about durability before the workshop, but direct engagement led to a reevaluation of these assumptions. These shifts reflect Wan et al. (2020), who emphasize that hands-on participation can build both trust and technical competence.

The peer-to-peer nature of the learning process further strengthened group cohesion and trust. Participants often referred to the social value of working collectively and the importance of horizontal knowledge exchange across age groups and professional backgrounds. These reflections align with Dabaieh and Sakr’s (2015) findings on the community-building potential of participatory building practices, as well as Sennett’s (2012) emphasis on mutual respect developed through craft-based collaboration.

Quantitative data gathered from post-workshop surveys confirmed the qualitative findings. More than 80 percent of participants reported strong agreement with statements related to learning outcomes, material awareness, collective engagement, and future motivation. The alignment between coded

themes and survey results reinforces the argument that embodied learning can translate into durable perceptual and behavioral changes. These results also validate Wan et al.'s (2020) proposal that sustainable rural development can benefit from high-impact, low-tech architectural practices grounded in local resources and collective action. While participants reported physical exhaustion, exposure to heat, and initial uncertainty as challenges, these difficulties were often reinterpreted as integral aspects of the learning journey. This perspective supports Cretney's (2016) notion that community-based resilience is cultivated not through avoidance of hardship but through cooperative adaptation and reflection.

A notable outcome of the study was the sustained interest participants expressed in applying their learning to other contexts. Many intended to engage in similar workshops, share their experiences with peers, or promote earthen building as a viable construction method in their professional or academic circles. These intentions suggest that the workshop functioned not only as a short-term educational platform but also as a catalyst for longer-term ecological citizenship and civic engagement. The integration of material experience, collective labor, and reflective practice created a multifaceted space for transformation that extended beyond the physical construction itself.

6. **Conclusion**

The research offered theoretical contributions by situating experiential and peer-based learning within the framework of architectural resilience. It showed that material engagement and collective work can be powerful tools for transforming both individual perception and group dynamics. These insights enrich current discussions on sustainable education, environmental psychology, and participatory design, providing evidence that informal construction environments can serve as meaningful pedagogical spaces.

From a methodological perspective, the integration of frequency-based thematic coding with survey validation offered a replicable model for evaluating the outcomes of participatory learning. This dual approach ensured that qualitative insights were corroborated with measurable patterns, reinforcing the value of combining narrative interpretation with structured data.

Technologically, the study reaffirmed the potential of stabilized rammed earth as a sustainable construction method that is both accessible and scalable. By enabling participants to gain hands-on experience in shaping, mixing, and assembling earthen materials, the workshop demystified

alternative construction technologies and positioned them as viable solutions within broader ecological and economic frameworks.

The study has certain limitations. The sample size was modest, and the data collection occurred shortly after the workshop, which may limit the ability to assess long-term impacts or behavioral changes. Moreover, the specificity of the context may affect the generalizability of the findings. These constraints point toward valuable opportunities for future research, such as conducting longitudinal studies to track participants' application of skills over time, or comparative studies across different geographies to evaluate contextual adaptability.

In conclusion, the study highlighted that participatory construction is not merely a means of shelter production but also a mode of knowledge creation, social bonding, and ecological transformation. Through collaborative action, shared reflection, and direct engagement with earth as a building material, participants developed both practical competencies and a renewed sense of connection to place, community, and sustainability. These findings carry significant implications for future disaster recovery strategies, sustainable design education, and the democratization of construction knowledge.

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PROJECTING DIALOGUE: TRANSFORMING A LAO VERNACULAR ROOF INTO A HYRBID DEBATE SPACE

Heritage Architecture as a Platform for Learning and Civic Discourse

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Abstract. In Luang Prabang, Laos—designated a UNESCO World Heritage Site—heritage buildings are increasingly "museified," preserved as static backdrops for tourism while their civic roles erode (Bear, Feldman and Avieli, 2020). Yet the city emerges as a migration destination for rural youth pursuing education, where informal learning centres persist within this landscape, bolstered by volunteers and NGOs; however, they are fragmented, underfunded, and susceptible to fluctuations in tourism economy. This study introduces a speculative design-research prototype that reimagines the vernacular Lao roof—traditionally a gathering space and carries symbolic importance—as an active pedagogical interface for decentralized civic discourse. The reconfigured, double-pitched roof structure integrates projection mapping, seating and a stage, transforming the cultural role of the roof from mere shelter and gathering space into a hybrid physical-digital debate arena. A workflow that integrates LiDAR capture, parametric modelling, VR staging, and projection mapping renders spoken dialogue into spatialized, multilingual text and visual emphasis across both virtual and physical models. The project demonstrates how digital technology can be woven into the inherent design principles of heritage architecture while remaining receptive to ongoing interactions with global networks. It offers a model for heritage-based educational design in which local spatial traditions and global networks intersect, advancing both cultural continuity and new forms of participatory learning

Keywords: *Hybrid Learning, Vernacular Architecture, Heritage based Education Design, Mixed-Reality Educational Interfaces; Digital Participation in Heritage Spaces*

1. Introduction

1.1. PROBLEM STATEMENT

Educational opportunities in Lao PDR remain deeply uneven. Despite high primary attendance, participation drops sharply thereafter: only 37 percent of upper secondary-aged youth are in school, and 60 percent are out of school entirely. Disparities are stark, with rural youth and those from the poorest households several times more likely to be excluded from education (UNICEF Lao People's Democratic Republic, 2025). These gaps constrain ambitions to position Luang Prabang as an educational hub for northern Laos, where linguistic diversity and uneven digital access further compound the challenge (Luang Prabang Provincial Government, 2023; KPL News, 2023).

Recent EdTech pilots, such as UNICEF/MoES's 2025 Eduten program, demonstrated short-term gains but also highlighted reliance on external infrastructure, raising doubts about scalability in the Lao context (UNICEF & MoES, 2025; Fitch Solutions, 2025).

At the local scale, grassroots informal centres where volunteers and NGOs provide language and digital literacy classes demonstrate community demand for alternative learning environments yet they are fragile and dependent on tourist flows Meanwhile, UNESCO heritage regulations and the growth of tourism in recent years have accelerated the conversion of historic buildings into commercial venues, undermining communal use and risking the city's reduction to an open-air museum (Leong, Takada and Yamaguchi, 2016; Bear, Feldman and Avieli, 2020; Wilcox, 2021; Wongpit and Sabhasri, 2022).

Within this context, the civic and educational potential of heritage architecture is underexplored. This gap prompts consideration of how vernacular heritage buildings might be reimagined as hybrid educational infrastructures that extend learning beyond classrooms, resist commodification, and activate heritage as a civic resource for collective learning and cultural continuity.

1.2. AIM AND OBJECTIVES

This research develops a prototype for a hybrid educational interface embedded in a re-adapted vernacular Lao roof. The orchestrated simulation integrates projection mapping and Virtual Reality (VR) sequences to evaluate the potential of roof structure as an active space for civic discourse.

The design works with vernacular form, multilingual exchange, and the existing informal learning networks in Luang Prabang, such as Big Brother Mouse. In the prototype, spoken contributions were converted into scripted text sequences and projected onto the readapted roof's surfaces, enabling the debate to traverse both physical and virtual realms.

1.3. SIGNIFICANCE

This research aligns with UNESCO's advocacy for inclusive, culturally rooted digital education, as articulated in frameworks such as Education 2030 and the Futures of Education report (UNESCO, 2016, 2021, 2023). By situating hybrid learning within vernacular Lao architecture, the project responds to UNESCO's call to bridge digital divides in under-resourced contexts while safeguarding cultural heritage as a living civic resource.

It also aligns with national educational priorities. The Ministry of Education and Sports' 10-year ICT in Education Strategy (2024) seeks to integrate digital tools across learning environments, while pilots such as the UNICEF/MoES's Eduten program have demonstrated both strong receptivity and measurable gains in classrooms (UNICEF, 2025). Yet these initiatives remain narrowly situated within formal schooling. By extending hybrid learning into vernacular heritage spaces, the project complements these agendas, proposing a civic and cultural dimension to Laos's digital education landscape.

Instead of developing a commercial solution, this project functions as a design experiment. It explores how digital augmentation can fit within indigenous architectural forms without erasing their cultural identity. Through simulated debate scenarios, the project tested how projections and interaction visibility host group participation across physical and virtual realms.

Immersive technologies have been widely adopted across cultural heritage. In museums, AR and VR extend exhibitions beyond static representation with projects at the British Museum and the State Hermitage Museum combining physical collections with digital reconstructions, while interactive XR objects and projection mapping experiments have been used to convey intangible heritage practices in situ (Banfi, 2021; Nikolakopoulou *et al.*, 2022; Spallone *et al.*, 2022). Recent studies highlight how digital storytelling functions as a measurable driver of presence, immersion in VR museums, with standardized UX frameworks emerging for assessing visitor motivation and engagement (Anwar *et al.*, 2025; Shu, 2025).

Beyond museum contexts, immersive technologies have supported community resilience and informal learning, as in post-disaster VR reconstructions of Amatrice and Accumoli, that fostered intergenerational dialogue (Di Giuseppantonio Di Franco *et al.*, 2025). These trends underline how digital heritage research has expanded from preservation to participation.

However, most of these applications still frame heritage as content to be displayed, consumed or gamified. In contrast, this project repositions heritage as an active infrastructure for education and discourse. It also contributes to broader discussions on decolonizing digital space, recognizing informal pedagogies, and adapting heritage buildings for contemporary civic needs.

2. Conceptual Framework and Design Methodology

2.1. GENERATIVE FRAMEWORK: MAPPING LEARNING, SPACE, AND TECHNOLOGY

The project began with the development of a matrix-style framework intended as a tool for designers and planners working in heritage contexts. The framework cross-references four domains:
(1) global development challenges and goals,
(2) learning types and patterns,
(3) vernacular architectural elements, and
(4) hybrid spatial toolkit (Fig. 1)

For the second domain, the research draws on Diana Laurillard's Conversational Framework (Laurillard, 2002, 2012), which has been widely used in learning design (Hollinshead and Pope, 2023). Seven recurring learning types were identified: acquisitional, inquiry, experiential, productive, discursive, collaborative and reflective learning. Together, these types outline the different ways knowledge is acquired and enacted. These categories provided a rigorous educational scaffold, ensuring that each architectural intervention connected to specific pedagogical processes instead of random technology use.

For instance, upon selecting a specific learning type and respective learning patterns, one can identify an architectural element in the building that supports the learning activity. This can then be paired with appropriate technologies to enhance its educational function.

While this paper focuses on the roof scenario in depth, the framework is designed for adaptation, allowing educators or designers in other contexts to swap learning modalities, architectural elements, or technologies to suit local needs. The matrix serves as a manual for transforming vernacular building elements into hybrid learning interfaces that respond to their immediate contexts. This aligns with phygital heritage methods that combine virtual and physical aspects for cultural engagement (Nofal *et al.*, 2018).

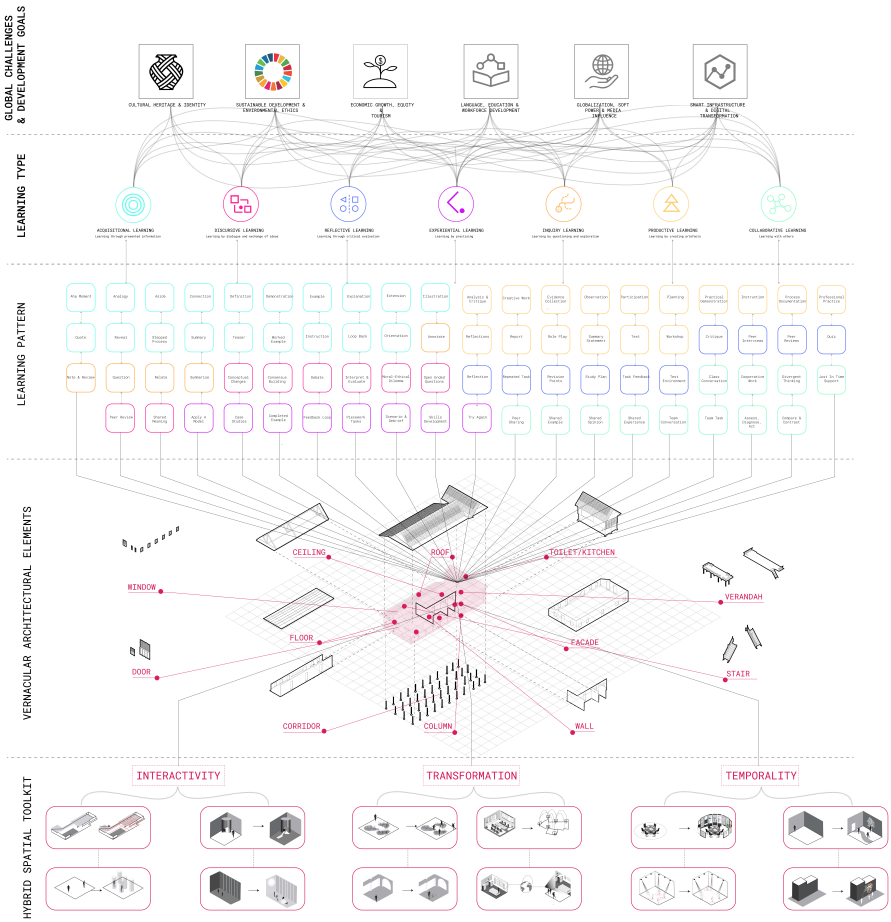


Figure 1. Conceptual design matrix mapping global development challenges, learning types, vernacular spatial elements, and hybrid digital tools. Matrix used to select the roof as the debate interface and its suitability for multi-plane projection.

2.2. SPECULATIVE DESIGN - RESEARCH AS METHODOLOGY

Centered on a scripted debate scenario, this project employs design-research methodology to explore how physical and virtual elements can be integrated within a vernacular heritage setting. The prototype served as an exploratory model for testing architectural forms, projection surfaces and spatial layouts in order to support a multilingual debate.

The study focused on legibility, placement, and sequencing as an integrated design issue, connecting projection flow, spatial functions, and

participation. Two parallel prototypes were developed: one was a digital reconstruction of the vernacular structure using Rhino and Unreal Engine. This was used to stage the debate sequence, which included refining camera angles, projection layout, and content focus. The other prototype was a 1:500 physical model, projection-mapped in MadMapper, examining how light, shadow, and surface shape affected perception and attention.

The exercise explored how the roof's vernacular geometry could function as an architectural interface connecting in-person and remote participants instead of just simply demonstrating technical feasibility. Future iterations may integrate real-time AI transcription and translation for the archiving and replaying of debates for learners in different places, thus extending the spatial experience beyond the event itself.

2.3. SITE, TYPOLOGY, AND CULTURAL RESONANCE

The chosen site is one of Luang Prabang's UNESCO-listed heritage buildings, part of the city's 611 designated heritage structures. This building currently hosts the Children's Cultural Centre, which supports civic learning with a public library, cultural workshop and exhibition spaces, as well as administrative offices. Its long history as an open, multi-purpose civic venue influenced the design of a hybrid debate space that reflects local identity and encourages public interaction.

The double-pitched wood carved Lao timber roof, which is a prominent feature of the building, was adapted into a self-supporting debate canopy. New folded surfaces were incorporated along the roof slopes to increase the total projection area and adjust viewing angles for audiences seated 5–7 m away. Seating tiers were positioned along the stage to maintain unobstructed sightlines to all projection facets (Fig.2).

Since the Children's Cultural Centre already plays a civic and educational role in Luang Prabang, the design is viewed not as a disruption but as an extension of its current mission. The intervention broadens its function from hosting local cultural programs to endorsing a hybrid format that connects both in-person and remote participants.

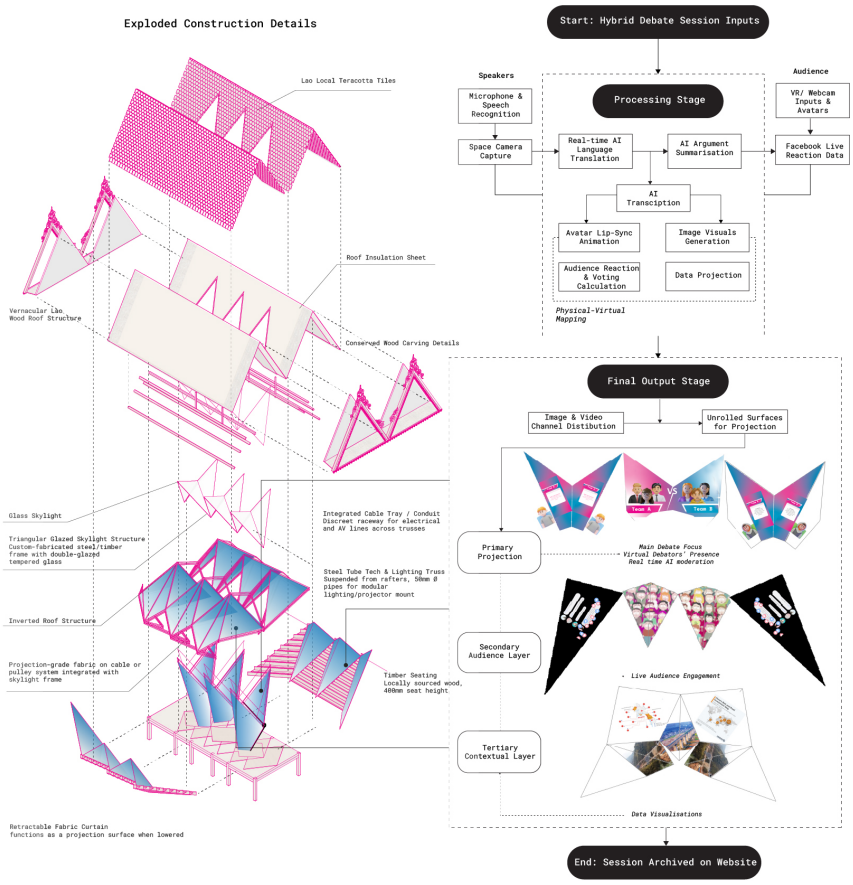


Figure 2. Exploded construction and system architecture. Architectural adaptation of double-pitch roof with folded projection planes and integrated seating.

3. Spatial Computational Workflow

As shown in recent digital heritage research, high-fidelity documentation gains value when it is integrated into interactive environments that foster public engagement (Nikolakopoulou et al., 2022). Building on this principle, the project approached computation as part of a situated design process. Site-specific architectural adaptations were paired with layered digital content to test how a reconfigured vernacular form might host, structure, and visually communicate a hybrid debate.

3.1. SITE CAPTURE AND ROOF ADAPTATION

A LiDAR scan of the existing heritage building provided the foundational dataset for reconstructing its original double-pitched roof. This was remodeled in Rhino and adapted into a self-supporting structure. New fabric projection planes and stepped timber seating were introduced, but these additions followed the existing structural rhythm, allowing the intervention to remain legible as part of the original roof form.

3.2. VIRTUAL DEBATE STAGING IN UNREAL ENGINE

The 3D model of the reconfigured roof was imported into Unreal Engine to stage a scripted debate sequence, connecting parametric modelling to immersive game engines. Avatars representing speakers and audience members were positioned according to the physical seating plan. Speech sequences were pre-recorded in English, with an AI-driven transcription and translation layer added into the scene. The folds were set at 12–18° from the original slope, a range determined through trial renders to maintain subtitle legibility at a minimum of 150 px font size without glare from the virtual light sources. These adjustments balanced visibility with the practical need to keep text readable for viewers about 5–7 m away.

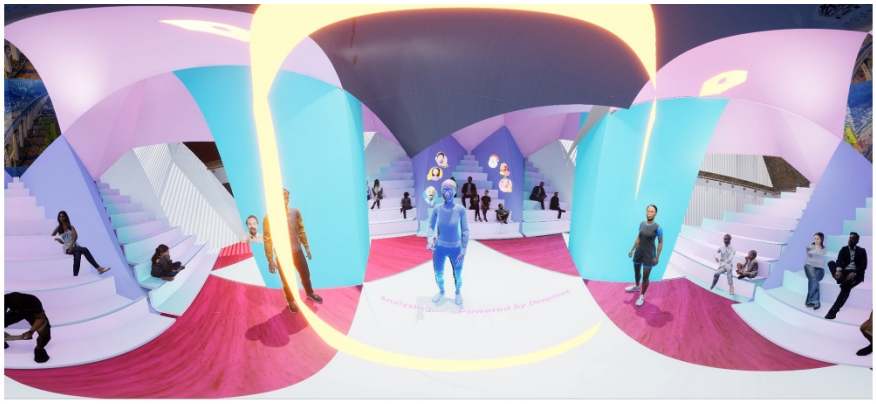


Figure 2. 360° VR frame of a scripted multilingual debate

3.3. PROJECTION MAPPING ONTO SPATIAL MODEL

Projection mapping sits on Milgram and Kishino's Reality-Virtuality Continuum. It redefines architecture as a hybrid medium that shifts between physical presence and virtual augmentation. This project embraced this idea, seeing projection as a cybernetic feedback loop where viewers, digital overlays, and spatial form continually influence each other.

A 1:500 physical model of the design intervention was projection-mapped via MadMapper in parallel. The digital output from Unreal was calibrated for each projection facet, aligning angles to minimize text distortion while maintaining legibility. This calibration maintained the same visual hierarchy as the VR environment and validated that the spatial–informational logic could be transposed across both virtual and physical media.



Figure 4. 1:500 projection photo. Synchronized virtual and physical staging of a scripted debate; projections arranged from top to bottom: main debate focus (primary), audience layer (secondary), thematic images and date visualizations (tertiary).

3.4. INTEGRATION AND ITERATION

Multiple rounds of testing at model scale informed the final configuration. Early prototypes revealed issues of distortion and overlapping captions; later iterations introduced staggered projection zones and adjusted folds to clarify visual separation between debate focus and contextual information. The workflow thus moved beyond technical calibration toward a design experiment in debate choreography—where physical geometry, projection mapping, and digital twin logic interacted to organise participation.

This iterative process demonstrated the potential of projection mapping not merely as an immersive tool but as a medium shaping how audiences follow and contribute to discourse.

4. Interaction Logic & User Experience

The adapted roof serves as the primary interface linking learners, the audience, and the debate content. Once the computational pipeline (see Section 3) has staged the event and aligned the physical and digital components, the design's interactive layer guides participants' engagement with the debate.

4.1. TARGET USERS & PEDAGOGICAL CONTEXT

The system accommodates both formal and informal learners, particularly students from rural provinces who travel to Luang Prabang in search of educational opportunities unavailable in their home regions. Many already participate in grassroots learning centres where language exchange, storytelling, and digital literacy are facilitated by local educators, visiting volunteers, or tourists (KPL, 2017; Allan, 2015). For many young people, these encounters are their primary exposure to foreign languages, global perspectives, and new skills—occurring not only in structured lessons, but also in everyday exchanges with visitors.

In this context, the hybrid debate interface builds on these informal networks, maintaining the immediacy of face-to-face interaction while enabling participation from beyond the city. A local student seated within the adapted roof arena could debate alongside a peer connecting remotely, with both voices and ideas shared in the same architectural and visual space. Beyond students, potential users also include community educators, civic groups, and NGOs who could host thematic discussions on cultural or environmental issues within space. Each group interacts with the architecture in different ways, from taking the central stage, to observing from tiered seating or contributing remotely via projection-linked channels.

4.2. SPATIAL INTERACTION FLOW

A debate session begins as local and remote participants take their positions. In the physical arena, speakers stand on the central stage beneath the retractable projection curtains of the roof, while audience is seated to ensure unobstructed sightlines to both the stage and projection facets. Remote participants, in the current demonstration, are represented by pre-scripted avatars within a virtual reconstruction of the same space; future iterations

could allow these avatars to be controlled live via VR or video-link input, enabling real-time participation.

As each speaker delivers their argument, speech is visualized on the architecture. In the current prototype, this is achieved through scripted text projections mapped to specific roof facets that correspond to the speaker's position. This creates a visual pairing between physical location and verbal contribution, boosting spatial awareness and sustaining participant immersion in the debate.

In a live system, AI transcription and translation could generate these captions in real-time, allowing multilingual dialogue to flow without losing its relationship to the shared spatial environment. Audience responses from social media platforms such as Facebook Live, commonly used by Laotians, currently represented by animated visual markers in the VR model, could be rendered as projected icons or keywords on peripheral surfaces, expanding the visual field of participation beyond the central stage.

4.3. PROJECTED INFORMATION HIERARCHY

The projection strategy is structured into three layers of content:

(1) Primary layer– Central panels display main debate focus, the presence of virtual debaters, and live or scripted subtitles in the active speaker's language.
(2) Secondary audience layer– Flanking folds show the virtual audience and visualizations of live audience engagement, positioned between seating tiers to remain in the viewer's peripheral awareness.
(3) Tertiary contextual layer– Upper roof slopes carry thematic images and data visualizations that sustain contextual awareness complementing the primary dialogue.

As projection facets are built into the roof geometry, information reads as part of the architectural volume rather than an external overlay. This integration allows on-site viewers to see, hear, and read the debate as a single spatial event, while remote participants encounter the same layered hierarchy within the VR environment.

Text and visual highlight are distributed across multiple spatial registers over the inclined planes of the roof, prompting participants to shift their eye line and attention in relation to each seating position. This choreography of space draws on Herbert Bayer's "extended field of vision," which is reinterpreted for a debate—immersing virtual media across the perceptual field to encourage navigation between simultaneous verbal and visual streams.

4.4. ACCESSIBILITY AND PARTICIPATION

The system is designed to function across diverse infrastructural conditions. In low-connectivity contexts, remote contributions can be transmitted as pre-recorded audio or text, subsequently mapped to an avatar with projected captions during the event. Audio-only participants can be represented by a simple lip-synced avatar with their speech transcribed on the corresponding roof facet to provide a stronger sense of presence.

The portability and moderate cost of projection hardware enable deployment in schools, community halls, and temporary outdoor venues. This flexibility allows learners from digitally under-resourced areas to participate in real-time without the need for high-end VR equipment.

5. Discussion & Implications: Toward a Situated Hybrid Learning Infrastructure

5.1. FROM VERNACULAR FORM TO HYBRID INFRASTRUCTURE

The project reimagines vernacular architectural elements as medium to facilitate learning. It adapts a Lao roof to encourage participation, guide interaction, and incorporate cultural meaning in modern education.

This approach counters the tendency of imported classroom and platform models to overwrite local spatial intelligence. Instead, it views the roof's geometry and openness as device for mediating how voices are heard, how information circulates, and how authority is negotiated within the hybrid space.

Digital augmentation here serves as a mode of spatial decolonization. Technology adapts to the site's cultural and material context rather than replacing it. The outcome is a model that is both transferable and specific to its context, combining architecture, cultural meaning, and digital tools into a single pedagogical system.

Comparable digital heritage projects remain largely exhibition oriented. This research project diverges from these trajectories by re-engineering vernacular form as an educational apparatus. This distinction reframes digital heritage from interpretive augmentation to infrastructural activation. Rather than presenting heritage sites as screens for cultural consumption, the prototype mobilizes vernacular architecture to host live discourse, connecting learners across geographies. In doing so, it shifts the field from conserving memory to enabling collective futures—positioning digital heritage not only as archive, but as a participatory civic platform for education.

5.2. TECHNICAL AND CONCEPTUAL BOUNDARIES

Both the VR sequence and physical projection model were scripted to allow controlled testing of text legibility across projection angles, visibility from seating positions, and alignment of multilingual captions with architectural elements. These constraints reduced the unpredictability of real-life debate but also clarified how digital overlays perform on angled and faceted surfaces.

At present, speech recognition and translation are simulated using standard ASR/MT pipelines. While transcription in English is generally reliable, accent variation among non-native speakers introduces errors, and translation into Lao remains inconsistent due to the limited resources available for low-resource languages. As a result, captions in the prototype serve as illustrative placeholders rather than fully dependable tools.

Scaling the prototype to a full-scale installation would also require technical adjustments: adapting projection brightness for daylight, calibrating across larger surfaces and refining surface geometry for diverse viewing angles.

5.3. IMPLICATIONS FOR FUTURE WORK

Future development of the prototype will involve participatory testing with local stakeholders in Luang Prabang. Pilot workshops will be planned with students from Souphanouvong University, informal learners from community centres such as Big Brother Mouse, and local educators and NGOs, who already facilitate civic and cultural learning. These sessions will stage mock debates with lightweight projection fabric set up in the physical space, combining on-site participants with remote peers from other province or countries connecting via simple web or mobile input.

Evaluation will focus on three dimensions: engagement (whether projection and translation enhance participation), accessibility (clarity of multilingual captions) and learning outcomes (confidence in debate and language skills). Local educators and community organisers will help determine discussion topics and adapt the format, ensuring that the technology aligns with local practices. This participatory process will provide critical feedback on the usability and cultural resonance, validating the hybrid vernacular space as a hybrid civic learning infrastructure rooted in community agency.

The methodology could extend to other vernacular elements that were documented previously—façade walls for interactive language-learning interface at Big Brother Mouse, or timber columns as weaving craft “phygital” scaffolds in Heuan Chan Heritage Museum in Luang Prabang (Fig.5). In broader terms, the project offers an alternative to the generic digital classroom

model by designing vernacular architecture, cultural practices, and digital tools together as one cohesive, context-sensitive pedagogical framework.



Figure 5. Future intervention types: (Top) façade wall for language learning in Big Brother Mouse. (Bottom) columns for interactive hands-on weaving in Heuan Chan Heritage Museum.

6. Conclusion

This project has explored the reconfiguration of a vernacular Lao roof into a hybrid debate interface, utilizing heritage architecture as apparatus for learning. By using digital modelling, VR staging, and projection mapping, the

project examined how a familiar architectural element could mediate discourse across physical and remote participants. Instead of attributing innovation to the novelty of digital tools, the workflow demonstrates that their value emerges from careful orchestration within a culturally situated framework. The scripted prototype offers a method for embedding computational systems into the architectural logic of place and reconceives hybrid learning as the creation of site-responsive infrastructure in which architectural form, cultural memory, and participant engagement are all inseparably intertwined.

Thus, the re-adapted vernacular structure is no longer merely a static relic or a passive space; it becomes an active participant of the learning environment itself — determining who is visible, how knowledge is produced. Collaborating with local communities is crucial to preserving the cultural significance of space while adapting it for contemporary use.

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DECOLONIZING WESTERN DESIGN LOGICS

A Comparative Architectural Analysis of Gerber Architekten's Projects in Germany and Saudi Arabia

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Abstract. Since the 1980s onwards, Saudi Arabia has focused on prestigious projects that reflect the country's cultural identity in a contemporary-traditional form. Examples include Tuwaiq Palace, the Qasr Al Hokom district, and the King Fahad National Library, all of which combine local cultural references with modern architectural elements. In 2016, 'Vision 2030' was introduced, which gives higher priority to the preservation and promotion of cultural identity. The central research question of this study is how decolonial architecture can be successfully implemented and systematically evaluated in the Najd region in order to support the goals of Vision 2030 for the development and preservation of architectural identity. Before the case studies, the term 'decolonization' is examined, and its theories are clarified according to the theorists (Mignolo, Quijano, and Tuck & Yang), transferring their political-philosophical thinking to an architectural-philosophical approach. Subsequently, the theory of 'critical regionalism' by Tzonis & Lefaivre and Frampton is examined, which sharpens decolonial approaches architecturally and shows that architecture must emerge in a local, cultural, and spatial context. The research thus provides a methodological evaluation approach that systematically analyses and evaluates architectural works in the Najdi context in terms of their cultural, climatic, and symbolic identity proximity. The results will serve to improve the quality of future architectural projects and strengthen the connection between built space and national identity. In addition, the study makes a significant contribution to the implementation of the Vision 2030 goals by formulating concrete guidelines for culture-based, context-related, and sustainable planning strategies and providing them as an evaluation grid.

Keywords: *Decolonizing Architecture, Critical Regionalism, Traditional Architecture, Saudi Architecture, Najd Identity*

1. Literature review

This section reviews the theoretical foundations of decolonization and their application to architectural identity. First, the theories of decolonization developed by Aníbal Quijano, Walter D. Mignolo, Eve Tuck, and K. Wayne Yang are outlined, with a particular focus on concepts such as power structures, power relations, and Eurocentrism. Their transfer into architecture is then examined through the lens of 'critical regionalism.' Liane Lefaivre and Alexander Tzonis, Kenneth Frampton, Stylianos Giamarelos, and Robert Adam provide key theoretical perspectives in this regard. Frampton's contribution is especially emphasised, as his interpretation of critical regionalism defines architectural identity as a form of resistance to global standardisation. The study then turns to the architecture of the Saudi cultural sphere in the Najd region. In his writings, Mohammed Mashary Alnaim presents central aspects and strategies that allow for an evaluation of Saudi regionalism. Particular attention is given to the concept of 'Salmani architecture' and the King Salman Charter Initiative. Complementary insights are provided by Yasser Mohamed Fadl, Suk Hee Yun, Tae Yeual Yi, and Monica Moscatelli, who, together with Alnaim, have published important studies on traditional elements, building materials, and strategic approaches to Najdi architecture. These contributions form the scholarly basis for the evaluation grid that will be applied to the case studies analysed in detail in the following chapters.

2. Theoretical framework: Decolonization and architecture

In decolonial theories, the examination of the concept of "modernity" is considered the starting point for understanding colonial power relations in the political world, which can also be applied to architecture. In The Darker Side of Western Modernity: Global Futures, Decolonial Options (2011), Walter D. Mignolo analyzes "modernity" not as a neutral description of historical change, but as an expression of a specifically European idea of power. He interprets it as a colonial ideology with which Europe legitimizes its global dominance. "Cosmopolitanism becomes a key concept of modernity to hide coloniality" (Mignolo 2011, 257). Thus, there is no classical modernism in architecture; rather, there is a colonial knowledge structure that presents Western modernism as a universal system. This is evident in specific construction projects: CIAM, with its Charter of Athens (1928), enforced functional separation and grid cities, ignoring social and cultural spatial traditions. Constantinos A. Doxiadis' office applied these principles to the Riad master plan in 1968. To this day, the city suffers from the grid and street layout, instead of the original linear settlement logic with shady alleys and introverted courtyards. Thus, the colonial approach led to a loss of social and cultural proximity (Al-Hathloul 1996; 2010).

Peruvian sociologist Aníbal Quijano coined the term “coloniality of power” in Coloniality and Modernity/Rationality (2000). He shows that power relations continue to exist even after colonialism (Quijano 2007, 168). Colonization appears as a Eurocentric power that is no longer exercised militarily, but through (1) knowledge, (2) culture, and (3) subjectivity. (1) Knowledge outside Europe is devalued and formalized as a universal paradigm through European products (ibid., 171). (2) Non-European cultures are considered primitive and irrational, while individualism serves as a means of differentiation (ibid., 173). (3) Subjectivity is determined by European standards such as “modernity”; other ways of thinking are considered backward or exotic (ibid., 173). Quijano's concept is evident in architectural projects in which Western planning and design norms dominate local structures.

From this perspective, architecture can be described as a hegemonic knowledge structure. Eurocentric design logics such as CIAM, Bauhaus, and International Style prevail over local contexts: axial order, reduced volumetry, abstract forms, or glass facades are used globally, regardless of climate (Frampton 1983). This differs significantly from the climate-adapted, modest mud houses of Saudi Arabia, which were considered backward in modern times. Urban planning also marginalized local needs, social relationships, and communal spaces (Al-Hathloul 1996; 2010), while functional zones, car-oriented structures, and administrative axes were prioritized (Frampton 1985).

Eve Tuck and K. Wayne Yang sharpen the debate in Decolonization is Not a Metaphor (2012). They reject metaphorical approaches and define decolonization as the return of what colonization has taken, whether materially or in the form of rights and power (Tuck/Yang 2012, 21). Applied to architecture, this means that local architects, societies, and user groups must take on the central role in planning processes. The question “How do you implement a European concept in Saudi Arabia?” is not decolonial. Instead, it must be: “How does a concept emerge from the climate, religion, tradition, and history of Saudi Arabia?” The resulting spaces should have social, religious, and family references, not just be representative. Tuck and Yang emphasize that decolonization without reparation is a distortion (ibid., 17) and must be “accountable to Indigenous sovereignty and futurity” (ibid., 35).
The approaches of Mignolo, Quijano, and Tuck & Yang show that a foreign office can only plan decolonially if it critically reflects on its role, shares or relinquishes planning authority, and ties its design logic to local knowledge and context.

TABLE 1. Comparison of approaches with transfer to architecture (own elaboration)

Theorists	**Central idea**	**Example: CIAM; grid system, separation of functions, etc.**	**Can foreign planning offices plan in a decolonial way?**
Walter D. Mignolo	Modernity = colonial project	Eurocentric planning style – Ignores local building forms – Uniform instead of contextual	Permitted if: – Local knowledge is taken seriously – Made visible in design – No symbolic participation
Aníbal Quijano	Power remains after colonialism – Through knowledge, culture and subjectivity	– Technocratic instead of social – Plans over people's heads – Hierarchises spaces	Only acceptable if: – Local voices are actively involved – Power asymmetries are named – Planning is not top-down
Eve Tuck & K. Wayne Yang	Decolonisation = genuine restitution – No metaphor, no symbolism	– Removes local control – Abstract, without participation – No room for self-determination	Not acceptable if: – No restitution of decision-making power – Local actors without control – Symbolic decorative elements without effect

For Tuck and Yang, it is clear that decolonization is not synonymous with reform, but rather represents a restitution. In contrast, Mignolo and Quijano allow more room for a decolonial process by including the participation of Western actors, as long as they critically question and reflect on their epistemic stance and take local dimensions into account. For Quijano, decolonization is an abolition of Eurocentrism and knowledge structures. His focus is on questioning what knowledge structures contain. A Western planning office may therefore plan decolonial designs if it justifies them with local perspectives. For Mignolo, the ‘decolonial option’ is an alternative to a radical break. He accepts that the decolonization of colonial systems can be developed through critical reflection and transformation from the inside out. He therefore believes that a Western planning office can plan decolonial designs if it recognises marginalised knowledge and works together with the local population in participatory processes.

3. Architecture and Identity: Concepts and Theories

In the previous section on the debate surrounding colonial theories, it was shown that colonial power and knowledge structures deliberately abolish

culture and dominate subjectivity. Where culture is destroyed or marginalised, identity loses its foundation. In other words, the loss of culture entails the loss of identity. Against this backdrop, Alexander Tzonis and Liane Lefaivre formulated the approach of 'critical regionalism' in the early 1980s as a conscious reaction to cultural uprooting by international standards, with the aim of critically reclaiming cultural identity rather than simply reproducing it. The approach was later further developed by Kenneth Frampton in his essay *Towards a Critical Regionalism* (1983). Tzonis and Lefaivre describe critical regionalism as a two-sided concept: on the one hand, it is used as part of liberation movements, while on the other hand, it can serve oppression and exaggerated national pride. Frampton, by contrast, sees regionalism as a necessary bridge to a human and context-based architecture (Frampton 1983, 20–21).

In architectural theory, Kenneth Frampton defined the concept of critical regionalism as an "architecture of resistance" against the placelessness of global modernism (ibid, 21). This interpretation differs from the original conception of Alexander Tzonis and Liane Lefaivre, who understood the term more analytically and in relation to design tactics.

Frampton's Critical Regionalism is characterised by several key elements. He emphasises the importance of considering climate, light, wind, and topography as form-determining factors in architectural planning (ibid, 26). In contrast, Tzonis and Lefaivre placed greater emphasis on the symbolic path as a narrative space. Frampton, however, calls for an architecture that speaks through its construction, materials, and spatial logic rather than through symbolic façades (ibid, 27). This entails a rejection of decoration that superficially imitates old forms and thereby loses its connection to place, function, and culture.

Another important aspect is tactile (constructive) perception. Frampton advocates a return to the physicality and haptic experience of architecture (ibid, 28), which goes beyond the formal and cultural reflection described by Tzonis and Lefaivre. In addition, Frampton criticises the influence of modern technology, media, and the global economy on building (ibid, 20–22), which was less of a concern for Tzonis and Lefaivre.

The following table summarises the most important ideas of 'critical regionalism' by Tzonis and Lefaivre (1981) and Frampton (1983). It illustrates and compares the concepts, highlighting the respective aspects that are relevant for architectural identity.

TABLE 2. Critical Regionalism: Tzonis & Lefaivre vs. Framptont (own elaboration)

Aspect	**Tzonis & Lefaivre (1981)**	**Frampton (1983)**	**Relevance for features of architectural identity**
Main idea	Critical development of local forms	Architecture as cultural resistance	No imitation, but engagement with local culture: cultural continuity should be maintained Approach to tradition
Dealing with tradition	Reflection instead of imitation = critical translation instead of copied tradition: no formal copy	Tradition should not be decorative, but materially and constructively integrated	Identity as a transformation of tradition: characteristics should not be folkloric, but functional and culturally based.
Relation to place	Place = cultural and symbolic	Place = physical (topography, climate, light)	Identity results from integration into landscape, climate, materials and spatial experience
Design method	Abstract analysis of regional principles	Concrete derivation of form from environment and technology	Identity is reflected in forms derived from climate, place and technology – not from stylistic forms.
Understanding of technology	hardly discussed	Viewed critically because it often forces standardised solutions	Technology must be adapted and consciously anchored locally
Role of perception	Legible, recognisable culture in space	Physically tangible spaces	Identity becomes tangible through material, light and scale → Architecture feels local
Attitude towards globalisation	hardly discussed	Critical: warning against the displacement of local identities by global standards	Identity needs contextual reference: either as resistance to globalisation (Frampton) or as culturally understandable design (Tzonis & Lefaivre)

Both approaches to critical regionalism, as outlined by Tzonis & Lefaivre and by Frampton, emphasise that architecture must be created within a local, cultural, and spatial context. Tzonis & Lefaivre focus on cultural legibility and symbolic meaning, while Frampton highlights physically tangible spaces as

expressions of constructive truth. The conclusion for architectural identity is that a healthy and developed identity of place can only be achieved through a transformative, reflective, continuous, narrative, and integrated implementation of local culture, consistently derived from climate, location, and technology.

Building on the theories previously presented by Tzonis & Lefaivre (1981) and Frampton (1983), Frampton later expanded his approach in the article *Ten Points on an Architecture of Resistance*. Through a methodical transformation into practical strategies, this essay serves as the basis for deriving dynamic values in the developed evaluation grid.

4. Methodology

The case study analysis is presented through a structured evaluation grid rather than narrative description. The grid contains fixed and dynamic values. The fixed values derive from Najdi tradition and culture and are grouped into three dimensions: the socio-cultural dimension, including religion, traditional forms, privacy, social interaction, hierarchy, and hospitality; the technological-ecological dimension, covering climate adaptation, traditional techniques, materials, and symbolic climatic effects; and the semiotic dimension, addressing legibility, ornament, decoration, and iconographic expression. Many aspects overlap, and repeated characteristics increase their relevance for identity.

The dynamic part is represented by the transformative dimension, which incorporates strategies from critical regionalism and contemporary practice. It considers climate, landscape, culture, technology, urbanism, religion, politics, and society. Each characteristic is rated 0 (absent), 1 (superficially integrated), or 2 (fulfilled). Results are converted into percentages for each dimension, with the transformative dimension weighted double, as it is crucial for the future development of architectural identity.

Four cases were selected: the King Fahad National Library (2002–2015) and the King Salman Science Oasis (2010–2021) in Riyadh, both by Gerber Architekten and considered decolonial projects; the Otto Stern Library in Frankfurt (2009–2011), also by Gerber, representing a non-contextual German design; and the Justice Palace/Qasr Al Hokm (1984–1992) in Riyadh by Rasem Badran, regarded as an iconic identity-oriented contemporary work. The comparison highlights the contrast between decolonial strategies of Western architects, non-contextual design, and a regionally rooted architectural approach.

5. Case Study

TABLE 3. Evaluation grid: Overview of criteria for case study analysis (own elaboration)

No.	Dimension/ Typ	Aspect	Feature	Relevar	Case 1 (KSA) King Fahad National Library	Case 2 (KSA) King Salman Science Oasis	Case 3 (GER) Otto-Stern-Library	Case 4 (KSA) Qasr Al Hokm
Explanation	(Socio-Cultural, Technological/Ecological, Semiotic/Symbolic, Transformative Dimension)	Thematic focus	Observable design element	Decolonial relevance: High / Medium / Low	(Riyadh, Saudi-Arabien – Gerber Architekten) scale: 0/1/2	(Riyadh, Saudi-Arabien – Gerber Architekten) scale: 0/1/2	(Frankfurt am Main, Germany – Gerber Architekten) scale: 0/1/2	(Riyadh, Saudi Arabia – Rasem Badran) scale: 0/1/2
1	Socio-Cultural / fixed	Religious, Orientation	the clear orientation towards the Qibla *التوجه الواضح نحو القبلة*	H	2	2	0	2
2	Socio-Cultural	Religious	Prayer room *غرفة الصلاة*	H	0 (*see Figure 48)*	2 (*see Figure 49,50)*	0	2
3	Socio-Cultural	traditional, social interaction	Al-Kursi (fixed exterior seat) *الكُرسي (المقعد)*	L	2	0	0	2 (*see Figure 42)*
6	Socio-Cultural	Religious, generosity, hospitality	Multiple entrances (separate access) *المدخل المنفصل*	L	2	2	0	2
7	Socio-Cultural	Spatial hierarchy, traditional	guest room (Majlis Placement) *المجلس*	M	0	0	0	2
9	Socio-Cultural	traditional, generosity, hospitality	Outdoor Spaces Near Access *مساحة التقاء في الشارع امام المبنى*	L	2	2	2	2 (*see Figure 42,24)*
10	Socio-Cultural	social interaction, technology, traditional	Tarma *طرمة طرَمات*(Tarmāt) Small ledge in the wall above the door	M	0	0	0	1 (*see Figure 42)*

11	Socio-Cultural	Religious, Climatic, Privacy, Technology	Alfuraj *الفُرُج* Singular: *فُرْجَة* (Furjah) Opening, gap in the façade > small opening	H	0	0	0	2 (*see Figure 10,42)*
12	Socio-Cultural	Religious, Climatic, Privacy, Technology	Dorisha window *الدريشة*	H	0	0	0	2
13	Socio-Cultural	traditional, social interaction	(Al-Bāb / Doorway) *الباب* Plural: *الأبواب* (Al-Abwāb)	M	0	0	0	2 (*see Figure 42)*
14	Socio-Cultural	Religious, Privatsphäre,	Gender-based spatial separation *الفصل بين النساء والرجال في توزيع الفراغات*	H	2	0	0	2
17	Technological/ Ecological	Climatic, Raumhierarchie, traditional	Urban compactness Density, closed building structure, highly introverted *الكثافة، هيكل المبنى المغلق، الانطواء الشديد*	H	1	2 (*see Figure 29)*	1	2 (*see Figure 42)*
18	Technological/ Ecological	traditional, Climatic, Religious, symbolik, technology, social	Hof-Typologie (Courtyard Typology) *الحوش, الفناء الداخلي*	H	0	0	2	2 (*see Figure 42)*
19	Technological/ Ecological	Climatic, social, Religious	Riwāq= "Colonnade / Portico" *الرواق*	H	2 (*see Figure 13)*	2 (*see Figure 14)*	2 (*see Figure 15)*	2 (*see Figure 16)*
20	Technological/ Ecological	traditional, Climatic, Religious, technology	Solid blunt walls *الجدران المصمتة*	H	0	0	0	2 (*see Figure 6,42)*

21	Technological/ Ecological	Material, historic structure, traditional, Climatic	Traditional Materials in Najdi Architecture *المواد التقليدية في عمارة نجد*	H	0	0	0 (*see Figure 9)*	2 (*see Figure 42)*
22	Technological/ Ecological	technology, traditional, Climatic	(Al-Mizrab, Al-Mizram / Roof Drain) *المزراب أو المزرام*	L	0	0	0	0
23	Technological/ Ecological	technology, traditional, Climatic	North façade *الواجهة الشمالية*	H	1	2	1	2
24	Technological/ Ecological	technology, traditional, Climatic	South façade *الواجهة الجنوبية*	H	1	1	1	2
25	Technological/ Ecological	technology, traditional, Climatic	East and West façade *الواجهة الشرقية والغربية*	H	0	2	1	2
26	Technological/ Ecological	technology, traditional, Climatic	Courtyard planting/trees *زراعة/أشجار الفناء الداخلي*	H	0	1 (*see Figure 25)*	2 (*see Figure 23)*	2 (*see Figure 24)*
27	Technological/ Ecological	technology, traditional, Climatic	Exterior planting / vegetated forezones *التشجير الخارجي / المساحات الخضراء الخارجية*	M	2 (*see Figure 18)*	0	1	2 (*see Figure 17)*
28	Technological/ Ecological	technology, traditional, Climatic	Openings (windows, passive ventilation inlets, roof chimneys) *الفتحات (نوافذ، فتحات تهوية سلبية، مداخن السقف)*	H	0	0	2	2
29	Technological/ Ecological	technology, traditional, Climatic, social	Courtyard water basin *حوض الماء في الفناء*	M	0	0	0	2

30	Semiotic/Symbolic	traditional, social interaction, decoration	Shurfah / Shuraf *الشُرْف* Singular: *شُرْفَة* (Shurfah) *عرائس السماء*	L	0	0	0	0
31	Semiotic/Symbolic	traditional, decoration, Climatic	Allahj opening *اللهج*	L	0	0	0	2 (*see Figure 42)*
32	Semiotic/Symbolic	traditional, decoration	Al-Hadair decorative triangles *الحدایر*	L	0	0	0	2 (*see Figure 42,43)*
33	Semiotic/Symbolic	traditional, decoration	recessed line (Alhakaf) *الحَقَّاف*	L	0	0	0	0
34	Semiotic/Symbolic	traditional, decoration	Al-Zernuq corner finial *الزَّرْنُوق*	L	0	0	0	2 (*see Figure 10)*
35	Semiotic/Symbolic	traditional, decoration	Al-Farigha wall recess *الفارغة*	L	0	0	0	1
36	Semiotic/Symbolic	traditional, decoration	Al-Wazra lower wall recess *الوَزْرَة*	L	0	0	0	1
37	Semiotic/Symbolic	traditional, soziale Interaktion	Ornamentation, Inscriptions and Decorations *الزخارف والنقوش النجدية*	L	0	2 (*see Figure 38,39,40)*	0	2 (*see Figure 43)*
38	Semiotic/Symbolic	traditional, soziale Interaktion, decoration	Najdi colors: Tones of local materials *ألوان نجد: ألوان المواد المحلية*	H	2	2 (*see Figure 29,38)*	0	2 (*see Figure 6,10*)

39	Semiotic/Symbolic	traditional, decoration	Culturally rooted iconographic symbol *رمزية أيقونية متجذرة ثقافيًا*	L	2 (*see Figure 7,33)*	2 (*see Figure8)*	0	2 (*see Figure 42,43)*
40	Transformative Dimension / dynamic (strategy)	Climatic, environmental	Climatic adaptation *التكيّف المناخي*	H	2 (*see Figure 32,33,34)*	2 (*see Figure 29)*	0	2 (*see Figure 24*)
41	Transformative Dimension / dynamic (approach)	topography, natural site	Site integration *الاندماج مع الموقع*	H	2 (*see Figure 20,34,41)*	2 (*see Figure 29,30,31)*	2	2
42	Transformative Dimension / dynamic (strategy)	cultural, traditional, technology	Local material reinterpretation *إعادة تفسير المواد المحلية*	H	2 (*see Figure 32,33,34)*	2	0	2
43	Transformative Dimension / dynamic (approach)	sensory, experiential	actile design *التصميم الحسي*	L	2 (*see Figure 54)*	2 (*see Figure 30,31)*	2 (*see Figure 53)*	2
44	Transformative Dimension / dynamic (approach)	cultural, resistance	Resistance to visual uniformity (Originality) *مقاومة التوحيد البصري (التميز)*	H	2 (*see Figure 41)*	2 (*see Figure 38)*	1	2 (*see Figure 6,24*)
45	Transformative Dimension / dynamic (strategy)	technology	Reinterpretation of elements in modern technology *إعادة تفسير العناصر في التكنولوجيا الحديثة*	H	2 (*see Figure 12,32)*	2 (*see Figure 11)*	0	0
46	Transformative Dimension / dynamic (approach)	traditional, technology	Didactic narrative *السرد المعبر*	H	2 (*see Figure 28,35,36,37,41)*	2 (*see Figure 29,38,39,40)*	0	2
47	Transformative Dimension / dynamic (approach)	cultural, traditional, technology	Transformative integration of traditional elements *التحويل منهجياً للعناصر التقليدية*	H	2 (*see Figure 32,35,36,37)*	2 (*see Figure 38,39,40)*	0	2

48	Transformative Dimension / dynamic (approach)	traditional, technology	Showing structural mass instead of decoration *إظهار الكتلة البنائية بدلاً من الزخرفة*	H	2 (*see Figure 7,41)*	2 (*see Figure 29)*	2 (*see Figure5*)	2
49	Transformative Dimension / dynamic (approach)	Climatic, Religious, symbolik, technology, social	Fully covered courtyard with light-permeable roof *الفناء الداخلي و المنفذ المغلق للضوء*	M	2 (*see Figure 26,2,44)*	2 (*see Figure 30,31)*	2	2 (*see Figure 45)*
50	Transformative Dimension / dynamic (approach)	Climatic, Religious, symbolik, technology, social	Water as a transformative element *المياه كعنصر متحول منهجياً*	M	0	0	0	0
50	Transformative Dimension / dynamic (approach)	Climatic, technology	Vegetation as a transformative element *العنصر النباتي كعنصر متحول منهجياً*	M	1	1	0	0
50	Transformative Dimension / dynamic (approach)	politically	Representative appearance *المظهر الاستعراضي*	H	2 (*see Figure 32,33,3 435)*	2 (*see Figure 38)*	0	2 (*see Figure 6*)

Achieved scale	44	40	24	79
Maximum scale	94	94	94	94
Total Socio-Cultural	10	8	2	21
Number of fields	11	11	11	11
Summer in percent	**45%**	**36%**	**9%**	**95%**
Total of 10 points	4,55	3,64	0,91	9,55
Total Technological/Ecological	10	11	13	24
Number of fields	13	13	13	13
Summer in percent	**38%**	**42%**	**50%**	**92%**
Total of 10 points	3,85	4,23	5,00	9,23
Total Semiotic/Symbolic	4	6	0	14
Number of fields	10	10	10	10
Summer in percent	**20%**	**30%**	**0%**	**70%**
Total of 10 points	2,00	3,00	0,00	7,00
Total Transformative	23	23	9	20
Number of fields	13	13	13	13
Summer in percent	**88%**	**88%**	**35%**	**77%**
Total of 10 points	8,85	8,85	3,46	7,69

Total in percent (average value of the total percentage)	48%	49%	23%	84%
Result in percent (Transformative dimension is weighted twice)	**56%**	**57%**	**26%**	**82%**

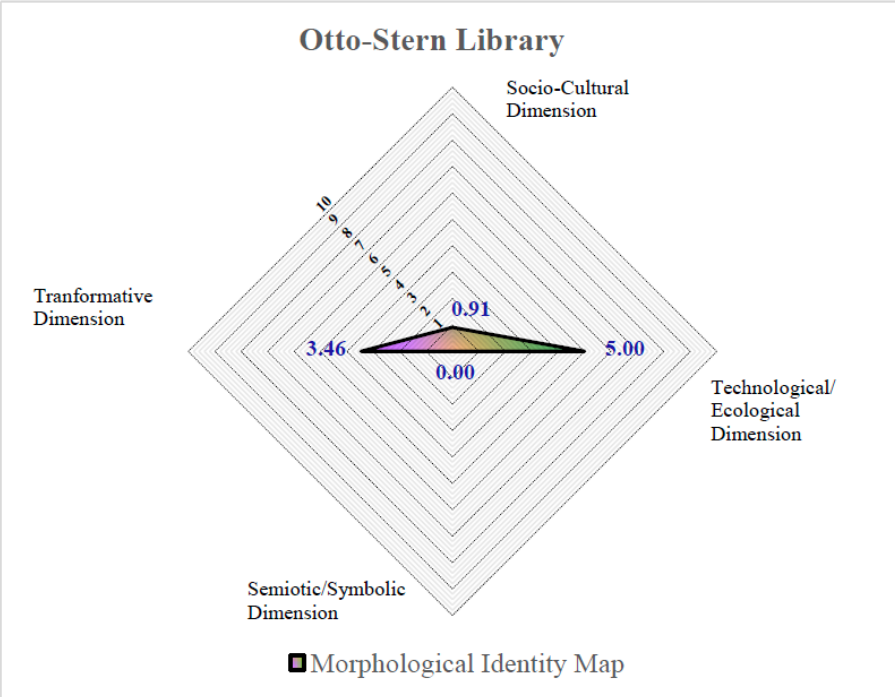


Figure 1. Evaluation result (Case 3), Otto Stern Library in Frankfurt, Germany. Source: Authors.

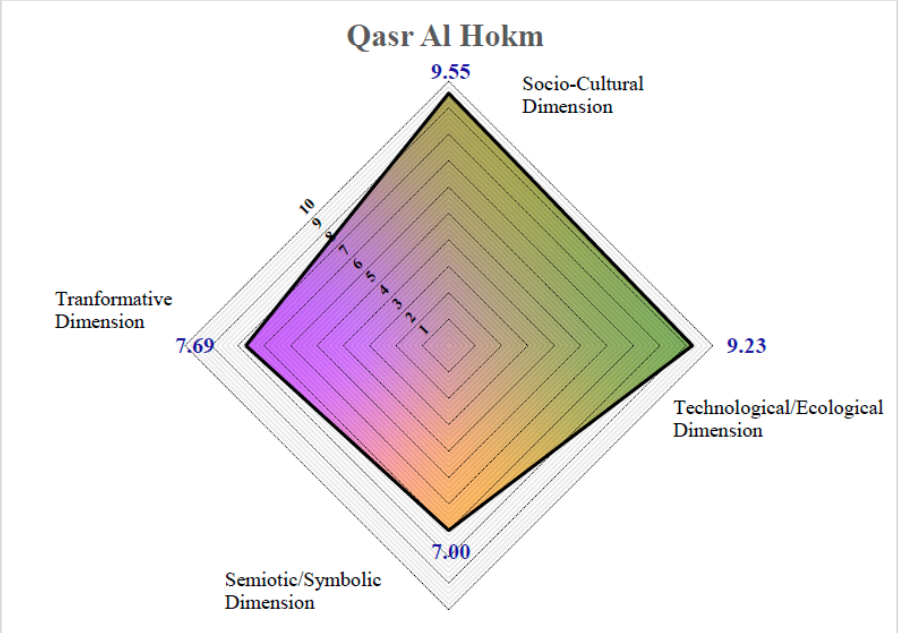


Figure 2. Evaluation result (Case 4), Qasr Al-Hokm in Riyadh, Saudi Arabia. Source: Authors.

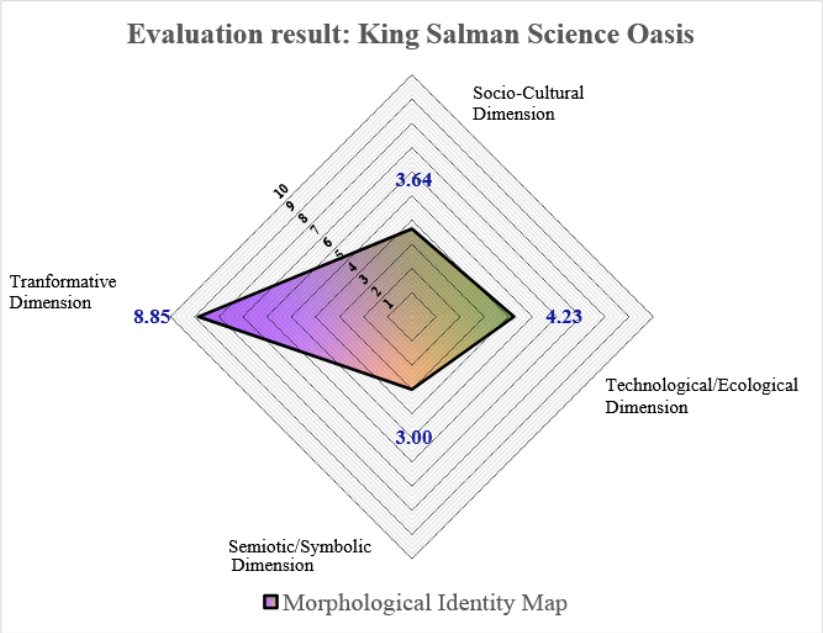


Figure 3. Evaluation result (Case 2), King Salman Science Oasis in Riyadh, Saudi Arabia. Source: Authors.

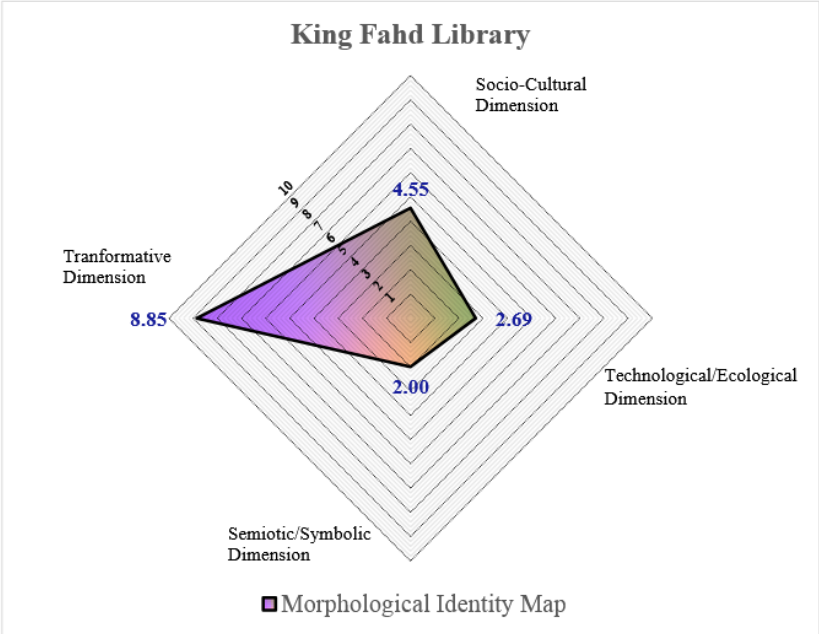


Figure 4. Evaluation result (Case 1), King Fahad National Library in Riyadh, Saudi Arabia. Source: Authors.

The results show the fluctuation between high ratings for (Case 4) and low ratings for (Case 3), as expected, but (Case 1) and (Case 2) show interesting results. Both have similar ratings: (Case 1) with 54% and (Case 2) with 47%. In the socio-cultural dimension, (Case 1) wins out over (Case 2) because it took gender segregation into account and provided benches in the existing building. In addition, (Case 2) provided a prayer room with associated washrooms. In the technological/ecological dimension, (Case 2) wins over (Case 1) with its many blunt, closed walls, targeted façade openings facing the sun and the integration of plants in the interior. In contrast, (Case 1) fulfils the exterior greening with palm trees. In the semiotic/symbolic dimension, (Case 2) wins over (Case 1) in the technological/ecological dimension. (Case 1) has integrated a culturally anchored iconographic expression in the form of a 'tent' into the façade, while (Case 2) has designed the roof as a curved, floating carpet shape and decorated the façade with ornaments developed from traditional Najd patterns. Both have used Najd colours. In the transformative dimension, both (Case 1) and (Case 2) achieve the same score. Both fulfil all aspects except for the feature 'water as a transformative element' and use vegetation only superficially as a transformative element, as the planting is integrated in a classic way in beds in each case.



Figure 5. Facade motif (Case 3) –golden metal cladding as an outer shell. Source: Authors.



Figure 6. Facade motif (Case 4) – plain, massive facade. Source: Authors.



Figure 7. Facade motif (Case 1) – recalling the traditional Bedouin tent. Source: Authors.



Figure 8. Facade motif (Case 2) – roof recalling a flying carpet. Source: Authors.

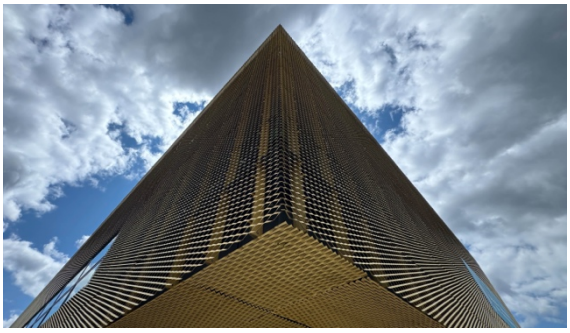


Figure 9. Corner perspective (Case 3) – perforated metal cladding, used in Germany but avoided in Saudi Arabia. Source: Authors.

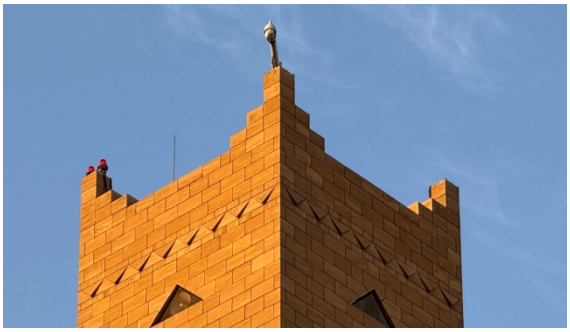


Figure 10. Corner perspective (Case 4) – facade clad in local Riyadh limestone, combining the solidity of Najdi heritage with contemporary construction techniques. Source: Authors.

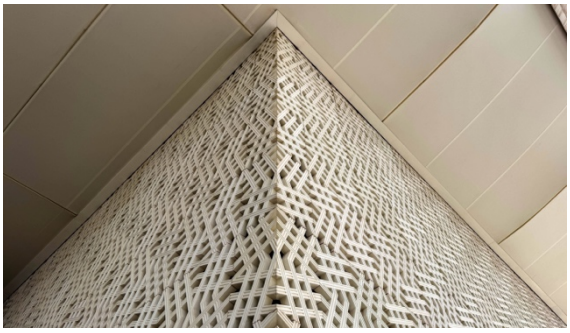


Figure 11. Corner perspective (Case 2) – GRC (glassfibre reinforced concrete) panels with geometric ornamentation. Source: Authors.



Figure 12. Corner perspective (Case 1) Textile façade – Teflon-coated fibreglass membrane cloth attached to a grid of pre-stressed stainless-steel cables in a recognizable Arabic pattern, shading the building from the harsh sun without blocking the light. Source: Authors.



Figure 13. Riwaq (Case 1) – continuous shaded walkway surrounding the building, providing climatic comfort and circulation. Source: Authors.



Figure 14. Riwaq (Case 2) – single-sided steel Riwaq at the administration wing and adjacent to the parking area. Source: Authors.

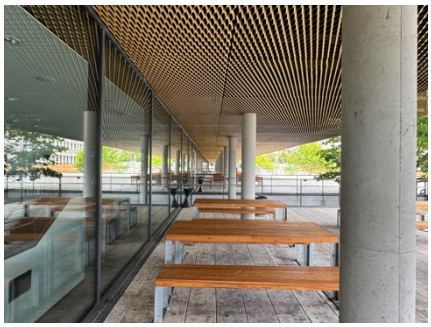


Figure 15. Riwaq (Case 3) – Riwaq only on the southwest side; southeast and northwest sides feature shaded recesses. Source: Authors.



Figure 16. Riwaq (Case 4) – massive Riwaq echoing the character of historic Najdi palaces in a contemporary manner. Source: Authors.



Figure 17. Exterior planting / vegetated forezones (Case 4) – landscaped outdoor areas with native vegetation. Source: Authors.



Figure 18. Exterior planting (Case 1) – landscaped outdoor areas with palm trees. Source: Authors.





Figure 19. Bridges and voids (Case 3) – architectural composition using bridges and open voids at a smaller and denser scale compared to Case 1. Source: Authors.

Figure 20. Bridges and voids (Case 1) – delicate bridges and vast voids linking the existing structure and the extension. Source: Authors.



Figure 21. Glass elevator (Case 1) – visible glazed elevator positioned within the interior space. Source: Authors.

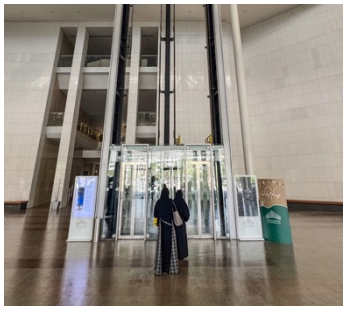




Figure 22. Glass elevator (Case 3) – same principle as in Case 1, a visible glazed elevator integrated into the interior space. Source: Authors.

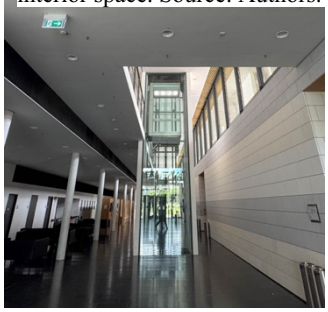




Figure 23. Courtyard planting/trees (Case 3) – small courtyards with trees, designed primarily to provide daylight to the lecture halls. Source: Authors.



Figure 24. Courtyard planting/trees (Case 4) – palm trees for air filtration, cooling, and shading of the courtyard. Source: Authors.



Figure 25. Vegetation as a transformative element (Case 2) – planting in interior planters, transferring traditional ground-based greenery to a controlled indoor environment for microclimate improvement, shading, and dust reduction. Source: Authors.

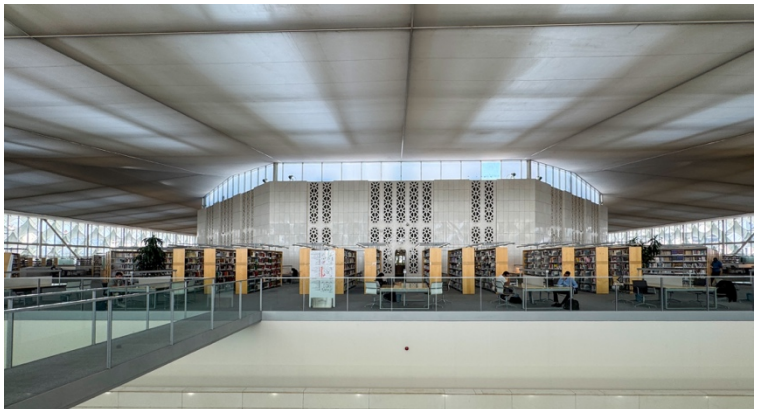


Figure 26. Roof landscape (Case 1) – former main roof converted into a light-filled reading landscape. Source: Authors.



Figure 27. Roof structure (Case 1) – The new roof with skylights and white membranes for gentle light distribution throughout the interior. Source: Authors.



Figure 28. Didactic narrative (Case 1) – contrast between the massive, plain facade of the existing building and the light-appearing glass extension, separated by an air space and consciously used as a narrative device of the building's history. Source: Authors.



Figure 29. Design approach (Case 2) – reinterpretation of the traditional wadi as a spatial organising element, transformed into a sequence of galleries; resistance to visual uniformity through adaptation to the topography and deliberate placement of building volumes beneath a floating, curved roof reminiscent of a flying carpet. Source: Authors.



Figure 30. Transformative integration of traditional artefacts (Case 2) – roof as a shaded bazaar canopy with light bands, creating the impression of a floating luminous body. Source: Authors.

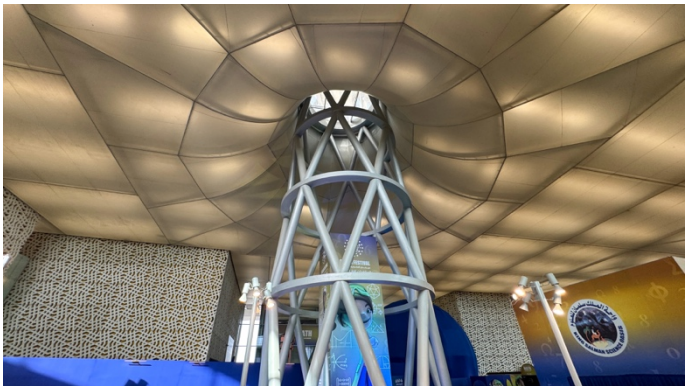


Figure 31. Visible construction instead of decoration (Case 2) – steel-constructed supports for daylight introduction, one forming a tall wind tower as a visual signal guiding visitors into the building. Source: Authors.



Figure 32. (Case 1) The innovative reinterpretation of the tent element in contemporary technology as a parametrically designed PTFE-coated fibreglass fabric façade, serving as sun shading, daylight control, and visual identity. Source: Authors.

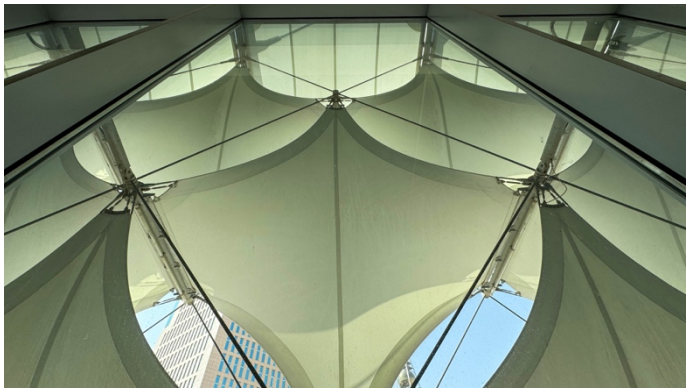


Figure 33. (Case 1) interior view showing multiple aspects of transformative features, including parametrically replicated tent elements in visible construction, didactic narrative through contemporary design, and reinterpretation of local materials. Source: Authors.



Figure 34. Case 1 – front view of the same location as Figure 33, with elements that enable views while reflecting sunlight, as a feature integrating the building into the topography through visual connections. Source: Authors.

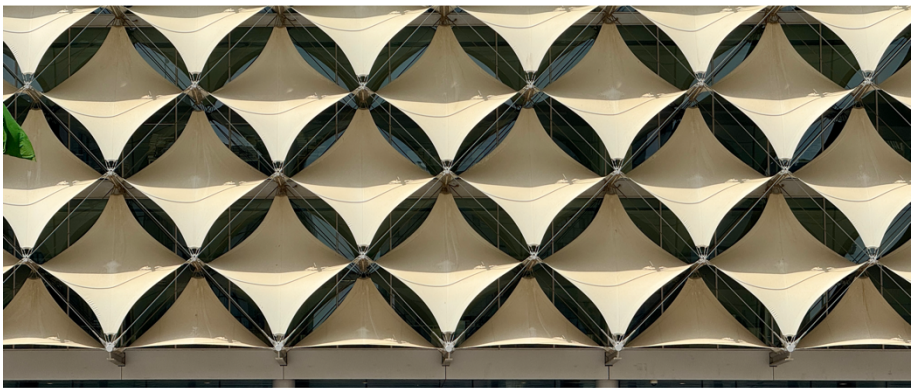


Figure 35. (Case 1) close-up of the facade from a frontal perspective, showing how parametrisation intentionally creates a pattern derived from Najdi tradition. Source: Authors.



Figure 36. (Case 1) vector graphic of the King Fahad National Library facade pattern, redrawn by the authors for comparison with the similar motif in Figure [35]. Source: Authors.



Figure 37. Case 4 – interior view of a "Wazra" in the Imam Mohammad bin Turki bin Abdullah Mosque at Qasr Al-Hokm, showing a pattern similar to that in Figure 34. Source: Authors.

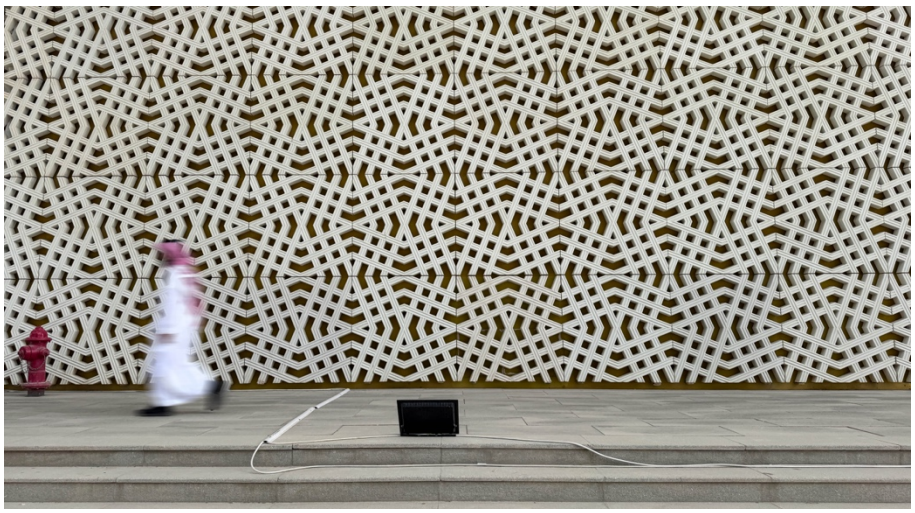


Figure 38. (Case 2) – facade ornamentation of the King Salman Science Oasis as transformed Najdi patterns. Source: Authors.

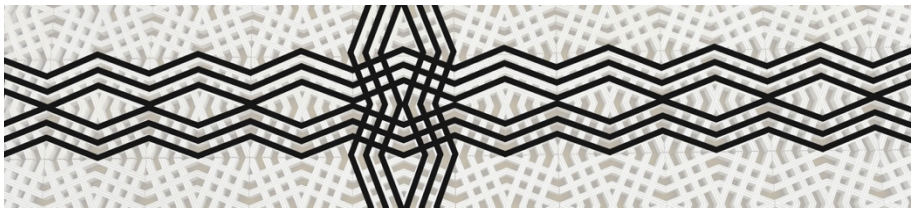


Figure 39. (Case 2) – redrawn facade pattern of the King Salman Science Oasis to analyse and interpret its design concept. Source: Authors.



Figure 40. "Al-Hadair" motif from Qasr Al-Murabba, formed as rows of triangles and reminiscent of the simplified patterns of King Salman Science Oasis. Source: Authors.



Figure 41. (Case 1) – model of the King Fahad National Library showing the existing structure with its orthogonal wings and the extension as a simple square frame. Source: Authors.



Figure 42. (Case 4) – Qasr Al-hokm showing various transformed traditional elements, including Tarma, Furga, Allahj opening, traditional door and outdoor bench. Source: Authors.



Figure 43. (Case 4) – didactic narrative shown through contemporary construction in stone and concrete with clearly readable joints and transformed Allahj window openings. Source: Authors.



Figure 44. (Case 1) – roof with skylights, possible due to Germany's climate allowing such small openings. Source: Authors.

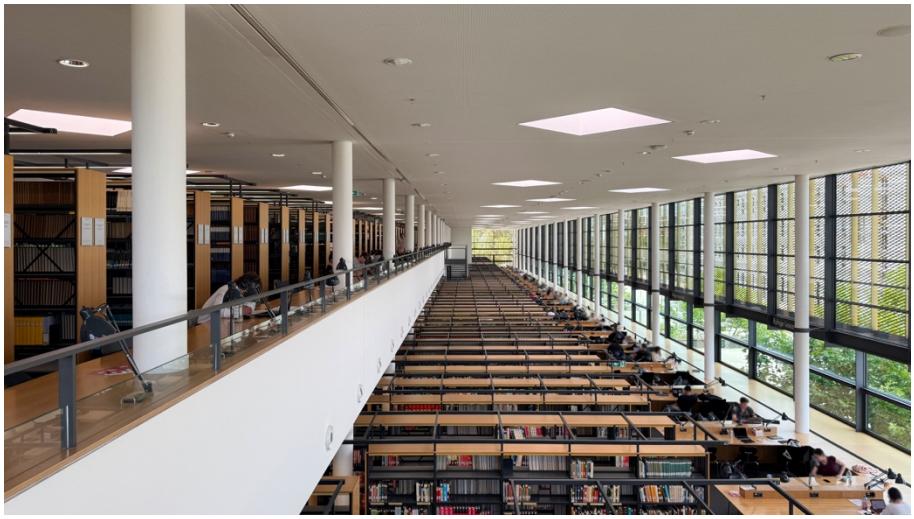


Figure 45. (Case 3) – roof with skylight openings, climatically feasible in Germany without excessive heat gain, unlike in Saudi Arabia. Also demonstrates space-efficient planning typical in Germany, in contrast to the more generous layouts in Saudi Arabia that express prosperity and status. Source: Authors.



Figure 46. (Case 3) – visible grid structure with exposed supports at the Otto Stern Library. Source: Authors.



Figure 47. (Case 1) – visible grid structure with exposed supports at the King Fahad National Library, recalling the modular grid of modernism exemplified by Mies van der Rohe's Neue Nationalgalerie in Berlin. Source: Authors.

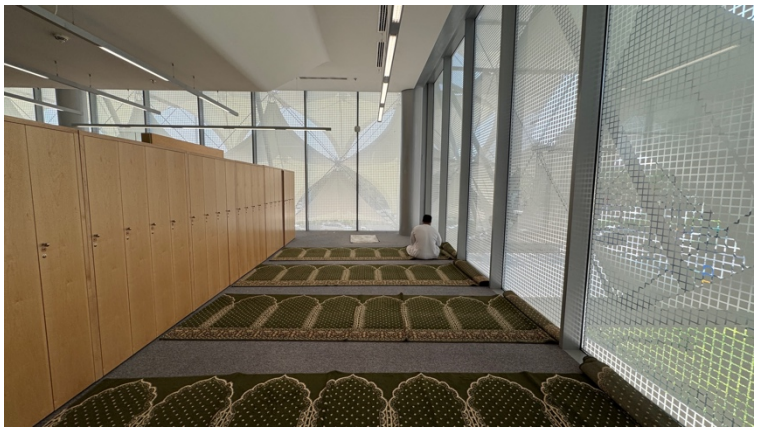


Figure 48. (Case 1) – The authors assume that the corner was retrofitted as a prayer area, with unsuitable carpets laid at inappropriate spacing. Source: Authors.



Figure 49. (Case 2) – enclosed prayer room with dedicated ablution facilities (wudu) as shown in Figure (49) provided as part of the original architectural plan. Source: Authors.

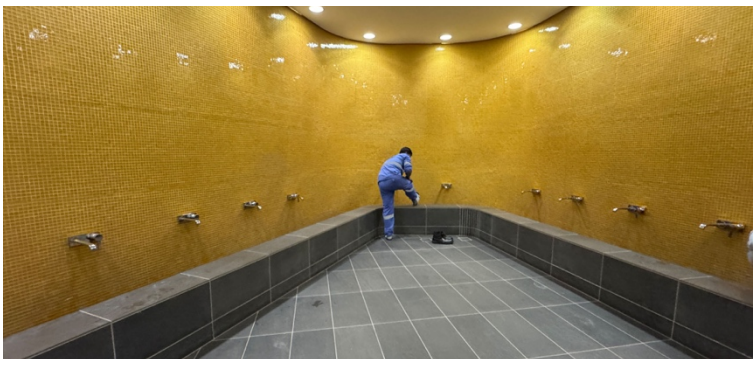


Figure 50. (Case 2) – wudu area with dedicated washing facilities, located near the prayer room. Source: Authors.



Figure 51. (Cases 1 & 3) – two doors, right in the King Fahad National Library and left in the Otto Stern Library, both made of wood and flush with the surrounding wooden surface. Source: Authors.



Figure 52. (Cases 1 & 3) – same wood as in Figure X, used for the bookshelves in both the King Fahad National Library and the Otto Stern Library. Source: Authors.

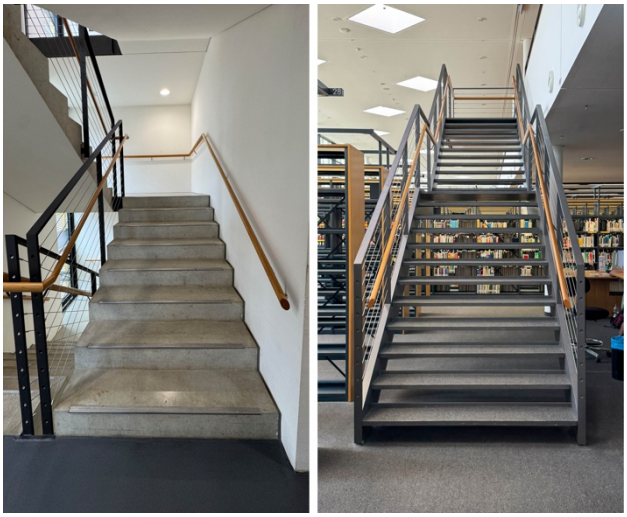


Figure 53. (Case 3) – tactile design expressed through the use of hard material for stairs in enclosed stairwells, creating a sense of effort when ascending, contrasted with carpeted steps in the reading room staircase to enhance tactile comfort, improve room acoustics, and encourage quietness. Source: Authors.



Figure 54. (Case 1) The King Fahad National Library, the flooring in the enclosed stair hall on the left is made of hard material, making the ascent physically perceptible, while in the entrance area a glossy, smooth surface conveys a sense of attentiveness and an impressive appearance; in contrast, the carpeted floor in the reading room offers tactile comfort. The original facade is preserved as a new interior wall, allowing the body to physically experience the materiality and spatial history. Source: Authors.

6. Conclusion

The study shows that the approach of critical regionalism is a suitable instrument for the emergence of decolonial architecture, as it integrates cultural, social, and climatic aspects into architectural design logic. Architecture can in this way become both contemporary and locally rooted. The results confirm that decolonisation can also be achieved by international planning offices, but it gains real depth only when rooted in local practice.

The case studies demonstrate strategies that reinforce the cultural, technical, and symbolic identity of buildings. They also show how traditional elements can be transformed into new expressions, such as the tent-like façade of the King Fahd National Library, which unites aesthetic, climatic, symbolic, and didactic functions. Yet shortcomings are evident in the choice of materials, pointing to the need for more context-sensitive specifications and a reduced reliance on glass and metal façades, particularly in international commissions.

The study further shows that modernity must be recognised not as neutral but as a colonial instrument. A truly decolonial architecture becomes possible only when architects acknowledge this and orient their design logic toward context, tradition, climate, and society. In this light, the paper contributes to Vision 2030 by outlining context-based and culture-based strategies that can serve as benchmarks for future identity-oriented projects.

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IV. BUILDING INFORMATION MODELING (BIM) & GRAPH MACHINE LEARNING

TOWARD A ROBUST AI FOR BIM

Dataset Challenges and Implications for the AEC Industry

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Abstract. The architecture, engineering, and construction (AEC) industry stands at the threshold of a technological revolution driven by the hopeful convergence of artificial intelligence (AI) and Building Information Modeling (BIM). This paper examines the current state of AI-BIM integration, exploring both the transformative potential and the substantial challenges that must be overcome for widespread adoption. We investigate various AI approaches, from traditional expert systems to modern machine learning techniques, and their applications in BIM technology. The study reveals that while AI technologies offer unprecedented opportunities for design optimization and generative design exploration, their implementation faces critical challenges related to data availability, quality, standardization, and the creation of comprehensive training datasets, what we term the "corpus problem." Through analysis of AI systems, we demonstrate that successful AI-BIM integration requires not only technological advancement but fundamental changes in industry practices and data sharing protocols. Our findings suggest that the future of AI in BIM lies in multi-modal approaches that combine the interpretability of expert systems with the pattern recognition capabilities of modern AI, while addressing the complex, three-dimensional, semantically rich environments that BIM models represent.

Keywords: *Artificial Intelligence, Building Information Modeling, Generative Design, Expert Systems, AEC Industry*

1. Introduction

The fields of architecture, engineering, and construction (AEC) are undergoing a significant transformation with the increasing integration of artificial intelligence (AI).

AI refers to the development and implementation of computer systems that can perform tasks typically requiring human intelligence, encompassing various techniques such as machine learning (ML), deep learning, natural language processing (NLP), computer vision, and neural networks. Concurrently, Building Information Modeling (BIM) has become a cornerstone of modern architectural practice, providing a digital representation of a building's physical and functional characteristics used for analysis, design, and management throughout its lifecycle.

The convergence of AI and BIM holds immense promises for revolutionizing the entire building lifecycle. AI can significantly improve design efficiency and quality by analyzing BIM data to optimize designs, generate recommendations for improvements, and even automate tasks like creating 3D models from 2D drawings or detecting clashes and errors. This leads to faster decision-making and increased safety across the construction and operation phases. Generative design, an AI-powered approach, further allows architects to explore a vast array of optimal design alternatives based on specific constraints and parameters.

Despite these profound benefits, the full implementation of AI in BIM faces several significant challenges and restrictions. A primary hurdle lies in data-related issues, particularly the quality, volume, and consistency of the "corpus" (the large, structured datasets used to train AI models). BIM models often present standardization and format inconsistencies across different software platforms, varying levels of detail, and inconsistent parameter naming, making it difficult to assemble robust datasets for AI (Kyivska et al., 2020)..

Furthermore, the contextualization of objects within a complex building environment poses a challenge for AI systems to truly understand semantic meaning and complex interactions between elements. Concerns also extend to data privacy and security, and the potential for AI bias if training data is incomplete or skewed.

Historically, despite early interest in the 1970s and 1980s, expert systems—an early form of AI in a way—saw limited practical application within BIM solutions, highlighting persistent challenges in bridging the gap between AI research and commercial implementation (Liebowitz, 1995).. While AI shows promise in visualization and conceptualization, effectively addressing the engineering aspects of architecture within BIM remains an area requiring further exploration.

This paper will explore the current landscape of AI integration with BIM, delving into the benefits and the critical challenges that impede its widespread adoption. By examining the intricacies of data management, interoperability, and the inherent complexities of architectural design, this paper aims to shed light on the roadmap towards a more robust future for the AEC industry.

2. What is Artificial Intelligence?

Artificial Intelligence (AI) is the development of computer systems that can perform tasks typically requiring human intelligence, such as learning, reasoning, problem-solving, perception, and decision-making (Gupta & Nagpal, 2020).

They achieve intelligent behavior through a combination of key technologies, including machine learning, which uses algorithms to identify patterns in data and make predictions without being explicitly programmed for every scenario. Neural networks, composed of interconnected layers of nodes inspired by the structure of the human brain, play a crucial role particularly in deep learning, where multiple layers enable the recognition of complex patterns.

These systems rely heavily on extensive data processing, using large datasets to train models to recognize associations and generate accurate responses. Statistical methods further enhance performance by enabling systems to make probabilistic decisions and manage uncertainty. Underpinning all of this is substantial computational power, with advanced processors, especially GPUs, executing millions of simultaneous calculations to support the sophisticated mathematical operations required. The core principle relies on replacing programming-specific rules for every situation. AI systems learn general patterns from examples and apply that learning to new, unseen situations. Modern AI, like large language models, combines massive neural networks, enormous datasets, and substantial computing power to produce surprisingly human-like capabilities.

Consider an architecture designer planning a multi-story house. A trained AI model could assist by identifying missing or inadequate vertical circulation elements—such as stairs or elevators—potentially in real time. The system could also evaluate whether proposed circulation elements comply with building codes and safety standards.

Such an AI system would require training on extensive datasets containing examples of vertical circulation systems used in multi-story buildings, enabling it to recognize patterns and standards for connecting floors effectively and safely.

3. What is an expert system?

An expert system refers to a computer-based program or software designed to emulate the problem-solving capabilities of a human expert in a specific domain. These systems leverage artificial intelligence (AI) techniques such as knowledge representation, inference, and logical reasoning to simulate the expertise and decision-making abilities of human specialists. Unlike today's AI systems, typical expert systems do not use neural networks in their traditional form (Gupta & Nagpal, 2020).

3.1 HISTORY AND RESEARCH

The technology of expert systems emerged in the late 1960s and gained significant attention in the 1970s and 1980s. They are recognized as one of the earliest successful implementations of artificial intelligence. Edward Feigenbaum is sometimes termed the "father of expert systems".
Pioneering work includes Dendral (1960s), which was developed at Stanford University. It focused on interpreting mass spectrometry data to identify chemical compounds, demonstrating the potential of capturing human expert knowledge. Then came Mycin by the early 1970s, also from Stanford, which aimed to diagnose infectious blood diseases based on patient symptoms and medical test results, showcasing the ability of expert systems to reason from a knowledge base of rules. Followed by XCON in the 1980s, which was developed by Digital Equipment Corporation (DEC), XCON was widely adopted in the industry for tasks like configuring computer systems.
The 1980s saw a surge of interest, with commercial expert system shells becoming available. However, interest waned as more advanced AI techniques like machine learning gained prominence. Despite this, the concepts and techniques from expert systems continue to influence AI research today.

3.2 ARE EXPERT SYSTEMS CONSIDERED AI?

Expert systems are considered a specific application or subfield of artificial intelligence. While AI is a broad field encompassing various techniques like machine learning, natural language processing, and computer vision to replicate intelligent behavior in multiple domains, expert systems specifically aim to replicate human problem-solving abilities within a designated domain. Expert systems typically do not use neural networks in their traditional form. Instead, expert systems typically comprise four main components:

1. Knowledge Base: Contains a vast amount of domain-specific information, facts, and rules. This knowledge is captured from human

specialists. Rules are generalized conditions (IF statements) that, if fulfilled, trigger an action (THEN part of the IF statement), modifying facts or deriving conclusions.

2. Inference Engine: A crucial component that applies logical rules and deduction techniques to process user input or system data and draw conclusions based on the available knowledge. This can be done through deductive (forward) or abductive reasoning.

3. User Interface: Allows the user (e.g., architect) to interact with the system.

4. Explanation Module: Provides a justification for the system's output or recommendations.

Expert systems differ from procedural computer programs because they use generalized rules and inference instead of hard-coded, stepwise solution procedures. They are built to address specific problems within specific domains. They leverage heuristic "rules of thumb", encapsulating professional practices, common sense, shortcuts, and insights characteristic of highly experienced professionals. This provides more flexibility in handling missing information and uncertainty compared to procedural programs.

The use of heuristic reasoning means their conclusions might be less reliable and often associated with a "certainty factor". They cannot guarantee a solution to a problem, nor that the solution is necessarily correct, but they can handle problems intractable by procedural methods. They excel at finding solutions faster than procedural programs by exploiting shortcuts (Coats, 1988).

3.3 APPLICATIONS OF EXPERT SYSTEMS IN ARCHITECTURE

Expert systems have been increasingly used in architecture to improve decision-making and automate routine tasks. They can assist architects in tasks such as designing buildings, optimizing energy efficiency, evaluating the structural integrity of a building, generating design options, and evaluating design alternatives, as well as providing data-driven insights and recommendations.

Examples of their application include rule-based representation of design, expert systems for construction inspection, automating building design, building element selection, and knowledge-based BIM systems for maintenance (Burggräf et al., 2021).

3.4 EXPERT SYSTEMS VS. "SMART OBJECTS"

While both expert systems and "smart objects" in programming incorporate intelligence or autonomous behavior, they are not the same. Expert systems

are a specific type of AI application focused on emulating human expertise, typically rule-based, where "Smart objects" encompass a broader range of intelligent behaviors and may utilize various AI techniques beyond just rule-based reasoning, such as machine learning or neural networks. They often have embedded sensors, connectivity, and processing capabilities for autonomous or context-aware behavior. In BIM, "smart objects" are digital components with embedded intelligence, containing data about properties, specifications, and behaviors, allowing them to interact and adapt within the model.

4. Generative design

Generative design is a design exploration process that leverages the power of artificial intelligence (AI) to produce numerous design alternatives. Rather than a designer creating a single design, they input specific design goals and parameters into generative design software. These parameters can include performance or spatial requirements, materials, manufacturing methods, and cost constraints.

4.1 HOW GENERATIVE DESIGN WORKS

The software then explores all possible permutations of a solution, rapidly generating a multitude of design options. This process is often described as an iterative design process that produces outputs meeting specified constraints to varying degrees. It mimics nature's evolutionary approach to design through genetic variation and selection (Wikipedia, 2023).

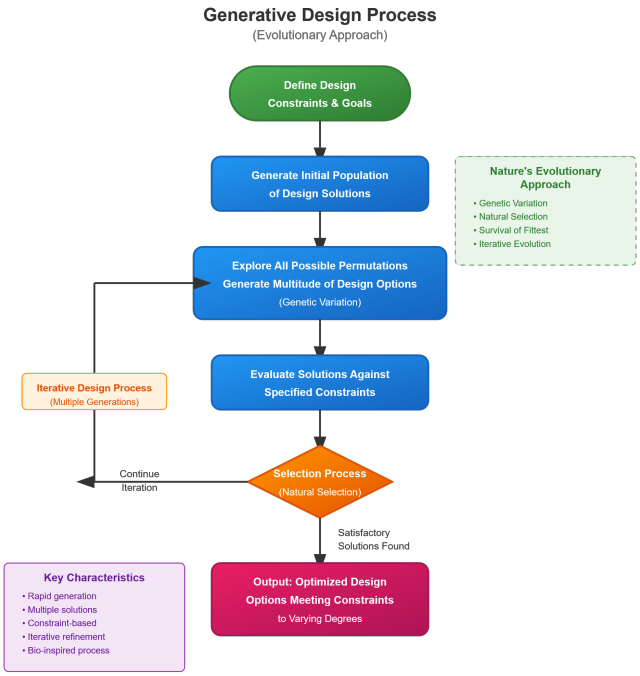


Figure 1: Generative Design Workflow

The workflow for generative design typically involves several stages: In a generative design process, the system begins by generating design options using algorithms and parameters defined by the designer. These options are then analyzed to evaluate how effectively they meet the predefined goals. Following this, the designs are ranked according to their performance, and this ranking informs how the designs should be evolved or further developed. The designer then explores the various options, comparing them against the original criteria, before finally integrating the selected design into the broader project.

4.2 IS GENERATIVE DESIGN CONSIDERED ARTIFICIAL INTELLIGENCE (AI)

Generative design is inherently an AI-powered approach. It is considered artificial intelligence because it utilizes machine learning algorithms to generate design iterations based on constraints identified by the designer or engineer. The computer learns from a dataset of existing designs that meet desired constraints and then uses this training data to generate new, potentially optimal, designs. AI helps in identifying design constraints, generating a large number of design iterations, and then selecting the best design from those generated.

4.3 BENEFITS AND PURPOSE

The use of generative design offers significant benefits:
Exploration of Vast Solutions: It allows designers to explore a much wider array of design solutions than would be possible manually, especially for complex, multi-criteria problems.
Optimization: It helps find optimal or near-optimal designs based on specific criteria such as energy efficiency, structural integrity, aesthetic appeal, and more.
Efficiency and Automation: By automating parts of the design process, generative design can help designers explore more possibilities and find better solutions. For instance, BricsCAD BIM uses AI and generative design to translate 2D sketches into detailed 3D models and conceptualize models based on user-defined parameters.
Improved Performance: It leads to designs that can be lighter, stronger, more efficient, and more affordable. It can also generate design solutions that are more sensitive, responsive, and adaptive to complex ("wicked") problems.
Collaborative Process: Generative design fosters a collaborative design process between humans and computers, where the computer assists in exploration and evaluation.

4.4 KEY APPROACHES AND IMPLEMENTATIONS

Several approaches and tools embody generative design:
Autodesk's Approach: Integrated into software like Autodesk Revit, Autodesk's generative design features allow for data-driven decision-making by generating design alternatives based on goals, constraints, and inputs. Autodesk also acquired Spacemaker, a platform using AI and generative design to rapidly create, optimize, and evaluate design alternatives ("Generative Design for Architecture, Engineering & Construction", n.d.; University, 2018).

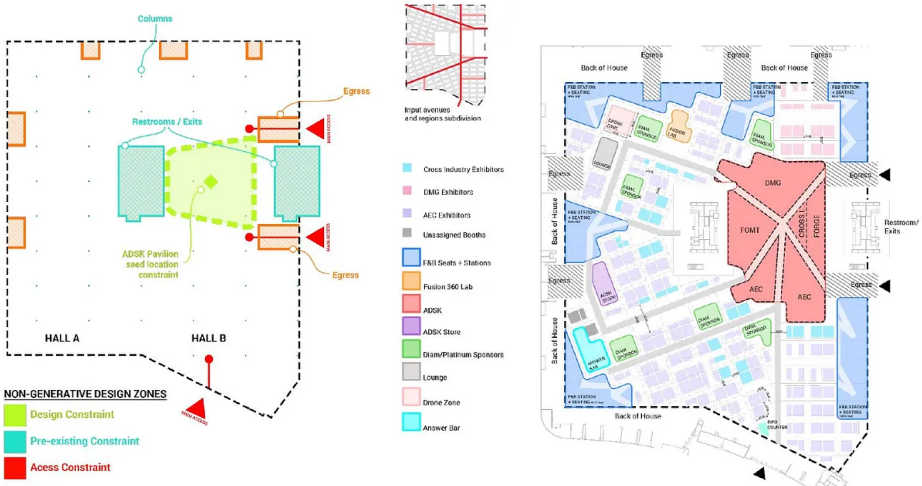


Figure 2: Autodesk Approach to Generative Design

Genetic Algorithms (GAs): Inspired by natural selection, GAs generate an initial population of solutions and evaluate them based on a fitness function, iteratively "evolving" them to find optimal designs. John Jero's work is mentioned in the context of genetic algorithms.
Shape Grammar: Developed by George Stiny and James Gips in the 1970s, shape grammar provides a systematic method using a set of rules to generate and explore design possibilities. It defines how individual elements or shapes can be combined or manipulated to create larger designs, maintaining desired characteristics or styles. Also, Robert J. Krawczyk's research work draws inspiration from rule-based geometrical designs.
Compared to traditional top-down design, generative design uses a "bottom-up paradigm," allowing solutions to evolve towards an optimal state. While it excels in visualization and conceptual exploration, the engineering aspects of architecture, such as structural integrity and material properties, require further integration with AI.

5. How would AI be implemented for Architecture?

Given the example of analyzing a plan and advising about a missing vertical circulation element, two directions might be valid. If the analysis is just two-dimensional and looking at plans, then computer vision models might be the most suitable, particularly Convolutional Neural Networks (CNNs), which excel at analyzing architectural drawings, floor plans, and 3D models to detect missing elements such as stairs. Object detection models like YOLO or R-CNN are also essential, as they specialize in identifying and locating specific architectural components within building layouts.

A more advanced solution would involve hybrid approaches that integrate Vision Transformers for interpreting spatial relationships between floors and circulation elements, Graph Neural Networks to model connectivity and movement across different building levels, and rule-based systems merged with neural networks to assess compliance with building codes.

In contrast, other AI types are less effective for this task such as language models like GPT are not suited for spatial visual analysis, though they can aid in interpreting code requirements; GANs are better for generating new designs rather than analyzing existing ones; and traditional expert systems may assist with rule enforcement but lack the visual recognition capabilities needed. Ultimately, the most effective solution would be a multi-modal system that combines visual analysis through computer vision with a knowledge graph of building codes, allowing for both accurate element recognition and rule-based validation.

However, the problem at hand is to deal with three-dimensional data of smart objects in a Building Information Modeling environment. Hence, the optimal AI approach might lie in more advanced and tailored approaches to volumetric and semantic data. 3D computer vision models such as 3D Convolutional Neural Networks (3D CNNs) can process voxel data or point clouds directly from BIM models, while specialized networks like PointNet and PointNet++ are effective at analyzing complex 3D spatial relationships. Graph Neural Networks (GNNs) are particularly well-suited for BIM applications, as BIM models are inherently graph-structured, consisting of rooms, connections, and adjacencies, allowing GNNs to model intricate spatial relationships and flow patterns across floors (As et al., 2018).

Geometric deep learning further enhances this by directly leveraging BIM's geometric and semantic data to understand spatial constraints, element hierarchies, and dependencies. An ideal solution would involve a multi-modal fusion system that integrates 3D object detection to identify architectural components, semantic segmentation to distinguish building zones, knowledge graphs to encode building codes and design rules, and spatial reasoning modules to analyze circulation flow. This approach would be superior for BIM because it offers native 3D comprehension rather than relying on 2D interpretation, leverages rich semantic metadata (such as materials and systems), supports real-time analysis throughout the design process, and integrates seamlessly with parametric workflows. Additionally, the system can utilize BIM’s structured data format (e.g., IFC) to interpret not only geometry but also the functional relationships between building elements.

6. The required datasets, the corpse

For training such a model, you would need a significant, reliable dataset with structured data in order to build the type of intelligence required. For an AI model to effectively deal with Building Information Modeling (BIM) information and achieve the necessary level of intelligence, it absolutely requires a significant, reliable dataset with structured data.

6.1 WHAT IS A CORPSE?

In the context of AI language, the term "corpse" is not a technical term for AI itself. However, the sources explain its etymological connection to the term "corpus," which is highly relevant in AI. Specifically, "corpus" comes from the Latin word meaning "body". The modern word for a dead body, "corpse," is derived from this same Latin root.
When used in the realm of artificial intelligence, the term "corpus" does not refer to a physical body. Instead, it metaphorically refers to the "body," or collection, of data used to train the AI. This corpus is the material the AI reviews to become intelligent in its designed purpose. For example, a large and rich corpus allows Large Language Models (LLMs) like ChatGPT to have conversational text-based chats, answer complex questions, or generate original creative works. Without a corpus to feed an AI, the AI cannot learn. The larger the corpus, the more proficient or intelligent the AI can become.

6.2 HENCE, THE NEED FOR A SIGNIFICANT DATASET (DATA VOLUME)

AI algorithms, particularly deep learning models, rely heavily on large volumes of data for training, learning, and making predictions. For AI to be effective in BIM, there is a need for thousands of models to train robust AI systems. A larger "corpus," which refers to a large and structured set of texts or data, is directly correlated with the AI's proficiency or intelligence. Without a sufficient corpus, the AI cannot learn.
Data Quality and Completeness
The quality and accuracy of the BIM data can directly impact the performance of AI algorithms. Inaccurate or incomplete data can lead to incorrect predictions or recommendations, which can have serious consequences in architecture. Challenges include:
Quality and Completeness Issues: Many BIM models are incomplete or contain errors, and inconsistent modeling practices can result in "technically correct" but practically problematic models.
AI Bias: AI systems can be biased if trained on incomplete or biased data, leading to unfair or inaccurate recommendations.
Data Complexity, Standardization, and Contextualization (Structured Data)

BIM models are inherently complex and data-rich, containing a vast array of information from design specifications to real-time sensor data. This structured nature is beneficial, but adapting it for specific AI tasks is challenging. The intelligence required from AI in BIM depends on its ability to understand and process this inherent structure, which includes:

Data Complexity and Structure: BIM models are highly complex, integrating geometry, properties, specifications, and relationships, making it challenging to create comprehensive and manageable datasets for AI.

Interoperability and Standardization: A significant challenge is the lack of standardization and format inconsistency across different BIM software platforms (e.g., Revit, ArchiCAD, Tekla). Varying levels of detail and inconsistent parameter naming hinder the integration of data into a cohesive dataset suitable for AI training (Hetemi et al., 2020).

Annotation and Labeling Challenges: AI training requires labeled data, but BIM elements often lack consistent semantic labels. Manual annotation is extremely time-consuming due to the complexity of BIM models, and automated annotation tools struggle with contextual understanding of building elements. For instance, scaling 2D image labeling to 3D CAD and BIM requires adapted techniques like 3D bounding boxes, surface segmentation, and point-level annotation.

Contextualization of Objects: Buildings are complex entities with numerous interacting components, and AI needs to understand the context and relationships between different elements. This includes understanding spatial relationships (e.g., a door's location relative to a corridor or room) and semantic meaning (e.g., distinguishing a guest room door from a fire-stopping door based on its zone and function). Without this contextual understanding, AI might struggle with generalization across different building types or design decisions.

Hierarchical Decomposition and Relational Data: BIM data can be broken down hierarchically (Project, Building, System, Element/Component levels) and includes relational data (e.g., system dependencies, space adjacencies, structural load paths). AI models need to process this multi-layered data to provide insights.

7. Major Challenges in Creating BIM Datasets for AI

The difficulties in creating such datasets, sorted by magnitude, include:

Data Privacy and Proprietary Concerns: Building designs often contain sensitive information and intellectual property, making organizations reluctant to share models.

Standardization and Format Inconsistency: Multiple software platforms, varying levels of detail, and inconsistent naming conventions.

Scale and Diversity Requirements: The need for thousands of diverse models (residential, commercial, industrial) across various geographies.
Quality and Completeness Issues: Incomplete or erroneous models, and varying levels of detail.
Annotation and Labeling Challenges: Time-consuming manual annotation and difficulty for automated tools to grasp context.
Versioning and Life Cycle Representation: Capturing temporal aspects and changes across design, construction, and operation phases.
Storage and Processing Requirements: Large file sizes and the need for significant computing resources.
Domain Knowledge Requirements: Deep understanding of AEC industry practices to create useful training data.
Data Augmentation Limitations: Difficulty in artificially expanding dataset size while maintaining realism and adhering to building codes.
Ultimately, the ability of AI to enhance BIM capabilities, such as optimizing designs, identifying construction issues, predicting building performance, or enabling generative design, hinges on the availability of these high-quality, comprehensive, and well-structured datasets.

8. Discussion and Conclusion

The integration of artificial intelligence with Building Information Modeling represents both one of the most promising opportunities and one of the most significant challenges facing the architecture, engineering, and construction industry today. This paper has explored the multifaceted landscape of AI-BIM convergence, demonstrating the complex relationship between technological potential and practical implementation barriers.
The promise of AI in BIM is undeniable. From expert systems that can emulate human expertise in specific architectural domains to generative design algorithms that can explore vast solution spaces far beyond human capability, AI technologies offer transformative possibilities for the entire building lifecycle. Modern approaches utilizing computer vision, graph neural networks, and geometric deep learning show particular promise for understanding the three-dimensional, semantically rich environments that BIM models represent. These technologies can potentially revolutionize how we approach design optimization and documentation, construction planning, and building maintenance.
However, the path to widespread AI-BIM integration is full of substantial challenges that extend far beyond mere technological considerations. The fundamental barrier lies in what this paper terms the "corpus problem", the critical need for massive, high-quality, standardized datasets that can serve as the foundation for training robust AI systems. The AEC industry's

fragmented software ecosystem, inconsistent modeling practices, and proprietary concerns create a perfect storm of obstacles to dataset creation.

The data challenges are particularly critical in BIM contexts. Unlike other domains where AI has achieved remarkable success, building information modeling involves inherently complex, multi-layered data structures that require a sophisticated understanding of spatial relationships, building codes, material properties, and contextual dependencies. The heterogeneity of building types, regional variations in construction practices, and the proprietary nature of architectural designs further complicate efforts to assemble comprehensive training datasets.

Perhaps most significantly, this analysis reveals that successful AI-BIM integration requires more than technological advancement; it demands fundamental changes in industry practices, data sharing protocols, and professional workflows. The transition from rule-based expert systems of the past to modern machine learning approaches represents not just a technological evolution but a paradigm shift in how the industry conceptualizes and implements intelligent design assistance.

Looking forward, the most promising path appears to lie in hybrid approaches that combine the interpretability and domain-specific knowledge of traditional expert systems with the pattern recognition and generalization capabilities of modern AI. Multi-modal systems that can process both geometric and semantic information while maintaining awareness of building codes and design constraints offer the greatest potential for practical implementation.

The future of AI in BIM will likely be characterized by incremental progress rather than revolutionary breakthroughs. Success will depend on the industry's ability to address fundamental data infrastructure challenges while developing AI systems that can work effectively with incomplete, inconsistent, and proprietary datasets. This will require substantial collaboration between software vendors, architectural firms, academic institutions, and regulatory bodies.

Ultimately, the convergence of AI and BIM represents more than a technological upgrade; it embodies a fundamental reimagining of the design process itself. As we move toward this future, the question is not whether AI will transform BIM, but rather how quickly the industry can overcome the structural barriers that currently limit its potential. The organizations and professionals who successfully navigate these challenges will find themselves at the forefront of a more intelligent, efficient, and responsive built environment.

The journey toward AI-enhanced BIM is complex and demanding, but the potential rewards, more sustainable buildings, reduced construction waste,

improved safety, and enhanced design quality, make it one of the most important technological transitions the AEC industry has ever undertaken.

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ARCHITECTURAL INFORMATICS AS A TOOL FOR ADAPTIVE RECONSTRUCTION

Retrofitting Identity in Post-war Syria

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Abstract. This research addresses the challenge of preserving the identity of a city during post-war reconstruction (PWR) by proposing an Algorithmic Retrofitting Workflow (ARW). The study focuses on retrofitting cratered walls; a prominent damage found in damaged residential buildings in post-war Syria. This adaptive, algorithmic reconstruction was developed within a controlled environment, tested on open-source data, and applied to real-world scanned environments. The retrofitted solutions adapt to the complex crater geometry, generating solutions that respond to the damage using standard bricks and custom bricks. The results of ARW offer an alternative to demolishing damaged buildings, a common solution that causes the loss of a city's identity. It also demonstrates how informatics-based digital workflows can provide quick, affordable reconstruction that doesn't require highly skilled professionals, bridging the gap between digital tools and post-war reconstruction. Post-war reconstruction should be informed by the remnants of the city and retrofitted instead of being built from scratch.

Keywords: *Post-war Reconstruction, Urban Identity, Architectural Informatics, Algorithmic Workflow, Retrofit Design*

1. Introduction

"[To] wipe a nation's history, you wipe their architecture" (Hafez, 2020). The rising frequency and intensity of conflicts have left many cities in a state of limbo, paralyzed by neglect and unable to fully recover while still

preserving their cultural and architectural identity (ICRC, 2017). Identity is one of the most neglected aspects in post-war reconstruction (PWR), primarily due to the urgency of prioritizing temporary, quick-relief solutions, which slowly become the reality of post-war cities (Pullan and Azzouz, 2019).

In response to the destruction, cultural heritage sites are often prioritized in PWR efforts (Stanley-Price, 2007), while ordinary residential buildings, carrying no cultural significance, tend to be excluded from the process. Although they comprise most of the city's urban fabric, residential buildings are often neglected and demolished because the repair of their non-standard elements is prohibitively expensive and time-consuming (Clifford, 2021). Studies done by ICONEM (2016), Buthke et al.(2020), and Li et al. (2023) demonstrated the use of digital tools, such as LiDAR 3D scanners, to restore and preserve heritage structures. However, this potential has yet to be extended to ordinary residential buildings. On the other hand, Dörfler et al. (2016) utilized a mobile robot for on-site assembly of dry brickwork, Johns et al. (2020) attempted to revive vernacular building methods both using both 3D scanning and robotic construction, Al Nouri et al. (2021) emphasized the role of data collection using a LiDAR 3D scanner to document the urban scale damage in post-war Syria, while Grangeot et al. (2024) explored material upcycling to restack concrete rubble using a 2D scanning algorithm and robotic arms to drill and anchor the rubble. However, the use of digital tools and digital workflows in post-war environments is underexplored as post-war cities face multifaceted challenges that hinder recovery:

(1) Lack of resources (skilled workers, materials, funds, etc.)
(2) Identity loss from hostility and misguided reconstruction.
(3) Difficulty of reusing non-standard, complex geometry.
(4) Limited accessibility (political instability, safety risks, etc.)

Therefore, this research aims to bridge this gap by proposing the use of architectural informatics in PWR for long-term, localized reconstruction. A bottom-up approach that restores the city's identity by working within the predefined building conditions, rather than imposing top-down, standard reconstruction plans for new structures that have no relation to the city's pre-war identity. It is expected that this research will challenge the dominant 'scratch and rebuild' approach by applying algorithmic digital workflows to retrofit, adding new parts to the existing, non-standard geometries of cratered walls found in ordinary, residential buildings in post-war Syria.

1.1 RESEARCH AIMS AND OBJECTIVES

This research focuses on **cratered walls**, a large opening in the non-structural walls of the reinforced concrete frame building, often caused by missile strikes, shelling, or artillery. **Reinforced concrete frame** (Figure 1) is the most dominant structural typology in residential buildings in Syria (Alhourani et al., 2013). Therefore, the cratered wall was selected due to its frequency and the minimal structural intervention required, as the damage occurred within the non-load-bearing infill walls, thus preserving the building's structural integrity.

The primary goal of this study is to show the potential of architectural informatics in post-war reconstruction by applying a digital workflow to retrofit the non-standard geometries of cratered walls found in ordinary, residential buildings in post-war Syria. To develop a retrofitting algorithm that integrates localized design informed by the user's needs. An algorithm that maximizes the use of standard bricks over customized bricks.

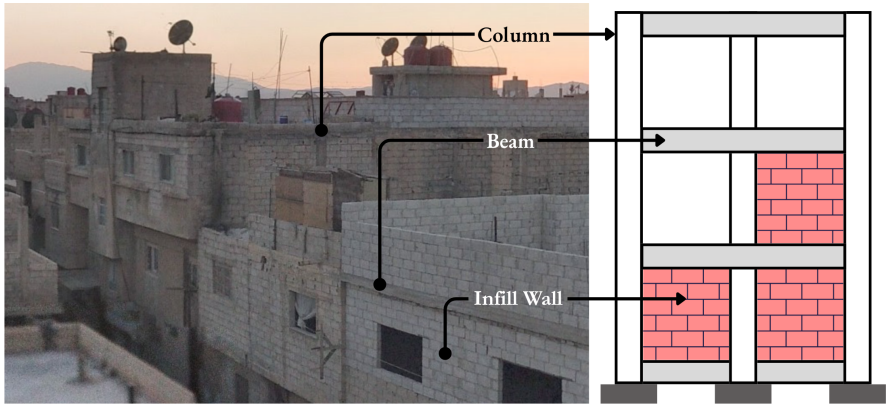


Figure 1. Reinforced Concrete Frame Residential Buildings. *Image via Google Earth*

2. Research Methods

2.2 PRELIMINARY RESEARCH

A remote **visual survey**, conducted through Google Street View (GSV), identified seven recurring damage typologies in the 61 buildings surveyed in post-war Syria. These damage typologies were categorized into 3 major categories according to UNOSAT (2019) findings:

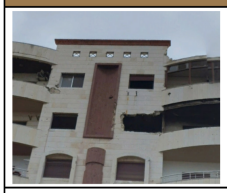
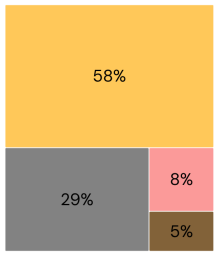
1. Moderate Damaged (5-30% collapse, minor non-structural damage):
   - Cratered Wall: Openings in non-load-bearing walls.
   - Blown-out Window: Shattered window with minor wall damage.

- Bullet Pitting: Shallow impact marks on the surface.
- Charring: Burn marks caused by fire or explosions.

2. Severe Damage (30-75% collapse, significant structural loss)
   - Partial Damage: Significant part of the building structure collapsed.
   - Top Floor Damage: Upper floor slab and roof damaged.
3. Total Damage (75-100% collapse, major or total structural loss)

Table 1 shows one representative building for each damage typology. Among all moderately damaged buildings in the GVS dataset, Cratered Wall was the most recurring damage typology, accounting for **58%** of the 38 moderately damaged buildings.

TABLE 1. Damage Catalog in Post-war Syria.

1. Total Damage	2. Partial Damage	3. Top Floor Damage	4. Cratered Wall
			
Total Damage	Severe Damage	Severe Damage	Moderate Damage
35°20'17"N 40°08'11"E	34°44'13"N 36°42'48"E	35°20'17"N 40°08'34"E	35°19'36"N 40°08'16"E
5. Blown out window	**6. Bullet Pitting**	**7. Fire / Charred**	**# of Moderate Damage**
			
Moderate Damage	Moderate Damage	Moderate Damage	
34°44'05"N 36°42'29"E	35°20'20"N40°08'37"E	35°20'19"N40°08'36"E	

2.2 ALGORITHMIC RETROFITTING WORKFLOW (ARW)

A single algorithmic parametric workflow was developed to simulate retrofitting cratered walls in a post-war residential building in Syria. The objective is to reuse damaged yet structurally stable buildings instead of demolishing them. The crater-damaged area was manually traced as a **closed polyline** to represent the **damaged curve**, the area where the retrofitting algorithm (ARW) is applied (Figure 2).

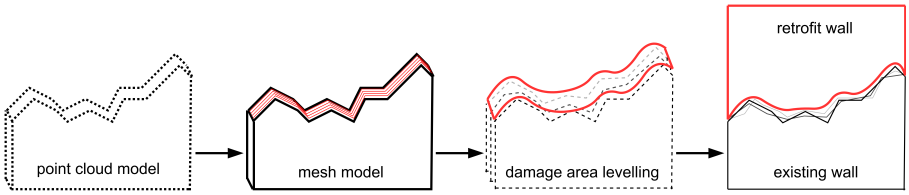


Figure 2. Retrofit Area Extraction Process

2.3 TOOLS

Rhinoceros 3D was used to construct the base model. Subsequently, Grasshopper was used for the ARW scripting, and GhPython components performed key stages: (1) Brick pattern generation, (2) Lintel formation, (3) Non-standard brick generation, (4) Clustering non-standard bricks. Together, these tools enable a flexible digital workflow that adapts to various crater damage curves for retrofitting (Figure 3).

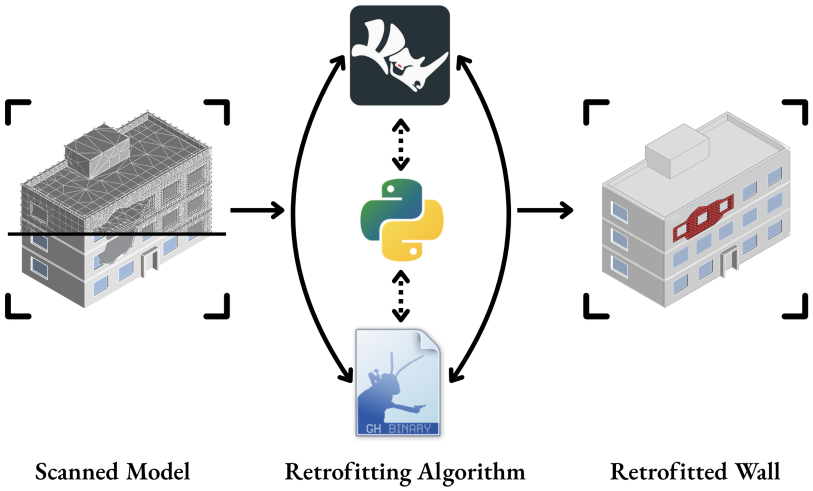


Figure 3. Digital Tools used for ARW's Digital Workflow

2.4 ALGORITHM STRUCTURE

This section introduces the algorithm's structure (Figure 4). ARW inputs the damage curve, generates staggered bricks, categorizes bricks, forms lintels, trims nonstandard bricks, filters small pieces, clusters nonstandard bricks, adds Syrian Ablaq-style, and extrudes the final retrofitted wall.

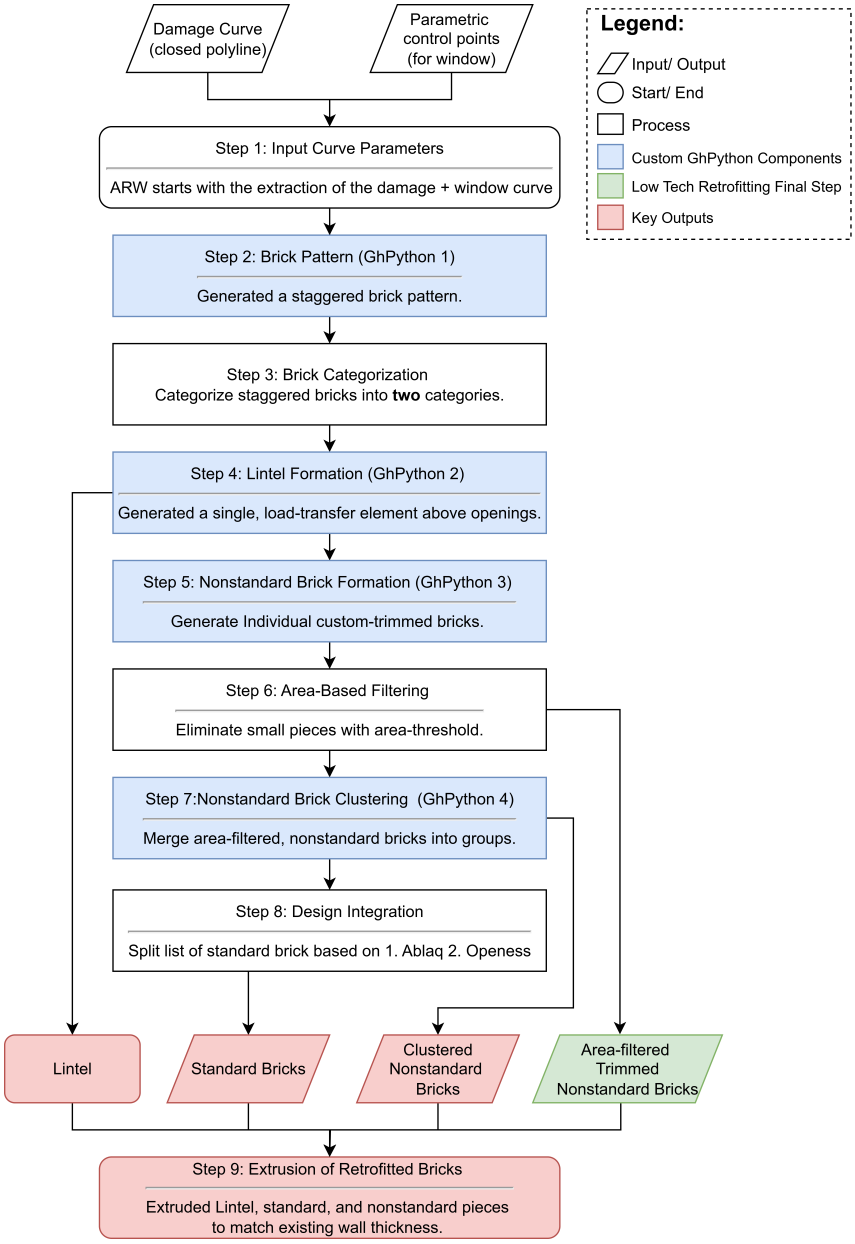


Figure 4. Methodology Flowchart: Algorithmic Retrofitting Workflow

Once the damage curve is manually extracted, it is input into Grasshopper to start the retrofitting algorithm (Figure 5).

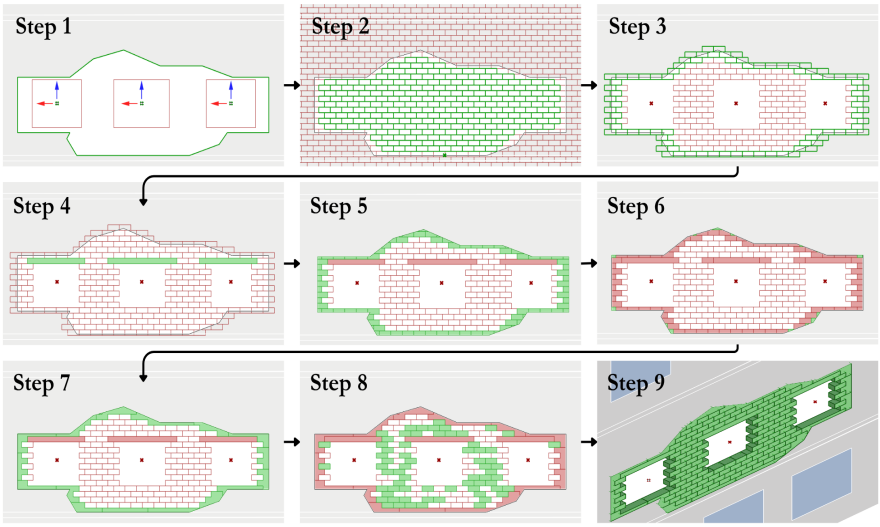


Figure 5. Steps of the Algorithmic Retrofitting Workflow (ARW).

2.4.1. Step 1: Input Curve Parameters

First, the extracted damage curve is inputted and smoothed using the 'Smooth Polyline' component. Following this, parametric window points are placed within the damaged area. These points act as the window's center with sliders controlling the window's length, width, and fillet radius. This allows for flexibility in design customization, supporting both rectangular and circular geometry windows.

2.4.2. Step 2: Brick Pattern (GhPython component 1)

Guided by the existing hollow cement brick pattern (Figure 1) found in Syrian residential buildings, a **staggered brick pattern** is generated. The first GhPython script generates three key outputs for the subsequent steps:

1. **Original_grid:** the full grid of the staggered bricks pattern.
2. **Grid_cells:** list of bricks with all corner pts fully within damage curve.
3. **Lowest_pt:** the lowest point along the damage curve.

The lowest point acts as the anchor point for the brick generation to follow realistic construction logic, beginning from the bottom upwards. The Original Grid helps identify the non-standard bricks, while Grid Cells help identify the standard bricks.

2.4.3. Step 3: Brick Categorization

This step categorizes bricks into two categories:

- **Standard Bricks:** Corners fully enclosed within the damage curve.
- **Initial Nonstandard Bricks:** Corners intersected with damage curve.

The output 'Original Grid' is intersected with the damage line using 'Curve-Curve Intersection' to extract the Initial Non-standard Bricks. Simultaneously, the standard bricks intersecting with the parametric window curve(s) are removed through the 'Point in Curves' component.

2.4.4. Step 4: Lintel Formation (GhPython component 2)

The second GhPython script forms the lintel – a horizontal structural beam above the window openings. It takes the standard bricks from the previous step and the parametric window curve(s) from Step 1, intersecting them to extract the bricks that intersect with the window curve(s). The script then sorts the intersecting bricks along the X-axis, selects the highest bricks along the Z-axis, and joins their curves into a planar Brep. Finally merging all brick faces to form a singular lintel.

2.4.5. Step 5: Nonstandard Bricks Formation (GhPython component 3)

The third GhPython script takes the list of nonstandard bricks from the previous step and splits each brick along the damage curve. Only the portions that fall inside the damaged area are kept. The bricks are split along the intersected damage curve using a two-point intersection, resulting in a series of trimmed brick shapes that fit within the irregular cratered wall.

3.2.6. Step 6: Area-Based Filtering (Low-tech approach)

This step filters out bricks smaller than 15% of original size using 'Larger Than' component. These discarded pieces, shown in green in Figure 6, can be filled with mortar during on–site assembly, saving both time and material.

In cases where custom digital fabrication is not possible, the retrofitting process can conclude at this step. This low-tech approach ensures that the retrofitting proposal remains applicable and accessible in a post-war environment with limited resources.

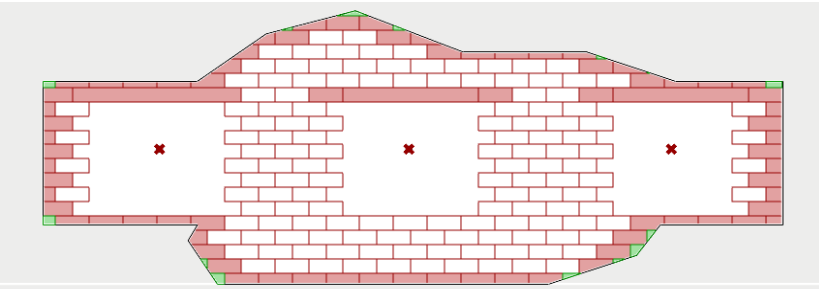


Figure 6. Bricks smaller than 15% of the original size, highlighted in green.

2.4.7. Step 7: Non-standardized Brick Clustering (GhPython component 4)

The fourth and final GhPython script clusters the non-standard bricks into larger clustered modules, by grouping nearby bricks until reaching the target area. The 'target area' size can be adjusted according to the constraints of the dimensional limits of the available fabrication method. This step provides key advantages (Figure 7):

(1) Reduces the total number of pieces that need to be fabricated.
(2) Speeds the reconstruction time of cratered walls.
(3) Simplifies reconstruction with clear edges to align the standard bricks.
(4) Minimizes mortar use by merging the non-standard pieces.

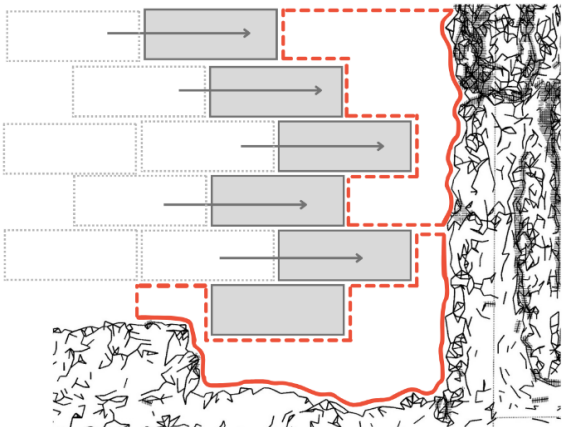


Figure 7. Custom Edge in Straight Red Line and Standard Edge in Dashed Red Line.

2.4.8. Step 8: Ablaq Style Design Integration

Inspired by the contrasting black and white stones seen in the traditional Ablaq architectural style (Figure 8), which originated in Syria, this step introduces a contrasting brick pattern. The list of standard bricks is passed through the 'Random Split List' component to assign the desired percentage of **contrasting bricks**, controlled by a user-defined percentage, along with a seed value, which allows users to generate multiple distribution variations to compare and choose from.

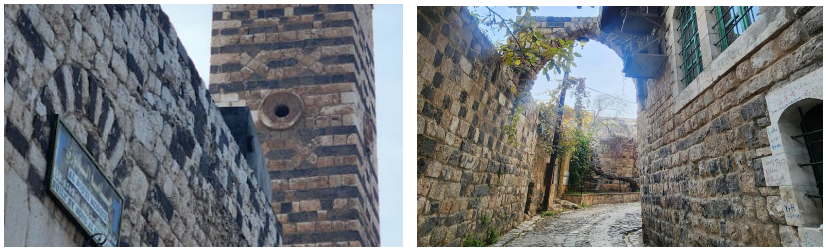


Figure 8. Traditional Ablaq Style in Hama, Syria, (left) Al-Nuri Mosque, (right) Residential *Photos by Alwan (2025)*

2.4.9. Step 9: Brick Extrusion

The standard and non-standard bricks are then extruded. This step unifies the depth dimension of the retrofitted wall with the existing wall. However, the current extrusion applies to the 2D pattern derived from the 2D damage curve. In reality, catered walls have a 3D depth that exhibit uneven geometry and material disintegration (Figure 9). Future work should incorporate depth variations to develop 3D retrofitting solution.

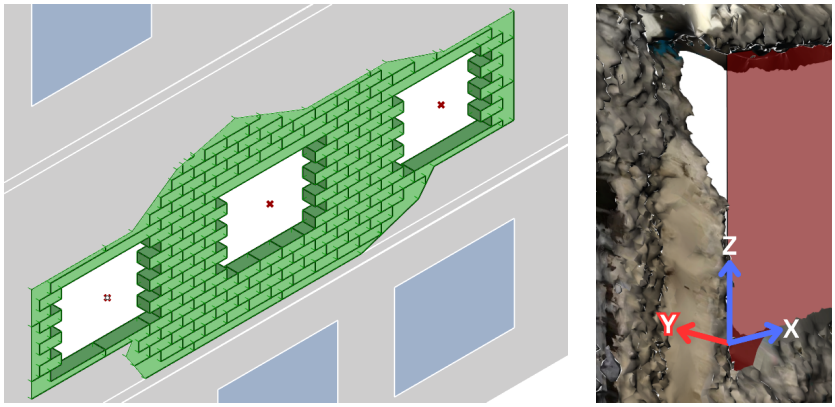


Figure 9. (Left) ARW Brick Extrusion, (Right) Limitation along the Y-Axis.

3. Results: Retrofitted Cratered Walls

This section presents the results of the ARW in two phases: **(I) algorithm adaptability** and **(II) design application parameters**. Phase I tests the algorithm on low-accuracy open-source GSV data, while Phase II tests the algorithm on high-accuracy 3D scan data. Together these two phases generate **site-specific retrofit solutions** that are both **practical** and **time-effective**, without the need for demolition. The results demonstrate how digital workflows enable residents to quickly simulate and compare multiple reconstruction solutions, unlike conventional methods, which rely on skilled professionals and are time-consuming.

3.1 PHASE I: ALGORITHM ADAPTABILITY

Damage in post-war buildings is highly irregular; no two cratered walls are ever alike (Diefendorf, 1989). Therefore, Phase I acknowledges PWR complexity by applying the ARW to the collected Google Street View (GSV) dataset on 14 craters from 6 cratered wall buildings (Figure 10). The algorithm was tested on cases where the crater damage occurred at the center

of the wall, around window openings, and on cases where the damage was extended to the ceiling or floor slabs.

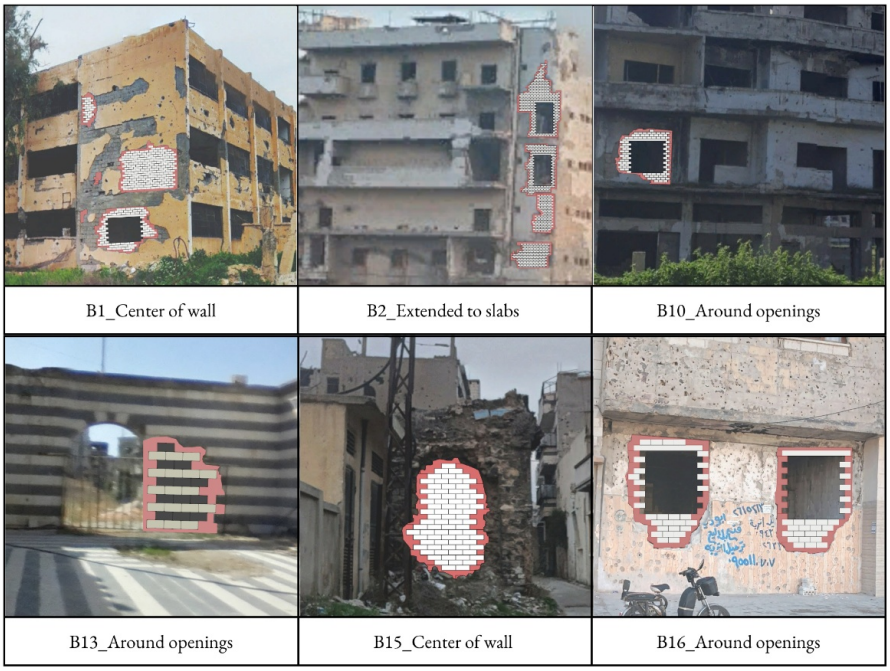


Figure 10. ARW applied to 14 cratered walls found in six buildings from GSV data.

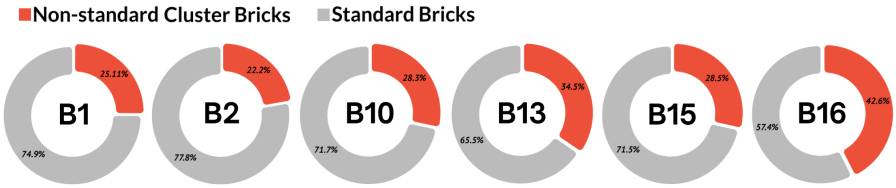


Figure 11. ARW applied to 14 cratered walls found in six buildings from GSV data.

Phase I findings from Table 2:

(1) The ARW generates more standard bricks, making up 74% of all retrofitted walls, than nonstandard ones, enabling a time-, cost-, and labor-efficient process (Figure 11).
(2) In small craters, the ARW only generates cluster bricks, as the area is too small to fit a full standard-sized brick.
(3) The ARW adapts and scales on all small, medium, and large craters.

TABLE 2. Phase I Findings per Retrofitted Building.

Building Tag*	Crater Tag	Total Std. Bricks (#)	Total Custom Clusters (#)	Std. Area %	Custom Area%
B1	B1-C1	21	6	52.5%	47.5%
	B1-C2	198	17	83.2%	16.8%
	B1-C3	81	11	72.4%	27.6%
	B1-C4	0	2	0%	100%
	B1-C5	0	1	0%	100%
B1-Total	**5**	**300**	**37**	**74.9%**	**25.1%**
B2	B2-C1	268	34	79.4%	20.6%
	B2-C2	155	28	74.1%	25.9%
	B2-C3	133	18	76.9%	23.1%
	B2-C4	160	14	79.8%	20.2%
B2-Total	**4**	**716**	**94**	**77.8%**	**22.2%**
B10	B10-C1	**91**	**15**	**71.7%**	**28.3%**
B13	B13-C1	**29**	**7**	**65.5%**	**34.5%**
B15	B15-C1	**76**	**16**	**71.5%**	**28.5%**
B16	B16-C1	31	8	58.5%	28.5%
	B16-C2	25	8	56.1%	41.5%
B16-Total	**2**	**56**	**16**	**57.4%**	**42.6%**

3.2 PHASE II: DESIGN PARAMETER APPLICATION

Phase Two applied the retrofitting algorithm to a 3D-scanned damaged residential building (Figure 12.a) located in Zamalka, a town northeast of Damascus. While Phase 1 demonstrated the algorithm's capability to adapt to diverse crater geometries, it lacked accuracy due to the perspective distortion and low quality of the Google Street View (GSV) imagery. This affected the precision of the extracted crater outlines. To overcome this limitation, Phase 2 utilized a 3D scanned model (Figure 12.b), provided by the Reparametrize Foundation, to produce accurate results tailored to the precise conditions of the buildings. The use of a LiDAR 3D Scanner captures the dimensions of the crater boundary with relative accuracy within a short period, while the Insta 360 camera attached to the scanner captures the building's material composition.

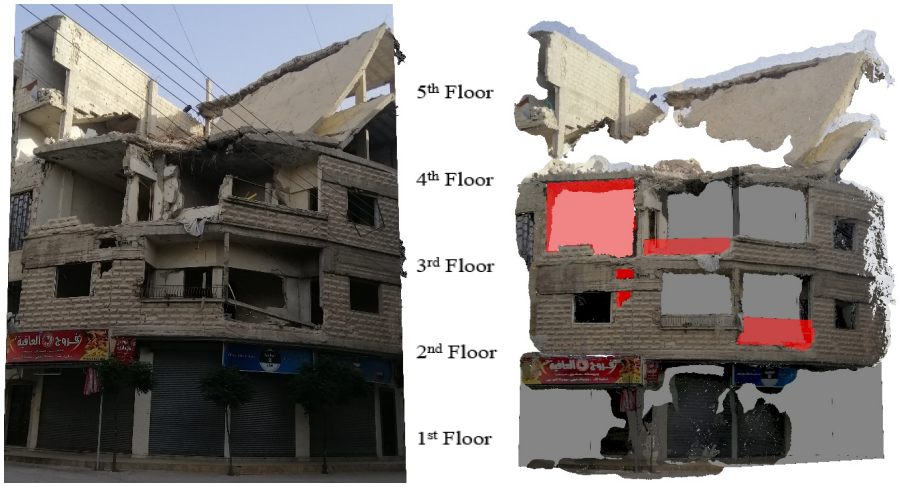


Figure 12. Left (a) Picture of Damaged Building. *Right* (b) 3D Scan of Damaged Building.

The selected building exhibited one major cratered wall on the 3rd floor, two minor craters on the 2nd floor wall, two cratered balcony walls on the 2nd and 3rd floors, and total collapse of the top floors 4th and 5th that cannot be retrofitted (Figure 12.b).

A **Quadrant chart** (Figure 13) visualizes the range of retrofitting solutions. Two adjustable parameters were used to explore the user-defined design integration of the algorithm:

(1) **Ablaq Pattern Percentage:** How many contrasting bricks?

(2) **Openness Percentage:** How many and how big is the window opening?

The X-axis represents the percentage of green bricks, used as placeholders for Ablaq pattern, while the Y-axis represents the openness percentage, based on the size of the window openings. Nine unique configurations, based on the max, mid, and min values, were generated to show the range of possible retrofit outcomes (Figure 14).

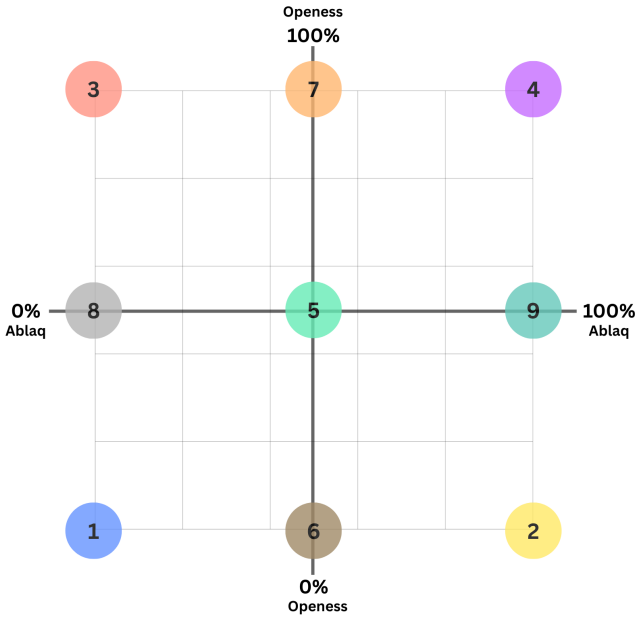


Figure 13. Location of the nine configurations on the quadrant chart.

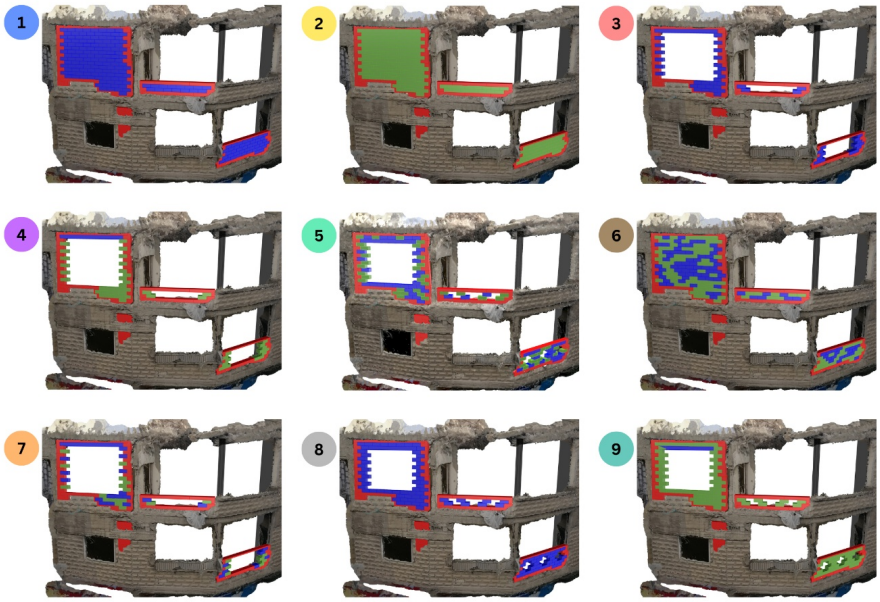


Figure 14. Visualization of the Nine Configurations.
Clustered non-standard bricks (red), Standard bricks (blue), Contrasting bricks (green).

Among these nine outcomes, Solution 5 (50% openness, 50% Ablaq) was visualized to show the final result of the retrofitting process. The result, Figure 15, shows a building whose architectural identity was restored and its structure rehabilitated, making it habitable for its residents once again. The 4th and 5th floors were cleared up as the damage was too severe to be retrofitted. Phase II results showcase how the Algorithmic Retrofitting Workflow (ARW) effectively adapted to the complex crater geometries, generating retrofitted solutions that respond to the damage using custom cluster bricks, standard bricks to fill the wall, and a range of customizable design parameters for window and contrasting brick placement that revives the traditional Syrian Ablaq architecture.



Figure 15. Visualization of Solution 5 of the Ablaq Style Retrofitted 3D Scanned Building.

4. Discussion

Post-war reconstruction should be informed by the remnants of the city to prevent the gradual loss of our identities. Furthermore, digital workflows and digital tools can offer more efficient, cost-friendly solutions that help post-war cities recover while preserving their identity.

4.1 CONTRIBUTIONS

(1) Proposes a new PWR methodology that challenges the conventional 'scratch and rebuild' approach. The workflow makes irregular damage repair accessible, cost-effective, and time-efficient by minimizing the number of custom-fabricated pieces. Most importantly, it gives residential buildings a second chance to survive.
(2) The algorithm adapts to a low-tech approach. In the context where custom fabrication tools such as on-site or off-site concrete 3D printing are not available, the outcome can end at Step 6 in the methodology. Like traditional stone cutting techniques, Step 6's outcome generates a single diagonal cut that can be done manually if necessary.
(3) This ARW integrates traditional design parameters that enable participatory design through user-controlled, flexible customization – a solution not found in current wall patching methods.
(4) This research shifts the preservation focus from monumental to ordinary, residential architecture.

4.2 LIMITATIONS

(1) This research traces the crater damage as a single, closed polyline catching the wall irregularity in the X-Z axis. Yet in reality, the damaged edges of the crater have irregularities along all XYZ directions.
(2) At this time of this research, the ARW is on Rhinoceros, which is not user-friendly to the general public.

4.3 FUTURE WORK

(1) The ARW relies on the manual extraction of the damage curve. This process should be replaced by an auto-detection process to enhance and streamline the process.
(2) This ARW is intended to be implemented on non-load-bearing infill walls found in reinforced concrete frame structures. Future work should integrate structural evaluation tools to assess both the existing damaged wall and the retrofitted wall.

(3) Incorporate all three axes (XYZ) of the crater damage to address irregularities along the depth and ensure seamless integration of the retrofitted wall within the existing structure.
(4) Currently, the design integration is limited to two parameters, window size and Ablaq pattern. Future development should explore other brick patterns and additional parameters informed by residents to identify their preferences and needs regarding the retrofitted wall.
(5) Adapt the ARW into a user-friendly platform, such as a website or an application, that allows locals to easily generate various retrofitting solutions and guide them through the steps of the retrofitting reconstruction.
(6) Conduct real-world tests to compare the ARW to the existing, conventional post-war reconstruction methods in Syria. Comparing speed, accuracy, and amount of material used of both conventional and retrofitting reconstruction processes.

5. Conclusion

This research highlights the significance of identity in PWR by retrofitting cratered walls in damaged residential buildings in post-war Syria. This Algorithmic Retrofitting Workflow (ARW) offers an alternative solution to the issue of demolishing damaged buildings, a dominant and expedient solution that causes the erosion of identity over time.

This adaptive algorithmic reconstruction was initially developed within a controlled environment, then tested on open-source data, and finally applied to real, accurate scanned environments, validating its effectiveness. ARW effectively adapts to the complex crater geometries, generating retrofitted solutions that respond to the damage using custom cluster bricks, standard bricks, and customizable design parameters. It demonstrated how informatics-based digital workflows can provide a time-effective and affordable reconstruction solution that does not require highly skilled professionals – bridging the gap between digital tools and post-war reconstruction.

While a single building may appear insignificant in isolation, it is a part of a larger urban fabric, one that collectively forms the “neighborhoods” we call home. PWR should be informed by the remnants of the city to prevent the gradual loss of our identities. The new Syria should not be built from scratch but retrofitted.

Acknowledgements

The retrofitting results, presented in Section 3.2, were made possible thanks to the 3D scan data provided by the Reparametrize Foundation and scanned by students from the Reparametrize Lab at the University of Damascus.

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BLOCKCHAIN WEAVING AS ARCHITECTURE

A Framework for Transforming the Nomadic Heritage into Immutable Memory

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Abstract. This paper presents a novel framework for preserving nomadic textile heritage through blockchain-based immutable storage, specifically targeting Al Sadu weaving traditions. The authors formalize weaving patterns as integer matrices ($M \in \mathbb{Z}^{mxn}$) and encode them as Non-Fungible Tokens via custom Solidity smart contracts on Ethereum, creating cryptographically secured, provenance-tracked digital representations. Using Grasshopper parametric modeling to generate geometric patterns, the system demonstrates feasibility of decentralized cultural heritage preservation with embedded access control and ownership mechanisms. However, the research critically acknowledges fundamental tensions between discrete mathematical representation and continuous material culture, highlighting constraints including blockchain storage inefficiencies, loss of tactile and intangible dimensions, and risks of excluding originating communities from technologically mediated preservation systems. The work advances computational heritage research by revealing how distributed ledger technology can enable unprecedented decentralization and permanence while simultaneously exposing the profound challenges of translating embodied cultural practices into computational abstractions—underscoring the imperative for

culturally responsive governance frameworks that balance technological innovation with community agency and living tradition.

Keywords: *Weaving, Smart contract, Blockchain heritage*

1. Weaving as cultural heritage in the context of a nomadic lifestyle

Weaving, in the context of nomadic cultures, is far more than a technical craft—it is a dynamic and embodied expression of identity, environmental adaptation, and social continuity. Across various nomadic societies, textile production serves as both a functional necessity and a symbolic system that encodes cosmology, gender roles, and kinship. When situated within a mobile lifestyle, weaving reveals itself as a crucial medium through which intangible cultural heritage is preserved, transformed, and transmitted.

Among nomadic peoples, textiles are deeply intertwined with the material conditions of mobility. In the arid regions of the Arabian Peninsula, the Bedouin practice of Al Sadu weaving exemplifies how textiles mediate between function and tradition. Women weave geometric patterns using goat and camel hair on portable ground looms to produce tent panels, cushions, and bags—objects that structure the interior of mobile shelters while reflecting desert iconography and tribal affiliation (UNESCO, 2020; A-Ogayyel, 2020). These weavings are both spatial and cultural artefacts: they delineate domestic spaces within tents and also narrate a collective memory of migration, hardship, and belonging (Chuluunbaatar, 2025).

Similar patterns emerge in Central Asia, where nomadic Kazakh and Kyrgyz communities produce ala kiyiz and shyrdak felted textiles. The vivid motifs not only insulate yurts but serve as mnemonic devices, often referencing animals, myths, and cosmological beliefs (Meyer, 2024). These practices remain vital today, despite increasing sedentarisation and marketization, underscoring the resilience of nomadic cultural expression through textiles.

Gendered knowledge transmission is a core dimension of weaving heritage in nomadic societies. Among the Yörük nomads in Anatolia, women traditionally serve as custodians of carpet weaving techniques passed down orally and experientially. However, globalization and tourism have shifted this dynamic. As Öter (2010) illustrates, the commodification of carpets for external markets risks distorting symbolic motifs and undermining traditional material integrity. While tourism may provide economic opportunities, it can inadvertently lead to the homogenization of motifs that once held deep cultural specificity.

A similar tension is evident in the nomadic embroidery traditions of Mongolia, where coin and knot motifs stitched into clothing and household items encode clan affiliation, fertility rites, and historical memory. Chuluunbaatar (2025) argues that this embroidery functions as a "sophisticated intangible heritage," intricately linked to oral histories and cosmological beliefs. As with other nomadic groups, these traditions are maintained primarily by women, whose role as cultural transmitters is essential to the survival of this heritage.

Ecological adaptation is another crucial aspect of nomadic weaving. As Monisha (2003) documents in Ladakh, the nomadic pastoralists of the Himalayas utilize yak and sheep wool to produce textiles suited to extreme climates. Their weaving reflects not only technical adaptation to cold environments but also conveys social information such as rank and lineage. The practice of weaving becomes a repository of environmental knowledge, with materials and techniques adapted to regional flora, fauna, and climate.
Furthermore, recent scholarship points to weaving as a repository of spatial intelligence and mobility knowledge. Bedouin weaving patterns are not only decorative but index navigational paths and seasonal rhythms (Alazhari, 2021). In this sense, textiles themselves become cognitive maps, woven through lived experience and ancestral movement.

Efforts to safeguard nomadic weaving heritage are increasing through institutional and community-driven initiatives. The Al Sadu Society in Kuwait, for example, has implemented intellectual property protections and educational programs to promote intergenerational transmission while resisting market dilution. Similarly, the DOBAG (Doğal Boya Araştırma ve Geliştirme Projesi) initiative in Turkey has worked to revive natural dye practices and empower rural women through ethical carpet production, aligning heritage preservation with economic sustainability.

In conclusion, weaving in nomadic contexts embodies a convergence of cultural, environmental, and economic functions. It is not merely a craft, but a living tradition that encapsulates worldviews, survival strategies, and aesthetic languages. As nomadic lifestyles evolve under modern pressures, protecting weaving practices demands strategies that go beyond conservation —requiring support for cultural autonomy, material sustainability, and the social roles that sustain this unique form of heritage.

2. Interplay between Blockchain as a decentralised ledger and cultural heritage preservation

The application of blockchain technology to cultural heritage preservation offers an innovative, decentralised framework for provenance, authenticity, and participatory engagement. At its core, blockchain functions as an immutable ledger, meaning once data—such as metadata about an artifact—is written, it cannot be altered or tampered without detection. This feature safeguards trust and provenance in digital and physical heritage contexts (Stublić et al., 2023).

Distributed ledger architectures can provide cryptographically secure time-stamped records of heritage objects or metadata. These systems ensure transparency, traceability, and public verification, reducing reliance on central authorities. A prominent case is ARCHANGEL, a blockchain-based system deployed by national archives in the UK, Estonia, and Norway to guarantee the long-term integrity of audiovisual archives through temporal content hashing (Collomosse et al., 2019).

Similarly, frameworks like VERAONET or TrustChain have been proposed to link artifact metadata and institutional records in decentralized, immutable chains, preserving integrity across institutions (Trček, 2022; Vacchio & Bifulco, 2022). Blockchain also enables the execution of smart contracts (SCs), external code that operates deterministically on-chain. These SCs can automate heritage workflows such as authentication validation, rights management, sharing permissions, or incentive mechanisms, all recorded immutably. Ramachandran and Kantarcioglu (2017) demonstrated how smart contracts can securely capture data provenance within scientific archives, preventing unauthorized modification while distributing verification across participants. In heritage contexts, similar contracts can verify custodial transfers or community-based custodianship models using transparent logic enforced by consensus.

However, despite their robust logic, blockchain computations lack tangible form. They are abstract, computationally embedded mechanisms running on distributed nodes rather than physical artifacts. Unlike a woven textile or carved relic, smart contracts and ledger entries are invisible unless rendered through interfaces or visualizations. This immateriality may raise concerns about cultural legibility and the ways in which decentralised computation can be understood and accessed by heritage stakeholders.

Non-Fungible Tokens (NFTs) offer a strategy for resolving this representational challenge by tokenizing digital or digitized heritage objects and embedding metadata and provenance records directly on-chain. NFTs function as immutable digital certificates, making blockchain data tangible

through token identities and visual assets (Stublić et al., 2023; Ilmi et al., 2024). For example, digitized heritage such as 3D scans of monuments, traditional textiles, or archival materials can be minted as NFTs with embedded hash-links to original files in distributed storage networks like IPFS, providing a visible, verifiable token representation of complex backend processes. Empirical research supports the relevance of this approach. A 2025 study in Humanities and Social Sciences Communication found that NFTs enhance psychological ownership and cultural identification when provenance and traceability are transparently embedded (Xue et al., 2025). This suggests that tokenized digital heritage not only reinforces trust in the documentation process but also supports emotional and symbolic attachment to cultural assets.

Comprehensive architectures integrating smart contracts, NFT layers, and consensus protocols are already being proposed to manage permissions, digital rights, and collaborative stewardship of heritage assets. In a field application in Algeria, Boumezbeur (2024) used terrestrial laser scanning, cryptographic hashing, and blockchain-based storage to document cultural sites, while deploying smart contracts to govern access for both researchers and local communities.

These examples illustrate how the integration of decentralized computation and cultural stewardship is no longer theoretical. Blockchain's role as both infrastructure and medium is becoming foundational for ensuring the long-term integrity, transparency, and participatory governance of heritage assets. Smart contracts allow encoded workflows to replace institutional opacity with verifiable openness, while NFTs transform abstract computation into accessible representations that can be shared, owned, and engaged with. The challenge lies in aligning technical systems with human meaning—building interfaces, protocols, and ownership structures that reflect the values, traditions, and responsibilities of cultural memory.

3. Blockchains as State Machines

Blockchains are perceived by most as a decentralized ledger technology, where a network of computers holds the same ledger in storage, with a mechanism to reach consensus on what is true on the ledger. Blockchains function as state machines, where each transaction represents a state transition that modifies the shared ledger across decentralized nodes (Vukolić, 2016). This creates an ordered sequence of states that ensures all participants maintain a consistent view of the ledger, enabling trust among untrusted parties (Benčić & Žarko, 2018).

Smart contracts, seen as software automatons (Hu 2020), extend this state machine model by embodying rules and protocols that transition between

states based on predefined conditions. This allows complex transactions to execute without centralized intermediaries, using state machine replication techniques to maintain consistency across nodes (Vukolić, 2016; Xiao et al., 2020). For example, a smart contract can automate fund transfers only when specific conditions are met. Blockchain interoperability further reinforces the state machine perspective by enabling state transitions across multiple blockchain environments, which is crucial for evolving ecosystems like decentralized finance (Liu et al., 2019). For our purposes, we use the Ethereum blockchain and the Ethereum Virtual machine as the operational infrastructure of our research, viewed under a lens of state machines, rather than as a mechanism for transactions.

4. Technical and Computational Description of the Al Sadu Textile Weaving

This research's motivation is the immutable preservation of mutable, nomadic, impermanent cultural heritage through the means of a permanent, immutable digital means, in the effort to save and be able to restore it for the future. Al Sadu weaving is a traditional textile craft that has its origins in Bedouin cultures, particularly in Kuwait and neighbouring regions. This weaving technique uses goat hair, wool, and cotton, producing textiles that are robust, durable, and functional. The raw materials are selected for their strength and weather resistance, which are essential in the harsh desert environment where the Bedouins traditionally reside (النجادة, 2019).

The weaving technique itself employs a horizontal loom, where the weaver interlaces vertical warp threads with horizontal weft threads. Al Sadu textiles often feature intricate geometric patterns and symbols that convey cultural significance. These designs serve not only decorative purposes; they are integral to the cultural identity and storytelling of the Bedouin people (Alnajadah, 2018; , Baird & Yağcıoğlu, 2021).

The colours used in Al Sadu textiles are derived from natural dyes, creating an earthy palette that reflects the surrounding landscape (النجادة, 2019). One notable aspect of Al Sadu weaving is its role in the construction of utilitarian items such as tents, bags, and cushions—each piece serves a practical function and represents a piece of cultural heritage.

The weaving process is a labour-intensive skill passed down through generations, generally performed by women (القندى, 2020). The aesthetic and technical qualities of Al Sadu textiles, combined with their cultural significance, make them a unique element of Kuwaiti heritage, embodying ideals of sustainability through the use of natural materials and traditional processes (القندى, 2020).

The computational description of an Al Sadu textile can take many forms, starting from modelling the textile weaving into a matrix format, and where via computational analysis complex patterns can be replicated (Győry, 2016; , Lomov et al., 2001), to a weaving simulation via computer aided design (Raharno & F., 2024) and to colour and material analysis, where we ensure that colours are replicated accurately, Kuo et al.'s work on color analysis systems could provide practical insights for matching the unique palette of Al Sadu textiles with precision (Kuo et al., 2012). Interestingly digital Fabrication techniques, from weaving robots to automated looms could potentially augment productivity, without sacrificing quality. This addition, could ensure that the art of weaving is preserved, evolving it to meet modern demands. (Buechley, 2006; Cherenack & Pieterson, 2012).

4. Methods: Encoding the Al Sadu as a matrix using parametric software

To operationalise our research via our prototype we have developed a script in Rhinoceros/Grasshopper that generates a simplified textile weaving pattern. We then feed this pattern in the form of a matrix to a smart contract on the Ethereum blockchain, where a non-fungible token gets created for that pattern. The Grasshopper algorithm is designed to generate a parametric pattern by processing a series of input values and organizing them into structured visual output. The workflow begins with a set of numeric inputs controlled through sliders, which define the parameters of the pattern such as scale, resolution, and repetitions. These inputs are then processed through a combination of mathematical operations, including additions, divisions, and multiplications, to derive a range of intermediate values that modulate the geometric behaviour of the pattern.

Subsequently, the data is structured into organized sequences using list management tools, which group or separate values based on specific rules or ranges. This structured data is then translated into geometrical components — triangles or rhombi —which form the basis of the visual pattern. The algorithm includes transformation operations that manipulate these geometries, in order to position or scale them dynamically within a grid. As the geometry is refined (Figure 1), the algorithm uses data panels to display the output values at various stages, offering insight into how numeric parameters correspond to various spatial configurations. These outputs represent also key values like RGB colour codes, coordinate triplets, and other properties necessary for visualizing and de-construct the final pattern into its subcomponents. The algorithm is capable of generating various patterns that match the geometric patterns emerging out of the Al Sadu

weaving techniques. The matrices are then exported into a text format and prepared for insertion into the solidity blockchain smart contract.

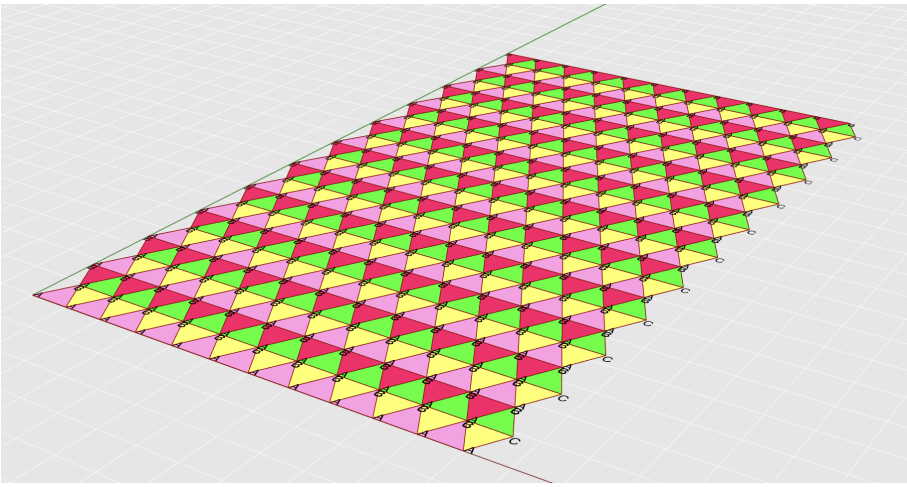


Figure 1. Al Sadu Geometric patter elaborated in Grasshopper

5. Encoding the Al Sadu matrix in a solidity smart contract.

Our matrix representation follows the mathematical definition of matrices as ordered rectangular arrays of elements, formalized as:

$$M \in \mathbb{Z}^{mxn} \text{ where } M = \{a_{ij} \mid 1 \leq i \leq m,\ 1 \leq j \leq n,\ a_{ij} \in \mathbb{Z}\} \quad (1)$$

We created a solidity smart contract that uses the matrix to encode the model of an Al Sadu fabric into the matrix. The code (Dounas 2025) is a modified standard non-fungible token smart contract based on the Open Zeppelin Libraries (OPEN ZEPPELIN 5.4.0) modified so that it can save the matrix (Figure 2)

```
15    // Structure to represent a matrix
16    struct Matrix {
17        uint256 rows;
18        uint256 cols;
19        bool exists;
20        address creator;
21        bool isLocked; // Prevents further modifications
22    }
23
24    // Mapping from tokenId to Matrix info
25    mapping(uint256 => Matrix) public matrices;
26
27    // Mapping from tokenId to matrix data: tokenId => row => col => value
28    mapping(uint256 => mapping(uint256 => mapping(uint256 => int256))) public matrixData;
```

Figure 2. Struct and Mappings of the Matrix inside the Smart Contract Definition

Critical in the smart contract is also the mechanisms for setting the matrix data through a minting function and then retrieving each column and row, so that one can re-create the Al Sadu fabric, by reading the data and driving a weaving either manually or through a machine. The system uses two primary data structures: Matrix Struct: Stores metadata including dimensions (rows/columns), existence status, creator address, and lock state and Nested Mapping: Implements the actual matrix data storage using tokenId => row => col => value structure

5.1.1 Key Functionality

Matrix Creation: The mintMatrix function creates new matrix NFTs with customizable dimensions (up to 100x100) and optional metadata URIs. Each matrix is assigned a unique token ID and records its creator for provenance tracking. Data Management: Users can manipulate matrix contents through individual value setting (setMatrixValue) or efficient batch operations (setMatrixValuesBatch). The contract provides comprehensive data retrieval methods, including single-cell access, entire row/column extraction, and dimension queries. Access Control: Robust permission systems ensure only authorized users (owners, approved addresses, or operators) can modify matrix data. The contract implements standard ERC721 approval mechanisms alongside custom authorization checks. Matrix Locking: A unique feature allows permanent matrix immutability through the lockMatrix function, preventing further modifications while preserving read access—ideal for finalizing artistic works or mathematical proofs.

5.1.2 Security Features

The contract leverages Solidity 0.8.19's built-in overflow protection and implements multiple security layers:

1. Bounds checking for matrix dimensions and indices
2. Existence verification for all operations
3. Comprehensive access control validation
4. Safe minting with recipient verification

5.1.3 Technical Innovations

The contract's nested mapping architecture enables efficient storage and retrieval of sparse matrices—storing only non-zero values while maintaining constant-time access. Event emission (MatrixCreated, MatrixValueSet,

MatrixLocked) provides transparent operation logging for off-chain indexing and analytics.

One criticism that is prevalent in using blockchain to store data is that the mechanism is not very computationally efficient. Our prototype is also an unoptimised one, where a matrix value is stored for each colour on the weaving of the fabric, where as there are many optimisation techniques that can be followed that will allow for a more optimum storage on the blockchain. This does not alleviate the inherent blockchain issues but reduces the amount of gas and storage to be used for each Al Sadu pattern. Spatial optimisations that can be applied to the encoding of the matrix are: Sparce Matrix Storage, where only non-zero cells are stored, where zero can be mapped to the white colour for the cloth, Run-Length Encoding, where a series of cells can be set into one integer mapped to one colour for a continuous colour weave, where as numerical optimisations such as bit-packing – where we can pack smaller integers into a 256-bit storage slot – can be used to reduce the bit load of the matrix. Further optimisation, that depend on the usage, could be encoding just the Delta between different weaving patterns, hence reducing the computational load when storing similar patterns, or completely off-loading the pattern unto an external storage with has verification. We have not yet developed particular optimisation mechanisms, electing to develop first a series of patterns that can then be optimised once we have a volume of Non-Fungible Tokens to produce.

6. Use and Encoding of the Al Sadu spatially

Many times, Al Sadu fabrics are used in beduin tents as parts of the decoration or as dividers, including the exterior fabric. Our encoding system can be extended spatially via the representational use of graphs, where a graph can represent the main structural system of the tent (central poles for the vertical forces, ridge poles for connection between central poles) along with the guy rope/stays for the tension elements, and ground stakes for the anchor points. Poles, Stays and anchors can be represented by edges, edges and nodes. The surface elements of the tent can be represented via topology and appropriate libraries exist in terms of connecting these topologies with the graph (Jabi 2024). In sequence, the matrix NFTs presented here can be used to present the patterns of the Al Sadu weavings on the surface of the tent, with a surface graph orchestrating their pattern arrangement on the final surface.

7. Constraints and Limitations: Restoring a full Al Sadu fabric from the blockchain storage

Our research faces significant limitations across technical, cultural, and methodological dimensions that constrain its practical application and theoretical validity. The most prominent technical barrier lies in blockchain storage inefficiencies, where our unoptimized prototype requires substantial gas costs that scale quadratically with matrix dimensions—potentially making large-scale heritage digitization economically prohibitive—while Ethereum's throughput limitations create bottlenecks for complex pattern storage operations. Equally critical is the fundamental inadequacy of discrete integer matrix representation in capturing the continuous, multi-dimensional properties of traditional textiles, as the $M \in \mathbb{Z}^{mxn}$ formalization cannot encode tactile qualities, material variations, or three-dimensional structural elements, resulting in significant information loss that compromises authenticity. From a cultural heritage perspective, the digitization process transforms embodied practices into computational abstractions, omitting critical intangible elements such as weaving rhythms, social production contexts, and ceremonial significance, while lacking mechanisms for verifying cultural authenticity or establishing legitimate authority for heritage representation. Methodologically, our Grasshopper algorithm generates geometrically similar but potentially culturally distinct patterns through parametric logic that cannot replicate traditional weavers' tacit knowledge and culturally specific aesthetic judgments, while the theoretical matrix-to-textile reconstruction process faces substantial challenges in translating discrete values back into material specifications and weaving instructions. Furthermore, the immutable storage model conflicts with the organic evolution characteristic of living cultural traditions, potentially freezing dynamic heritage practices in static digital forms rather than accommodating the intergenerational modifications that reflect changing materials, tools, and aesthetic preferences inherent in traditional textile development. Of particular importance is the constraint of being able to reproduce an Al Sadu fabric from the stored blockchain version and as such we are in the process of developing mechanisms that are designed to overcome these constraints.

8. Conclusions

Al-Ogayyel Rana (2020) confirms Homi K Bhabba’s (1994) suggestion that repeating the past by representing in different forms is an attempt to establish authority over unfamiliar situations. Partially this means that we attempt to gain knowledge about the things of the past so that we have a

contemporary position towards them. This research's motivation has been the immutable preservation of mutable, nomadic, impermanent cultural heritage through the means of a permanent, immutable digital means, in the effort to save and be able to restore it for the future. We presented a a pioneering computational framework for cultural heritage preservation that fundamentally reconceptualises traditional textile practices through the lens of mathematical abstraction and blockchain technology. By formalising Al Sadu weaving patterns as matrix-based Non-Fungible Tokens, we have demonstrated the feasibility of creating immutable, cryptographically secured digital representations of intangible cultural heritage, while simultaneously revealing the profound complexities inherent in translating embodied cultural practices into computational forms. Our implementation of the MatrixNFT smart contract establishes a novel paradigm for heritage tokenisation that extends beyond mere digitisation to enable programmable cultural assets with embedded provenance, ownership, and access control mechanisms. However, the constraints identified—particularly the fundamental tension between discrete mathematical representation and continuous cultural meaning, the economic inefficiencies of blockchain storage, and the risk of excluding originating communities from technologically mediated preservation systems—underscore the critical need for more nuanced approaches that bridge computational efficiency with cultural authenticity. The work contributes to computational design research by illustrating how mathematical formalisation can both enable and constrain cultural representation, while highlighting the imperative for interdisciplinary methodologies that integrate technical innovation with ethnographic understanding and community participation. Future research must address the optimisation of blockchain storage mechanisms, develop culturally responsive governance frameworks, and explore hybrid preservation models that honour both the immutable security of distributed ledgers and the dynamic evolution of living cultural traditions. Ultimately, this research demonstrates that while blockchain technology offers unprecedented opportunities for decentralised cultural heritage preservation, its successful implementation requires careful navigation of the complex interplay between technological capability, cultural responsibility, and community agency—a challenge that positions computational design as a critical mediator between digital innovation and cultural continuity.

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BIM-BPMN INTEGRATION FRAMEWORK FOR CONSTRUCTION WORKFLOW MANAGEMENT

Improving Process Interoperability in the AECO Sector

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Abstract. The Architecture, Engineering, Construction and Operations (AECO) industry faces persistent challenges in process interoperability, where fragmented workflows and disconnected stakeholder communication hinder efficient project delivery. This research explores the integration of building information modelling (BIM) and business process modelling and notation (BPMN) as a framework to enhance the management of information and knowledge in construction projects through structured workflow mapping and visualisation. By leveraging artificial intelligence (AI) as a supplementary tool, this integrated framework supports process compliance checking and improves collaboration across disciplines. The study focuses on process interoperability, using BPMN to model complex workflows and BIM to visualise lifecycle data, bridging stakeholder gaps. A practical case study implementation on concrete delivery demonstrates how this integration enables a shared understanding of workflows while automating data synchronisation between process execution and BIM model updates. AI-assisted tools —specifically, natural language processing (NLP) for regulatory knowledge extraction and preliminary validation support—supplement manual BPMN modelling while ensuring alignment with regulatory requirements. Initial results suggest improved workflow efficiency, optimised resource allocation, and faster decision-making through real-time process visualisation and direct BIM-BPMN data exchange. The implemented framework shows potential benefits in workflow transparency and reduced manual data handling errors. This research contributes to the broader discourse on innovation in the AECO sector by proposing an approach for process interoperability and highlighting the role of hybrid human-AI approaches in fostering effective collaborative solutions. By clarifying the synergies among BIM,

BPMN, and AI, this work advances the understanding of how digital tools can transform construction workflows while addressing practical limitations in current implementations.

Keywords: *Business Process Management (BPM), Building Information Modelling (BIM), Workflow Integration, Construction Technology, Digital Construction*

1. Introduction

The Architecture, Engineering, Construction, and Operations – AECO – sector continues to face persistent challenges in process interoperability, where fragmented workflows and disjointed communication hinder efficient project delivery (Bataw et al., 2016; Kannengiesser & Roxin, 2016; Aljabr & Ali, 2024). Despite decades of digitalisation efforts, including the adoption of Building Information Modelling – BIM –, significant gaps remain in how process information is captured, shared, and acted upon across disciplines (Nyqvist et al., 2025; Ren & Zhang, 2021). These challenges are compounded by the industry's reliance on static documentation formats and heterogeneous software ecosystems, which limit real-time coordination and create barriers to informed decision-making (Kannengiesser & Roxin, 2016). Recent research highlights that such interoperability issues are further exacerbated by the lack of standardised information formats for integrating process models with digital platforms (Ye et al., 2024)

BIM has established itself as a central repository for project data, supporting detailed representation of physical and functional aspects of a built asset (Aljabr & Ali, 2024). However, BIM alone does not fully address the need to structure, visualise, and especially manage the processes that generate, validate, and use this data (Nyqvist et al., 2025; Ye et al., 2024). Conversely, Business Process Model and Notation – BPMN – offers a standardised visual language for mapping complex workflows, clarifying roles, and identifying dependencies, but lacks intrinsic linkage to the physical and spatial environment provided by BIM. As noted by Kannengiesser and Roxin, (2016), BPMN's "flat" structure and monolithic models challenged modularity and adaptability, while its complexity creates barriers for domain experts. Ren and Zhang (2021) further highlight this gap, noting the lack of systematic methodologies to develop BIM interoperability solutions that address both technical and process dimensions.

So that the BIM and BPMN integration creates opportunities to bridge this gap, enabling process models that are directly connected to the project's data-rich environment. Research has demonstrated that such integration can significantly enhance efficiency, accuracy, and collaboration within the AEC industry (Nyqvist et al., 2025). However, implementation challenges remain prevalent, including technical issues, lack of standardisation, and resistance

to change (Aljabr & Ali, 2024). Ye et al. (2024) further illustrate the potential of this integration through their framework for smart contract generation and visualisation, which aligns process automation with BIM data. Recent studies also highlight the promise of agile process modelling approaches, such as Subject-Oriented BPM (S-BPM), to address limitations in traditional methods through stakeholder involvement and iterative design (Kannengiesser & Roxin, 2016). While S-BPM has shown potential, its integration with BIM remains underexplored. These findings align with broader research emphasising that digital transformation in construction requires holistic approaches combining technological innovation, business process management, and ecosystem evolution (Nyqvist et al., 2025).

This paper presents a case study of BIM-BPMN integration applied to the concrete delivery process, a workflow characterised by its time sensitivity, multi-actor coordination, and quality-critical decision points. The objective is to demonstrate how linking process models to BIM models can improve communication, streamline compliance verification, and strengthen collaborative decision-making.

2. Background and Related Work

2.1. INTEROPERABILITY CHALLENGES IN THE AECO INDUSTRY

Interoperability remains a complex and persistent challenge in the AECO sector, significantly hindering seamless collaboration among diverse stakeholders and systems. The fragmentation of tools, heterogeneity of data formats, and divergent organisational practices contribute to the creation of data silos, miscommunication, and inefficiencies in project delivery. Prior research has approached this challenge from multiple perspectives: Poirier et al. (2014) identify three primary dimensions of interoperability barriers—technological, organisational, and procedural—which are further influenced by contextual factors like regulations and market conditions. Muller et al. (2015) define interoperability as the ability for agents to exchange data, information, and knowledge, yet highlight persistent barriers in strategic, conceptual, and technological perspectives. The scientometric analysis by Ozturk (2020) reveals exponential growth in interoperability studies, particularly in engineering (53.7%) and computer science (19%) domains, underscoring the technical focus of current solutions while highlighting gaps in process and organisational dimensions.

2.1.1. Conceptual Barriers and Semantic Challenges

Conceptual barriers arise from syntactic and semantic mismatches in how different stakeholders interpret the same information. For instance, what an architect considers a design feature may be understood differently by a structural engineer or energy analyst, leading to implicit misunderstandings and a loss of shared meaning. This aligns with the notion of "cognitive interoperability" discussed by Mutis and Issa (2012), where gaps in understanding and representation hinder consensus across disciplines. Ozturk (2020) notes that while Industry Foundation Classes – IFC – and other standards aim to standardise data exchange, "there are still data errors and data loss" due to inconsistent interpretations of shared models. Similarly, Ren and Zhang (2021) emphasise that material information, critical for structural analysis, is often missing or inconsistently represented between architectural and structural models, leading to manual rework and errors. These interpretation challenges are compounded by the lack of standardised protocols across disciplines (Aljabr & Ali, 2024), creating a cascading effect of misaligned expectations throughout the project lifecycle.

2.1.2 Technological Barriers and Implementation Challenges

Technological barriers pertain to challenges in data exchange caused by proprietary or non-standardised formats, import/export difficulties, and performance inefficiencies in middleware, such as XML-based exchanges in web services. The reliance on Industry Foundation Classes (IFC) as a common schema has been a focal point for addressing these issues, though limitations persist due to vendor-specific implementations and incomplete standards adoption (Doe et al., 2024; Poirier et al., 2014). Doe et al. (2022) emphasise that the AECO sector's reliance on file-based exchanges (e.g., IFC files) exacerbates these issues, as they limit object-level queries and incremental updates, unlike the object-based approaches adopted in sectors like Oil & Gas.

Empirical evaluation reveals more severe limitations than theoretical discussions suggest. Golabchi and Kamat (2013) demonstrate through case studies that IFC round-trip exchanges between major BIM platforms result in substantial data loss, with complex elements such as curtain walls, stairs, and parametric components particularly affected. Even within the same software family, version compatibility issues persist, with imported IFC elements losing their parametric properties and being converted to generic models rather than maintaining their original family classifications. Research has highlighted that software interoperability issues and data management challenges significantly impact the effective use of BIM technologies (Aljabr & Ali, 2024).

Ren and Zhang (2021) identify six technical route segments for interoperability between architectural design and structural analysis, noting that even with IFC-based workflows, "information inconsistency is more of a software implementation problem." Their proposed invariant material

signatures aim to bridge gaps in material data representation, demonstrating how technical solutions must address both data loss and semantic alignment. However, current evidence suggests that achieving reliable round-trip data exchange remains problematic, with imported elements often requiring manual reconstruction and validation (Golabchi & Kamat, 2013) .

2.1.3. Organisational Barriers and Change Management

Organisational barriers involve misaligned structures, unclear role definitions, fragmented authority chains, and human factors that obstruct the coordinated flow of information. As noted by Poirier et al. (2014), organisational interoperability requires aligning business practices and contractual setups to enable seamless collaboration, a challenge exacerbated by the AECO sector's project-based, multidisciplinary nature. Muller et al. (2015) link these barriers to the lack of coordination in BIM adoption, creating a "vicious cycle" where interoperability limitations hinder BIM's potential.

Recent studies have identified resistance to change, high training and software costs, and insufficient technical knowledge as primary barriers to effective BIM implementation (Aljabr & Ali, 2024). Complementing these findings, Ozturk's (2020) scientometric analysis emphasises the need for "knowledge-integrated, ontology-based, IT-based managed, collaborative, automated, well-visualised, and sustainable outcomes," highlighting the interplay between technical and process dimensions. Ren and Zhang (2021) further contextualise this by linking interoperability solutions to project delivery methods (e.g., Design-Build vs. Design-Bid-Build), showing how contract structures influence information flow. The absence of standardised BIM protocols and templates has been identified as critically hindering successful integration efforts.

2.1.4. Economic Impact and Industry Costs

The economic implications of interoperability failures are substantial. The National Institute of Standards and Technology (NIST) has quantified the cost burden of inadequate interoperability at $15.8 billion annually for the U.S. construction industry alone, with manual data re-entry accounting for 69% of interoperability-related costs (Golabchi & Kamat, 2013). This economic burden is driven primarily by time spent on overcoming non-interoperability challenges, including manually re-entering data from application to application, using duplicate software, and time lost to document version checking.

2.1.5. Evolution from Data Exchange to Knowledge Integration

These compounded issues have limited the realisation of Building Information Modelling (BIM) as a truly interoperable, lifecycle-spanning knowledge repository. While BIM promises integrated models for architecture, structural, and MEP systems (Muller et al., 2015), its adoption is hampered by technical gaps, such as inconsistent IFC file transfers and material data loss (Doe et al., 2022). The focus has shifted from merely achieving data exchange to fostering knowledge alignment and shared understanding. Current BIM systems face a fundamental limitation in their lack of higher-level abstraction layers that can recognise and define complex architectural entities. While these systems efficiently manage individual components (walls, rooms, doors), they cannot semantically understand whether a collection of spatially arranged rooms constitutes a "building," an "apartment," or distinct functional zones. This semantic gap means that BIM models function as aggregations of discrete objects rather than hierarchical compositions of meaningful architectural entities, limiting their capacity for intelligent reasoning about building-level concepts and programmatic relationships.

Research demonstrates that current IFC certification processes involve only minimum requirements rather than ensuring no-loss interoperability, creating a false sense of compatibility among software vendors (Golabchi & Kamat, 2013). Technical implementation faces significant challenges related to proprietary data formats and version compatibility, with software vendors reluctant to expose semantic data that might reveal proprietary information and trade secrets, limiting true interoperability. As BPMNs are intrinsically related to higher abstraction layer entities (process, actor, scheduling, etc.) can be more effective in reducing interoperability issues.

The shift toward knowledge integration has highlighted the critical role of ontologies in achieving semantic interoperability. Ontological studies have emerged as essential frameworks for transforming raw data exchange into meaningful knowledge sharing across heterogeneous systems (Özturk, 2020). These approaches focus on standardising the meaning and relationships of entities, products, and processes rather than merely facilitating data transfer. Ontology-based research studies are particularly crucial for accelerated BIM adoption, as they enable systems to understand not just the structure of exchanged data but its contextual significance and relationships within the broader project ecosystem. This semantic layer becomes especially important when integrating process models like BPMN with BIM data, as it ensures that workflow decisions are based on properly interpreted building information rather than syntactically correct but semantically ambiguous data exchanges.

Over the years, research and practice have demonstrated that addressing interoperability requires not only technical standards but also process alignment and collaborative ecosystems that treat shared data as dynamic and actionable rather than static artefacts. For example, Doe et al. (2024)

highlight the need for a "golden thread of data and information" embedded in standards like ISO 19650 to ensure accountability across the building lifecycle. Doe et al. (2022) propose a hybrid interoperability ecosystem combining distributed and centralised federated models, leveraging object-based standards like IFC and APIs to bridge workflows.

2.2. BIM AND BPMN INTEGRATION: THEORY AND IMPLEMENTATION

The integration between BIM and project management processes remains an ongoing challenge for the industry. While various attempts have been made to address this issue, no effective solution has been achieved to date. Researchers such as Poirier et al. (2014) and Doe et al. (2024) have explored multidimensional frameworks, but challenges persist due to the sector's fragmented workflows and legacy systems. While solutions like BIM servers (e.g., BIMserver.org) and collaboration formats (BCF) have been explored (Muller et al., 2015; Doe et al., 2022), gaps persist in semantic connectivity and dynamic workflow integration.

Recent comprehensive studies have identified key success factors, including coordination between project parties, enhanced stakeholder collaboration, and the implementation of standardised protocols (Aljabr & Ali, 2024). While Ozturk (2020) identifies visualisation, ontology, and collaboration as high-impact keywords in interoperability research, practical gaps persist in aligning BIM with dynamic workflows. Research has shown that successful BIM-project management integration requires addressing multiple dimensions simultaneously: technological readiness, organisational culture adaptation, and comprehensive training programs (Aljabr & Ali, 2024).

2.2.1. Theoretical Integration Framework: BIM-BPMN Convergence

BIM and BPMN offer complementary strengths that can address these challenges. BIM provides a rich, object-oriented digital twin of a built asset, encompassing spatial, material, and lifecycle data. BPMN, on the other hand, offers a standardised, executable visual language for representing complex, multi-stakeholder workflows. Integrating these two domains aims to bridge the longstanding gap between the "what" (physical and informational building data) and the "how" (process execution and coordination).

The theoretical foundations of this integration align with the "process dimension" of interoperability proposed by Poirier et al. (2014), which emphasises mechanisms for information generation, management, and exchange across project networks. Ren and Zhang (2021) exemplify this approach by using BPMN to model geometric and material information flows between architectural and structural models, explicitly linking process

steps (e.g., "simplify architectural model") to BIM data requirements. Their case study demonstrates that automating material information checking reduced transfer time from 11 minutes (manual) to 2 minutes, validating the efficiency gains of integrated approaches. This 82% time reduction was achieved by them through the invariant material signature method, was automatically extracted and validated material properties (such as mass density, Young's modulus, and Poisson's ratio) from IFC files across different software platforms. In addition to the time savings, the automated approach also eliminates human error in material parameter transfer. The scalability of these benefits becomes particularly significant in larger, more complex projects where manual information transfer would exponentially increase both time requirements and error probability.

An integrated framework supports stakeholder-centric collaboration by explicitly linking roles, dependencies, and impacts through interconnected process and model representations. This alignment enhances visibility, reduces ambiguity, and facilitates proactive conflict detection. Ren and Zhang (2021) propose Business Process Model and Notation (BPMN) to map information transfer between architectural and structural models, offering a process-centric complement to BIM's data-centric approach, with their framework demonstrating how "invariant signatures" can standardise material properties across software, reducing manual interventions.

2.2.2. Implementation Considerations and Technical Challenges

However, implementing such integration requires addressing technical, organisational, and human dimensions. Tool selection is critical—for example, using Camunda for BPMN execution and Autodesk Revit as the BIM environment. As Doe et al. (2024) note, solutions like middleware or Linked Data approaches must accommodate the AECO sector's distributed nature while adhering to global standards (e.g., IFC, ISO 19650). Successful integration requires addressing technical modularity (e.g., adaptors for proprietary systems), semantic clarity (e.g., reference data libraries), and organisational buy-in—lessons echoed in the Oil & Gas sector's Open Industrial Interoperability Ecosystem – OIIE – (Doe et al., 2022).

Mechanisms for real-time data synchronisation, user training, and change management are essential to overcome siloed expertise. The integrated system must support dynamic updates, notifications, and bidirectional data flow, ensuring that BPMN tasks reflect changes in BIM data and vice versa. However, the IFC specification's focus on results rather than application processes means that complex parametric relationships and constraints cannot be preserved during data exchange, resulting in the loss of intelligent object behaviour when models are shared between platforms (Golabchi & Kamat, 2013).

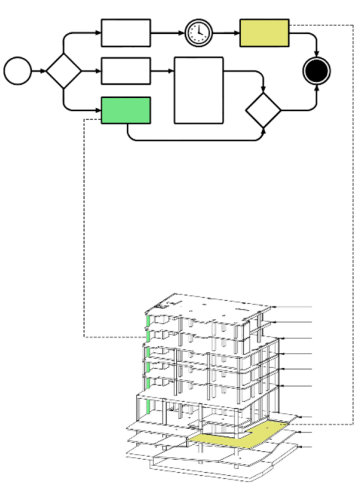
While BIM enables sophisticated clash detection and spatial conflict resolution for physical building elements, BPMN provides complementary

capabilities for detecting process-related constraints and workflow inconsistencies. BPMN can identify temporal conflicts between activities, resource allocation problems, role assignment errors, and procedural violations that would not be apparent through geometric analysis alone. This process-level constraint checking becomes particularly valuable when coordinating multi-stakeholder workflows, as it can detect potential bottlenecks, missing approvals, or conflicting responsibilities that could compromise project delivery even when the physical design is conflict-free.
Current evidence suggests that organisations adopting phased and role-specific approaches to BIM integration demonstrate higher success rates, with particular emphasis on continuous training, stakeholder engagement, and the establishment of cloud-based collaborative platforms (Aljabr & Ali, 2024). This approach transforms static data into living, actionable knowledge, fostering a more collaborative and efficient project delivery process, though technical limitations continue to constrain the full realisation of this vision.

3. Methodology

3.1. CONCEPTUAL FRAMEWORK

The proposed framework integrates Building Information Modelling and Business Process Model and Notation to enhance process interoperability in construction projects. The BIM layer serves as a centralised, object-oriented repository of project data across the asset lifecycle, including geometry, materials, scheduling, and performance attributes. The BPMN layer represents project workflows in a standardised, visual format, enabling clear communication of tasks, decision points, and stakeholder responsibilities. Together, these layers form a unified environment in which process execution and model updates are tightly coupled. This BIM–BPMN integration constitutes the tested core of the framework and is demonstrated in this study through the case of a concrete delivery process.



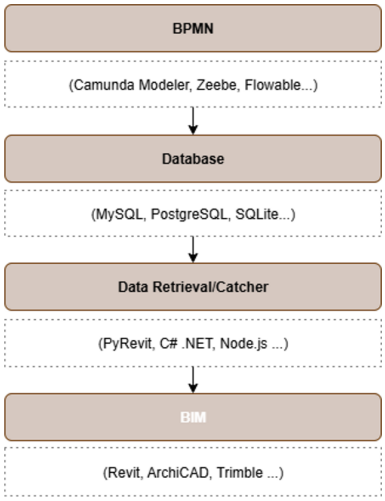


Figure 1. BPMN and BIM models mapping, *Figure 2:* Data flow and possible tools

3.2. BIM-BPMN CASE STUDY METHOD

The cement concrete delivery workflow was selected to demonstrate the potential of BIM–BPMN integration for improving process interoperability. BPMN process variables were directly linked to the corresponding BIM model elements, providing spatial and lifecycle context to every step in the workflow. The process model was refined and validated through iterative expert reviews, ensuring completeness and clarity in stakeholder roles. This method allowed for a seamless connection between operational tasks and the physical model of the project, creating a coherent environment for decision-making and process monitoring.

3.3. DATA SOURCES AND TOOLS

BIM–BPMN Case Study Implementation

- **BIM environment:** Autodesk Revit, containing project-specific delivery-related data.
- **BPMN modelling:** Camunda Modeller, used to create and visualise the concrete delivery process workflow.
- **Linking:** Manual association between BIM elements and BPMN process nodes for spatial and lifecycle context.

3.4. REGULATORY COMPLIANCE VALIDATION

To ensure regulatory adherence of the manually created BPMN workflows, an AI-assisted validation layer was implemented to analyse the logical

structure of the generated XML code against construction regulations and quality standards. This validation system employs natural language processing to cross-reference BPMN process elements with predefined regulatory rulesets, automatically identifying potential compliance gaps such as missing safety checkpoints, inadequate quality control sequences, or temporal violations of building codes. The AI validation operates as a quality assurance tool that supplements human expertise rather than replacing it, providing automated detection of regulatory inconsistencies that might be overlooked during manual review. This approach ensures that the BIM-BPMN integration maintains both operational effectiveness and regulatory compliance throughout the implementation process.

Although previous experiments demonstrated that current AI tools cannot autonomously generate reliable BPMN models due to layout inconsistencies and domain-specific interpretation challenges (Al-Siah & Fioravanti, 2024), but tools proved valuable for knowledge extraction tasks. Large language models were utilised in generating the knowledge logical connection, extracting stakeholder roles and dependencies, and parsing regulatory requirements into structured notes helps in the manual BPMN modelling process. This hybrid approach leveraged AI's text processing capabilities while maintaining human control over critical modelling decisions till achieving better tools to be fully reliable.

4. Case Study: BPMN-BIM Integration for Cement Concrete Delivery

The cement concrete delivery and casting process was chosen as the demonstration scenario due to its time-sensitive nature, multi-stakeholder coordination, and direct impact on structural quality. It was chosen as a trade-off between complexity and meaningfulness. In many projects, concrete test results influence downstream design decisions, yet this information is often trapped in static formats (e.g., PDFs), limiting real-time use. The case study applies the proposed BPMN–BIM integration framework to optimise workflow visibility, automate decision points.

4.1. MODELLING ENVIRONMENT AND SETUP

The modelling environment combined the Camunda Modeller, used for workflow creation, with Camunda Web/Tomcat for process execution. The BIM environment was Autodesk Revit, which was linked using the PyRevit hook, importing the data from a local MySQL database that contains the BPMN data. Building element references were mapped using both Element IDs and GUIDs, ensuring precise cross-referencing between the process and the model. Role-based access control in Camunda was configured to assign

permissions tailored to six distinct participant lanes—Inspector, Project Engineer, Construction Manager, Contractor, Quality Control, and Lab Technician—so that each user could only modify the tasks relevant to their responsibilities. This configuration preserved process integrity while providing each actor with targeted control over their part of the workflow.
Initial process knowledge extraction was supported by AI tools, which analysed project documentation and regulatory texts to identify key process elements and stakeholder interdependencies. Although previous testing confirmed that AI cannot reliably generate complete BPMN models autonomously due to graphical inconsistencies and complex text interpretation limitations (Al-Siah & Fioravanti, 2024), these tools effectively structured preliminary information and generated logical connections that guided the manual modelling process in Camunda Modeller. This approach reduced initial analysis time while ensuring modelling accuracy through human expertise until more reliable automated solutions become available.

4.2. WORKFLOW STRUCTURE

The BPMN model established explicit dependencies between participants through the use of swimlanes, clearly defined tasks, and message flows. See the full model in the appendix. Automated notifications and escalation mechanisms ensured that critical issues were addressed promptly. For example, if the Inspector identified site preparation problems, the system automatically triggered a “Report an Issue” message to the Project Engineer, initiating a closed-loop process that continued until formal approval was granted. Timer events were also incorporated to escalate delays, such as when the Lab Technician did not receive samples within the prescribed timeframe.

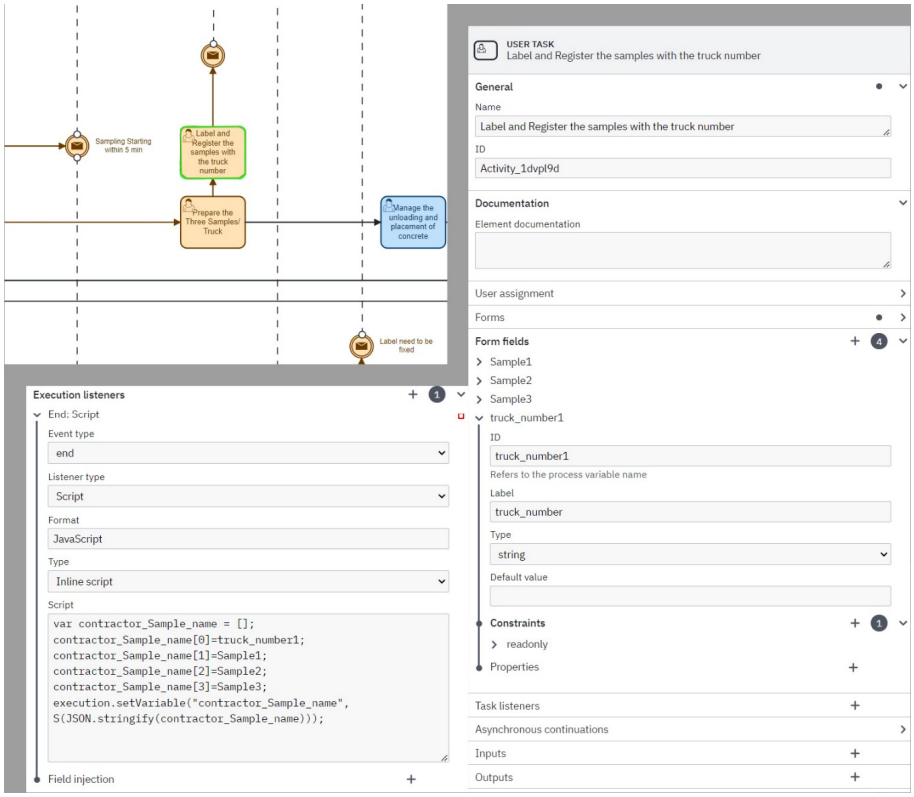


Figure 3. Samples registering process

To ensure compliance, the process embedded both general internal company standards and the provisions of the country regulation –Jordanian ones have been used in this case study– thereby aligning workflow execution with legal and procedural requirements. The repetitive nature of concrete deliveries was modelled as a loop, represented by orange-coloured tasks in the BPMN diagram, allowing multiple quality-control checks and approvals to be performed until a batch was confirmed to meet specifications and go through the sampling process see Figure 3: Samples registering process . In cases where a batch failed inspection, a “Send Reject the Truck” message was automatically dispatched to the Contractor, triggering the rescheduling of delivery without manual intervention.

A dedicated documentation lane, highlighted in red, was included to capture all process outputs in a read-only format. This design prevented retroactive modifications while ensuring that records remained digitally accessible to authorised stakeholders. By structuring the workflow in this manner, the

model facilitated both operational efficiency and data integrity, providing a clear, enforceable sequence of activities across multiple participants.

4.3. BPMN–BIM DATA SYNCHRONISATION

On the casting day, the Construction Manager assigned specific target elements for concrete placement, linking each to its corresponding BPMN and BIM IDs. Batch IDs, identified issues, and sample data were stored in JSON lists, enabling structured retrieval and traceability throughout the process. Real-time updates to the BIM model were achieved using custom Python scripts developed with PyRevit, along with a C# data-fetching utility connected to the MySQL database. These tools updated Revit element properties, such as compressive strength, based on the results reported by the Lab Technician. The updates also allowed for the inclusion of relevant comments, for example, early casting completion and modifications to material properties, which were applied only to the targeted elements, see Figure 3: BIM model updating. Execution listeners and process variables, including reason_reject_truck and mix_design, were used to control workflow progression, with conditional expressions determining whether the process would advance to placement or require re-preparation.

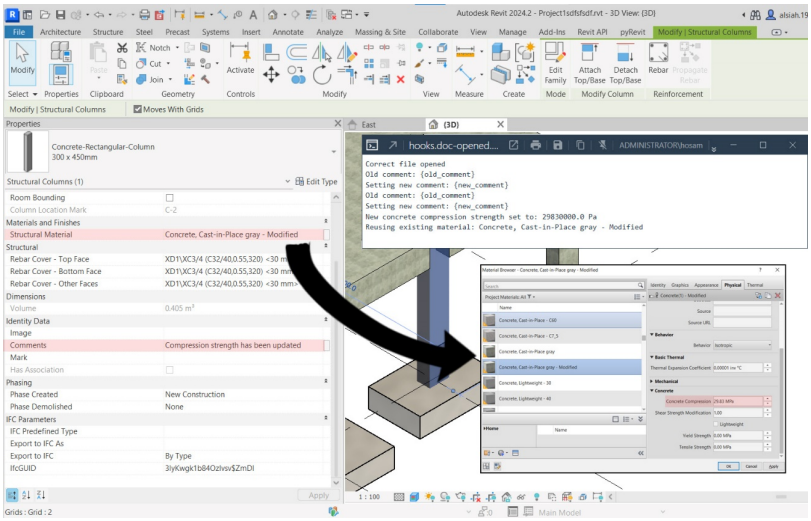


Figure 4: BIM model updating

5. Results and Discussion

The application of the BIM–BPMN integration framework to the concrete delivery process appeared to produce measurable improvements in workflow

clarity, coordination efficiency, and data reliability. The BPMN model's explicit mapping of tasks, responsibilities, and decision points seemed to enable stakeholders to follow the process sequence more unambiguously. The use of swimlanes and message flows helped clarify interdependencies, which may have reduced the likelihood of missed or delayed actions.

In addition, real-time data exchange between the BPMN environment and the BIM model was associated with shorter delays between on-site events and their reflection in project records, as inspection results, delivery statuses, and preparation approvals were immediately visible to authorised participants. Direct synchronisation between lab results, inspection notes, and BIM element properties appeared to reduce the need for manual transcription, potentially decreasing mismatches between field data and design records and thereby improving the reliability of project documentation.

By linking process and product data, the integrated model may have supported a more proactive approach to quality management. Stakeholders could anticipate potential downstream impacts of delivery issues and adjust schedules, resource allocation, or preparation activities accordingly.

Overall, the findings suggest that BIM–BPMN integration in a live construction process can help transform sequential, document-based workflows into more connected, responsive systems. While the approach appears to support technical interoperability and enhance collaborative decision-making, its effectiveness would benefit from further testing across a broader range of real-life projects to confirm the generalisability of these results and better understand its implications for broader process automation.

6. Conclusion and Future Work

This paper has demonstrated how integrating Building Information Modelling (BIM) and Business Process Model and Notation (BPMN) can address key process interoperability challenges in the AECO sector. Using the concrete delivery workflow as a case study, the framework linked process tasks directly to BIM elements, enabling real-time data synchronisation, improving coordination, and ensuring compliance with quality and regulatory requirements.

The implementation showed tangible benefits:

- Increased workflow transparency and shared understanding across disciplines.
- Faster decision-making through immediate process–product feedback loops.
- Reduced manual data handling errors by automating information transfer between environments.

- Strengthened compliance through embedded checks and secure, auditable documentation.

While the case study confirms the value of BIM–BPMN integration, it also revealed the importance of careful role-based access design, clear data mapping strategies, and stakeholder training to fully realise the benefits.

This study focused on a manually developed BIM–BPMN integration; earlier experiments with AI-assisted BPMN generation highlighted both opportunities and current limitations. Using large language models to convert textual descriptions into BPMN code proved promising for reducing manual modelling time, but also revealed challenges, including inconsistent diagram layouts, occasional misinterpretation of AECO-specific terminology, and limited graphical fidelity. These findings, discussed in detail in prior work, indicate that further domain-specific training and hybrid human–AI modelling approaches will be required before such automation can be reliably deployed.

Future work will focus on:

- Extending the integrated framework to additional workflows, such as equipment installation and safety inspections.
- Enhancing visualisation tools to support real-time monitoring of process status in the BIM environment.
- Investigating scalable approaches to linking BIM–BPMN models with broader project management platforms.
- Exploring selective automation, where appropriate, to further reduce repetitive manual tasks without compromising control.

By reinforcing the connection between design data and execution processes, the proposed approach offers a practical pathway toward more integrated, responsive, and collaborative construction project delivery.

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Appendix

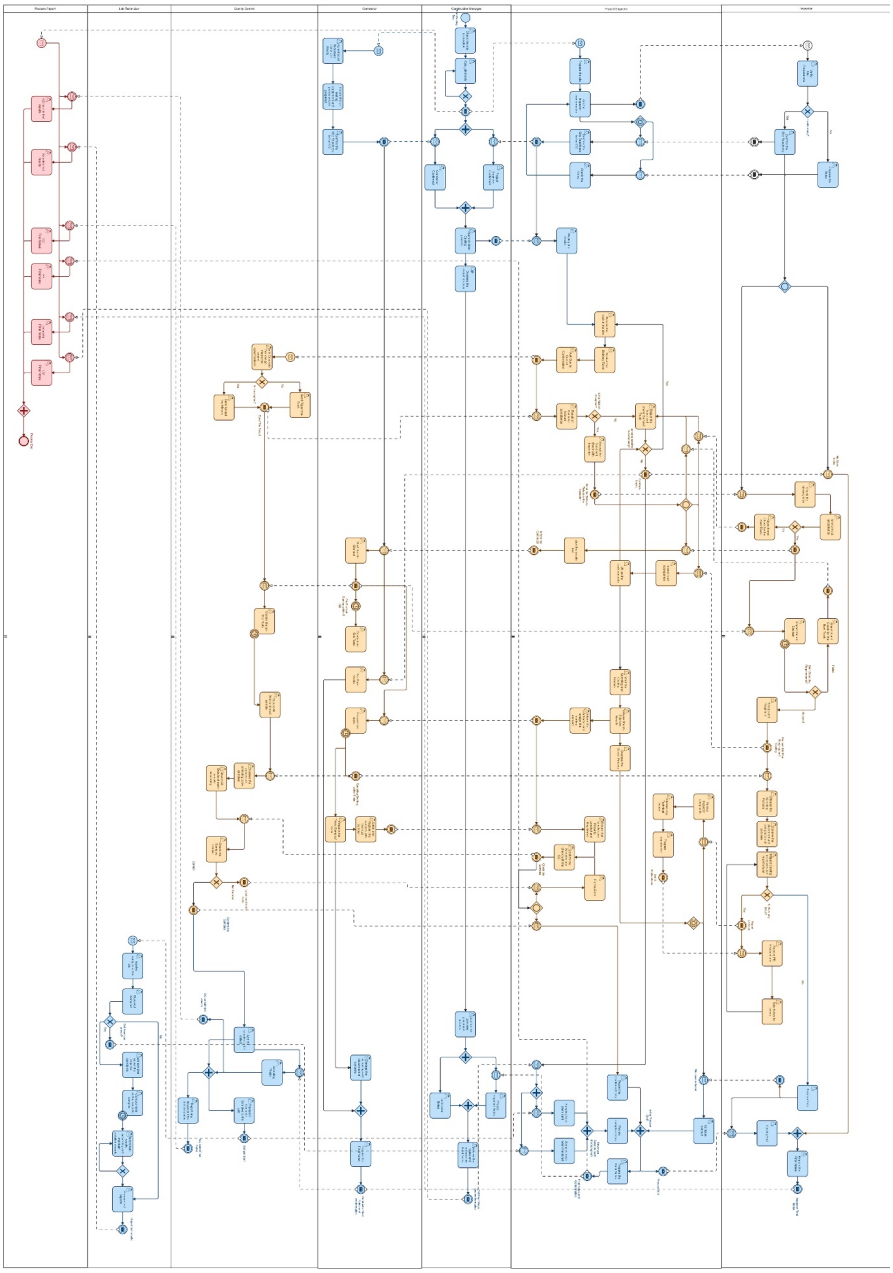


Figure 5: Full BPMN model

AI-ENHANCED DECISION-MAKING IN CONSTRUCTION MANAGEMENT

Opportunities, Challenges, and Future Directions.

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Abstract. Construction management faces persistent challenges involving complexity, uncertainty, and the marginalization of local building traditions due to globalized, standardized practices. Recent advancements in artificial intelligence (AI) offer transformative potential in this domain by providing predictive insights, optimizing resource allocation, and improving risk assessment. This paper investigates how AI-enhanced decision-making can improve operational efficiency in construction management while simultaneously promoting cultural inclusivity and resisting the unintended reinforcement of western-centric norms. The study employs a critical literature review and analytical synthesis approach, examining a range of AI tools including machine learning (ML), deep learning (DL), and natural language processing (NLP), with a focus on their potential to support ethical, inclusive, and context-aware practices. special attention is given to real-world case studies such as the Saudi architecture map, AI-assisted structural design tools (e.g., Skyciv), and multi-agent collaboration platforms (e.g., Quible.ai), which illustrate both culturally grounded and practice-oriented applications of AI in construction planning. Findings highlight both the benefits and risks associated with AI implementation. On one hand, AI improves decision-making by enabling predictive scheduling, real-time monitoring, and enhanced communication among stakeholders. On the other hand, reliance on western-trained datasets risks embedding algorithmic bias and digital colonialism leading to the erosion of local architectural identities and vernacular design practices. This paper proposes a conceptual framework for integrating indigenous knowledge, vernacular construction techniques, and culturally specific planning norms into AI decision models. Key components of this framework include: the use of locally curated datasets, integration with building information modeling (BIM) and internet of things (IoT) tools, participatory AI development involving local stakeholders, and

ethical governance structures. Furthermore, the study emphasizes the importance of explainable and human-centric AI to maintain transparency and accountability in construction decisions. By aligning technological advancement with cultural preservation, this research contributes to the emerging field of decolonized ai in construction. It encourages a shift away from one-size-fits-all construction models toward adaptive, sustainable, and culturally grounded practices that reflect regional identities. the study offers valuable insights for policymakers, architects, engineers, and AI developers who seek to balance innovation with cultural responsibility.

Keywords: *Artificial Intelligence (AI), Construction Management, Decolonizing Design, Sustainable Construction, Saudi Architecture Map.*

1. Introduction

The construction industry is undergoing a profound transformation driven by globalization, urbanization, climate change, and increasing resource scarcity factors that collectively demand more efficient, resilient, and sustainable management practices (Lu et al., 2020). Traditionally, decision-making in construction has been dominated by standardized, globalized methodologies that frequently marginalize local construction practices, indigenous knowledge systems, and culturally embedded sustainability strategies (Ozkan et al., 2022). This disconnect underscores the urgent need for a more inclusive and context-aware approach to construction management, especially in regions seeking to reclaim and evolve their architectural and cultural identities (Dabaieh et al., 2021).

Artificial Intelligence (AI) has emerged as a transformative force in construction, offering advanced tools to enhance decision-making across project lifecycles. These include predictive analytics (Salman, 2025), automated scheduling, and real-time risk assessment (Pan & Zhang, 2021). Machine Learning (ML) and Deep Learning (DL) algorithms contribute to the optimization of resource allocation, while Natural Language Processing (NLP) enhances stakeholder communication and project documentation (Zhang et al., 2023). However, the implementation of AI is not without challenges. Many systems are trained on Western-centric datasets, embedding cultural and structural biases that risk reinforcing industrialized construction norms while sidelining vernacular and indigenous practices (Boukabous & Azizi, 2022).

While AI offers immense potential for efficiency and innovation, its uncritical deployment may inadvertently contribute to digital colonialism favoring Eurocentric efficiency metrics and architectural values over culturally responsive design paradigms (Couldry & Mejias, 2019; Ahmed &

Tsouros, 2023). This tension has led to a growing call for the development of explainable and ethical AI systems that integrate local knowledge, reflect cultural priorities, and support sustainable and equitable construction outcomes (Sanchez, 2024).

This paper explores the role of AI in reimagining construction management through a decolonial lens. It examines how AI can be harnessed not only to optimize operational performance but also to empower inclusive, culturally grounded decision-making processes. The study critically reviews existing AI applications, identifies associated challenges such as data bias and technological homogenization and proposes future strategies for aligning AI with context-sensitive, ethical, and sustainable construction practices.

2. Background and Literature Review

2.1. EVOLUTION OF DECISION-MAKING IN CONSTRUCTION MANAGEMENT

Over the last decade, construction management has been increasingly influenced by globalization, environmental regulations, and digitalization, pushing the industry to adopt smarter and more sustainable decision-making models (Lu et al., 2020). While conventional methods emphasized cost, time, and quality control through deterministic planning, these models often neglect the complex socio-cultural dimensions of construction, especially in non-Western contexts (Samarasinghe et al., 2022). In regions with strong indigenous architectural traditions, standard global practices may override local wisdom and sustainable vernacular approaches, creating tension between modernity and cultural continuity (Dabaieh et al., 2021).

2.2 AI APPLICATIONS IN CONSTRUCTION: CURRENT STATE OF THE ART

Artificial Intelligence (AI) rapidly transforming construction management by enabling predictive analytics, intelligent scheduling, and automated risk assessment (Pan & Zhang, 2021). Machine learning algorithms have demonstrated high accuracy in forecasting project delays and budget overruns, especially when trained on large datasets from prior projects (Rasheed et al., 2023). Deep learning models are now used to automate visual site inspections and detect safety hazards in real-time (Zhang et al., 2023). In parallel, natural language processing (NLP) tools are being developed to improve stakeholder coordination, extract insights from project documents, and even assist in regulatory compliance (Wang & He, 2022). These applications mark a significant shift toward data-driven, AI-assisted construction environments.

2.3 ETHICAL AND CULTURAL CRITICISMS AI IN CONSTRUCTION

Despite its technical promise, AI's adoption in construction has raised ethical concerns. A growing body of literature highlights that AI models often reflect biases embedded in the data they are trained on frequently originating from industrialized, Western contexts (Boukabous & Azizi, 2022). These models risk reinforcing global hierarchies by promoting standardized construction models and sidelining traditional, indigenous, or climate-appropriate practices (Ahmed & Tsouros, 2023). The lack of transparency in many AI systems further compounds the issue, limiting stakeholders' ability to question or modify AI-generated recommendations a phenomenon that has been criticized as a form of "digital opacity" (Sanchez, 2024). As such, AI may unintentionally contribute to a form of digital colonialism, where local identities and sustainable methods are marginalized in favor of dominant narratives of efficiency and progress (Couldry & Mejias, 2021).

2.4 GAPS IN LITERATURE: TOWARD CONTEXT-AWARE AND DECOLONIZED AI SYSTEMS

While current research highlights AI's potential to improve construction outcomes, less attention has been given to how these technologies can be adapted to diverse cultural, environmental, and social contexts. Few AI systems explicitly incorporate vernacular building knowledge, traditional materials, or indigenous planning systems (Dabaieh et al., 2021). Moreover, most AI research in construction has focused on technical performance rather than ethical integration, cultural sensitivity, or local empowerment. Sanchez (2024) argues for the development of explainable and participatory AI frameworks that reflect community values and support inclusive, bottom-up decision-making. This highlights the urgent need for research that bridges technical innovation with culturally grounded, decolonized construction practices.

3. AI's Opportunities in Construction Management

The integration of artificial intelligence (AI) into construction management offers transformative opportunities that span technical, economic, environmental, and cultural domains. When thoughtfully implemented, AI can significantly enhance efficiency, promote sustainability, and open pathways for more inclusive and responsive decision-making processes.

3.1 PREDICTIVE ANALYTICS AND PROACTIVE PLANNING

AI-driven predictive analytics enables early identification of potential risks, project delays, and cost overruns through real-time analysis of historical and ongoing data (Rasheed et al., 2023). These capabilities allow project managers to make proactive decisions, reducing downtime and minimizing unforeseen disruptions. In complex projects with multiple stakeholders and dynamic timelines, AI models trained on past project data can generate adaptive schedules and provide accurate forecasts, improving both time management and budget control (Pan & Zhang, 2021).

3.2 INTELLIGENT RESOURCE ALLOCATION AND SUSTAINABILITY

Machine learning algorithms offer optimization models for resource allocation ensuring labor, equipment, and materials are used efficiently (Lu et al., 2020). AI can help reduce material waste by forecasting demand more precisely, suggesting alternative local materials, or recommending lean construction practices. Furthermore, AI-powered simulations can evaluate energy consumption, emissions, and life cycle impacts of construction decisions, aiding in the design of greener, more sustainable structures (Zhang et al., 2023).

3.3 REAL-TIME MONITORING AND QUALITY ASSURANCE

Computer vision systems combined with deep learning allow for real-time site monitoring, quality checks, and safety assessments (Zhang et al., 2023). These tools can detect non-compliance in workmanship, track worker movement to ensure safety protocols, and provide visual progress updates. Such automation not only enhances quality assurance but also reduces dependency on manual inspections, increasing operational efficiency while ensuring regulatory compliance.

3.4 ENHANCING COMMUNICATION THROUGH NATURAL LANGUAGE PROCESSING

Natural language processing (NLP) tools are increasingly used to extract insights from construction documents, contracts, and communications, reducing errors and misunderstandings (Wang & He, 2022). NLP-powered chatbots and digital assistants can also provide real-time support for field workers and managers, translating technical language or responding to queries based on project data. This improves collaboration across multicultural and multilingual teams and supports faster decision-making.

3.5 EMPOWERING CULTURALLY RESPONSIVE AND LOCALIZED DESIGN

Beyond operational efficiency, AI presents an opportunity to support the decolonization of construction by integrating local knowledge systems and cultural priorities into the design process. When trained on diverse and representative datasets, AI models can assist in recommending vernacular design strategies, traditional materials, or passive cooling techniques suited to specific climatic and cultural contexts (Dabaieh et al., 2021). This contextual intelligence allows AI to serve not only as a tool for productivity but also as a medium for cultural continuity and place-based innovation (Sanchez, 2024).

Characteristic	Predictive Analytics	Resource Allocation	Real-Time Monitoring	Communication Enhancement	Culturally Responsive Design
Planning	Proactive decisions	Efficient labor, equipment use	Visual progress updates	Reduces errors, misunderstandings	Vernacular design strategies
Sustainability	Downtime reduction	Reduce material waste	Safety protocol tracking	Faster decision-making	Place-based innovation
Economic	Budget control	Alternative local materials	Operational efficiency increase	Real-time support for workers	Traditional materials recommendation

Figure 1. AI Opportunities in Construction Management

Figure 1 illustrates the multifaceted opportunities that AI offers across key areas of construction management planning, sustainability, and economics through applications such as predictive analytics, resource allocation, real-time monitoring, communication enhancement, and culturally responsive design. Each intersection highlights how AI can contribute to more efficient workflows, reduce waste, enhance decision-making, and support the integration of local materials and vernacular design strategies for context-aware, sustainable development.

An emerging example of this trend is Quible.ai, a multi-agent AI platform designed specifically for architecture, engineering, and construction (AEC). It enables teams to query data conversationally, collaborate directly within 3D models, and rapidly locate specifications across complex designs. By reducing reliance on fragmented tools, Quible.ai removes software friction and strengthens coordination between architects, project managers, and engineers. Its ability to ‘talk to your building model’ demonstrates how

practical AI applications can accelerate decision-making while ensuring clarity across stakeholders (Quible.ai).

4. Challenges and Ethical Concerns

While AI offers substantial promise in construction management, its adoption is not without risks. These challenges span ethical, technical, social, and epistemological dimensions. A critical understanding of these concerns is necessary to ensure that AI is applied responsibly and inclusively in the built environment.

4.1 ALGORITHMIC BIAS AND CULTURAL EXCLUSION

A primary concern in AI systems is the risk of algorithmic bias, particularly when models are trained on datasets predominantly derived from Western or industrialized contexts (Boukabous & Azizi, 2022). These biases can manifest in the prioritization of Eurocentric design values standardization, speed, and cost-efficiency over locally relevant metrics such as thermal comfort, social cohesion, or spiritual significance in design (Ahmed & Tsouros, 2023). Consequently, AI tools may unintentionally marginalize indigenous knowledge systems, reinforcing global hierarchies in construction practices.

4.2 DATA SOVEREIGNTY AND DIGITAL COLONIALISM

Many regions in the Global South lack control over their own construction data, with cloud-based platforms and AI vendors often headquartered in the Global North (Couldry & Mejias, 2021). This raises concerns about data sovereignty and the extraction of local knowledge for global commercial benefit. The unchecked deployment of AI technologies can result in what scholars describe as "digital colonialism," wherein decision-making tools developed externally displace local agency and override contextual knowledge (Sanchez, 2024).

4.3 LACK OF TRANSPARENCY AND EXPLAINABILITY

Most AI models used in construction are based on complex algorithms that offer limited interpretability, especially for non-expert users (Rasheed et al., 2023). This opacity poses risks in high-stakes construction decisions, where explainability and accountability are essential. Stakeholders may find it difficult to contest or understand AI-generated recommendations, potentially leading to overreliance on opaque systems and a reduction in human oversight.

4.4 TECHNICAL AND INSTITUTIONAL BARRIERS

Deploying AI requires technical infrastructure, skilled labor, and data integration, all of which are often lacking in small to medium-sized construction firms, especially in developing regions (Pan & Zhang, 2021). Furthermore, institutional resistance to technological change and fears of job displacement may hinder adoption. Without appropriate training and change management strategies, AI may exacerbate existing inequalities rather than bridge them.

4.5 ENVIRONMENTAL AND RESOURCE TRADE-OFFS

While AI can support sustainable construction practices, its own environmental footprint should not be ignored. Training large-scale AI models consumes significant computational power and energy, contributing to carbon emissions (Lu et al., 2020). Additionally, the deployment of AI-powered devices (e.g., sensors, drones, and computing systems) raises concerns about e-waste and resource depletion, especially if life-cycle impacts are not properly managed. Figure 2 highlights key issues associated with implementing artificial intelligence (AI) in the construction industry reflecting broader societal and ecological impacts.

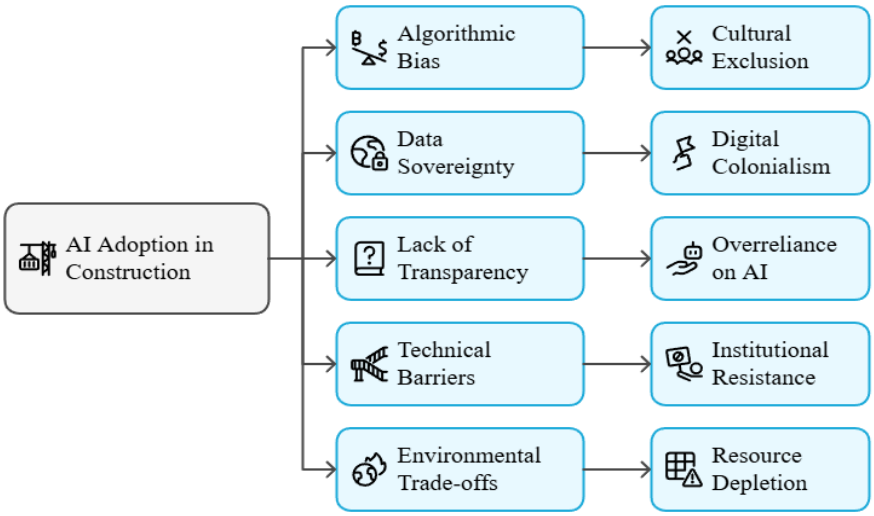


Figure 2. Challenges and Ethical Concerns in AI Adoption.

5. Toward Decolonized and Inclusive AI in Construction Management

As AI becomes integral to construction management, it is essential that its adoption supports not only efficiency but also cultural relevance and ethical practices. Decolonizing AI means aligning technology with diverse knowledge systems, empowering local communities, and avoiding one-size-fits-all solutions rooted in Western norms. This paper introduces a dual-impact framework (Figure 3) to highlight the balance needed between operational efficiency and cultural integrity in AI deployment. While AI offers clear benefits such as predictive analytics, smart resource allocation, and real-time monitoring, it also poses risks if built on biased or non-representative data. These include reinforcing algorithmic bias, undermining local design traditions, and contributing to digital colonialism. Integrating AI into construction is therefore not only a technical process but also a cultural and ethical one. To succeed, AI must enhance performance while respecting and preserving regional architectural identities. This framework supports a more inclusive vision for the future of smart construction.

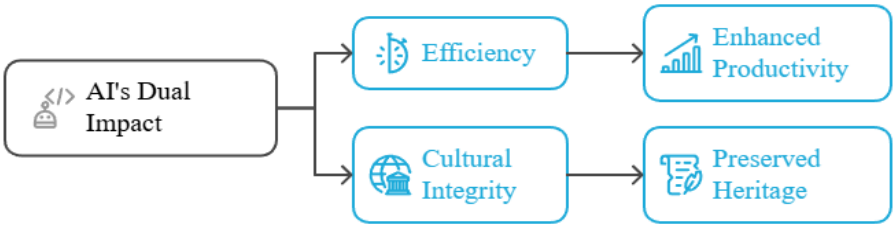


Figure 3. AI's Dual Impact on Construction Management.

To demonstrate how the proposed framework could be operationalized, consider a pilot scenario in a mid-scale housing project in Riyadh. In this case, a Building Information Modeling (BIM) platform is enriched with the Saudi Architecture Map dataset and connected to an AI collaboration tool such as Quible.ai. Stakeholders can query vernacular design elements conversationally, test sustainable material options, and visualize design trade-offs in real time. The AI system integrates IoT-based environmental data (e.g., thermal comfort, energy demand) with culturally curated architectural norms to generate recommendations that balance efficiency, sustainability, and local identity. Figure 4 illustrates the conceptual workflow, showing how localized datasets, BIM, IoT, and AI platforms can be combined into an inclusive decision-support cycle.

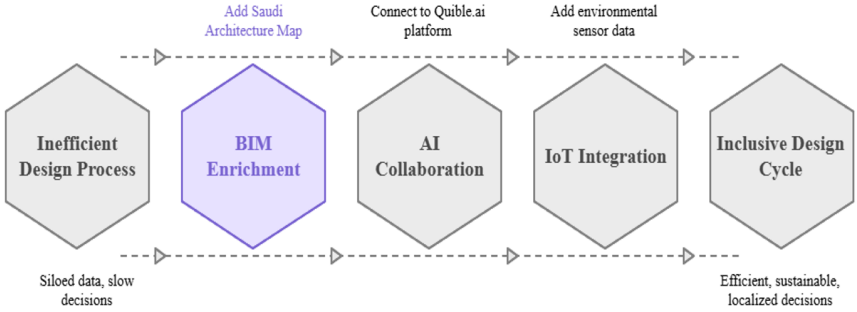


Figure 4. AI-Driven Decision-Making Framework Diagram

5.1 INTEGRATING INDIGENOUS KNOWLEDGE AND VERNACULAR PRACTICES

One of the central goals of decolonized AI is the recognition and incorporation of indigenous and vernacular knowledge into computational models. Traditional construction methods often rooted in centuries of environmental adaptation, social cohesion, and sustainable practices contain valuable insights for modern construction (Dabaieh et al., 2021). AI systems trained on regionally curated datasets can help identify, preserve, and adapt these practices for contemporary use, enabling more resilient and locally appropriate construction solutions (Sanchez, 2024).

5.2 CULTURALLY RESPONSIVE DESIGN RECOMMENDATIONS

AI systems can be configured to go beyond functional performance by incorporating cultural, spiritual, and aesthetic values into design recommendations. For example, algorithms can be trained to respect local spatial norms, religious orientations, or community-based planning structures (Ahmed & Tsouros, 2023). In this way, AI becomes a partner in culturally responsive architecture enhancing, rather than replacing human-centered design processes.

5.3 PARTICIPATORY AI DEVELOPMENT AND GOVERNANCE

Decolonized AI systems require inclusive design processes in which communities, not just developers or external experts, are actively involved in shaping how technology is used. This includes participatory data collection, co-design of decision-support tools, and governance frameworks that ensure transparency, accountability, and equity (Sanchez, 2024). Empowering local stakeholders with digital literacy and access to decision-making tools can

democratize the construction process and counterbalance centralized technological control.

5.4 ETHICAL DATA PRACTICES AND LOCALIZED DATASETS

Creating representative and ethical AI begins with responsible data practices. This involves curating diverse, localized datasets that capture the unique architectural, climatic, and social realities of different regions (Boukabous & Azizi, 2022). These datasets must be owned and governed by local institutions to ensure sovereignty over how knowledge is extracted and applied. Privacy protections, informed consent, and open data access should also be embedded into AI infrastructure.

In practice, curating localized datasets requires robust governance and clear ownership structures. National ministries of culture and housing, in partnership with universities and professional bodies, can act as custodians of architectural datasets, ensuring that the data reflects regional traditions while meeting technical standards. Funding mechanisms may include government-backed research programs, private-sector sponsorships, and international cultural heritage grants. Importantly, data ownership should remain with local institutions to prevent external monopolization and ensure sovereignty. Establishing regional data hubs with open-access policies, community-driven contributions, and transparent auditing processes will provide a foundation for ethical, culturally aligned AI adoption.

5.5 SYNERGIZING AI WITH BIM AND IOT FOR LOCAL IMPACT

The integration of AI with Building Information Modeling (BIM) and Internet of Things (IoT) technologies presents an opportunity to contextualize smart construction in local realities. BIM can be enriched with localized material libraries and traditional construction modules, while IoT sensors can provide real-time environmental feedback that supports adaptive and climate-resilient building strategies (Pan & Zhang, 2021; Zhang et al., 2023). AI acts as the connective intelligence, guiding decision-making in ways that align with both global sustainability goals and local cultural values.

5.6 STAKEHOLDER TRAINING AND CHANGE MANAGEMENT

Beyond technical infrastructure, the success of AI integration in construction depends heavily on stakeholder readiness. Training programs are essential to equip architects, engineers, contractors, and policymakers with digital literacy skills tailored to AI-enabled platforms. Such programs should emphasize not only technical operation but also the cultural and ethical implications of AI decision-making. Change management strategies are

equally crucial: phased implementation, transparent communication of benefits, and active engagement with professional associations can reduce resistance to adoption. Universities, vocational training centres, and industry associations have a key role in creating continuous professional development pathways. By embedding AI literacy within education and practice, the industry can ensure that technology adoption enhances not disrupts existing knowledge ecosystems.

6. Future Directions:

As illustrated in Table 1, ensuring that AI in construction management supports inclusive and sustainable futures requires a multifaceted approach focused on the following strategies:

- **Explainable and Human-Centric AI:** AI systems must be transparent and interpretable, allowing engineers and decision-makers to understand and guide automated outputs.
- **Ethical Governance:** National frameworks should regulate AI usage, enforce data ethics, and engage local stakeholders to ensure equitable deployment.
- **Cross-Regional Collaboration:** Global cooperation can help build inclusive datasets that reflect underrepresented architectural traditions and reduce cultural bias.
- **The Saudi Architecture Map: A Scalable Model for AI Alignment:** A pioneering example of culturally aligned planning is the Saudi Architecture Map initiative (Figure 5), launched by His Royal Highness the Crown Prince. This national strategy classifies 19 architectural styles based on regional identity and includes three integrated design approaches: traditional, transitional, and contemporary. It reflects a formal commitment to preserving cultural heritage while embracing innovation. This initiative presents a **scalable model** for other countries seeking to integrate AI while honoring cultural and environmental specificity.
- **Inclusive Data Ecosystems:** Regionally curated datasets are key to training context-aware AI. Collaboration between academia, industry, and government can ensure data sovereignty and cultural relevance.

Beyond these strategies, empirical validation is essential. Future work should focus on launching pilot studies in diverse regional contexts to test AI systems with real-world data, materials, and practices. Additionally, establishing regionally governed data hubs can support the continuous development of inclusive datasets and ethical AI adoption. These steps will help bridge the gap between conceptual models and practical

implementation, advancing culturally grounded and technically effective AI in construction.

TABLE 1. Future Directions for Sustainable AI in Construction Management

Future Direction	Focus Area	Example
Explainable AI	Transparency and usability	SkyCiv's structural design interface,
Ethical Governance	Regulation and equity	The European Union's (EU) Artificial Intelligence Act.
Cross-Regional Collaboration	Inclusive datasets	UNESCO - Global Architecture Data Project
The Saudi Architecture Map	Cultural alignment	National strategy for regional styles (Crown Prince Initiative)
Empirical Validation & Data Hubs	Real-world testing & dataset curation	Regional AI pilot studies and open-access hubs.

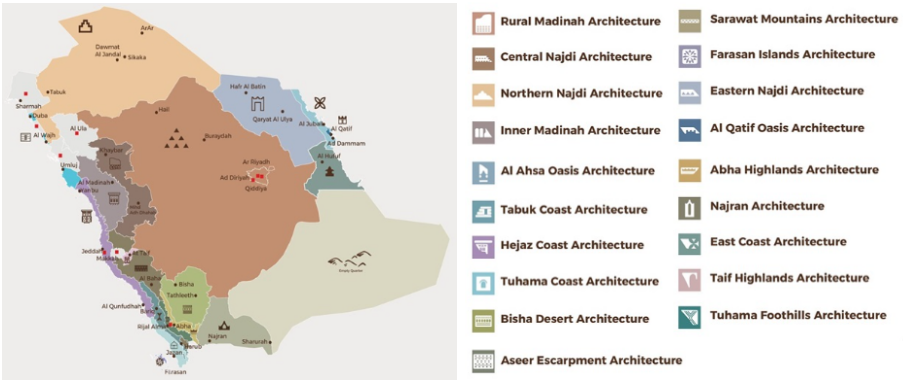


Figure 5. Saudi Architecture Characters Map.

7. Conclusions

This study critically examined the evolving role of artificial intelligence in construction management, emphasizing its dual capacity to enhance operational efficiency and promote culturally inclusive, context-aware decision-making. Through a comprehensive review of AI tools including machine learning, deep learning, and natural language processing, the paper identified both significant opportunities and complex challenges associated with the deployment of AI in diverse built environments. Key findings include:

1. AI offers measurable operational benefits, including predictive analytics, intelligent resource management, real-time site monitoring, and improved stakeholder communication.

2. However, without cultural calibration, AI risks perpetuating digital colonialism, especially when trained on Western-centric datasets that overlook local construction practices and architectural values.
3. Explainable and human-centric AI systems are essential to ensure transparency, accountability, and trust across stakeholders in the construction ecosystem.
4. Initiatives such as the Saudi Architecture Map provide scalable models for aligning AI systems with national identity, regional architectural heritage, and sustainable development goals.
5. Ethical data governance and the development of inclusive data ecosystems are critical for mitigating algorithmic bias and ensuring that AI reflects the social, cultural, and environmental specificities of diverse regions.
6. Conceptual application diagrams and platforms such as Quible.ai illustrate how AI can support real-time, context-aware decision-making, reduce software friction, and operationalize research frameworks in practice.
7. Future Research Directions: Integrative frameworks combining AI with BIM, IoT, and vernacular design principles should actively involve local stakeholders in co-creating decision-support tools, reinforcing participatory and culturally grounded approaches.

Overall, this paper contributes to the discourse on decolonizing AI in construction, advocating for adaptive, participatory, and culturally sensitive technologies. By embedding local knowledge, ethical values, and stakeholder-centered strategies into AI frameworks, the construction industry can advance more inclusive, sustainable, and contextually appropriate practices for the future.

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V. URBANISM AND SMART CITIES

OPTIMIZING URBAN BLOCK TYPOLOGIES FOR SOLAR RADIATION REDUCTION AND ENHANCED VIEWS

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Abstract. This study presents a performance-driven approach to urban block typology design within a proposed context inspired by the climatic conditions of Cairo, Egypt. The objective is to minimize solar radiation exposure while maximizing visual connectivity toward open green spaces. The methodology integrates parametric modeling and multi-objective optimization to explore a design space defined by three parameters: height variation, block orientation, and spatial arrangement within a site. The analysis is carried out in two phases. First, single U-shaped block configurations are assessed to determine the optimal height distribution and orientation angle (ranging from −40° to +40°) that achieve the lowest solar exposure while enhancing view potential toward a designated park area located to the northeast. Second, three of the best-performing single-block configurations are arranged within a representative urban plot (90 × 160 meters) to explore how different spatial placements influence the environmental performance of the shared outdoor space. Results indicate that specific arrangements and orientation strategies can significantly reduce solar radiation within the urban domain while improving view access from residential units toward the park. The study proposes a replicable design workflow for optimizing form-based parameters and contributes to the development of climate-responsive urban blocks that balance environmental efficiency with spatial quality in hot-arid conditions.

Keywords: *Parametric design, Environmental performance, Performance-based design*

1. The Urban Block as a Unit of Urban Form

The urban block is a fundamental element of urban form that defines the configuration of streets, plots, and buildings, influencing circulation, density, and land use patterns (Marshall, 2005). It not only shapes the functional layout of cities but also plays a critical role in shaping the microclimate, daylight access, and thermal comfort (Ratti, Baker, & Steemers, 2005). The design and arrangement of blocks directly affect how urban spaces perform socially and environmentally.

1.1. ENVIRONMENTAL PERFORMANCE AND URBAN MORPHOLOGY

Recent studies have emphasized the importance of urban morphology in determining environmental performance. Key parameters such as building height, orientation, and spatial arrangement can significantly reduce solar heat gain and improve thermal comfort, especially in hot-arid climates like that of Cairo (Emmanuel, 2005; Shashua-Bar, Pearlmutter, & Erell, 2011). Vernacular urban forms in arid regions often employ compact massing and narrow streets to create shaded, cooler environments (Fathy, 1986), principles which contemporary design tools can now re-evaluate using simulation-based methods.

1.2. VISUAL ACCESS AS A SPATIAL QUALITY INDICATOR

In addition to thermal concerns, visual connectivity and access to open or green spaces significantly influence user experience. Views toward natural or significant urban features are associated with greater mental well-being, perceived safety, and spatial orientation (Kaplan, 1992; Nasar, 1994). The design of urban blocks affects both the quality and extent of views, which are often overlooked in performance-based design methods that prioritize energy or microclimate metrics alone.

2. The Role of Parametric and Performance-Driven Design

The advancement of parametric tools and multi-objective optimization techniques enables designers to evaluate a wide array of block configurations against multiple performance metrics simultaneously (Turrin, von Buelow, & Stouffs, 2011). These tools allow for systematic exploration of design parameters such as height variation, orientation, and form composition—facilitating data-driven decision-making rather than relying solely on formal or stylistic preferences (Del Ferraro, Stouffs, & Hee, 2018).

The pressures of rapid urbanization and intensifying climate-related challenges have driven a paradigm shift in architectural and urban design toward performance-based strategies. Integrating quantitative performance metrics—such as energy efficiency, solar access, thermal comfort, and microclimate responsiveness—into the early stages of the design process enables the development of urban environments that are both resilient and environmentally responsive (Wienold & Christoffersen, 2006; Kaftan & Zukowska, 2021). Performance-driven design emphasizes the optimization of building form, orientation, and materiality to enhance environmental outcomes and user well-being (Reinhart & Davila, 2016).

Parametric modeling platforms like Rhinoceros combined with Grasshopper (Rhino-GH) support this approach by enabling iterative simulations across a broad design space. These tools allow designers to evaluate design variations using environmental indicators, including solar radiation and daylight availability, early in the design process (Jabi, 2013). Within this workflow, plugins such as Colibri allow for systematic design space exploration by automating the generation and documentation of simulation runs. Input variables and results are recorded in CSV format, along with snapshots of each iteration, facilitating traceability and comparison (Colibri, TT Core Studio, 2016).

Design Explorer, a visualization platform developed in tandem with Colibri, provides an intuitive interface for navigating and analyzing this high-dimensional data. The platform generates interactive parallel coordinate plots and scatterplot matrices to explore relationships between design parameters and performance outputs. It also supports the visualization of model images and, when available, 3D previews through JSON exports (Leach, 2017). Together, Colibri and Design Explorer empower architects and urban designers to identify optimal solutions across multiple performance criteria, making performance-driven design more accessible and actionable during early conceptual phases (Salama & Wiedmann, 2013; Oxman, 2008).

3. Climatic Context and Motivation

This study explores a hypothetical urban context inspired by the climatic conditions of Cairo, Egypt, where solar exposure is intense, and shade provision is essential for urban comfort (Shady, 2012). Designing with environmental responsiveness in such settings involves balancing massing and orientation to optimize both solar protection and visual permeability.

With rising temperatures and increasing demand for sustainable design, new models for climate-adaptive urban form are essential (Salat, 2009).

Despite the growing body of work on sustainable urban design, few studies combine solar radiation mitigation and view optimization at the block scale. This research addresses that gap by developing a simulation-based methodology for generating and evaluating urban block typologies using both criteria. It aims to demonstrate how performance-based urban form generation can support the creation of liveable, climate-sensitive environments through adaptive form strategies.

4. Methodology

This study adopts a simulation-based parametric methodology integrating environmental analysis and multi-objective optimization to explore performance-driven design strategies for urban blocks. The objective is to minimize solar radiation exposure while maximizing visual access toward a park located at the northeast edge of a hypothetical urban plot measuring 90 × 160 meters.

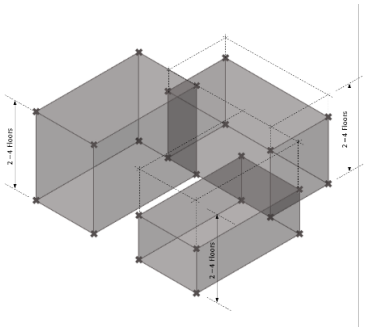


Figure 1. Diagram showing the geometric variations of a single U-shaped block

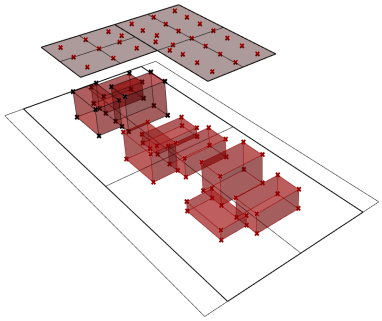


Figure 2. Perspective shot illustrating the spatial relationship between the urban block and the adjacent park to the northeast.

The workflow is implemented using Rhinoceros + Grasshopper, supported by environmental simulation tools from Ladybug Tools and Colibri. The method unfolds across two main design phases: the first focusing on optimizing individual block orientation and volume, and the second exploring spatial arrangements of multiple blocks.

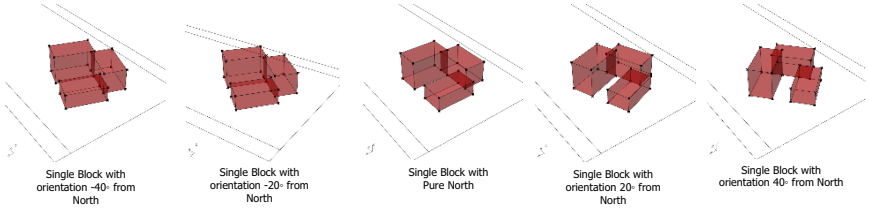


Figure 3. Illustration of the U-block rotated at three distinct angles (−40°, 0°, and +40°)

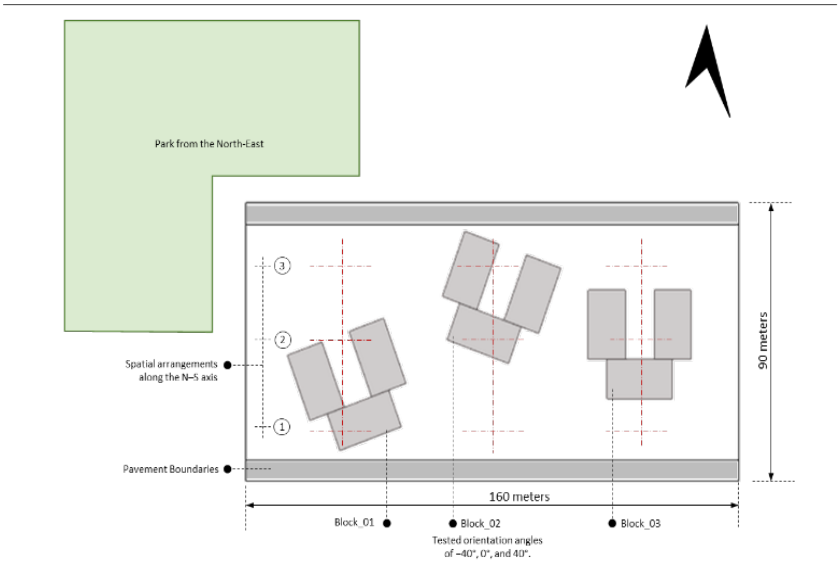


Figure 4. Plan view showing different spatial arrangements of the three optimized U-blocks within a 90 × 160-meter plot.

4.1. E

To assess each design alternative, the following environmental indicators were evaluated using Ladybug Tools:

4.1.1. Solar Radiation Analysis

The Ladybug Radiation Analysis component calculates the total incident solar radiation (kWh/m²) on surfaces over a given period, using climate data from a Cairo EPW file. The environmental analysis in this study was conducted for a typical summer day in July, focusing on the critical hours between 9:00 AM and 3:00 PM—when solar radiation is at its peak and outdoor thermal discomfort is most pronounced. This includes direct, diffuse, and reflected radiation. Radiation was analyzed on:

- Building façades: to assess solar gain exposure and inform façade orientation and shading.
- Ground/urban block scale: to understand how different block configurations influence solar exposure across the site.

This helped identify block forms and orientations that reduce heat gain while maintaining passive daylighting.

4.1.2. View Percent Analysis

The Ladybug View Analysis component quantifies how much of a predefined target area (e.g., a public park) is visible from building façades. A percentage score is generated based on the visible surface area, offering insight into the quality of views from each unit.View analysis helped evaluate the spatial relationship between buildings and open space, favoring configurations that enhance visual connection to the park.

4.1.3. Visibility Percent Analysis

Visibility, in this context, assesses whether there is a clear line of sight from a given point on the façades (north and east) to the park or other target areas, factoring in obstructions from adjacent buildings or block configurations. This metric is computed either using Ladybug's isViewPossible component or via custom ray-tracing methods. Unlike the overall view percentage (which measures how much of the park is visible), visibility focuses on whether the view is possible at all from specific critical points, contributing to legibility, psychological comfort, and urban liveliness.

By combining these three analyses, the methodology enables a multi-objective evaluation of each design proposal. This comprehensive approach informs design decisions that balance thermal performance with visual comfort and spatial quality—key parameters in sustainable urban design.

4.2. TWO-PHASE SIMULATION-BASED

This two-phase simulation-based method allows design decisions to be evaluated across multiple scales:

- From individual building performance (form tuning),
- To urban block strategies (layout optimization).

4.2.1. Phase 1: Optimization of a Single U-Shaped Block

To identify the optimal height variation and orientation for a U-shaped block with an open side facing generally north, targeting minimal solar exposure and maximum view toward a predefined park zone

Design Variables:

- Height variation: each leg of the U-block varies from 2 to 4 floors.

- Orientation: opening angle shifted in 20 increments from -40° to +40° from true north.

Simulation Tools:

- Ladybug Radiation Analysis for solar exposure on surfaces.
- Ladybug View Analysis to assess visibility from test points toward a target (simulated park).
- Grasshopper + Colibri to enable design space exploration by systematically combining multiple input and generating all possible permutations of design scenarios parameters.

The evaluation criteria for the simulation phases are based on two key performance indicators: total solar radiation and visibility score. The solar radiation is measured in kilowatt-hours per square meter (kWh/m^2) and calculated for both vertical and horizontal surfaces of the building envelope. This metric helps assess the level of thermal exposure each design alternative receives, which is critical in hot arid climates like Cairo where minimizing heat gain is essential. The second metric is the visibility score, which quantifies the percentage of test points on the building's façade or within its interior that maintain a clear, unobstructed view toward a designated green space or park. This score reflects the quality and extent of visual connectivity from residential units to meaningful external landmarks, contributing to both spatial experience and psychological comfort. Together, these indicators allow for a balanced evaluation of environmental performance and visual amenity in urban block configurations.

4.2.2. Phase 2: Urban Block Composition Analysis

This phase aims to evaluate how the spatial arrangement of three previously optimized U-shaped blocks within a 90 × 160 m urban plot influences environmental performance, particularly regarding solar radiation mitigation and visual access to a designated green area located at the northeastern corner of the site.

The three blocks used in this phase are based on the outcomes of the single-block optimization conducted in Phase 1, which defined optimal height configurations and orientations to reduce solar exposure and improve views. In Phase 2, these blocks are composed within the larger urban plot in several layout scenarios.

Design Variables:

- Block configuration: The three blocks are placed in different spatial arrangements along the N–S axis, with tested orientation angles of −40°, 0°, and 40°.
- • Each configuration incorporates the top three block designs corresponding to each tested orientation.

Simulation Tools:

- Ladybug Radiation Analysis: assess solar radiation on the open spaces between blocks.
- View Analysis: evaluate outward visibility from residential units toward a garden area in the northeast of the site.

The evaluation criteria for Phase 2 focus on two main performance indicators: urban space radiation exposure and average view scores across the three-block configuration. The first metric, urban space radiation exposure, measures the total solar radiation received on the ground-level open spaces between and around the buildings, expressed in kilowatt-hours per square meter (kWh/m²). This metric is essential for assessing the thermal comfort and usability of outdoor urban spaces, especially in hot arid climates like Cairo where excessive solar gain can limit outdoor activity. The second metric is the average visibility score, which represents the mean percentage of observation points across all residential units in the three blocks that maintain a clear line of sight toward the designated park area. This score reflects the overall visual quality experienced by occupants, with higher percentages indicating stronger spatial and psychological connectivity to green space. Together, these two criteria provide a comprehensive understanding of how different block arrangements perform in balancing environmental comfort with visual amenity at the urban scale.

5. Results

The results from the first phase reveal significant variation in total solar radiation exposure, ranging from 4,130.85 kWh/m² to 5,248.28 kWh/m², across block typologies with volumes varying between 2,592 m³ and 5,184 m³. A subset of block configurations with fixed volume (3888 m³) and leg number variations (2, 3, and 4-legged U-shaped blocks) was selected for further analysis.

TABLE 1. Environmental Performance Metrics for a single Block of Volume of 3888 m³ | View Percent, Visibility Percent, and Solar Radiation Values

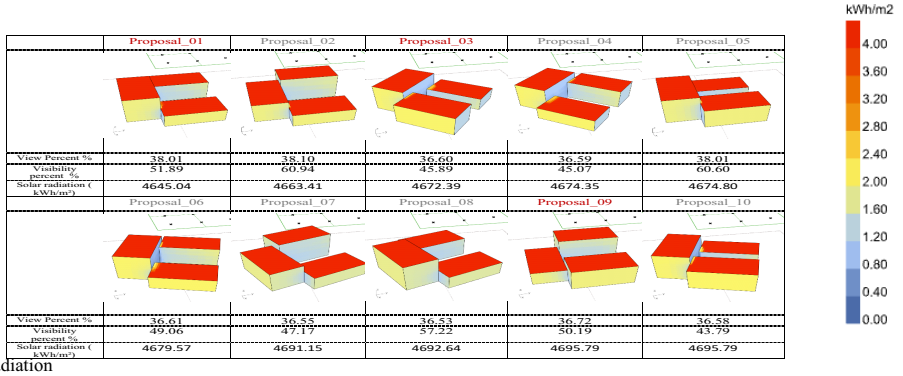
	P.D_01	P.D_02	P.D_03	P.D_04	P.D_05	P.D_06	P.D_07	P.D_08	P.D_09	P.D_10
Block_01	4	3	4	4	4	4	3	4	4	4

Number of floors										
Block_02 Number of Floors	3	4	2	3	2	3	4	3	3	2
Block_03 Number of floors	2	2	3	2	3	2	2	2	2	3
Orientation	0	0	-40	-40	0	-20	20	20	40	-20

These configurations demonstrated solar radiation levels ranging from 4,645.04 to 4,800.34 kWh/m², reflecting a balanced compromise between geometric complexity and environmental performance. A multi-objective optimization process was applied to identify block designs achieving solar exposure below 4,700 kWh/m², while simultaneously maximizing view percentage and visibility toward adjacent open spaces.

From this refined group, the top three alternatives for each orientation scenario were selected for further analysis in Phase 2. The best-performing blocks were aligned along orientations of −40°, 0°, and +40°, presenting the most effective balance between solar protection and external visual access, as summarized in Table 2.

TABLE 2. Solar Radiation Analysis for Various Block Orientations with Fixed Volume for a single block



Incident Radiation

In the second phase, the focus shifted to evaluating the spatial arrangement of three optimized U-blocks within a 90 × 160 m urban plot. The urban space radiation exposure across different configurations ranged from 23,717.07 kWh/m² to 24,064.07 kWh/m². Meanwhile, the average view scores across the residential units in the three-block compositions varied significantly, from 24% to 61.66% visibility toward the designated park area.

TABLE 3. Environmental Performance Metrics for Urban Block | Visibility Percent, and Solar Radiation Values

		D.P._01	D.P._02	D.P._03	D.P._04	D.P._05	D.P._06	D.P._07	D.P._08	D.P._09
Orientation	Block_01	40	40	40	0	40	40	40	40	40
	Block_02	40	40	2	2	2	0	40	40	40
	Block_03	40	40	0	40	0	40	-40	40	0
	Block_01	-1	-1	-1	-1	0	-1	-1	0	-1
	Block_02	0	-1	0	0	-1	-1	0	-1	0
	Block_03	0	0	0	0	1	0	0	1	1
		D.P._10	D.P._11	D.P._12	D.P._13	D.P._14	D.P._15	D.P._16	D.P._17	D.P._18
Placement along Axis N-	Block_01	40	40	40	40	0	40	40	40	-40
	Block_02	40	2	-40	0	40	40	0	40	40
	Block_03	0	-40	40	40	0	40	0	0	40
	Block_01	-1	-1	-1	-1	-1	-1	-1	0	-1
	Block_02	-1	0	-1	0	0	-1	0	0	0
	Block_03	0	1	0	0	0	-1	0	1	0

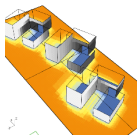
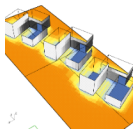
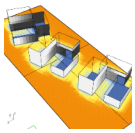
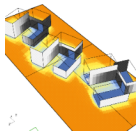
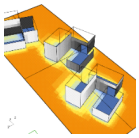
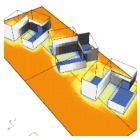
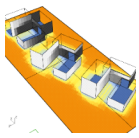
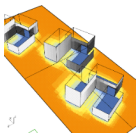
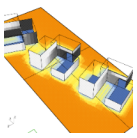
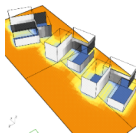
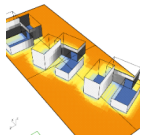
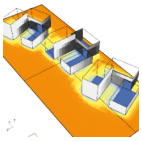
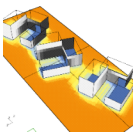
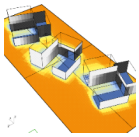
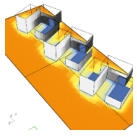
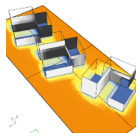
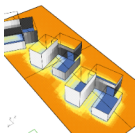
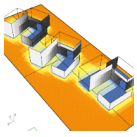
A targeted analysis was conducted on configurations with urban radiation levels below 23,800 kWh/m². These alternatives demonstrated view scores exceeding 50%, indicating a favorable balance between environmental shading and visual quality. Based on this dual-criteria evaluation, a total of 18 design alternatives were identified as optimal, offering the best trade-offs between minimizing solar exposure in urban open space and maximizing view accessibility from within n the blocks, Table 4.

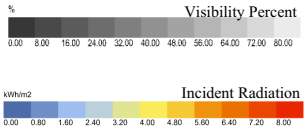
6. Discussion

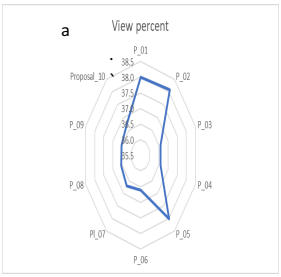
The results of the simulation-driven analysis offer valuable insights into how variations in urban block typology, height, orientation, and spatial composition affect environmental performance at both the building and urban scales. In Phase 1, the individual U-block configurations demonstrated that strategic manipulation of building leg heights and orientation could significantly reduce solar radiation on façades while maintaining or improving visual access to the surrounding park. Among the evaluated options, proposals 02, 05, and 08 offered the most favourable trade-offs between minimizing solar gain and enhancing visual connectivity. Specifically, stepped height arrangements—where the southern leg is tallest and the northern leg is shortest—proved most effective in shielding the interior courtyard from excessive solar exposure.

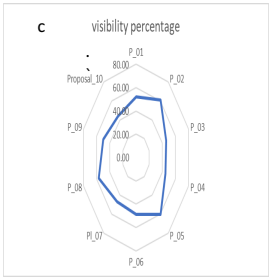
Orientations with open ends facing slightly off the true north (e.g., -20° to +20°) provided a better balance between solar shading and outward visibility, allowing units to benefit from natural lighting while limiting heat gain.

TABLE 4. Solar Radiation Analysis for Various Urban Block Orientations with Fixed Volume for three best proposals of the single block

	Proposal_01	Proposal_02	Proposal_03	Proposal_04	Proposal_05
					
Visibility percent %	53.27	58.26	52.73	52.77	50.17
Solar radiation (kWh/m²)	23747.94	**23767.27**	23775.88	23782.89	23787.88
	Proposal_06	Proposal_07	Proposal_08	Proposal_09	Proposal_10
					
Visibility percent %	57.1	50.09	52.94	58.54	56.13
Solar radiation (kWh/m²)	**23788.2**	23797.81	23798.86	**23817.95**	**23804.84**
	Proposal_11	Proposal_12	Proposal_13	Proposal_14	Proposal_15
					
Visibility percent %	55.68	54.07	52.89	52.31	52.18
Solar radiation (kWh/m²)	**23815.39**	23815.86	23801.01	23810.83	23804.04
	Proposal_16	Proposal_17	Proposal_18		
					
Visibility percent %	51.86	51.59	51.14		
Solar radiation (kWh/m²)	23810.92	23814.24	23806.07		







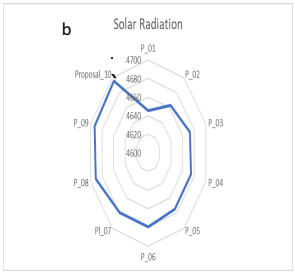


Figure 5. Chart Comparing a. View Percent, b. Visibility Percent, and c. Solar Radiation Across Design Proposals for a single block

In Phase 2, the focus shifted to the collective behavior of three optimized blocks within a 90 × 160 meter plot. The urban-scale evaluation revealed that block composition— different spatial arrangements across the urban block —plays a critical role in shaping microclimatic conditions and visual permeability. Arrangements that allowed for greater spacing and diagonal alignment between blocks tended to reduce cumulative solar radiation in shared open spaces, improving outdoor comfort. However, these same configurations sometimes resulted in reduced view scores for certain units, especially those positioned behind others or oriented away from the park. This highlights the inherent trade-offs in urban design between maximizing environmental performance and ensuring equitable visual access.

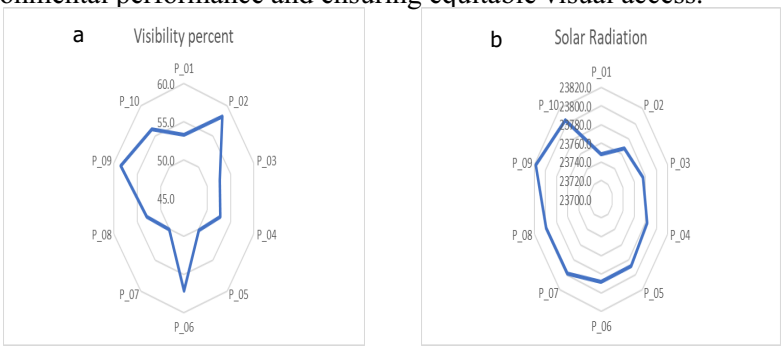


Figure 6. Chart Comparing a. Visibility Percent, and b. Solar Radiation Across Design Proposals for urban block

Across both phases, the multi-objective optimization process emphasized that there is no single "ideal" configuration, but rather a spectrum of well-performing solutions depending on the weighting of design priorities. The findings underscore the value of using computational design tools not to prescribe fixed forms, but to support informed decision-making in early-stage planning. By quantifying the relationship between form, orientation, and performance, designers can iteratively test and refine spatial strategies to meet site-specific climatic and experiential goals.

Furthermore, the simulations reinforce the importance of integrating environmental metrics such as solar radiation and visibility into urban design practice—especially in arid climates like Cairo's, where the balance between shading and openness must be carefully calibrated. The study ultimately

contributes a replicable process for performance-driven urban block design that is adaptable to other climatic and spatial contexts.

7. Conclusion

This study demonstrates the value of a simulation-based parametric approach for optimizing urban block design in hot-arid contexts. Through a two-phase analysis, it was shown that careful manipulation of block form, height, orientation, and spatial arrangement can significantly influence environmental performance at both the building and urban scales.

In Phase 1, the optimization of individual U-blocks revealed that stepped height configurations, particularly those with taller southern legs and shorter northern legs, can effectively reduce solar radiation while preserving outward visibility. Orientations slightly rotated from true north (−20° to +20°) offered an optimal balance between solar control and visual access.

In Phase 2, the performance of three-block compositions within a larger urban plot highlighted the trade-offs between urban space radiation exposure and equitable visibility. Diagonal and staggered arrangements showed potential for improving microclimatic comfort in open spaces but occasionally at the expense of individual unit views.

Overall, the findings suggest that there is no universally optimal design, but rather a set of high-performing alternatives that vary according to project priorities. The integration of environmental metrics such as solar radiation, view score, and visibility percentage into early-stage urban design enables data-informed decisions that support the creation of livable, climate-responsive environments.

Beyond its analytical results, this research contributes to the broader discourse on performance-driven urban design by demonstrating how multi-objective optimization can be systematically applied to reconcile visual and solar criteria at the block scale—an area often treated separately in previous studies. By bridging these parameters within a unified computational workflow, the study advances the state of the art in parametric urban modeling and provides a replicable framework adaptable to other hot-arid contexts.

Future extensions of this work will incorporate additional microclimatic dimensions—such as airflow simulation and vegetation integration—to evaluate thermal comfort and urban cooling potential. Considering the psychological and environmental benefits of green views will further enrich the evaluation of visibility. By expanding the framework in this direction, the research aims to develop a more holistic understanding of environmental and perceptual performance in sustainable urban form generation.

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SUSUTAINABLE REVITALIZATION OF HISTORIC URBAN DISTRICTS:

Impacts on Spatial and Cultural Identity in Historic Cairo

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Abstract. Historical districts are considered as living testaments to a city's rich cultural heritage and architectural legacy; it also provides a glimpse into the city's evolution over time. These areas are function as living urban entities, allowing residents and visitors experience the continuity of cultural presence and recognize the city's identity. However, historical districts are facing deterioration due to the pressures of urban development, population growth, and infrastructure needs. Therefore, many countries, including Egypt have adopted sustainable revitalization strategies to safeguard these valuable historical areas for future generations. While these strategies are increasingly advocated, their specific impacts on the spatial and cultural identity of historic districts remain significantly understudied. This study establishes a comprehensive framework for assessing spatial and cultural identity in Historic Cairo through the development of key identity indicators and an innovative assessment model. Employing a mixed-methods approach that integrates narrative analysis, qualitative evaluation, and quantitative measurement, the research identifies critical dimensions of urban identity and their interrelationships. The resulting assessment model provides urban planners and policymakers with actionable tools to evaluate and guide revitalization projects, emphasizing the importance of integrated strategies that maintain authentic character while supporting sustainable development.

Keywords: *Sustainable Rrevitalization, historic districts, cultural identity, spatial identity, Historic Cairo.*

1. Introduction

Historic urban districts are vital parts of a nation's cultural and historical heritage. They form recognizable areas defined by their traditional architecture and urban layout (Bandarin and van Oers, 2012).These districts function as dynamic urban ecosystems where architectural heritage, social practices, and historical narratives converge to shape a city's unique identity. The resulting synthesis of cultural influences produces distinctive spatial configurations and land-use patterns that reflect historical evolution (Elsheshtawy, 2008). As emphasized by the Venice Charter, heritage is "imbued with a message from the past," imposing a collective obligation to preserve this legacy (ICOMOS, 1964).These districts thus represent irreplaceable records of civilizational continuity and architectural innovation (UNESCO, 2011).

However, rapid urbanization, population pressures, and infrastructure demands threaten their integrity, often eroding the very qualities that make them culturally significant (Fahmi and Sutton, 2010). In response, many countries with participation and support of international organizations that concern of history and built heritage have sustainable revitalization strategies which have been emerged as critical tools for preserving these districts. Yet, while these strategies seek to balance conservation with development, their effects on the spatial and cultural identity remain understudied particularly in terms of how residents and visitors perceive and interact with revitalized spaces (AlSayyad, 2011). Focusing on Historic Cairo, Egypt this study addresses this gap by:

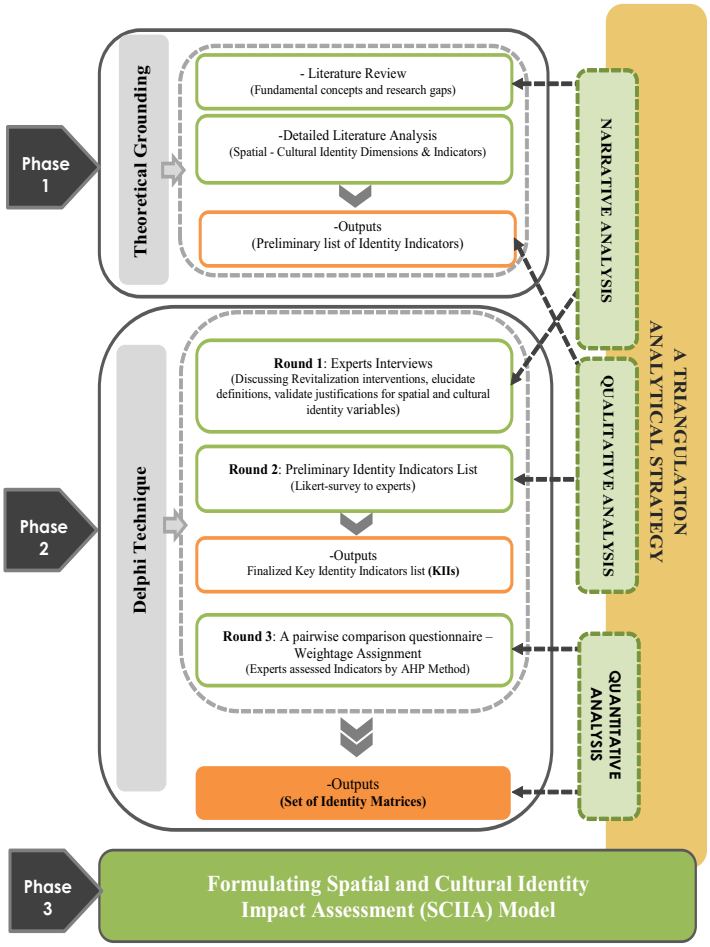
- **Developing criteria and indicators** to measure spatial and cultural identity.
- **Proposing an evaluative tool** to assess the impacts of revitalization interventions on these identity dimensions, with emphasis on the lived experiences of local communities and visitors.

By bridging theory and practice, this research aims to provide urban planners and decision-makers with a standardized framework for balancing heritage conservation with sustainable development.

2. Research Methodology

The study employs a triangulation analytical strategy, integrating narrative, qualitative, and quantitative analyses to ensure methodological rigor. The investigation is structured into three sequential phases illustrates in figure1:

1-Theoretical Grounding: This phase entails a comprehensive literature review to explore fundamental concepts and research gaps concerning the revitalization of historic districts, with a particular focus on Historic Cairo. A subsequent detailed literature analysis investigates spatial and cultural identity within urban heritage contexts, identifying key dimensions and



potential indicators.

Figure1. Research Methodology. Source: Author

2-Delphi Technique: In this phase, the Delphi technique was applied in the first round to elucidate definitions, validate justifications for spatial and cultural identity variables within historic Cairo context. The qualitative analysis applies thematic analysis to systematically evaluate literature review findings and expert interview transcripts, identifying recurring themes and patterns associated with spatial and cultural identity. This process enabled the refinement of the preliminary indicator list. The updated indicators were then resubmitted to the expert panel in a second Delphi round for validation. This structured methodology ensures the development of a finalized Key Identity Indicators list (KIIs), grounded in expert consensus and aligned with the study's objectives.

The KIIs was utilized to design a pairwise comparison questionnaire, which was administered during the third Delphi round. Experts assessed the relative significance of each indicator using the Analytic Hierarchy Process (AHP) method, enabling the calculation of weighted values for indicators. The

resulting AHP-derived weights provided a systematic and empirically grounded prioritization of identity factors to establish a set of structured Identity Matrices which is a base to develop a spatial and cultural identity index system (SCII).

3- Formulation of the Assessment model: Building on the outputs of the previous phases, the researchers developed an identity assessment model tailored to Historic Cairo. This model designed to support the evaluation of post-revitalization interventions and their impacts on spatial and cultural identity.

3. Literature Review

3.1. THE SIGNIFICANCE OF HISTORIC URBAN DISTRICTS

Historic urban districts serve as tangible manifestations of cultural memory, characterized by distinctive architectural typologies, urban morphologies, and socio-spatial practices (Bandarin and van Oers, 2012). These districts function as dynamic ecosystems where built heritage and intangible cultural narratives intersect to shape urban identity (Elsheshtawy, 2008). International frameworks, such as the Venice Charter (ICOMOS, 1964) and (UNESCO, 2011), emphasize their role as irreplaceable records of civilizational continuity. However, rapid urbanization and developmental pressures increasingly threaten their integrity, eroding the spatial and cultural qualities that define their significance (Fahmi and Sutton, 2010).

3.2. INTERNATIONAL GUIDELINES OF HERITAGE PRESERVATION

Systematic approaches to heritage conservation are grounded in international charters, particularly those of ICOMOS, which advocate for:

1. **Authenticity** and integrity in preservation (ICOMOS, 2008).
2. **Inclusivity** through community engagement (ICOMOS, 2008).
3. **Sustainability** in adaptive reuse (El-Basha, 2021).

These principles aim to balance preservation with socio-economic development, though their implementation often overlooks local perceptions of identity (AlSayyad, 2011) (Fadhil and Al-Zaidi, 2023).

3.3. URBAN REVITALIZATION: STRATEGIES AND CRITIQUE

The concept of revitalization has expanded significantly in recent years. Initially rooted in urban planning and landscape design, it now extends to diverse facets of contemporary life including personal renewal in spiritual, physical, and financial domains. Its definition varies across disciplines such as architecture, social sciences, and economics (Wilczkiewicz and Wilkosz-Mamcarczyk, 2015). Within urban contexts, revitalization serves as a key strategy for redefining a city's identity, balancing modernization with the preservation of socio-cultural and heritage values. This process necessitates reconciling historical legacy, cultural memory, and place identity with contemporary economic, political, and social imperatives. At its core, revitalization seeks to arrest or reverse the decline of historic urban areas (Doratli, 2007).

Given its complexity, revitalization requires a multidimensional approach, integrating not only physical restoration but also social and economic regeneration within a sustainable, long-term framework. Successful strategies must harmonize conservation objectives with physical integrity, social inclusion, economic viability, and environmental sustainability. This demands the strategic translation of research and innovation into practical, context-sensitive solutions (Doratli et al., 2004).

(Lotfi and Aly, 2025) study examined the conceptual foundations of revitalization, identified seven core strategies, each comprising primary and secondary activities, methodological tools, and policy alternatives. The research delineates critical criteria, policies, and principles for the sustainable revitalization of historic urban districts, organizing them into seven thematic phases:

1. **Holistic Vision** – Integrated planning for comprehensive urban renewal.
2. **Economic Perspective** – Leveraging financial mechanisms for regeneration.
3. **Public Spaces** – Enhancing social interaction through urban design.
4. **Interactive Architecture** – Adaptive interventions fostering engagement.
5. **Sustainability** – Ecological and long-term resilience in redevelopment.
6. **User-Centric Approach** – Prioritizing community needs and participation.
7. **Historic Core Conservation** – Balancing preservation with adaptive reuse

Yet, critiques highlight a gap in evaluating post-revitalization impacts on spatial and cultural identity, particularly in how residents experience transformed spaces (Yung and Chan, 2012).

3.4. THE ROLE OF HISTORIC DISTRICTS IN SHAPING IDENTITY

Historic districts encompassing buildings, monuments, and urban landscapes play a pivotal role in sustaining collective memory, cultural continuity, and a sense of belonging. These spaces function as anchors for individual and communal identity, with historic structures acting as material conduits to the past, thereby preserving cultural narratives and shared heritage (Smith, 2016). Moreover, heightened place attachment fosters emotional connections to heritage sites, reinforcing local identity (Lewicka, 2011).

Public spaces within historic urban environments are instrumental in shaping social and cultural identity. The range and character of activities hosted in these spaces determine their capacity to engage diverse social groups, facilitate intergenerational exchange, and sustain civic participation. As Farhan et al. (2020) argue, such interactions are critical for the adaptive revitalization of public realms across temporal and contextual boundaries.

Identity is inextricably linked to historical continuity, as the past constitutes a foundational element of self-conception. Based on Lowenthal study in 2015; (Chappell, 2017) contends that the significance of place derives not from architectural scale but from its mnemonic power, while (Cuno, 2010) frames identity as a dynamic construct rather than a fixed entity. (Maalouf, 2011) further asserts that identity serves as a marker of distinction for individuals and communities, with cautioning that its absence engenders dislocation.

3.5. BALANCING IDENTITY AND URBAN REVITALIZATION

The conflict between conserving heritage and pursuing urban development is a recurring challenge, with modernization initiatives frequently compromising the authenticity of historic settings (Holtorf and Fairclough, 2013). While revitalization projects are promoted as a means to adaptively reuse heritage structures, preserving their cultural value while meeting modern needs (Pendlebury et al., 2009). Such approaches face significant criticism. Scholars like (Yung and Chan, 2012) contend that revitalization often overlooks the social aspects of heritage, particularly the deep-rooted connections between communities and their surroundings. For long-time residents, the significance of place stems from daily lived experiences and historical continuity, fostering opposition to redevelopment that prioritizes

economic or aesthetic upgrades over preserving the original built fabric. This underscores the need to conceptualize heritage not just as tangible architecture, but as an emotionally charged space shaped by collective memory and habitation (Lotfi and Aly, 2025).

3.6-HISTORIC CAIRO: URBAN MORPHOLOGY AND IDENTITY CHALLENGES

Historic Cairo stands as one of the world's most culturally and architecturally rich urban heritage areas. Its historical depth encompasses a broad spectrum of urban forms and monuments ranging from the early Islamic settlement of Al-Fustat and the medieval core of Fatimid Cairo, to Mamluk palaces, the Citadel, domestic architecture, religious complexes, and historic markets. These layers collectively reflect Cairo's longstanding role as a political, religious, and cultural capital of the Islamic world, earning it inscription on the UNESCO World Heritage List in 1979 in recognition of its exceptional historical, archaeological, and urban significance(Williams, 2008) (Raymond and Wood, 2007).

As (Saad, 2017) illustrates, the city's urban fabric is defined by the predominance of linear spaces and a high degree of geometric irregularity, particularly within the private, residential quarters. This spatial configuration is not arbitrary, but rather the product of an organic, evolutionary process that has produced distinctive spatial identities across different urban spheres. This context which characterized by relatively regular geometries and higher accessibility fosters civic functions and supports visual orientation, while the private sphere with its enclosed, irregular, and complex layout prioritizes territoriality, privacy, and social cohesion. These morphological patterns are closely intertwined with the city's cultural logic. The minimal presence of formal public squares, for instance, challenges conventional Western planning ideals and emphasizes the embeddedness of social and cultural activities within informal and adaptive spatial typologies (Williams, 2008).

(Raymond and Wood, 2001) and (Elsheshtawy, 2008) demonstrate that the physical structure of historic Cairo contributes to distinct patterns of **place attachment**, **collective memory**, and **environmental identity**, reinforcing the idea that spatial form plays an active role in shaping the everyday experiences of residents. However, despite the richness of this spatial identity, the majority of revitalization efforts have emphasized physical rehabilitation over the preservation of socio-spatial continuity (Gharib, 2011).

DIMENSION	INDICATORS	DESCRIPTION	REFERENCES

4. Spatial and Cultural Identity: Adopted Criteria for Assessment

Spatial identity refers to the sense of self and belonging that individuals or groups develop in relation to physical, geographical, and built environments. It is shaped by the interactions between people and their surroundings, including places of residence, public spaces, landmarks, and the socio-cultural meanings attached to these spaces (Lynch, 1960) and (Relph, 1976),While **Cultural identity** refers to an individual's or group's sense of belonging to a particular culture or cultural group. It is informed by shared values, traditions, language, history, and customs, and it evolves through socialization, historical context, and interactions with others (UNESCO, 2011).

The preservation of spatial and cultural identity in historic districts relies on a multidimensional framework, as established in urban heritage literature (Lynch, 1960, Tuan, 1977).Based on previous literature review; the study adopts five key dimensions to assess spatial and cultural identity:

1-Physical-Spatial Dimension
2-Functional-Economic Dimension
3-Socio-Cultural Dimension
4-Perceptual-Visual Dimension
5-Governance & Policy Dimension

Each dimension is defined through a set of specific indicators, as outlined in the accompanying (table 1), to facilitate an integrated evaluation of revitalization outcomes on the perceived identity of the area by its users and local visitors. This analytical structure enables a nuanced understanding of the interplay between urban form, socio-economic dynamics, and institutional frameworks in shaping and sustaining the unique identity of Historic Cairo. The proposed indicators will undergo a subsequent evaluative process aimed at refining and consolidating a final set of identity indicators.

Physical - Spatial Dimension	Morphological Continuity	• Street patterns, plot divisions, and building typologies that retain historical character. • Preservation of Urban grain (scale, density, and layout).	(Lynch, 1960), (Van den Berg et al., 1982), (Relph, 1976).
	Architectural Authenticity	• Preservation of original façades, materials, construction techniques, design, and spatial characteristics.	(ICOMOS, 1964), (Jokilehto, 1999).
	landmark Density	• Presence of monuments, heritage sites, and symbolic structures that serve as identity anchors.	(Lynch, 1960).
	Quality of public spaces	• Historic squares, courtyards, and pedestrian zones that foster social interaction. • -Proportion of open spaces with cultural significance (e.g., bazaars, plazas).	(Gehl, 2013), (Madanipour, 2023).
Functional - Economic Dimension	Functional Continuity	• The extents to which historical buildings or areas maintain or sensitive adapt their original functions.	(Pendlebury et al., 2009).
	Local businesses continuity	• The capacity of a heritage area to maintain and develop diverse locally rooted economic activities (Local businesses vs. chain stores).	(Rypkema, 2006), (Serageldin, 1990).
	Gentrification pressures	• Emotional bonds and personal meanings attached to the historical environment. • Oral histories, local narratives, and traditions tied to the district.	(UNESCO, 2011), (Smith, 2016), (Eldaidamonya and Shetawy, 2015)
Socio-Cultural Dimension	Place Attachment	• Emotional bonds and personal meanings attached to the historical environment. • Oral histories, local narratives, and traditions tied to the district.	(Tuan, 1977), (Relph, 1976), (Lewicka, 2011).
	Collective Memory	• It reflects how residents and communities emotionally relate to the historic environment, and how revitalization either preserves, distorts, or erases these memory-based connections.	(Tuan, 1977), (Relph, 1976).
	Cultural Practices	• Ongoing use of spaces for traditional activities, rituals, or community events.	(UNESCO, 2003), (Graham, 2002).
	Social Interaction	• Street life, informal gatherings, and community events. • Diversity of users (locals, tourists, vendors) contributing to vibrancy.	(Brown and Lombard, 2014).
	Intergenerational continuity	• Young residents involved in heritage activities	(UNESCO, 2011), (Pendlebury et al., 2009).
Perceptual - Visual Dimension	Legibility	• Retention of urban layout, street patterns, and landscape features	(Lynch, 1960).
	Image-ability	• The quality of a physical environment that makes it visually coherent, easily navigable, and memorable.	(Lynch, 1960), (Nasar, 1990)
	Aesthetic Harmony	• Visual continuity in signage, street furniture, and lighting. • Use of traditional materials or motifs in street upgrades. • Absence of disruptive modern interventions.	(Orillard, 2012)
Governance & Policy Dimension	Heritage protection policies	• Formal laws, regulations, guidelines, and administrative measures put in place by governments, international organizations, or local authorities to safeguard, conserve, and manage cultural heritage.	(UNESCO, 2003), (ICOMOS, 2006).
	Tourism management	• Avoidance of "museumification" (excessive tourism displacing locals). • Balance between tourism promotion and cultural preservation.	(Brown and Lombard, 2014), (Ashworth and Tunbridge, 2011).

	Community participation	• Degree of local involvement in heritage management, planning processes and decision-making.	(Waterton and Smith, 2010).

5. Application of the Delphi Technique

The Delphi Technique is a structured, expert-based research method designed to gather, refine, and build consensus on complex issues through iterative rounds of surveys, interviews, and feedback (Landeta, 2006). This approach is particularly valuable in fields requiring specialized judgment, experience, and foresight, such as urban identity studies, heritage planning, or indicator development (Balasubramanian and Agarwal, 2012).
In this study, the researchers implemented the Delphi method across three sequential rounds. A panel of 11 experts was carefully selected, representing diverse disciplines including urban planning, heritage conservation, architecture, public policy, and governmental decision-making.

5.1. ROUND 1: EXPERTS INTERVIEWS AND PRELIMINARY INDICATOR DEVELOPMENT

The first round consisted of individual, semi-structured interviews conducted separately with each participating expert. All interviews were audio-recorded with consent to ensure accurate data capture. Each interview was divided into two thematic sections; the first section explored background information and addressed open-ended questions concerning revitalization strategies, perceptions of spatial and cultural identity, existing policy frameworks supporting identity-based revitalization initiatives, and critical challenges in preserving historic districts. This allowed experts to articulate their perspectives on theoretical and practical dimensions of urban heritage conservation.
The second section focused on evaluating the current state of historic Cairo, with particular attention to case studies of past revitalization projects. Experts analyzed these cases to identify successes and failures in preserving spatial and cultural identity, providing grounded insights into relative barriers and opportunities.
Following these discussions, the research team presented a preliminary list of indicators derived from the literature review that mentioned in (table 1). Experts collaboratively refined this list, suggesting modifications to exclude irrelevant indicators, approve validated ones, and propose additional

criterions capable of effectively assessing spatial and cultural identity in revitalization contexts.

5.1.1. Discussion of Round 1 findings

Expert interviews revealed contrasting evaluations of heritage revitalization projects in historic Cairo. Several participants highlighted Al-Darb Al-Ahmar and Al-Azhar Park as examples of identity-conscious redevelopment, noting their success in balancing spatial heritage preservation with functional upgrades. These projects were particularly commended for prioritizing resident needs and user experience while maintaining the districts' cultural authenticity.

Al-Moez Street project exposed fundamental tensions in heritage management models. While some experts praised its economic outcomes—particularly its successful rebranding as a tourist-oriented cultural market—others criticized its underlying governance model. They emphasized three key shortcomings; the marginalization of local stakeholders in decision-making processes, the privileging of tourist experience over resident needs and the absence of sustainable maintenance mechanisms. Through structured discussion, experts refined the preliminary indicators, proposing key modifications:

- **Conceptual Clarification**
  - Replaced *"Image-ability"* with *"Sensory Memory Continuity"* to better capture multisensory place identity.
- **Critical Additions**
  - Added *"Ritual & Routine"* to account for intangible cultural practices.
  - Incorporated *"Public Interest Supremacy"* to prioritize community needs over tourism/investments interests.

5.2. ROUND 2: VALIDATION AND FINALIZATION OF KEY IDENTITY INDICATORS (KIIS)

The second round focused on establishing experts' consensus through systematic validation of the revised indicators. The research team circulated the updated list derived from Round 1 findings to the same experts' panel, requesting two primary evaluations:

1. **Qualitative Assessment**
   Experts critically examined each indicator's conceptual relevance to spatial and cultural identity preservation in historic urban contexts.
2. **Quantitative Ranking**
   Participants evaluated indicator significance using a 5-point Likert scale (1 = minimal relevance; 5 = essential relevance), enabling standardized metric comparison.

Through this dual evaluation process; as shown in table 2, indicators receiving consistently low rankings (≤ 2.5 mean score) were eliminated. The round concluded with the establishment of the Key Identity Indicators (KIIs) list based on experts' consensus and aligned with the study objectives.

TABLE 2. Ranking Identity Indicators. (Source: Author)

Dimensions	Indicators	Experts Evaluation											Average
		Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10	Expert 11	
Physical - Spatial Dimension	Morphological Continuity	5	5	5	5	5	5	5	5	5	5	5	5
	Architectural Authenticity	5	5	5	4	5	5	4	4	3	4	5	4.45
	Landmark Density	5	4	3	5	5	4	4	3	3	3	4	3.91
	Quality of public spaces	5	5	4	4	4	3	5	3	3	5	4	4.09
Functional - Economic Dimension	Functional Continuity	3	2	4	3	1	3	2	2	4	3	1	2.55
	Local Business Continuity	5	3	5	5	5	5	4	3	5	5	4	4.45
	Gentrification pressures	3	5	4	3	3	4	1	4	5	4	5	3.73
Socio-Cultural Dimension	Place Attachment	4	5	5	4	5	2	4	3	3	3	4	3.82
	Collective Memory	5	4	5	5	5	2	5	3	5	2	3	4
	Cultural Practices	5	4	4	3	4	4	4	4	4	4	5	4
	Social Interaction	5	5	4	4	3	4	3	3	5	4	5	4.09
	intergenerational Continuity	5	4	3	3	5	5	5	5	5	3	4	4.27
	Ritual & Routine	3	3	4	3	3	1	2	3	2	1	2	2.45
Perceptual - Visual Dimension	Legibility	4	5	3	4	5	3	4	2	3	4	5	3.82
	Image-ability	5	4	5	5	5	5	5	2	1	2	3	3.82
	Sensory Memory Continuity	5	5	5	5	5	4	4	5	3	5	4	4.55
	Aesthetic Harmony	5	5	4	3	5	4	4	1	5	3	5	4
Governance & Policy Dimension	Heritage protection policies	5	5	5	4	5	4	5	2	3	5	5	4.36
	Tourism management	4	5	3	5	5	3	4	5	3	3	4	4
	community participation	5	4	4	3	5	5	5	3	5	5	5	4.45
	Public Interest Supremacy	3	4	2	1	4	3	2	3	2	1	2	2.45

- Indicators receiving low rankings ≤2.5 were eliminated.
- (5-point Likert scale (1 = minimal relevance; 5 = essential relevance)

5.3. ROUND 3: A PAIRWISE COMPARISON OF KIIS

The final round applied Analytic Hierarchy Process (AHP) method to prioritize the validated Key Identity Indicators (KIIs) through pairwise comparisons. Experts assessed all possible KIIs pairs using standardized 9-point scales (Hsin Yuan and Shang Yu, 2011), ensuring consistent judgment of relative importance. The process incorporated eigenvalue-based weight

calculations, geometric mean aggregation of experts' inputs. As shown in the following tables 3, this phase generated hierarchically weighted KIIs, forming the basis for structured Identity Matrices. The empirically derived weights enabled objective prioritization of identity factors, providing a quantitative foundation for developing an identity index system.

TABLE 3. Pairwise comparison of AHP model. (Source: Authors)

Dimensions		D1				D2		D3					D4			D5			
	Indicators	Morphological Continuity	Architectural Authenticity	Landmark Density	Quality of public spaces	Local Business Continuity	Gentrifeation pressures	Place Attachment	Collective Memory	Cultural Practices	Social Interaction	Intergenerational Continuity	Legibility	Sensory Memory Continuity	Aesthetic Harmony	Heritage protection policies	Community participation	Tourism management	Weight
D1- Physical-Spatial Dimension	Morphological Continuity	1	0.26	0.95	2.73														0.48
	Architectural Authenticity	3.8	1	3.59	10.4														0.27
	Landmark Density	1.06	0.28	1	2.88														0.14
	Quality of public spaces	0.37	0.1	0.35	1														0.09
D2-Functional-Economic Dimension	Local Business Continuity					1	1.94												0.751
	Gentrification pressures					0.52	1												0.248
D3-Socio–Cultural Dimension	Place Attachment							1	0.03	0.03	0.05	1.1							0.278
	Collective Memory							35	1	1.1	1.58	38.5							0.268
	Cultural Practices							31.9	0.91	1	1.44	35.1							0.185
	Social Interaction							22.1	0.63	0.69	1	24.3							0.149
	Intergenerational Continuity							0.91	0.03	0.03	0.04	1							0.119
D4-Perceptual - Visual Dimension	Legibility												1	2.94	1.83				0.53
	Sensory Memory Continuity												0.34	1	0.62				0.18
	Aesthetic Harmony												0.55	1.61	1				0.29
D5-Governance - Policy Dimension	Heritage protection policies															1	2.48	1.06	0.433
	Community participation															0.4	1	0.43	0.369
	Tourism management															0.94	2.34	1	0.197

5.3.1. Discussion of Round 3 findings

The following figure 2 presents the AHP weightings percentage assigned by the experts across seventeen identity indicators. Notably, Local Business Continuity receives consistently high prioritization (50–90%), underscoring its critical role in sustaining place identity, while Gentrification Pressures and Quality of Public Spaces exhibit greater variability, suggesting divergent expert perspectives on their relative impact. Morphological Continuity and Legibility frequently rank among the top indicators,

emphasizing the importance of physical and perceptual coherence in urban environments. In contrast, Intergenerational Continuity and Sensory Memory Continuity receive comparatively lower weights, indicating their secondary influence in expert evaluations.

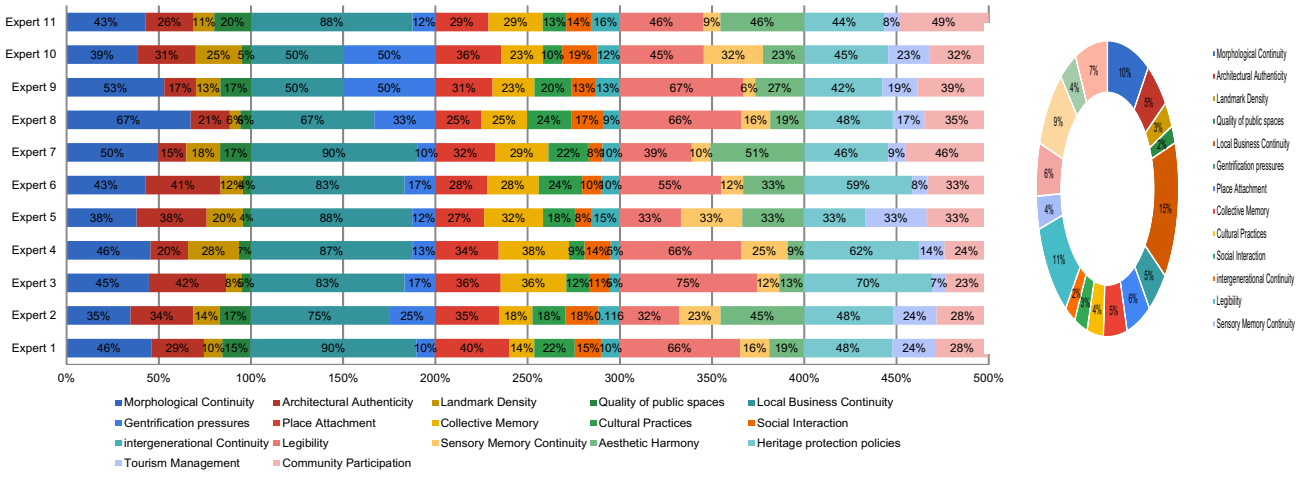


Figure 2. Percentage of experts' responses for all Identity Indicators. Source: Authors

The distribution of weights reveals patterns in expert consensus, with Architectural Authenticity, Heritage Protection Policies, and Collective Memory maintaining moderate to high importance, whereas Tourism Management and Community Participation display fluctuating valuations, reflecting contextual or disciplinary differences. Discrepancies in certain indicators, such as Aesthetic Harmony (9–51%) and Cultural Practices (9–24%), highlight the subjective nature of identity assessment as shown in figure 3.

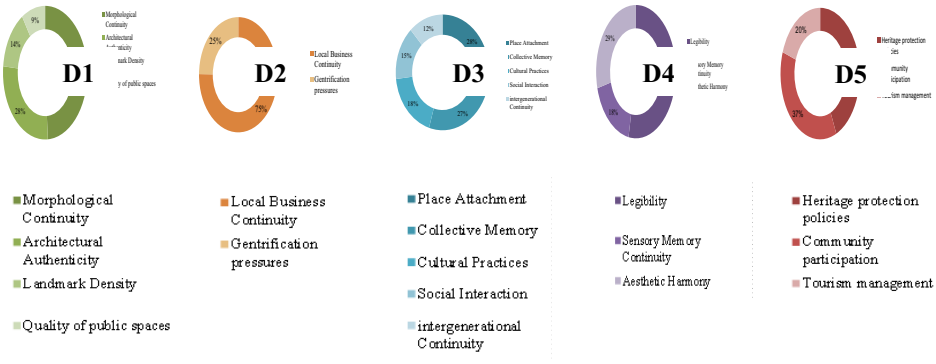


Figure 3. Percentage weight ratio for each dimension. Source. Authors

6. SCIIA Model Formulation

The SCIIA Model is a participatory framework designed to evaluate and guide identity-sensitive revitalization in historic urban districts. While initially tailored for Historic Cairo's unique socio-spatial dynamics, the model's modular design permits adaptation to other heritage districts through contextual recalibration of its weighted parameters. This analytical tool enables systematic evaluation of post-revitalization interventions' impacts on both spatial configuration and cultural identity preservation. As shown in figure 4, the model incorporates the weighted identity parameters from the AHP analysis, ensuring measurement consistency with the established theoretical framework.

Figure 4. SCIIA Model framework. Source: Author

It systematically integrates spatial and cultural dimensions through four sequential phases:

1. **Preparatory Phase:** The SCIIA model initiates with a dual preparatory process: (1) *scope definition*, where the target revitalization area is spatially delimited through historical and morphological analysis; and (2) *stakeholder engagement*, employing a multi-tiered participatory approach that integrates local actors (residents, artisans, business owners) with institutional actors (heritage experts, NGOs, municipal authorities) to establish shared assessment priorities. This phase ensures contextual grounding while identifying potential conflicts between community needs and conservation objectives.

2. **Assessment Phase:** The model evaluates five identity dimensions that mentioned before through mixed-methods and tools shown in table 4, each dimension's weighted indicators are systematically applied to measure identity impacts.

TABLE 4. Methods and Tools for KIIs list. Adapted by: Authors

DIMENSIONS	INDICATORS	METHODS	TOOLS
Physical - Spatial Dimension	Morphological Continuity	▪ Figure Ground Analysis ▪ Field surveys	▪ GIS Maps
	Architectural Authenticity	▪ Filed Surveys	▪ Photos ▪ Sketches ▪ Inventory forms
	landmark Density	▪ Lynch Analysis	▪ Photos ▪ Sketches ▪ maps
	Quality of public spaces	▪ Field Surveys ▪ Questionnaire Survey	▪ Photos ▪ Graphs ▪ maps
Functional - Economic Dimension	Local Business Continuity	▪ Interviews ▪ Business Surveys	▪ Tables ▪ Graphs ▪ Bar-charts
	Gentrification pressures	▪ Stakeholders interviews ▪ Policy review	▪ Tables ▪ Graphs ▪ Bar-charts
Socio-Cultural Dimension	Place Attachment	▪ Interviews ▪ Ethnographic studies ▪ Participatory mapping	▪ Tables ▪ Graphs ▪ Bar-charts
	Collective Memory	▪ Oral history interviews ▪ Participatory mapping	▪ Sketches. ▪ photos
	Cultural Practices	▪ Interviews ▪ Field surveys	▪ photos ▪ Tables ▪ Graphs ▪ charts
	Social Interaction	▪ Questionnaire Survey ▪ Field surveys	▪ photos ▪ Charts ▪ Graphs
	Intergenerational Continuity	▪ Questionnaire Survey	▪ Tables ▪ Graphs ▪ charts
Perceptual - Visual Dimension	Legibility	▪ Visual surveys	▪ Photographs ▪ Sketches
	Sensory Memory Continuity	▪ Behavioural observation. ▪ User perception Questionnaire	▪ Sketchs ▪ Photos ▪ Tables ▪ Graphs ▪ charts
	Aesthetic Harmony	▪ Visual surveys	▪ Photos ▪ Sketches
Governance & Policy Dimension	Heritage protection policies	▪ Policy review	▪ Documents ▪ Laws ▪ Regulations
	Tourism management	▪ Policy review ▪ Observation checklists	▪ Tables ▪ Graphs ▪ Charts
	Community participation	▪ Stakeholders Interviews ▪ Questionnaire Survey	▪ Tables ▪ Graphs ▪ Bar-chart

DIMENSIONS	INDICATORS	METHODS	TOOLS
Physical - Spatial Dimension	Morphological Continuity	- Figure Ground Analysis - Field surveys	- GIS Maps
	Architectural Authenticity	- Filed Surveys	- Photos - Sketches - Inventory forms
	landmark Density	- Lynch Analysis	- Photos - Sketches - maps
	Quality of public spaces	- Field Surveys - Questionnaire Survey	- Photos - Graphs - maps
Functional - Economic Dimension	Local Business Continuity	- Interviews - Business Surveys	- Tables - Graphs - Bar-charts
	Gentrification pressures	- Stakeholders interviews - Policy review	- Tables - Graphs - Bar-charts
Socio-Cultural Dimension	Place Attachment	- Interviews - Ethnographic studies - Participatory mapping	- Tables - Graphs - Bar-charts
	Collective Memory	- Oral history interviews - Participatory mapping	- Sketches. - photos
	Cultural Practices	- Interviews - Field surveys	- photos - Tables - Graphs - charts
	Social Interaction	- Questionnaire Survey - Field surveys	- photos - Charts - Graphs
	Intergenerational Continuity	- Questionnaire Survey	- Tables - Graphs - charts
Perceptual - Visual Dimension	Legibility	- Visual surveys	- Photographs - Sketches
	Sensory Memory Continuity	- Behavioural observation. - User perception Questionnaire	- Sketchs - Photos - Tables - Graphs - charts
	Aesthetic Harmony	- Visual surveys	- Photos - Sketches
Governance & Policy Dimension	Heritage protection policies	- Policy review	- Documents - Laws - Regulations
	Tourism management	- Policy review - Observation checklists	- Tables - Graphs - Charts
	Community participation	- Stakeholders Interviews - Questionnaire Survey	- Tables - Graphs - Bar-chart

3. **Synthesis Phase:** The model employs AHP-derived weighted matrices to systematically prioritize the five identity dimensions based on expert and stakeholder consensus. This quantitative weighting system generates two critical evaluative outputs:

- Spatial Identity Score which quantifies built-environment impact.
- Cultural Identity Score that assesses intangible heritage effects.

Together, these complementary scores establish an evidence-based foundation for impact assessment while maintaining balance between tangible conservation priorities and intangible cultural values.

4. **Verification & Intervention Prioritization Phase:** The model validates findings through methodological triangulation, cross-referencing quantitative scores with qualitative stakeholder feedback to ensure contextual relevance. This phase establishes prioritized action tiers based on impact severity:

-Immediate Attention addresses critical threats to spatial-cultural integrity (e.g., active demolition), Moderate Attention mitigates incremental risks (e.g., incompatible renovations), and Maintenance required sustains stable heritage assets (e.g., preventive conservation).

6.1. MODEL OUTPUTS

Two key deliverables operationalize the assessment:

(1) The spatial-cultural identity index (SCII*)*, a standardized composite metric for cross-project benchmarking.

(2) Differentiated policy recommendations, including short-term interventions (emergency stabilization, regulatory adjustments) and long-term frameworks (participatory governance models, cultural continuity programs). These outputs bridge academic analysis with practical urban management tools for decision-makers.

6.2. IMPLICATIONS AND APPLICATIONS OF THE SCIIA MODEL

The SCIIA Model presents a framework for evaluating identity-sensitive revitalization in historic urban districts, addressing the persistent tension between spatial transformation and cultural preservation. By systematically integrating participatory methods, weighted identity dimensions, and phased analysis, the model advances both theoretical and practical approaches to heritage management.

6.2.1. Theoretical and Methodological Contributions

- **Balancing Tangible and Intangible Heritage**: The model's dual output bridges the gap between physical conservation and socio-cultural sustainability. This aligns with recent critiques of heritage practices that prioritize architectural authenticity over community identity (Smith, 2016). The AHP-weighted indicators ensure that subjective cultural values are quantified alongside morphological metrics, offering a more holistic assessment.

- **Participatory Rigor:** The *Preparatory Phase*'s multi-tiered stakeholder engagement mitigates the risk of top-down interventions, a common pitfall in UNESCO-recognized sites. By incorporating local actors and institutional experts early in the process, the model fosters shared ownership of revitalization outcomes, reducing potential conflicts.
- **Adaptability across Contexts**: While developed for Historic Cairo, the model's modular design allows recalibration for other heritage districts. For instance, cities with strong craft traditions might amplify the Socio-Cultural Dimension, while commercial hubs could prioritize Functional-Economic indicators. The tiered Verification Phase further ensures context-specific prioritization.

6.2.3. Practical Applications and Policy Integration

The SCIIA Model's outputs provide actionable tools for urban planners:

- **SCII as a Benchmarking Tool**: Enables cross-project comparisons, helping agencies allocate resources to districts with the highest identity vulnerability.
- **Governance Integration**: The *Policy Dimension*'s focus on tourism management and community participation aligns with SDG 11.4 (UN-Habitat, 2015) and the Faro Convention's emphasis on heritage democratization.

7. Future Research

The present study acknowledges several limitations that open potential avenues for further investigation. Future studies should broaden the expert panel across wider geographical and institutional contexts to enhance representativeness and robustness. The divergence of expert opinions on certain indicators also points to the need for clearer quantitative definitions of consensus, which could be achieved through advanced statistical measures of agreement. In addition, applying and validating the SCIIA model in ongoing or planned revitalization initiatives in Historic Cairo would both demonstrate its practical value and enable iterative refinement of its parameters.

8. Conclusion

This study underscores the critical role of sustainable revitalization in maintaining the spatial and cultural identity of historic urban districts, with a

focused application to Historic Cairo. Through a triangulated methodological framework that integrated narrative analysis, Delphi technique, and AHP-based quantitative assessment, the research developed and validated a set of Key Identity Indicators (KIIs) across five core dimensions: physical-spatial, functional-economic, socio-cultural, perceptual-visual, and governance-policy.

The findings reveal that while physical elements such as morphological continuity and legibility are essential for preserving spatial coherence, socio-cultural indicators hold equally significant weight in sustaining a community's lived identity. Importantly, the study demonstrates that revitalization strategies must extend beyond aesthetic or economic objectives to meaningfully engage with the intangible and participatory dimensions of place.

The SCIIA Model formulated in this research offers a replicable tool for assessing identity impacts in post-revitalization contexts. By quantifying spatial and cultural identity scores and aligning them with expert and stakeholder inputs, the model facilitates informed decision-making that respects heritage authenticity, supports community involvement, and balances conservation with contemporary urban needs.

Ultimately, the study advocates for a shift toward identity-sensitive revitalization frameworks which grounded in local values, multi-dimensional evaluation, and inclusive governance to ensure that urban heritage preservation remains responsive to both historical continuity and future resilience.

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A GAME-BASED PARTICIPATORY FRAMEWORK FOR HYBRID URBAN SPACE

A Strategy for Revitalizing Vernacular Heritage in Beijings Hutong Districts

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Abstract. In recent decades, the renewal of many historic urban districts has been influenced by colonial planning logic, often relying on formalized preservation or tourism-oriented redevelopment. While these approaches keep the physical form of neighborhoods, they often disrupt original community structures and local ways of life. By adopting Western urban governance models, such strategies lead to spatial homogenization and the loss of cultural diversity, reducing both the continuity of vernacular heritage and public involvement. Beijing's hutongs—a key example of vernacular urbanism in China face similar challenges. While the physical spaces of hutongs are declining, online discussions remain active on social media platforms, showing strong cultural resonance and emotional attachment. Through topic modeling and spatial analysis, we find that both locals and visitors are still very interested in hutong spaces. However, they lack effective ways to participate in spatial transformation. Urban planning remains centralized, and public actors are usually excluded from meaningful decision-making. There is a critical gap in connecting digital perceptions of space with real-world governance. This highlights the limits of current technology in spatial management, where digital tools are mainly used for documentation and control rather than for collaboration and co-creation. Such a management-focused approach reinforces a form of "digital colonialism," further weakening the growth potential of local places. In this study, vernacularity is understood not just as formal representation, but as the regeneration of everyday practices, cultural participation, and shared spatial interaction. To address these issues, this paper proposes a game-based hybrid urban participation framework that uses digital data to reshape physical spaces. Through an interactive platform combining digital maps, community mechanisms, and virtual–physical

coupling, the system encourages collaborative urban evolution via both online gameplay and offline participation. The framework is structured in three interconnected layers: The Data Discovery Layer uses the BERTopic algorithm and spatial clustering to analyze over 40,000 social media posts, identifying five geographically distributed thematic categories (e.g., festivals, community life) to generate a "virtual perception map" of persistent local expressions. This feeds into the Hybrid Mapping Layer, which subdivides the physical hutong area into a grid system mapped 1:1 to the virtual platform, creating traceable, upgradable units that allow digital behavior to influence real spatial change. Finally, the Participatory Gameplay Layer enables users to engage in interactive tasks, such as urban farming, festival events, or cooperative missions to earn virtual assets (e.g., Hutong NFTs), which directly affect the status and governance of physical space through features like climatic zones, role mechanics, and shared resource systems that simulate collaborative urban stewardship. Together, the three layers form a data-driven, space-mediated, and game-operated “third space.” Unlike traditional top-down or preservationist models, this framework puts more focus on public perception and interactive agency. While rooted in Beijing's hutongs, it offers a scalable, culturally embedded strategy for reactivating other vernacular historic districts, serving as both a local design prototype and an alternative governance model for more participatory, resilient urban futures.

Keywords: *Gamified Urban Participation，Hybrid Urban Space，Vernacular Site Revitalization，Data-Driven Design Strategy，Third Space Urbanism*

1.Introduction

1.1. BACKGROUND OF URBAN RENEWAL

Urban renewal, especially in the context of non-Western historical districts, often faces a "colonization" dilemma. This dilemma appears in formalized preservation measures and tourism-oriented development strategies, which tend to overlook the continuation of original community structures and cultures. As a result, cultural diversity is lost, and public participation is limited. Government-led renovation models, especially in traditional urban historic districts, often disregard the opinions and needs of residents. This not only worsens cultural homogenization and spatial uniformity, but also contributes to the disappearance of local characteristics and residents' cultural lifestyles (Said, 1978; Harvey, 2005). For example, in the Beijing Hutong area, which serves as a model of Chinese vernacular urbanism, its unique courtyard architecture and rich cultural history hold significant value for preservation. However, due to issues such as unclear property rights,

aging facilities, and population loss, it urgently requires renovation. Although tourism has brought economic benefits to the Shichahai renovation, it has also raised concerns among community residents about their identity and sense of belonging (Li, H., 2023). Meanwhile, despite the physical decay of the Hutong, discussions about it are still active on social media. This shows that both local residents and external tourists have a strong emotional attachment to Hutong culture, which opens the possibility for revitalizing Hutong culture through innovative digital participatory approaches.

1.2. THE RISE OF DIGITAL TECHNOLOGY

With the rise of digital technology, the use of digital tools in urban management has been growing. However, these tools are mainly used for management and representation, and have not yet been effective in promoting citizen participation. In urban planning and governance, digital technology is more often used for recording, monitoring, and strengthening top-down control, rather than encouraging collaboration and localized decision-making. Rob Kitchin (2014) states in Digital Twin Thinking that digital twins are not just virtual replicas of physical entities but also dynamic systems that update in real-time, capable of reflecting and predicting urban changes. He argues that digital twins should be used for more than traditional representations, and their role in decision-making and governance should be a priority (Kitchin, 2021). Still, the connection between digital space perception and urban governance is weak, and there are no effective mechanisms to turn digital participation into real spatial decision-making. The "Ladder of Citizen Participation" model by Sherry Arnstein (1969) shows that true citizen participation requires the transfer of power, not just formal involvement like information-sharing or consultation, but the real ability to influence urban renewal through digital interaction. In this way, digital technology provides a potential path to overcome the limitations of traditional urban renewal, creating a "third space" (Soja, E.W., 1996), where it boosts public engagement and a sense of belonging to the city. This space is not just where physical and virtual spaces meet, but also one that promotes public interaction and participation through gamification, driving significant changes in urban space.

For this reason, this study introduces an innovative Hybrid Participatory Framework, where digital technology and game mechanisms not only record and map urban spaces, but also act as tools for public collaboration and co-creation with the local city, forming a dynamic virtual-physical collaborative governance system.

For example, the EquiCity project introduces a multi-decision system by designing a Markov Decision Process (MDP) in the game. Traditional single-decision models often fail to find optimal solutions in complex urban renewal scenarios, while EquiCity adds various decision systems through gamification, promoting more inclusive decision-making, improving decision quality, and enhancing citizens' sense of participation (McGonigal, 2011). This study builds on this concept and suggests a game-based hybrid participation framework to connect digital and physical spaces, strengthen public participation and decision-making power in urban renewal, and encourage a more democratic and localized urban governance model.

2. Methodology and Mechanisms

To better understand the interaction between virtual and physical spaces and offer a new perspective on urban renewal and cultural heritage preservation, this study uses the three-layer metaverse architecture model proposed by Duan et al. (2021). It creates a layered structure for the interaction between virtual and physical spaces in Beijing's Hutong area. This structure consists of the Data Discovery Layer, Hybrid Mapping Layer, and Participatory Gaming Layer.

2.1. DATA DISCOVERY LAYER

The Data Discovery Layer gathers and analyzes social media data to identify discussion topics and the geographical distribution in the Hutong area. We gathered geotagged posts from social platforms (Weibo) for specific months in 2023 within the Second Ring Road of Beijing. After cleaning the data, irrelevant posts were removed, leaving about 200,000 relevant posts. Then, the BERTopic algorithm was used for semantic analysis, grouping these posts into topics like "historical nostalgia," "natural health," "commercial entertainment," and "festivals." These topics show the cultural sentiments and memories of specific places, and also highlight the tendencies of residents and visitors to engage with urban life. However, recognizing that social media data can be skewed by transient trends, tourist activities, or algorithmic biases—especially during special events or festivals—the data layer is designed not as a sole authority, but as one component of a multi-source calibration system. The algorithmically derived "virtual perception map" is subsequently reviewed and refined by a local steering committee comprised of long-term residents, community representatives, and cultural historians. This committee incorporates localized historical data, intangible cultural heritage records, and on-ground community knowledge to adjust the thematic weighting and geographical boundaries. For example, in some parts

of Beijing's Hutong, discussions about "historical nostalgia" were more common, showing a strong emotional connection from both residents and tourists to the traditional culture. In other areas, the "natural health" topic was more popular, reflecting the area's focus on ecology and sustainable development. To further analyze the geographical spread of these topics, we used spatial clustering techniques to create a virtual perception map. This map shows the distribution of different topics across the Hutong area. From these clustering results, we can clearly see how active each topic is in different regions and the interaction patterns of the residents. These topic areas form the data foundation for the virtual grids in the framework, providing the social basis and direction for updates.

The final determination of a server's theme is therefore a synthesis of data-driven insight, historical-cultural significance, and contemporary community need, ensuring that the platform's interventions are both relevant and culturally rooted. For example, in areas where the"natural health"topic is popular, the framework sets up an interest server around urban farming games. After users select this server, they are connected with the corresponding physical space in that area for interaction. In areas focused on entertainment and commercial activities, the server would lead to a game scene centered on entertainment market stalls. Through this data-driven design, the digital platform can create regional and customized gamified urban renewal plans based on specific geographical and cultural emotional needs.

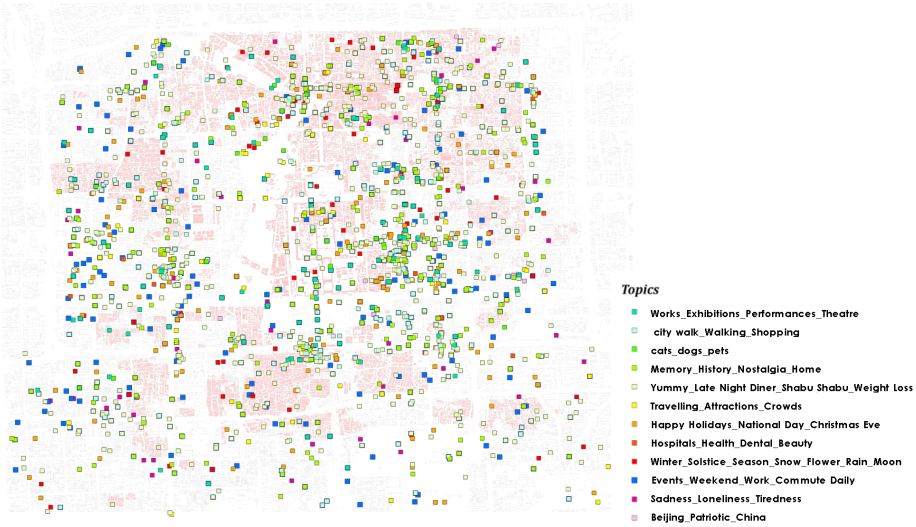


Figure 1. Social Media Data Categorization Map Using BERTopic for Hutong Discussions.

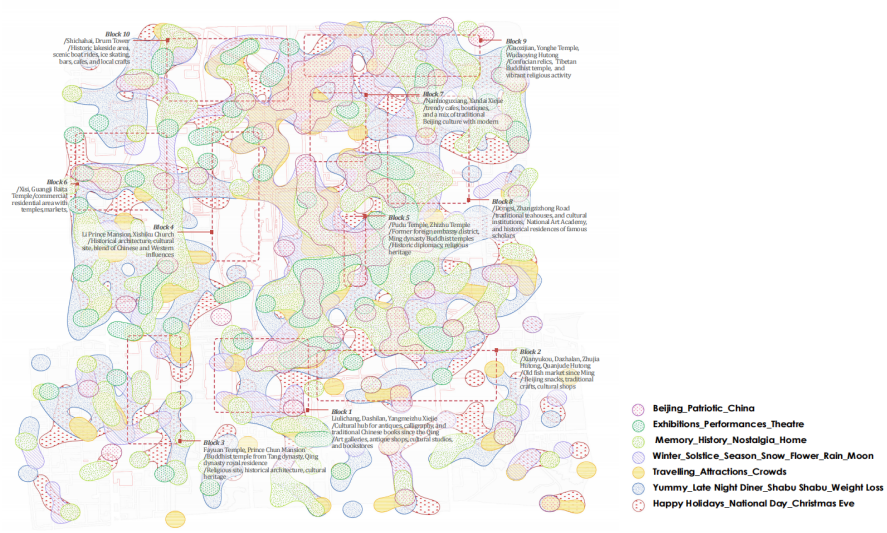


Figure 2. Aggregation of Social Media Data Map

2.2. HYBRID MAPPING LAYER

The core function of the Hybrid Mapping Layer is to create a 1:1 mapping between physical space and the virtual platform, forming an interactive relationship between the digital platform and the actual space. To do this, this study divides the physical Hutong space into a grid system, with each grid unit matching a corresponding, state-synchronized digital twin on the digital platform. Each physical grid measures 6×6 meters. The principles for dividing the grids take into account property boundaries, street texture, and scale feasibility, making sure that each grid's area matches the digital space. In this system, different physical spaces are mapped onto the digital platform based on renovation needs. For areas that do not need renovation or require only minor updates (such as private residences or office spaces), their digital grids will turn gray, showing that these areas do not participate in the current digital mapping. On the other hand, only areas that require updates and renovations will show their digital twin grids on the platform, and these grids will be activated, reflecting their renovation progress and status. Each grid not only corresponds to the specific conditions of the physical space but also shows relevant open data, such as grid area, property costs, street texture, and other detailed information.

This mapping process requires cooperation from platform operators (such as government or property owners) to ensure smooth integration between the digital and physical spaces. Renovation costs incurred in the early stages will be covered by later profits from the digital grids, ensuring the project's sustainable operation.

The role of the Hybrid Mapping Layer is to serve as the key infrastructure connecting virtual and physical spaces, allowing digital actions to directly impact the renovation and governance of physical spaces. Each digital grid is traceable, recording user behavior and resource status. This layer promotes a more flexible and collaborative urban renewal model, laying the groundwork for decentralized spatial management, moving away from the traditional centralized planning model. It gradually shifts the power of urban renewal, cultural preservation, and resource management to the digital hybrid space.

2.3. PARTICIPATORY GAMING LAYER

The design of the Participatory Gaming Layer aims to encourage user participation through gamified mechanisms. Players can earn virtual assets (such as Hutong Coins) by completing tasks and use these assets to influence the renovation of physical spaces. This layer not only boosts users' sense of participation and responsibility but also enables collaborative and decentralized governance of regional updates through game-based decisions.

The public logs into the platform as players and work together with others to make spatial decisions that affect the renovation of physical spaces. The tasks in the game are closely linked to the direction of space renovation, allowing players to express their personal aspirations for the space, making decisions that balance the historical information and memories of urban spaces with economic potential. These game choices determine the renovation direction of specific areas. The platform uses a multiplayer game-theory mechanism, where players can jointly decide the direction of grid renovation through bidding, negotiation, and other methods. Multiple players may participate in the renovation of a specific area, negotiating and reaching consensus on issues such as whether to upgrade a grid or how to use virtual assets to improve its functionality. This process, driven by the game-theory mechanism in the virtual environment, ensures that urban renewal is no longer controlled by a few experts but involves widespread participation from residents and players.

To further ensure that this widespread participation reinforces, rather than dilutes, local cultural authenticity, the gameplay mechanics are specifically designed to embed and reward local practices. This is achieved through a curated library of virtual assets—such as native plant species and traditional architectural elements—that grounds creative choices in the local context. Moreover, the platform incentivizes on-ground engagement by offering gameplay bonuses for participation in verified offline community events, effectively bridging the digital and physical communities. Critically, within the multiplayer negotiation mechanisms, proposals that garner strong support

from verified local residents are given procedural advantages, ensuring that the community's collective voice holds substantial weight in shaping the evolution of their space.

The platform includes a full economic system, using virtual currency (Hutong Coins) as an economic incentive. Players' decisions and actions in the game result in tangible economic returns, such as earning profits from renovating spaces or purchasing and claiming new grids with Hutong Coins. To ensure long-term fairness and sustainability, this economic system is underpinned by built-in governance mechanisms. For instance, soft limits are placed on the number of grids and the amount of virtual currency a single account can hold, preventing excessive concentration of assets. Additionally, a transaction tax mechanism is designed, with its revenue channeled into a community pool to fund public space renovations and subsidize resource-limited users, thereby mitigating the "Matthew Effect" and promoting broader inclusion. The platform returns the profits generated from space renovation to the players, creating a self-sustaining economic system. In this process, the platform will accept small developers to help manage the online-offline interaction, and the profits generated by the game will be directly transferred to developers through the platform. Hutong Coins, in the form of NFTs, continuously attract more residents and developers to participate, driving broader urban renewal and heritage preservation.

3. Project Case: The Farm

The experimental prototype of this study's framework was based on the "natural health" scenario in the Beijing Hutong area. Using hotspot analysis of topics like natural health in the data layer, a specific implementation area was selected. The choice of this experimental scenario matches the hot topics and community needs in the digital space and also follows the concept of sustainable development, making it the first experimental scene for platform implementation. Based on the identification of natural theme areas in the data layer, the digital platform's functionality was designed mainly around the "urban farm" model, which further supports the deep integration of virtual and physical spaces.

3.1. GAME MECHANISMS

On the platform, users can participate in planting games within specific grids using Hutong Coins in a shared way. Players make decisions based on the current resources of the site, suggested update directions, cost projections, and future expectations, clearly setting multiple development goals and guiding spatial transformation. The decision-making process in the game

includes choosing different types of farm spaces and service facilities, as well as managing multiple objectives.

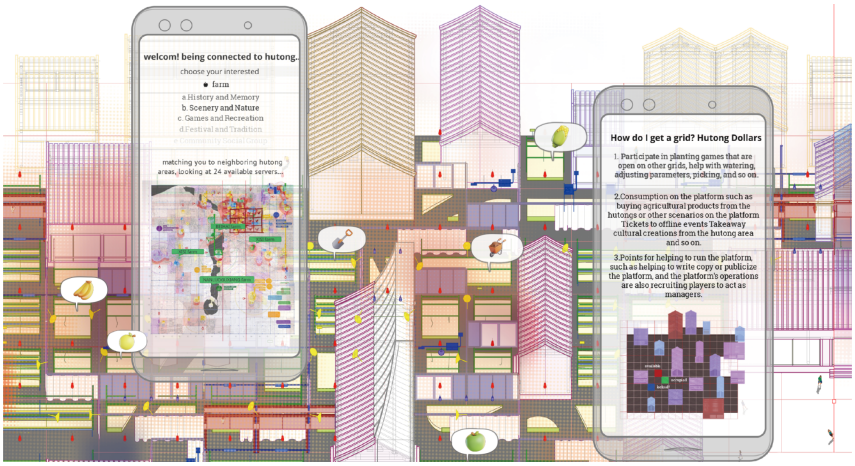


Figure 3. Platform Interface - Matching Areas for Game Participation

3.1.1. Farm Type Selection:

In the game, players can select different types of farm spaces based on their interests and needs. For example, the modular species farm can simulate planting needs under different climate conditions, including temperate, tropical, subtropical, mountainous, and rainforest climates. Crucially, the plant species available in each climate module are not generic but are specifically chosen to reflect the horticultural traditions and practical needs of Beijing's hutong life. Each climate type grows specific plants, and each type of plant has different planting costs and returns. For example, a tropical climate zone may require more temperature control equipment, while a mountainous climate zone may need stronger frost-resistant capabilities. The selection of these farm modules directly impacts the players' decisions and determines the direction of the area's renovation.

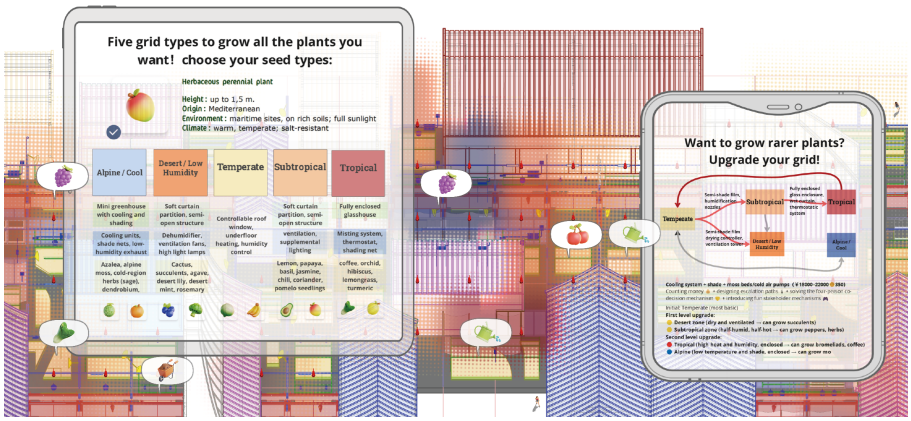


Figure 4. Electronic Platform Interface - Game Flow

3.1.2. Selection of Multifunctional Service Facilities

Players can also choose to build multifunctional service facilities within the farm area, such as seed cultivation rooms, warehouses, restaurants, and markets. For example, the seed cultivation room provides the initial resources required for planting, while the restaurant and market process and trade agricultural products. These service facilities improve the operational efficiency of the farm and encourage interaction and cultural heritage within the offline community.

3.1.3. Introduction of Energy Facilities

In the game, players can also choose to introduce energy facilities, such as energy batteries, which are provided by contractors on the platform and can be installed on-site. Contractors offer energy equipment suitable for the farm area. Through this mechanism, the platform simulates energy management digitization and provides a reference for green energy transformation in the real world.

During the game, players can also start votes on space development through an integrated voting system, deciding whether to change the resource allocation or update the direction of a specific area.

3.1.4. Integration with Local Cultural Calendar：

Beyond static facilities, the farm gameplay is dynamically tied to the local cultural calendar. The platform initiates seasonal ‘Cultural Questlines’ around traditional festivals such as the Mid-Autumn Festival or Lunar New Year. During these events, players might be tasked with collectively growing specific crops or decorating the virtual and physical farm space with traditional ornaments. Completing these quests yields unique rewards and

unlocks historical narratives about the festivals' significance in hutong life, seamlessly weaving cultural education into the core game loop.

3.2. SUSTAINABLE DEVELOPMENT MECHANISM DESIGN

In terms of sustainability, the platform introduces smart control systems to manage farm resources and integrates systems such as rainwater management, solar power generation, and smart grids. Through the smart currency system (such as Hutong Coins), players can easily regulate and manage sustainable resources on-site, helping to ensure the sustainable development of the space. The farm is equipped with a rainwater management system: rainwater is collected and purified, providing irrigation for the farm. Solar power provides energy, and smart control systems regulate energy usage through the smart grid, with surplus energy automatically traded. Additionally, the smart currency system uses blockchain and smart contract technologies in a microgrid energy trading system, optimizing the balance of energy supply and demand through energy tokens and demand response contracts to maintain cleaner operations (Saeed, N., Wen, F. & Afzal, M.Z., 2024).

There are also sustainable rewards and incentive mechanisms. For example, if a region increases the share of the smart energy system to more than 80% of the space's energy consumption, the platform will provide additional rewards. This not only motivates players to focus on sustainability but also encourages the use of green energy in urban renewal.

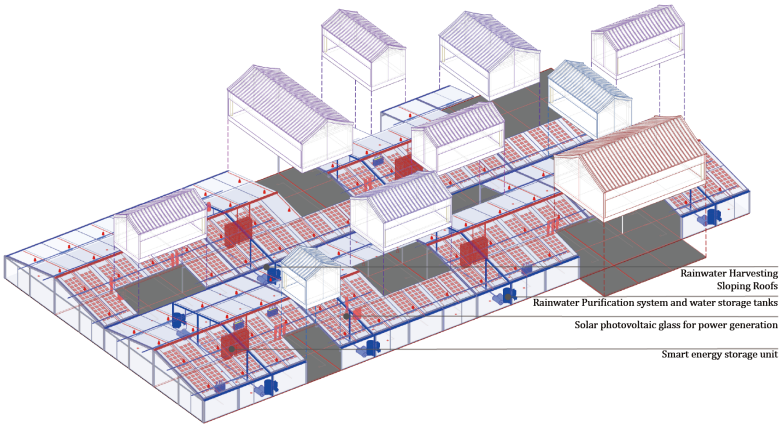


Figure 5. Sustainable Energy Management System

3.3. MAPPING OF ONLINE AND OFFLINE SPACES

In this framework, the digital platform and physical space affect each other, creating a "third space." Online players participate through Hutong Coins and tasks, choosing the renovation direction of the offline space. At the same time, offline renovations (such as facility construction, energy updates, etc.) also influence the progress of the game through the feedback mechanisms of the digital platform.

For example, smart agricultural equipment installed in the real world (such as water pumps and planting robots) plans corresponding automated transportation systems based on planting conditions in the digital space. The digital platform records the status of each grid and updates the physical space changes in real-time. This mutual feedback between online and offline spaces makes the spatial update process more flexible and collaborative, leading to a continuously evolving urban renewal model that integrates both virtual and physical spaces.



Figure 6. Electronic Platform Interface - Game Harvest

4. Limitations

While this study presents an innovative framework, its development and implementation face several interrelated challenges. The project remains in an experimental phase, and building a fully functional platform involves significant technical hurdles, particularly in achieving cost-effective and robust real-time synchronization between its digital and physical layers.

A central set of concerns revolves around digital equity and data bias. The framework's initial reliance on social media data risks amplifying the voices of digitally active groups and can be swayed by transient online trends. To mitigate this, the data discovery layer is conceived not as an autonomous authority, but as one input within a multi-source calibration system. This system integrates historical data, traditional surveys, and the essential oversight of a local steering committee to cross-verify digital findings, ensuring platform directions are not disproportionately skewed by any single demographic or temporal fluctuation.

Closely linked is the challenge of ensuring the platform's development remains deeply rooted in the local context. Beyond the data layer, this cultural grounding must permeate the entire user experience. The gamified activities and virtual assets are therefore intentionally curated to reflect local biodiversity, traditional practices, and the community's cultural calendar. This design is crucial to prevent the hybrid platform from becoming a generic digital overlay and instead foster a continuous dialogue between online engagement and offline, place-based life.

Further complexities arise in the realms of governance and law. Preventing virtual "land speculation" through carefully designed ownership limits and tax mechanisms, resolving complex property rights, safeguarding data privacy, and maintaining long-term user engagement are persistent issues that necessitate the co-development of detailed governance rules alongside the technical platform.

5. Conclusions and Future Work

Despite these challenges, this paper proposes an innovative game-based hybrid participation framework as a strategy for the decolonization of the renovation of Beijing's Hutong and similar heritage sites, emphasizing the potential of virtual-physical collaborative governance. By leveraging AI-driven data discovery, hybrid digital-physical mapping, and gamified participatory mechanisms, the framework empowers bottom-up collaboration and local cultural expression. It challenges top-down planning models by democratizing decision-making, localizing knowledge production, and revitalizing culture from within. Through the involvement of multiple stakeholders, it anchors spatial transformation and cultural narratives in the local context, thereby avoiding excessive reliance on external capital and tourism-centric development. Furthermore, the framework's integrated economic model and embedded sustainable design principles enhance urban resilience, particularly in areas such as energy,

water management, and local food production. The scalable three-layer structure offers a viable and replicable pathway for fostering culturally-grounded spatial regeneration in diverse urban contexts.

Looking ahead, our research will transition from conceptual design to practical implementation through a focused development pathway. The immediate next step involves building a simplified, web-based prototype centered on a core theme like the urban farm, to be piloted within a select Hutong courtyard. This initial phase is crucial for testing the coordination between online and offline interactions, gathering resident feedback, and validating the core gameplay loops. Subsequently, we will refine the platform's economic and governance mechanisms based on this real-world data, ensuring their fairness and viability while expanding to incorporate additional thematic scenarios and real sustainable data streams. The long-term vision is to evolve this prototype into a robust ecosystem by opening the platform to broader collaboration, establishing formal partnerships with local stakeholders, and ultimately scaling the framework to more historic districts, thereby promoting broader cultural and spatial regeneration.

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USING SOCIO-ECONOMIC INDICATORS, SMART TRANSIT SYSTEMS, AND URBAN SIMULATOR TO ACCELERATE ZEV ADOPTION AND REDUCE VMT

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Abstract. Globally, on-road transportation is the source of 15% of greenhouse gas (GHG) emissions and the cause of an estimated 385,000 premature deaths from PM2.5. The action by cities to reduce on-road emissions is critically important to meet IPCC targets, as cities are the source of 75% of global energy-related GHG emissions. In the City of Houston, Texas, on-road transportation is 48% of baseline GHG in their Climate Action Plan (CAP). To meet a 2050 target of net zero, the City Climate Action Plan (CAP) aims to reduce emissions 70% below a 2014 baseline and use renewable sources for a 30% offset. This is a challenging target, as Houston is a low density and auto-dependent city with 89% of on-road GHG emissions are from cars and small trucks and there is a low modal split for public transit. It also has uneven pattern of socio-economic indicators indicating barriers to ZEV adoption. Strategies include accelerating access to Zero Emissions Vehicles (ZEVs) and reducing Vehicles Miles Traveled (VMT) by 20% through public transit enhancements and city design. This paper shares methods for creating an on-road emissions baseline and evaluating policy strategies that use socio-economic indicators and Intelligent Transportation Systems (ITS) to accelerate adoption of ZEVs and reduce VMT. Improving the modal split is facilitated by smart parking and transit strategies that build in incentives,

data management and security, and ZEV fleet vehicle and driver management. The smart transit model demonstrates potential for increased reliability, ridership, and economic performance. Policy options are discussed and evaluated, and potential actions identified. To support the evaluation of these strategies, a simulation environment was developed using the Unity 3D game engine. This virtual platform enables dynamic modeling of urban mobility conditions, allowing for the analysis and visualization of transportation behaviors and policy scenarios in a controlled, interactive setting. Auto-dependent cities striving to meet 2050 emission targets can benefit from indicators, metrics, methods, and technologies discussed.

Keywords: *Reducing On-Road GHG Emissions, Smart Transit and Parking, Socio-economic Indicators for ZEV Adoption, ITS and Transport GHG Reduction, Smart Transit and GHG*

1. Introduction

Transportation is one of the largest contributors to climate change and public health risks. Even though different data has been reported on the impact of on-road transport on the human health, the most conservative data show that on-road transportation contributes to 53,000 death due to PM2.5 (Li et al., 2021). In addition, it is estimated to contribute about 15% of greenhouse gas (GHG) emissions (icct, 2019). Within cities, on-road transportation accounts for 75% of this 15% share of global GHG emissions and therefore cities bear a great responsibility of reducing GHG to meet the Intergovernmental Panel on Climate Change (IPCC). Two main approaches can be taken by city managers to reduce GHG emissions, first is to promote the use of zero-Emission Vehicles (ZEVs) by citizens, second is to reduce the Vehicle Miles Traveled (VMT) through investing in public transit, land-use, and demand management (Sims et al., 2014). Achieving these goals will combine technological, socio-economical and urban planning approaches.

Many government programs promote the adoption of ZEV vehicle in the United States (Jenn, et. Al. 2018), Europe (Martins, et al., 2024), and around the world (Sheldon et al. 2024). For example, California's Battery Electric Vehicle (BEV) program was one of the firs programs in the United States to promote EV adoption. The study done by Jenn showed that an increase in $1,000 rebate corresponded to an increase of 2.6% in EV sales in the US. Even though the impact of financial incentive policies is not uniform in European countries, Martins' study shows that

incentives can contribute to EV adoption. The study done by Sheldon on 23 countries around the world using data from 2010 to 2019, showed that subsidies are effectively boosting EV market penetration.

Parallel research on transport demand management highlights the value of time travelled, and strategies to reducing Vehicles Miles Travelled (VMT) through congestion pricing, parking restrictions, and transit-oriented development (Börjesson et al., 2014, Ding, C). The rapid deployment of Intelligent Transportation Systems (ITS) has added another dimension to this landscape (Wang, et al., 2024). Advances in smart parking, integrated fare collection, and real-time fleet management have been shown to improve transit reliability, optimize traffic flow, and reduce unnecessary miles traveled by vehicle.

Despite these advances, policymakers and infrastructure developers need tools that will enable them to fully understand and act upon the complex relationship between transportation systems and GHG emissions. Existing tools and modeling techniques require experts to run them and lack the ability to visualize and analyze data for non-technical users. The result is that city managers receive aggregated statistics or a fragmented knowledge that does not provide clear and granular information.

To equitably achieve 2050 greenhouse gas reduction targets from on-road transportation, cities will need to deploy strategies that utilize emerging technologies, switch fuels, and reduce vehicle miles traveled. This paper integrates planning and engineering research to demonstrate how large sprawling cities like Houston can meet aggressive climate action goals. Research includes development of socio-economic indicators for EV adoption, smart transit systems, and preparation of a baseline Urban Simulator to accelerate ZEV adoption and reduce VMT.

2. Cities Meeting Transportation GHG and EV Adoption Targets

The action by cities to reduce on-road emissions is critically important to meet IPCC targets, as cities are the source of 75% of global energy-related GHG emissions (UN-Habitat, 2025). In the City of Houston, Texas, on-road transportation is 48% of baseline GHG in their Climate Action Plan. To meet a 2050 target of net zero, the Houston Climate Action Plan (H-CAP) aims to reduce on-road transportation emissions 70% below a 2014 baseline and use renewable sources for a 30% offset (City of Houston, 2020).

2.1 CITY GHG EMISSIONS AND PROTOCOLS

The H-CAP utilized the C40 protocols for collecting and measuring GHG emissions data. The Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC). The GPC was created by C40, ICLEI, and the World Resources Institute (WRI). It provides a consistent framework for cities to create emissions baselines, set goals, and monitor progress (Doust, 2018).

2.2 H-CAP BASELINE EMISSIONS INVENTORY

The H-CAP GHG baseline for 2014 includes 49% from stationary energy sources (16,454,686 MTCO2e), 48% from transportation (16,140,987 MTCO2e), and 2% from waste (818,344 MTCO2e). On-road transportation is responsible for 99% of transportation emissions (15,932,882 MTCO2e) and the balance is from off-road and rail sources. Transportation emissions were estimated using the Environmental Protection Agency's (EPA) MOtor Vehicle Emission Simulator (MOVES) model with vehicle miles traveled (VMT) provide by Texas Department of Transportation (TxDOT).

2.3 ON-ROAD GHG EMISSIONS 2050 TARGET

The H-CAP provides a roadmap for meeting a net zero 2050 target. It establishes 2030 (33%), 2040 (58%), and 2050 (70%) below baseline GHG reduction goals and parallel development of renewable energy offsets. It includes performance assumptions for vehicle class and VMT reduction. Goals are to be met implementing a set of strategies and related actions.

2.4 PUBLIC HEALTH CO-BENEFITS

On-road transportation is a primary source of PM2.5. Reduction in PM2.5 is a co-benefit of meeting GHG emission targets. PM2.5 causes a variety of health impacts to the pulmonary, cardiac, vascular, and neurological systems (Li & Managi, 2021). The National Institutes of Health estimates there were over 8,400 premature deaths in Texas due to PM2.5 (Bryan & Landrigan, 2023).

3. Houston the Low-Density City

Houston's GHG 2050 targets for transportation are challenging. It is a low density and auto-dependent city with 89% of on-road GHG emissions from cars and small trucks and a low modal split for public transit. It also has an uneven pattern of socio-economic indicators representing barriers to ZEV adoption (Race, Houston-CAP On-Road Transportation GHG Emissions: Baseline, BAU, and Policy Scenario Analysis, 2019).

3.1 AUTO DEPENDENCY

Houston is a fast growing and low-density city. It is expected to grow from 2.52 million in 2020 to over 3.3 million people by 2050. Houston is a global outlier region with a low density, high per capita VMT and transportation energy consumption (Rodrigue, 2024). Houston's population per square mile is approximately 3,800 compared to Los Angles' 8,500, Chicago's 12,000, and NYC's 28,000 (Maciag, 2013). Houston's low-density results in congestion, long commutes, and a large percentage of GHG emissions from personal vehicles parked in peoples' driveways. Therefore, the pathway to zero emissions from on-road transportation will require a focus on accelerating adoption of ZEV and VMT reductions.

3.2 SOCIO-ECONOMIC PATTERNS AND THE AFFORDABILITY GAP

Houston has an uneven pattern of households that can afford new more expensive electric vehicles and related benefits. This results in an affordability gap and prevents poorer households from benefiting from lower transportation costs of owning an EV.

To better understand development of policies, strategies and related actions that can accelerate equitable adoption of EVs, researchers at University of Houston prepared an EV equity index (Race, Equitable Access to EV-Mobility, 2022). The index is comprised of internal and external indicators. Internal indicators include educational attainment, poverty level households, renter households, households with less than two cars. External indicators include public charging access, cost of EV, and existing EV incentives. Using census data, researchers mapped EV Equity Index (Figure 1). This map can be used to formulate policies and strategies to accelerate adoption, including public access charging, apartment charging for renters, and financial incentives.

In addition, Houston is comprised of communities that have a high percentage of households that cannot afford car loans equaling 10% of their household income. In 2022 only 19% of Harris County census tracts had median income households that could afford a new EVs. Even with Federal incentives of $4,000 for used EVs, only 44% of census tracts had median income households can afford a used EV (Figure 2).

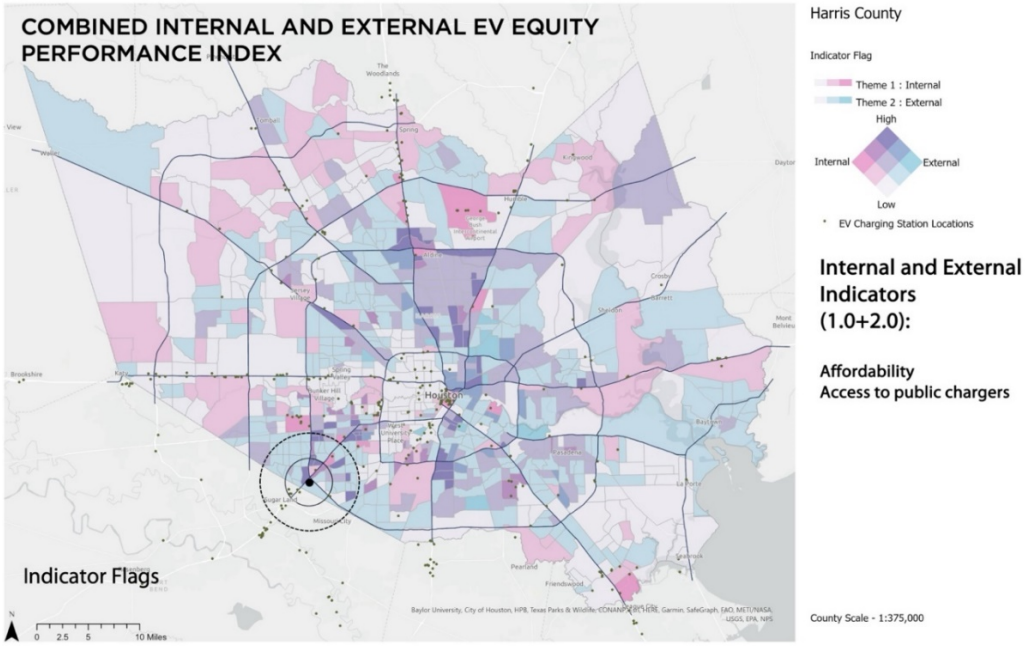


Figure 1. EV Equity Index.

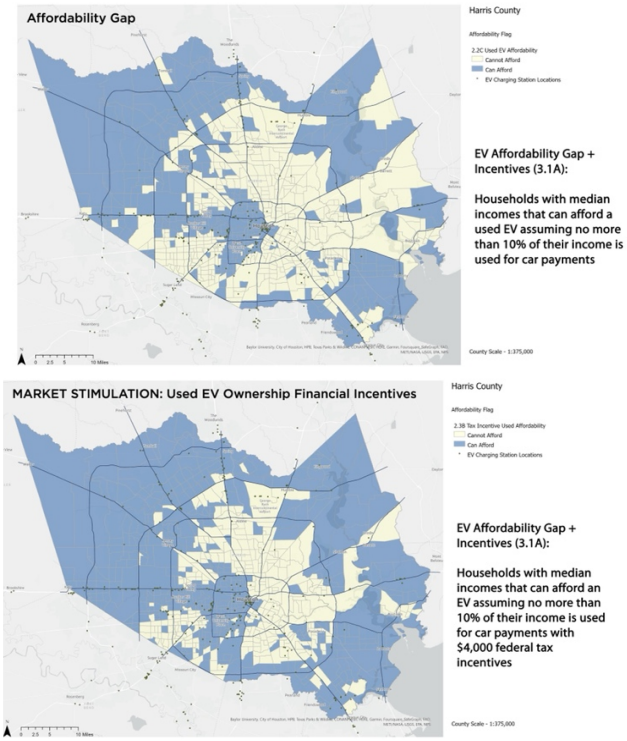


Figure 2. EV Ownership Affordability Gap.

3.3 EV ADOPTION CURVES AND CHARGING INFRASTRUCTURE

The Houston region has growing light vehicle EV fleet but is lagging in public access charging. In 2024, 10.2% of U.S. auto sales were EVs. The last quarter of 2024 was 10.9% (Alliance for Automotive Information, 2025). The Houston region EV adoption is growing faster than the national average. EV sales in the fourth quarter of 2024 were 14.53% the first half of 2024, and nearly 16% in the fourth quarter (Evolve Houston, 2024). In 2024, the national ratio of EV to (nonhome) public charger was approximately 1:22 (Price, 2025) compared to a 1:25.8 ratio in Texas (DOE, 2025).

4. Policy Options

In the Climate Action Planning process, the City of Houston explored policy options for meeting emission reduction targets. Variables included EV adoption rate assumptions, VMT reduction, and population growth. The H-CAP process included development of a business as usual (BAU) estimate and development of policy scenarios to inform community discussion, and a preferred scenario that became the basis for the H-CAP on-road transportation goals and strategies.

4.1 BUSINESS AS USUAL

A BAU estimate was prepared using data from the 2014 Baseline and 2050 population growth estimates from the Texas Development Board. The BAU assumed there was no policy or technology innovation and the VMT growth tracked population and fuel efficiencies stayed the same as the baseline.

4.2 POLICY SCENARIOS

Four policy scenarios were developed to explore the types of assumptions and actions would provide progress towards meeting a net zero GHG on-road transportation 2050 target. Scenario one assumed Houston would meet the Obama era car and small truck 2025 and truck 2027 standards. Scenario 2 assumed the same fuel efficiency standards but with an added 30% reduction in VMT. The third scenario assumed vehicles would be meeting “technical limits” of fuel efficiency and there would be a 40% reduction in VMT. The H-CAP Transportation Subcommittee discussion resulted in a preferred scenario 4 - - “technical limits” and a 20% reduction in VMT. This would reduce GHG from on-road transportation by 70% in 2050 (Figure 3).

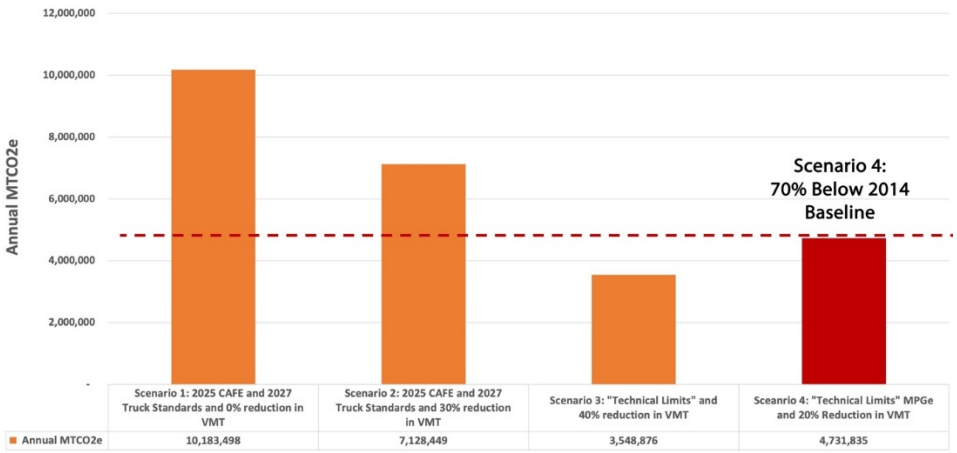


Figure 3. On-Road Transportation Policy Scenarios.

4.3 SUPPLY-SIDE IMPLICATIONS

Even with an assertive demand reduction policy for on-road transportation, there still is a performance gap. To close this gap, on-road transportation would need an estimated 15,490 gWh of renewable energy annually (Race, Houston-CAP On-Road Transportation GHG Emissions: Baseline, BAU, and Policy Scenario Analysis, 2019). Figure 4 indicates the 2030, 2040, and 2050 goals for GHG reductions and off-sets in renewable energy to meet 2050 net zero targets. Using data from National Renewable Energy Lab (NREL) for average gWh per acre, Houston's offsets would require about 67 square miles of community solar.

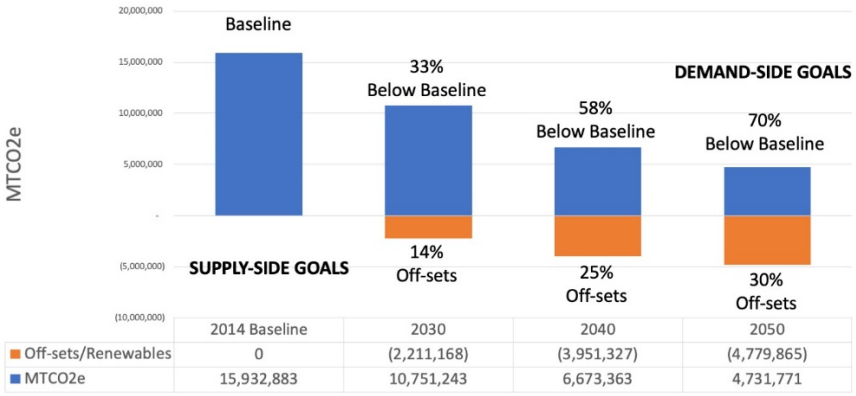


Figure 4. On-Road Transportation Goals.

5. Use of ITS and Smart Transit and Intermodal Optimization

The assumed 20% reduction in VMT is an aggressive goal. Sprawling Houston would have a lower VMT than Portland, Oregon. To achieve this, Houston will need to implement land use planning around transit, improve intermodal performance, and optimize public transit. As a low-density city, Houston must increase both transit penetration and its intermodal performance. METRO owns 30 park and ride sites. Many of these can be planned to support electrification of vehicles, diversify modes, and improve mode transfers (Figure 5).



Figure 5. Intermodal Transportation Hubs.

5.1 INTELLIGENT TRANSPORTATION SYSTEM

Applied technologies could include expanded use of Intelligent Transportation Systems (ITS), optimization of streets and highways and improving access to intermodal transportation hubs. Both the Texas Department of Transportation (TxDOT) and City of Houston Department of Public Works (DPW) have extensive Bluetooth sensor networks. They have installed Bluetooth trackers along highways and thoroughfares. TxDOT has set up the TranStar sensor network to measure travel speed and congestion on Houston highways. The sensors track Bluetooth devices (phones) as an electronic address. Each roadside reader senses addresses emitted by enabled devices as they pass (Houston TranStar, 2025). DPW integrates ITS infrastructure to improve safety, efficiency, and mobility. The system includes Bluetooth devices, Ethernet switches and routers, fiber optic cables, Closed-Circuit Television (CCTV) cameras, mid-block

counters, Dynamic Messaging Signs, and enhanced detection devices. ITS reduces delays at intersections, thereby controlling speeds and improving travel time (Houston Public Works, 2025).

5.2 SMART TRANSIT HUBS

METRO has 30 park and ride sites that can become smart transit hubs. Their design can reflect expected functions and approach to data management. A templet for smart transit hubs would provide common framework for planning, defining, and integrating intelligent transportation systems. This approach can serve as METRO's roadmap to evolving into smart transit service provider. The hub could be organized around four services:

- Smart Charging Infrastructure–strategies for placing charging stations across the park and ride facilities to ensure convenient access for electric vehicle users.
- Smart Parking Solutions–leveraging real-time data and advanced parking management systems to optimize parking space availability.
- METRO Pass System–enabling park and ride users to seamlessly transition between various transportation modes (buses, trains, and parking) using a single payment method.
- Intermodal Connectivity–allowing commuters to switch between EVs, buses, or trains with minimal effort and ensuring a smooth and efficient commuting experience supported by digital displays and user-friendly mobile applications.

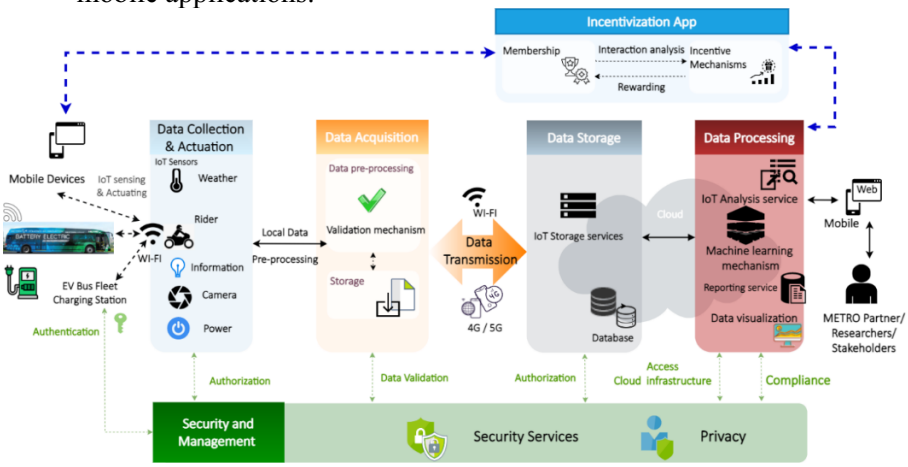


Figure 6. Smart Transit Hub Digital Services.

- The proposal applies smart technologies that improve the reliability, comfort, and affordability of transit services. The smart transportation intermodal hubs can be organized into four layers and supported with incentives and specialized security protocols (Figure 6).
- The Data Collection Layer enables the METRO system to collect data from its EV bus fleet and charging station and information about riders to improve their experience. Data will include images, GPS, Weather, etc. This layer involves privacy protection and authentication.
- The Data Acquisition Layer receives data from the data collection layer and stores it in the device and buses to apply the data validation mechanism to filter out unqualified data and to hide the private information in the images and videos before submitting it to the cloud. The data will be transmitted to the next layer after it is authorized. If we're using smartphone apps to collect data, users will be able to make decisions about what data is authorized and what modes of transportation is he interested in.
- The Data Storage Layer is a cloud server that consists of aggregating data that has been received from the Data Acquisition Layer.
- The Data Processing Layer is a cloud computing layer that provides resources to process aggregated data to verify its reliability and eliminate redundant data. This layer also applies data analysis, reporting, and data visualization services to retrieve as much knowledge as possible before providing it to the stakeholder application and designing incentives to engage riders to use public transport integrated with intermodal transport.
- Incentivization App presents the incentive mechanism service. Its main role consists of applying the game design elements we proposed for this architecture, acting as a link between the cloud server which provides incentives to users who favor EV-related services.
- Security Management is responsible for providing a secure service that combines varied security aspects such as data security in terms of data integrity, data access, authentication, authorization, and data privacy.

5.3 SMART EV CHARGING

The METRO's smart transit hubs will operate smart EV charging stations within the hub's Data Collection Layer, collecting usage patterns, occupancy data, energy consumption, and charging behavior (Oladimeji D, 2023). This integration will enable METRO managers to align charging services with real-time transit

schedules and passenger flow. Using the data collected, the application processing layer will employ predictive analytics to manage grid load and use the learning experience to size the number of EV charging station around the METRO network.

Given that charging transactions and location data are exchanged through a network, the Security Management framework governs all aspects of authentication, encryption, and user consent. End-to-end data protection ensures that EV charging data can be safely leveraged for system optimization without compromising user privacy.

The data collected will enable the following smart functionalities:

- Implement Incentivization model that uses gamification by rewarding users who regularly charge at METRO hubs or synchronize their EV trips with public transport usage (Pilla, 2025). Through a unified METRO Pass System, users can view real-time charger availability, reserve slots, and pay using the same digital wallet used for parking or bus fare.
- Reduce range anxiety and support EV adoption. Many users who live in apartment and rely on public transportation system will find the charging station and good resource.
- Generate actionable insights for infrastructure planning and service improvement. This will strengthen the regional vision for sustainable, data-driven urban mobility (Michalakopoulou, 2025).

6. Policy Evaluation Framework Methods

Enabling technologies such as intelligent transportation systems, smart transit hubs, and EV charging infrastructure provide essential tools for advancing decarbonization and sustainable mobility. However, their true impact depends on careful evaluation and integration within broader policy strategies. To address this need, we propose a policy evaluation framework that incorporates socio-economic indicators, technology adoption patterns, and spatial mobility data into a unified assessment platform.

A central innovation of this framework is the use of a Unity 3D-based simulation environment. Unity 3D is particularly well-suited for this application, as it enables the development of interactive, high-fidelity simulations that accurately represent urban mobility dynamics. This capability allows decision-makers to explore, visualize, and evaluate transportation interventions in a safe and controlled virtual environment (Kassim, 2021) (Martinez, 2025). Ultimately, this tool enhances the

rigor, transparency, and equity of policy design by enabling the testing of urban mobility strategies under realistic conditions.

6.1 ESTABLISHING A BASELINE GHG INVENTORY

A critical foundation of any rigorous policy evaluation framework is the establishment of a comprehensive baseline GHG emissions inventory for the transportation sector. This baseline serves not only as a diagnostic tool to quantify existing emissions, but also as a reference point for assessing the effectiveness of proposed interventions over time. To ensure both analytical accuracy and policy relevance, the inventory must capture emissions across multiple dimensions, including transportation modes, fuel types, spatial distribution, temporal variability, and socio-demographic characteristics. The process begins with the integration of high-resolution traffic activity data, typically derived from road segment-level vehicle counts, average travel speeds, and congestion patterns. These data are often sourced from transportation departments, GPS-based mobility datasets, or traffic sensor networks. Coupled with detailed vehicle registration records; disaggregated by vehicle type, fuel category, and model year. These inputs enable the estimation of vehicle fleet composition and usage patterns. Origin-destination matrices, reconstructed from mobile phone GPS traces, transit smart card records, or travel surveys, offer insight into the spatial structure of daily travel demand. This information is particularly important for capturing the variation in travel intensity and modal split across different urban neighborhoods, income groups, and employment zones. The resulting inventory enables the construction of a temporally and spatially resolved emissions map that reflects both the current state of the transportation system and its embedded disparities. Such granularity is crucial for modeling the marginal effects of policy interventions—such as electrification, congestion pricing, or land use reform on specific subpopulations or regions. Furthermore, a robust baseline enhances transparency and accountability in long-term climate action planning, supporting both municipal compliance with emission reduction targets and equitable policy design.

6.2 TARGETS, GOALS, AND ACTIONS

A central component of the policy evaluation framework involves the articulation and operationalization of SMART (Specific, Measurable, Achievable, Relevant, and Time-bound) goals. These goals offer a structured and transparent approach for guiding transportation decarbonization efforts, ensuring accountability, and

enabling iterative improvements over time. When clearly defined and contextually grounded, such goals help policymakers and stakeholders align investments and interventions with long-term climate, equity, and mobility objectives. A primary focus within this structure is the reduction of GHG emissions from the transportation sector. This aligns with federal and state-level carbon neutrality pledges and is supported by sector-specific carbon budgeting and lifecycle emissions modeling.

Achieving GHG reductions requires both technological transitions and behavioral shifts, including widespread electrification and mode substitution. Another critical dimension of this framework involves ZEV adoption goals. For example, a jurisdiction may set the goal of reaching 30% ZEV market share by 2035, with explicit provisions for equitable access across income brackets and geographic areas. Such targets are often embedded in state ZEV action plans and may be reinforced by incentives, infrastructure deployment mandates, and outreach campaigns targeting underserved populations. Income-based ZEV incentives and mobility credits can enhance participation from disadvantaged communities, mitigating existing disparities in EV adoption. In parallel, goals to reduce VMT address the underlying demand for car travel and aim to reduce overall transportation energy consumption. For example, Houston's goal is to reduce VMT by 20% reduction in VMT per capita by 2050. This is pursued through policies promoting transit-oriented development, active transportation infrastructure, and the integration of shared and public mobility options. Reductions in VMT not only cut emissions but also improve public health outcomes and reduce congestion. Complementary to these outcome goals are infrastructure and service provision benchmarks that support the adoption of cleaner and more efficient transport modes. These include adequate deployment of public EV charging stations. Such benchmarks serve as critical enablers of behavioral change by reducing range anxiety, improving transit reliability, and fostering mode shift. Each target and action are spatially and demographically contextualized to promote transportation justice. Geographic Information Systems (GIS) and socio-demographic data are used to map interventions to specific communities, accounting for factors such as income, racial composition, housing density, and transit dependency. This granularity ensures that policy interventions do not disproportionately benefit already advantaged populations and that the distributional impacts of decarbonization policies are explicitly assessed and addressed. By integrating these SMART goals within a broader equity-centered planning framework, cities can pursue transportation decarbonization in a way that is both technically effective and socially inclusive. The clear articulation of

such goals enables continuous performance tracking, adaptive management, and public accountability essential components of any resilient and just climate action strategy.

6.3 UNITY 3D-BASED SIMULATION PLATFORM

A key innovation introduced in this study is the proposal to deploy a Unity 3D as a dynamic, extensible simulation platform to visualize and evaluate urban transportation scenarios (Smajic, 2020). Traditionally used in gaming and virtual reality, Unity 3D has emerged as a powerful tool for scientific modeling due to its real-time rendering capabilities, advanced physics engine, and support for interactive user interfaces (Weißmann, Edler, Keil, & Dickmann, 2023). By leveraging these strengths, the proposed framework bridges the gap between technical analysis and policy communication in transportation planning. Unity's simulation engine enables the real-time modeling of multimodal transportation systems embedded within realistic urban environments. Unlike conventional GIS-based simulations that often present static maps and graphs, Unity provides immersive 3D visualizations of city blocks, road networks, public transport systems, and vehicle movements (Figure 7). These simulations are grounded in agent-based modeling approaches, allowing for the representation of heterogeneous traveler behaviors, vehicle interactions, and infrastructure usage patterns. Such behavioral realism enhances the credibility of policy testing, particularly when assessing mode shift dynamics, congestion responses, and equity implications. The framework supports integration with geospatial data such as OpenStreetMap road networks, city zoning shapefiles, and high-resolution satellite imagery, ensuring spatial fidelity. Additionally, the system incorporates empirical datasets including GTFS transit schedules, travel demand models, synthetic population distributions, and vehicle emissions coefficients sourced from EPA's MOVES model. These inputs enable the construction of finely calibrated simulation scenarios that mirror real-world conditions.

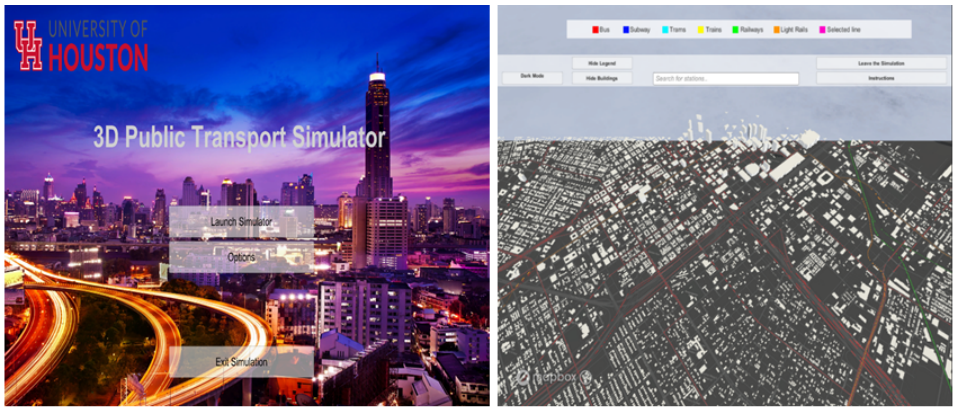


Figure 7. Public Transportation Simulator Unity platform example showing Houston as a case study to overlay traffic information on the top of 3D visualization.

A distinguishing feature of the Unity-based platform is its interactive feedback loop (Singh M, 2024) Policy levers such as congestion pricing, EV incentives, or curbside management rules can be modified in real time, with their impacts immediately visualized through animated changes in traffic density, mode shares, emissions levels, or charging network stress. This real-time responsiveness supports rapid prototyping and participatory engagement, making the platform suitable for stakeholder workshops and public consultations. Simulation modules developed within this framework allow for the exploration of a variety of policy and infrastructure interventions. For instance, low-emission zones can be simulated with varying levels of access restriction and enforcement rigor. Smart parking strategies can be analyzed in terms of search times and emissions trade-offs, while transit ridership changes can be tracked in response to ITS improvements or fare adjustments. EV charging behavior, including station choice and queuing delays, is modeled to assess grid load and range anxiety under different deployment scenarios. The versatility of Unity makes it applicable across a wide array of user groups. Urban planners can visualize the spatial implications of land-use policies and zoning changes; transportation agencies can evaluate system-wide impacts of ITS deployments or roadway redesigns; and policy makers can assess the effectiveness of fiscal and regulatory incentives. Community groups, especially those representing vulnerable populations, can better understand how specific scenarios influence local mobility patterns and environmental exposures. Unity's export functions enable the generation of emissions heatmaps, animated traffic flows, and dashboard interfaces tailored for both expert and non-expert audiences. These outputs enhance communication and

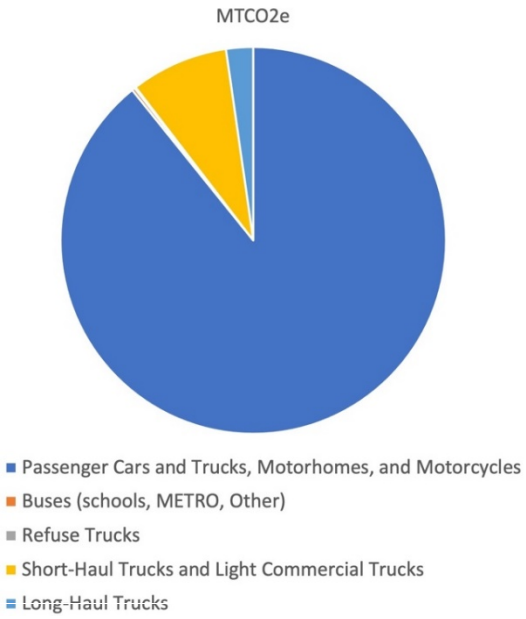
transparency, supporting informed decision-making and participatory governance. Moreover, the scalability of the simulation engine from neighborhood-level modeling to city-wide or regional analysis makes it suitable for both pilot testing and comprehensive transportation planning.
Ultimately, Unity's incorporation into this analytical framework enhances the depth, clarity, and accessibility of comparative scenario evaluation. Its immersive and interactive capabilities complement traditional quantitative analyses, fostering broader stakeholder engagement and more resilient decision-making processes.

7. Conclusions

To equitably achieve 2050 greenhouse gas reduction targets from on-road transportation, the City of Houston will need to deploy strategies that utilize emerging technologies, switch fuels, and reduce vehicle miles traveled. Strategies that are needed to meet targets in Houston are transferable. Other large, low-density cities with high VMT and low transit mode splits can adopt these methods.

7.1 FOCUS ON WHAT IS IN PEOPLE'S DRIVEWAYS

In Houston, the 2014 Baseline emissions revealed that 89% of GHG emission from on-road transportation are parked in peoples' driveways (Figure 8). This includes gasoline and diesel fueled cars and small trucks as well as recreational vehicles and motorcycles. Successfully achieving the 2050 net target will require across the board EV adoption regardless of income. EV adoption rates look healthy in Houston, but the end of federal incentives in 2026 will reset market demand when many of Houston communities cannot afford auto loans or do not have access to credit. The City of Houston will need to continue to work with partners to maintain and expand EV ownership.



- Focus on passenger cars and trucks, and other personal vehicles (89 % of MTCO2e).
- Short-haul trucks and commercial small trucks are important (8%).
- Long-haul trucks are a supply chain issue --national policy and regional partnerships are important (3%).

7.2 PROVIDE PUBLIC ACCESS AND APARTMENT CHARGING

Many of the next million people living in Houston will be living in apartments. Because 80-90% of charging happens at home, a major push for public charging will be necessary. In Houston, 57% households are renters and very few apartments have on-site charging. The Houston development code and accelerated permitting can incentivize apartment EV charging, while adding transit supporting densities. Public and private partners can create new business opportunities through public charging while increasing access for parts of Houston that are in charging deserts. A proactive approach is necessary.

7.3 IMPROVE METRO INTERMODAL EXPERIENCE

The H-CAP assumes a 20% reduction in VMT. This is a high bar for reductions in a sprawling city without a land use plan. Getting more people to use public transit will require improved first and last mile solutions, smoother intermodal experience, and financial incentives. METRO developing park and ride bus stations as transit and energy hubs can facilitate increased ridership, particularly

as the region grows and infill development increases densities that makes Houston more walkable and social. The smart transit hub concept developed for METRO provides a roadmap to integrating smart parking, incentives, and more seamless travel.

7.4 MODEL STRATEGIES TO OPTIMIZE THE SYSTEM

The Simulator to Accelerate ZEV Adoption and Reduce VMT is a ready tool that Houston can use to optimize transportation services. The simulator can model routes and headway times to accommodate ridership growth, predict rider miles and cost of rider miles, measure emission of various routes, and optimize intermodal transportation hubs. This type of tool can be used to manage and plan the system to improve modal splits and reduce overall VMT.

7.5 SUPPLY SIDE SOLUTIONS

In addition to supporting fuel switching and VMT reductions, Houston and low-density cities will require increased capacity in the power grid and distribution system to provide for the added demand from the transportation sector. As the demand-side strategies will reduce the GHG emissions by and estimated 70%, there is still an off-set of 30% required. This will require an estimated equiveillance of 67 square miles of community solar - - or some combination of wind, distributed solar, and utility scale solar. State policies and regional grid operators need to plan for the added demand.

Acknowledgements

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VI. ARCHITECTURAL EDUCATION & PEDAGOGY

دور الذكاء الاصطناعى فى تطوير التعليم الجامعي لهندسة العمارة

الحالة الدراسية: مادة التصميم المعماري

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ملخص. يتناول البحث بالدراسة موضوع AI ودوره في عملية تطوير أسلوب التعليم المعماري, فتبدأ الدراسة النظرية بلمحة عامة عن AI- ثم دوره في الهندسة المعمارية, وأنواع تطبيقاته المستخدمة في هذا المجال, ثم ينتقل البحث للتعريف بعملية التعليم المعماري ووحداتها, وفي أي مرحلة يمكن استغلال تطبيقات AI- والبحث في كيفية استخدام أدواته في التعليم المعماري, ثم سيناقش البحث بعض التجارب لتطبيق أدوات AI- في بعض كليات العمارة وخاصة في استديو التصميم المعماري, ليتم استنتاج الايجابيات من تطبيقه ثم السلبيات والتحديات والفرص. كما يشير إلى أن دمج AI في منهج التصميم المعماري مفيد لزيادة وعي المصممين بجميع مجالات التصميم المعماري، في شكل مدخلات وعملية ومخرجات. ومن خلال تحليل الدراسة لتجارب التعلم الممعماري في ضوء AI تستكشف إمكانات دمج تطبيقاته وتقنياته في التعليم المعماري، وكيف يمكن أن تستفيد ممارسة التصميم المعماري منها. وبالتالي فإنه يوفر نظرة ثاقبة حول كيفية تحويل تعليم التصميم المعماري نفسه بالنظر إلى التأثير المستقبلي AI على صناعة الهندسة المعمارية. سيعتمد البحث المنهج النظري و المنهج التجريبي التحليلي من خلال مقابلات و استبيانات خاص بالمصممين والطلاب لمعرفة أثرAI في مراحل التصميم المعماري, وسيعرض تجربة تطبيق AI وتطبيقاته في عدة جامعات وفي جامعة البوليتكنيكو دي باري الايطالية التي شاركت بها الباحثة خلال شهرين للاستفادة من النتائج التي توصلوا لها في إثراء التجربة المحلية. وفي نهاية البحث توجد مجموعة من النتائج والتوصيات للوصول إلى اقتراح لتطوير نهج جديد في عملية تعليم التصميم المعماري بواسطة الAI وأدواته في العمارة.

الكلمات المفتاحية: *تحسين العملية التعليمية، أدوات الذكاء الاصطناعي، التصميم المعماري، مشاريع معمارية.*

Abstract. The research studies the topic of AI and its role in the process of developing the architectural education method. The theoretical study begins with a general overview of AI, then its role in architecture, and the types of its applications used in this field. Then the research moves on to define the process of architectural education and its units, and at what stage can AI applications be exploited. And research into how to use its tools in architectural education. Then the

research will discuss some experiences of applying AI tools in some colleges of architecture, especially in architectural design studios, to conclude the positives from its application, then the negatives, challenges, and opportunities. The research also indicates that integrating AI into the architectural design curriculum is useful for increasing designers' awareness of all areas of architectural design, in the form of inputs, process, and outputs. Through the study's analysis of architectural learning experiences in light of AI, it explores the possibilities of integrating its applications and technologies into architectural education, and how architectural design practice can benefit from them. It therefore provides insight into how architectural design education can transform itself given the future impact of AI on the architecture industry. The research will adopt the theoretical approach and the experimental analytical approach through experience of applying AI and its applications in several universities and at the Italian Politecnico di Bari University, in which the researcher participated within two months to benefit from the results they reached to enrich the local experience. At the end of the research, there is a set of results and recommendations to arrive at a proposal for developing a new approach in the process of teaching architectural design using AI and its tools in architecture.

Keywords: *Improving the educational process, Artificial intelligence tools, Architectural design, Architectural projects.*

المقدمة

"العمارة مرآة المجتمع فهي تعكس ثقافة المجتمع بكل ما تشمله من معاني لكلمة الثقافة فهي افراز طبيعي للتفاعلات الحضارية و السياسية و الاقتصادية و الاجتماعية فهي الفن العلمي لاقامة مباني ليس من الخارج لتتوافر فيها شروط الجمال و الاقتصاد فقط و لكنها أيضا من الداخل لتتوافر فيها شروط البناء مثل الانتفاع و المتانة و الخدمات و التهوية و الاضاءة و الاقتصاد و ذلك لتفي باحتياجات الناس المادية و الروحية." [1]. كما أكد والتر غروبيوس في كتابه (نطاق العمارة الشاملة, 1970): "لكي تكون الهندسة المعمارية جيدة وناجحة ينبغي أن تعكس الحياة نفسها التي تنطوي على حميمية المعرفة البيولوجية والاجتماعية والتقنية, والمشاكل الفنية". نؤكد من خلال قوله على المعرفة التقنية, ونظراً لأن أدواتنا أصبحت رقمية أكثر فأكثر، فإن الميزات والأساليب التي تفرضها هذه الأدوات، قد قيّدت بشكل تلقائي ودون قصد مساحة التصميم الممكنة, فمهمة أي مهندس معماري لا تتعلق باستخدام أجهزة الكمبيوتر لتكرار أو أتمتة ما تمّ التفكير فيه وإنتاجه بالفعل، بل يتعلق بالسماح لأجهزة الكمبيوتر بالكشف عن شكل جديد تماماً من الذكاء المعماري.

كما اكتشف العديد من المهندسين المعماريين والباحثين مؤخرًا إمكانات خوارزميات التعلم الآلي المرتبطة بالذكاء الاصطناعي، وخاصة الشبكات التوليدية (GANs) ، في تحسين القدرات الإبداعية, ,كما يعتقد الباحثون أنه لا تزال هناك حاجة إلى بذل جهود في إنشاء مواد تعليمية لدعم بناء القدرات، ولضمان توافر الموارد الحاسوبية والأجهزة الأخرى ولسدّ الفجوة الرقمية, و بهذه الطريقة فقط يمكننا التأكد من عدم تخلف أحد عن الركب.

وجاء في المؤتمر الدولي السابع للعمارة والبيئة المبنية في طوكيو 2020م: "يعمل العديد من الباحثين على تطبيقات AI للتصميم المعماري ، وهناك عدد قليل من برامج التصميم تسمح باستغلال

خوارزميات التعلم الآلي، وبدأت بعض الشركات المعمارية الكبرى في تجربة أساليب التعلم العميق من أجل تطبيق البيانات المتراكمة على مدار سنوات من المهنة، مع الاهتمام بشكل خاص بالاستدامة البيئية وأداء المباني".

المشكلة: "تعاني برامج التعليم المعماري من قصور في الإمكانيات المادية في بيئة التعلم و وجود عدد كبير من عوامل الضعف المختلفة في نظم التعليم المتبعة حالياً ووجود آثار سلبية متعددة ناتجة عن الوضع الحالي. نتج عن ذلك وجود قصور وفجوات واضحة في أهداف ومخرجات التعلم المتوقعة مقارنة مع متطلبات عصر العولمة واحتياجات سوق العمل الفعلية" (Rizk ,2012) [2], مما يبرز أهمية وحتمية التفكير في سبل غير تقليدية للتغلب على تلك الفجوات وإكساب الطالب المهارات المطلوبة للممارسة المهنية بالتوازى مع العمل على تطوير اللوائح واستكمال الإمكانيات المادية والمالية والبشرية اللازمة والتي تستغرق سنوات حتى تدخل حيز التنفيذ. يزيد ذلك من أهمية دراسة تفاصيل أنماط وأدوات التعليم غير الرسمي كتطبيقات متاحة التنفيذ الفوري بالتوازى ودمجها مع التعليم الرسمي بالبرنامج التعليمي حيث تعتبر إشكاليات تنمية القدرة على التعلم والإبداع المعماري وتحويل المعارف المكتسبة الى ممارسة مهنية من أهم اشكاليات تعليم الهندسة المعمارية (Danaci ,2015) [3].

لذلك ومما سبق يمكن تلخيص مشكلة البحث في التالي:

- 1- إن المتغيرات التي أحدثتها تكنولوجيا المعلومات على الساحة المعمارية, وما يتبعها من متغيرات على الفكر والنتاج المعماري المعاصر ومناهج وطرق التدريس, ودخول مفاهيم جديدة في عمليات التعليم التي تطبق في الكثير من جامعات الدول المتقدمة, لكن بعض الجامعات لم تكمل الخطوات الجادة في استثمار هذا التطور التقني وثورة المعلومات مما يؤدي الي توسع الفجوة التي تقع بينها وبين العالم المتقدم والذي بدأ بدمج هذه التقنيات في العمل التعليمي المعماري.

- 2- عدم استثمار أدوات AI بالطريقة الايجابية في كليات العمارة وخاصة في عملية تعليم التصميم المعماري, بالإضافة لغياب الآليات لكيفية الاستفادة من تطبيقاتها وأنظمتها في عملية التصميم المعماري لاختصار الوقت والجهد.

أسئلة البحث: 1- هل سيوثر استخدام تطبيقات وأنظمة AI سلباً أم إيجاباً على عملية التعليم المعماري بشكل عام, والتصميم المعماري بشكل خاص؟

- 2- هل دمج (AI) في عملية التعليم المعماري تدريجيًا وفي المستقبل القريب، سيصبح جزء أساسي من العلوم والمعارف والمهارات الصعبة والهامة في هذا المجال, أو أنه غير كافٍ ليتم الاعتماد عليه بشكل كلي في المستقبل, وفي أي مرحلة من مراحل العملية التصميمية ستكون الضرورة ملحة للاستعانة بانظمة وبرامج الAI؟
- 3- هل سيتم اعتمادها من قبل بعض الجامعات المعمارية سواء (الحكومية او الخاصة) كأداة هامة ومساعدة للابداع والابتكار و وضع البدائل والاقتراحات في مشاريع التصميم المعماري؟ وماهي السنوات الدراسية الأكثر حاجة وتفاعل مع هذه الآلية الجديدة في التعليم المعماري؟, وهل يمكن إدراجها ضمن لوائح التعليم بشكل مستقل كمادة منفردة أو دمجها مع المواد الأخرى كالتصميم المعماري؟

- **أهمية البحث:** تكمن في:

1- الإلمام بأهمية مواكبة التكنولوجيا والاتجاهات الحديثة مثل (AI) على اعتبارها جزء لا يتجزأ من روح العصر الحالي والاستفادة من تطبيقاته في مجال عمليات تعليم التصميم المعماري.

2- المساهمة في وضع آلية جديدة في "العملية المعمارية" قادرة على التغيير والتطور مع مرور الوقت بمعونة (AI) تتميز بالمرونة و والاستدامة.
3- مناقشة إمكانية وضع سيناريوهات تطبيق تصاميم AI في العملية المعمارية التعليمية بإعادة تصور الطرق التي يتم التصميم بها وكيف تعبّر عن البيئة المبنية بطرق جديدة ومثيرة بعيداً عن التحيزات والآراء الشخصية فقط.
4- استكشاف للطرق التي قد تدعم بها تقنيات AI التصميم المعماري المنهجي والعقلاني .

- **الأهداف:** تحديد ايجابيات وسلبيات استخدام الذكاء الصنعي AI في التعليم المعماري للتصميم.
- محاولة تطوير مناهج التعليم المعمارية باستخدام تقنيات حديثة تبعاً للحاجة إليها وتماشياً مع ما هو جديد في مجال العمارة, وتحديد الفرص والتحديات في عملية تعليم التصميم المعماري بمعونة التطورات الحديثة كـ (AI).
- وضع مفهوم جديد للباحثين المستقبليين في هذا المجال وجميع أصحاب المصلحة ذوي الصلة باستراتيجيات AI لتحسين التعليم المعماري وخاصة في التصميم المعماري.

- **المنهجية: المنهج النظري** : يتناول الدراسات النظرية المتعلقة بموضوع البحث **من** جمع البيانات والمعلومات و الاحصائيات والبحث في المفاهيم والمصطلحات التي تتعلق ب AI والتعليم المعماري كي تشكل مرتكزاً نظرياً.
- **المنهج التطبيقي الاستنتاجي**: على صعيد التعليم المعماري الأكاديمي: القيام بعرض بعض التجارب لاستخدام الذكاء الاصطناعي AI في التعليم المعماري للتصميم في عدة جامعات هي: (تجربة مشروع تصميم مدينة مولفيتا في جامعة بوليتكنيكو دي باري الايطالية بمشاركة الباحثة,استوديو التصميم الشامل Comprehensive Design Studio جامعة أوكلاهوما Oklahoma - استوديو الهندسة المعمارية في جامعة كولومبيا), والقيام بتحليلها لوضع النتائج.

- **فرضية البحث:** يفترض البحث أنّ دمج AI في مناهج التصميم المعماري بشكل مستقل (كمادة منفردة) أو مدمج مع المواد الأساسية في الهندسة المعمارية مثل التصميم المعماري سيكون مفيد لزيادة وعي الطلاب المصممين بجميع مجالات التصميم المعماري, حيث يمكن إدخال AI في مقررات التصميم لطلاب الهندسة المعمارية وذلك لتوسع مداركهم وخاصةً في المشاريع المعقدة.

1- المفاهيم النظرية:

1-1 الذكاء الاصطناعي: أوضح بول وماكوورث (2010) أن AI هو مجال يدرس توليف وتحليلات العوامل الحاسوبية التي تطبق بذكاء، كما يمكن الإشارة إلى AI عموماً باسم التعلم الآلي وهو تقنية سريعة النمو للغاية. تركز الأبحاث حول الAI عادةً على التطبيقات القائمة على الصور والكتابة والصوت، (AI) هو فرع من فروع علوم الكمبيوتر، والذي يتضمن تطوير البرامج لإكمال المهام التي تتطلب ذكاءً بشرياً. تشمل خوارزميات AI التعلم، والإدراك، وحل المشكلات، وفهم اللغة، والتفكير المنطقي، ويمكن استخدام AI بعدة طرق كل يوم، من المساعدين الشخصيين إلى تنظيم الجداول، والهواتف المحمولة التي تقدم توصيات للأغاني، والسيارات ذاتية القيادة-Leyva) . (Vazquez,M[4], ويمكن أن يساعد المعماريين في النمذجة لاختبار التصاميم دون الذهاب مباشرة إلى موقع المشروع (Shourangiz, E., et al2011),[5] , يمكن استخدام AI لتحليل المدن والتخطيط وتصميم المدن (Batty, M., 2018), [6], ومع ذلك، يجب استخدام AI بمسؤولية وإيجابية لإخراج التغيرات في المدن والمجتمعات والشركات, و يمكّن AI من تقديم حلول للمشاكل التي يصعب حلّها بسبب تعقيدها (Yigitcanlar، T.، وآخرون، 2020) [7].

2- **التعليم المعماري:** التعليم المعماري كأساس للمهنة هو المسؤول عن تجهيز الشباب المهندسين المعماريين مع الأدوات المناسبة للتعامل مع مشكلات المجتمع الناشئة (سيلان، 2020) [8] ويقسم إلى:

- **التعليم النظامي:** هو تعليم رسمي قائم على منهج معين و الغرض منه هو تعليم الطلبة النظام الحالي والقيم والمعايير والأحكام المتعلقة بها.
- **التعلم غير النظامي**: ليس له تعريف واحد ولا يستند الى منهج محدد, وكما انه نوعٌ من التعليم يتلقاه الطالب طواعية لتحسين معرفتهم ومهاراتهم المعمارية, يمكن أن يكون له أهداف تعليمية, وقد يكون التعلم غير النظامي مقصوداً أو موجهاً احياناً، ولكن في معظم الحالات، يكون غير مقصود أوعرضي "عشوائي".

- إن التعليم المعماري يطوّر قدرة الطلاب على أن يكونوا قادرين على تصور وتصميم وإدراك فعل البناء في سياق ممارسة المهنة التي يعطي شكلاً ماديًا للاحتياجات للمجتمع والفرد. "إن الهدف الأسمى لتطوير التعليم المعماري هو ربطه بسوق العمل؛ لتقديم كادر مهني كفء بالمجال. لكن يشكل العامل الزمني عائق في تحقيق الأهداف وتحديد دقة النتائج؛ لأن زمن مخرجات التطوير بسوق العمل يختلف عن زمن المدخلات بالمرحلة الدراسية." [9].
- "ويشكل الميثاق الخاص بتعليم الهندسة المعمارية عن طريق مبادرة من اليونسكو و UIA إطاراً يوفر التوجيه والإرشاد للطلاب والمعلمين على اختلاف المؤسسات العاملة في التعليم والتدريب في مجال الهندسة المعمارية والتخطيط. يُنظر إلى الوثيقة على أنها "ديناميكية" وتتم مراجعتها بانتظام، مع الأخذ في الاعتبار الاتجاهات والاحتياجات والتطورات الجديدة في الممارسة المهنية، وكذلك في أنظمة التعليم. ليتم تطبيقه دولياً ويحتاج إلى ضمان الحماية والتنمية والتحرك العاجل", "وإن الاهتمامات الرئيسية، التي يعبر عنها الميثاق، هي الالتزام الاجتماعي للمهنة، أي الوعي بالدور و مسؤولية المهندس المعماري في مجتمعه، وكذلك تحسين نوعية الحياة من خلال المستوطنات البشرية المستدامة". [10].

2-1 وفيما يخص تعليم التصميم أوصى الميثاق بالآتي:

- القدرة على إشراك الخيال والتفكير الإبداعي والابتكار وتوفير قيادة التصميم.
- القدرة على جمع المعلومات وتحديد المشاكل وتطبيق التحليلات والحكم النقدي وصياغة استراتيجيات العمل.
- القدرة على التفكير ثلاثي الأبعاد في استكشاف التصميم.
- القدرة على التوفيق بين العوامل المتباينة، ودمج المعرفة وتطبيق المهارات في إنشاء حلول التصميم.

وهذا ما يساهم البحث في إثباته من خلال دمج الAI في عملية تعليم التصميم المعماري لاحقاً.

3- **AI و الهندسة المعمارية:** في السنوات الأخيرة ، ارتفعت التكنولوجيا والأتمتة في الهندسة المعمارية ، لتشمل الآن جميع جوانب الممارسة بما في ذلك تسليم المشروع والأداء والتقييم والفواتير, كما تخضع الهندسة المعمارية لتحول ثوري من خلال دمج AI والتعلم الآلي. تعيد هذه التقنيات تشكيل كيفية تصميم المباني وبنائها وحتى كيفية عملها بعد الانتهاء منها. تمثل الهندسة المعمارية المعتمدة على AI قفزة إلى الأمام في الكفاءة والإبداع والاستدامة، مما يمثل عصرًا جديداً حيث لا تكون الآلات مجرد أدوات بل متعاونين نشطين في عملية التصميم حيث "يقوم Nate Miller بصفته المؤسس والرئيس التنفيذي لوكالة التصميم الرقم Proving Ground ، بإجراء أبحاث وتطوير برامج تعتمد على البيانات لصناعة البناء. يقول: "إذا بحثت في العلم الكامن وراءAI وبحثت في التعلم الآلي ، فقد تجد أشياء مستقبلية للغاية."يتفق ميلر وخليل على أنه يقع على عاتق البشر تحديد كيف يمكن للآلات أن تساعد في حل المشكلات بطريقة أكثر ذكاءً مما كانت عليه في الماضي, وأيضا يقول مايكل كيلكي: "هناك دائماً تفاهم على أنه يجب أن تكون هناك طريقة أفضل للقيام بشيء ما".

"انظر إلى الخطوات الفردية، ثم انظر إلى المهام واكتشف طريقة للأتمتة_ اجعلها أسرع وأسهل_ عندما تبدأ في بناء تلك الأتمتة ، يمكنك تجميعها معًا في أتمتة أكثر شمولاً ", كما يقول:"لا يمكنك القفز على طول الطريق نحوAI الكامل والتعلم الآلي إذا كنت لا تعرف ما يعنيه ذلك فيما يتعلق بعملك, وعليك أن تكون ذكياً وأن تتعلم كيفية إدارة التعقيد." وبالتالي إن تجميع الأدوات هو ما سيساعد المعماريين حقاً على البدء في فهم إمكانات البيانات الضخمة وAI ، وعلى المدى القصير، تعزيز إنتاجيتهم.

- كما يقول دويتش: "في اللحظة التي يبدأ فيها تداخل الأدوات واستخدامها معاً، تصبح أكثر قوة". ويقول: "أي بيانات يمكنك جمعها اليوم ويمكن أن تساعدك غداً هي البيانات التي يجب عليك جمعها".لاستخدامها لتعزيز المهنة.
- وبالرجوع أيضاً إلى الدراسات السابقة نستنتج أنه: يمكن تطوير الهندسة المعمارية إلى نطاق عمل جديد يستخدم الأتمتة بكل مزاياها وعيوبها (Gunagama ، M، .D، et al، 2017).
- AI هو أحد الأساليب المتبعة في تطوير التصميم، وخاصة المعماري. مثل نماذج وكتل البناء المعقدة, كما أظهرت النتائج أن أكثر من 50٪ من المعماريين يساعدهم AI على صنع التصاميم المفاهيمية.

3-1 **دور الـ AI في عملية التصميم**: أحد أهم تأثيرات AI في الهندسة المعمارية هو قدرته على تعزيز عملية التصميم. تقليدياً يعتمد المعماريون على خبرتهم وحدسهم لإنشاء تصميمات تلبي المتطلبات الجمالية والوظيفية والتنظيمية. ومع ذلك تستطيع AI تحليل كميات هائلة من البيانات تتجاوز بكثير القدرة البشرية، وتحديد الأنماط وتوليد خيارات التصميم التي قد لا تكون واضحة على الفور. من خلال إدخال معلمات مثل ظروف الموقع وتوافر المواد وأهداف كفاءة الطاقة، يمكن للمعماريين استخدام AI لاستكشاف مجموعة أوسع من الاحتمالات، مما يؤدي في النهاية إلى حلول أكثر ابتكارا وتحسيناً.

- يمكن لخوارزميات التعلم الآلي أيضًا التنبؤ بكيفية أداء المبنى في ظروف مختلفة، مثل سيناريوهات الطقس المختلفة أو التغييرات في أنماط الاستخدام. تسمح هذه القدرة التنبؤية للمهندسين المعماريين باتخاذ قرارات أكثر استنارة في وقت مبكر من عملية التصميم، مما يقلل من الحاجة إلى المراجعات والتعديلات المكلفة لاحقاً. على سبيل المثال، يمكن للAI محاكاة كيفية تحرك الضوء الطبيعي عبر المبنى طوال اليوم أو كيف تؤثر المواد المختلفة على استهلاك الطاقة، مما يمكن المصممين من ضبط خططهم لتحقيق أقصى قدر من الكفاءة والراحة في المبنى.

3-2 **كيفية استخدام الAI في عملية التصميم**: الهدف الأساسي للتصميم المعماري هو خلق بيئات مريحة وصحية وآمنة ومستدامة للناس. يمكن أن يساعد AI في التحقق من الامتثال للقوانين المعمارية فضلاً عن تسهيل تصميم نماذج فريدة من نوعها, حيث تتغير احتياجات الإنسان والبيئة باستمرار، وتقع على عاتق المعلمين في هذا المجال مسؤولية تدريب الطلاب على تطوير حلول مستدامة ومسؤولية اجتماعية تعطي الأولوية لرفاهية الإنسان والبيئة, لذلك يمكن استغلال الـAI في التصميم المعماري من خلال:

3-2-1 جمع البيانات ومعالجتها Data Collection and Processing: بالنسبة للمراحل الأولية للتصميم، هناك كمية كبيرة من البيانات التي يتعين على المهندسين المعماريين معالجتها مثل: القوانين القانونية، تحليل البيئة المادية، احتياجات المستخدم والمتطلبات الوظيفية والحالات السابقة وما إلى ذلك, وكل تلك البيانات تحتاج إلى معالجة, بحيث يوفر AI دعماً كبيراً للتعامل مع كل هذا البيانات التي قد يكون من المستحيل معالجتها بدون مساهمة التقنيات الحسابية, بالإضافة إلى تقليل الوقت اللازم للفهرسة وتصنيف المعلومات المطلوبة للبدء بمراحل التصميم , وقد تكون هذه المرحلة غير ملحوظة ولكنها ذات تأثير مهم على عملية التصميم وتدعى المرحلة التحليلية للتصميم.

3-2-2 إنشاء خيارات التصميم بوساطة AI (البدائل التصميمية) AI to Create Design Options : يطبق AI على تحليل مخطط الأرض وإنشاءه الهدف الثلاثي المتمثل في إنشاء مخططات الطوابق، تأهيلهم، والسماح للمستخدمين بتصفح الخيارات والاستفادة منها. كما يمكن تطبيق التصميم التوليدي لتخطيط المساحة, والتحليل المعماري الآلي العميق. وفي دراسة لـ (شارما وآخرون، 2017) [11], يوضح كيفية استخدام شبكات (GANs) التوليدية لإنشاء اختلافات التصميم الفريدة والمبتكرة وذلك في مرحلة التصميم المبدأي حيث يتم وضع فكرة المشروع التي تدعى (Concept) شكل رقم(1-2).



شكل(1) يوضح الخيارات المتعددة لأحد التصميمات بتقديمها للمصممين.AIالداخلية التي يقوم أحد تطبيقات
المصدر:
https://www.researchgate.net/figure/Minimal-workflow-for-Midjourney-a-d-DALL-E-2-e-h-and-Stable-Diffusion-i-l-for_fig3_375757005



شكل(2) يوضح الخيارات المتعددة لأحد التصميمات الخارجية التي بتقديمها للمصممين. المصدر:AIيقوم أحد تطبيقات
https://bootcamp.uxdesign.cc/35-incredible-midjourney-prompts-for-breathtaking-architecture-design-b12028a1c9b3

3-2-3 تحليل أداء البناء Building Performance Analysis: يشير إلى العملية التي توضح سلوك المبنى تحت تأثيرات معينة يتم تقييم أدائها، ولكن وبدعم من AI وBIM، أصبح تنفيذه أسهل وموثوق أكثر. في الوقت الحاضر إنّ البرمجيات أو الإضافات المتخصصة في تحليل الأداء يتم استخدامها من خلال عمليات قابلة للتشغيل المتبادل مع برنامج BIM للحصول على نتائج أكثر فعالية وإنتاجية, بحيث يوجد نوعان رئيسيان لتحليل أداء البناء: أداء الطاقة و أداءالهيكلية.

3-2-4 نمذجة معلومات البناء Building Information Modelling: هي واحدة من أشهر المصطلحات في عالم البنيان المعاصر"BIM" كما تعتبر رائدة التنمية لأنها نهج متعدد التخصصات و يساهم في تقوية العلاقة بين مختلف المشاركين في صناعة البناء والتشييد مثل المهندسين المعماريين والمهندسين والمقاولين, BIM ليس فقط تغيير التكنولوجيا ولكن أيضا تغيير العملية. "الهدف الرئيسي للـ BIM هي لتقليل تكلفة المشروع، وزيادة الإنتاجية والجودة، وتقليل زمن تسليم المشاريع (الأزهر،2011)" [12], وأيضاً فيما يتعلق بالتعقيد الشديد للبنية المتعددة الطبقات والمتعددة التخصصات لبرنامج BIM، يعتبر AI العمود الفقري لها.

3-2-5 الـ AI في التمثيل المعماري AI in Architectural Representation: لقد كان التمثيل جزءاً من التصميم المعماري منذ الأيام الأولى للممارسة. في الوقت الحاضر ذهب التمثيل إلى مستوى متقدم جداً تحت تأثير التقنيات الحسابية وAI، وتوفير وسائل الإعلام البديلة للتصور و وسائل

التعبير المعماري الظاهري مثل تكنولوجيا الرسوم المتحركة المعمارية التي توفر الوضع الرقمي لتعزيز الصورة المعمارية (يانغ، 2020). [13], فهناك العديد من البرامج والأدوات التي توفر جودة عالية من المنتجات المرئية بمساعدة AI، مثل Vray الذي يعمل تحت عدة برامج مختلفة. بالإضافة إلى بعض البرامج Lumion وTwinmotion وCinema 4d من السهل جدا إنتاج وتحرير الرسوم المتحركة مع الأداء الواقعي. يرى دوناس (2020) أن الرسوم المتحركة هي الفهم الحسابي للتصميم المعماري, وباستخدام البرنامج يصبح من الممكن محاكاة مظهر المنتج المعماري تحت الظروف الجوية المختلفة مثل الثلج أو المطر [14].

- "ظهرت طريقة تمثيل جديدة أخرى مع الواقع الافتراضي (VR) والواقع المعزز (AR) في الهندسة المعمارية كتقنيات تفاعلية لتصور الهندسة المعمارية توفر وسيلة لرؤية الوضع الحالي والمستقبلي للمباني" (ألياجا، 2007) [15]. أضافت بعض البرامج الموجودة AR خيارات لأساليب التصور من خلال المكونات الإضافية مثل Enscape أو VRSketch، وبعضها الآخر برامج مثل EyecadVR وIrisVR لتسخير تجربة الواقع الافتراضي كوسيلة لتمثيل للمنتجات المعمارية.

3-2-6 الـ AI في البناء AI in Construction: لقد تطورت صناعة البناء من التقليدية إلى طرق البناء الحديثة ولذلك، فإنه يمكن استخدام دعم AI بشكل فعال من خلال التعاون مع الروبوتات، BIM وتقنيات الواقع المعزز. إحدى الطرق التي يدعمها AI التصنيع الإضافي أو الطباعة ثلاثية الأبعاد هي طريقة جديدة ولكنها فعالة لبناء المباني, والتي كانت في الماضي عملية مكلفة، لكنها في الآونة الأخيرة أصبحت أرخص وبأسعار معقولة، ومن الطرق الصديقة للبيئة في تشييد المباني (ماثور،2016) [16] . كما تتطلب عملية تصنيع البناء مستوى عال من الأتمتة، والتي تعتبر ضرورية لمهام العمل بالموقع والتي تحتاج إلى تكامل المعلومات والمادية المكثفة. **شكل(3-4).**

4- الـ AI في تعليم الهندسة المعمارية: أنّ التعليم المعماري يشكل أساس يُمارس, وكما أن مهنة الهندسة المعمارية تقع تحت التأثير القوي للتطورات التكنولوجية، فيجب أن يكون تعليمها أيضاً وفقا لتلك التطورات والتحديثات المعاصرة، وبناءً على أن AI يعتبر عامل فعّال في الهندسة المعمارية, فيجب أن يكون جزءاً من التعليم المعماري.

- "يتم دمج AI بشكل متزايد في عملية تعليم التصميم المعماري من خلال التصميم التوليدي و الخوارزميات، وأدوات الواقع الافتراضي التي تعمل بـ AI، وخوارزميات التعلم الآلي. هذه الأدوات تساعد الطلاب لاستكشاف خيارات التصميم وتحسين كفاءة الطاقة والسلامة الهيكلية للمشاريع، وتحليل كميات كبيرة من البيانات لتصميم قرارات مستنيرة" [17].
- ولكن كما ذكرنا في الفصول السابقة أن الهندسة المعمارية وAI لها جوانب متعددة وعلاقات معقدة, فإنّ التعليم المعماري لديه بنية معقدة وديناميكية للغاية, ولذلك، فإن تطبيق AI في تعليم الهندسة المعمارية يحتاج إلى نهج منظم ومتنوع. وقد بدأ الباحثون والمعلمون في معالجة هذه المشكلة بالحاجة إلى دمج التصميم الرقمي في تعليم التصميم المعماري (أوكسمان، 2008) [18]. يتم بالفعل تنفيذ أدوات AI في أجزاء كثيرة من العملية التعليمية بما في ذلك: تطوير المحتوى، وطرق التدريس، وتقييم الطلاب، والتواصل بين المعلم والطلاب. وخاصةً في التعليم المعماري فإنه مطلوب إجراءات أكثر فعالية من أجل تنفيذ AI في التعليم المعماري لتحقيق علاقة أقوى وأكثر صحة بين الهندسة المعمارية وAI.

4-1 استراتيجيات تنفيذ الـ AI في التعليم المعماري: التعليم المعماري لديه بنية معقدة مع وحدات مختلفة, وكل وحدة مختلفة الغرض والخصائص, وتتطلب الهندسة المعمارية نهج شمولي ومنظم بشكل جيد لتنفيذ AI في التعليم المعماري الذي يتكون من ثلاث وحدات: (وحدات النظرية والتقنية والتمثيل) (سيلان،2021) [8]، بالإضافة إلى استوديو التصميم يجب النظر فيها بشكل منفصل بالتفصيل، وبانسجام مع بعضهم البعض. تعرض الفصول الفرعية التالية استراتيجيات وأساليب تنفيذ AI في كل وحدة من وحدات التعليم المعماري.

4-1-1 الوحدة النظرية Theory Module: في التعليم المعماري المنهج النظري هو الجزء الذي ينمي فيه طلاب الهندسة المعمارية ثقافتهم ومعرفتهم, ويتكون في الغالب من مواد لتاريخ العمارة والنظريات المعمارية وبعض المواد حول الجوانب القانونية والأخلاقية للمهنة. وهي الوحدة الأقل تأثراً بـالتطورات في تقنيات AI في الوقت الحالي. لكن، لا تزال هناك بعض المساهمة المحتملة للـ AI في مجال المواد النظرية من خلال توفير جمع البيانات، وتخزينها، ومعالجتها.

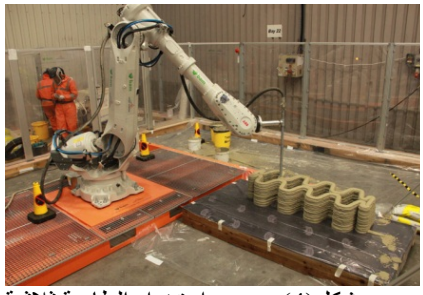
4-1-2 وحدة التمثيل Representation Module: وهي المكان الذي يتواجد فيه الطلاب ويعملون ويتعلمون بأساليب مختلفة لتعكس اهتماماتهم بأفكار التصميم على وسائل الإعلام المختلفة. إنها الوحدة العملية التطبيقية التي من المحتمل أن تكون الأكثر تضرراً من تطورات الـ AI ، وقد يصبح شيئًا أكثر من مجرد تعليم كيفية استخدام التقنيات الرقمية وأجهزة الكمبيوتر في صياغة الأفكار ورسمها وتنفيذها، فقد تصبح أدوات تصميم حقيقية في المستقبل.

- وفقا لشيلو(2019)، يمكن اليوم الاستفادة من الآلات في تطوير خريطة المعرفة المعمارية، وتدريبهم للمساعدة في خلق خيارات التصميم القابلة للحياة. وتعدّ المواد في وحدة تمثيل التعليم المعماري هي المكان الأنسب لهذا التحول النموذجي.
- كما إنّ التصميم البارامتري والخوارزمي قيد التشغيل حالياً في جدول أعمال الهندسة المعمارية وله مكان إلى حدّ ما في مناهج التعليم المعماري, ولكن محاولات وضع أدوات التصميم الناشئة هذه على أساس الجهود الشخصية والتفاني من المعلمين والطلاب, لكن النهج المؤسسي هو الهدف لتكون هذه الأساليب أجزاء فعالة, كما يجب أن تكون أساليب التصميم البارامتري والخوارزمي التي تتأثر بـ AI في المقررات الإجبارية وليست الاختيارية للجميع, وأن يكون الطالب على دراية بأهمية طرق هذا التصميم, وأن يتقن الطلاب استخدام هذه الأدوات لكي يوجهوا طاقتهم واهتمامهم نحو جوانب أكثر فعالية في التصميم, بالإضافة إلى ذلك، يؤثر AI أيضاً على التمثيل من خلال أساليب جديدة مثل الواقع الافتراضي والواقع المعزز والطباعة ثلاثية الأبعاد.
- يجب أن يكون الطلاب على دراية بهذه الأساليب الرقمية الاتصالات لخلق عروض تقديمية أكثر إثارة للإعجاب, كما أن الحقائق البديلة تساعد الطلاب أيضاً لتجربة تصميماتهم بمقياس 1/1 و بشكل وثيق، حتى يتمكنوا من البدء في تصميمهم بنهج أفضل, كما تساعد أدوات الطباعة ثلاثية الأبعاد الطلاب في نمذجة أفكارهم من خلال تمكينهم من المحاولة بشجاعة في تصميم وابتكار أشكال معقدة دون الشك في إمكانية أن تتجسد هذه المشاريع إلى نماذج ومجسمات مادية شكل(5).
-
- **4-1-3 الوحدة الفنية Technical Module:** تتضمن مواد لتجهيز طلاب الهندسة المعمارية بالمعرفة والمهارات التي يحتاجون إليها لممارسة المهنة من مواد البناء والأساليب والهيكل وأنظمة التحكم البيئي.
- يمكن أن يؤثر AI على الدروس التدريبية في هذه الوحدة بشكل أكبر بشكل فعال من خلال برامج BIM وأدوات تحليل الأداء والبناء. بالإضافة إلى رسم الخرائط عن طريق برامج القياس التصويري مثل Pix4d أو ما شابه يمكن استخدام الأدوات لإجراء التصوير المساحي, ومعالجة الصور الرقمية والبيانات لأغراض البناء وتوليد مكان ثلاثي الأبعاد.
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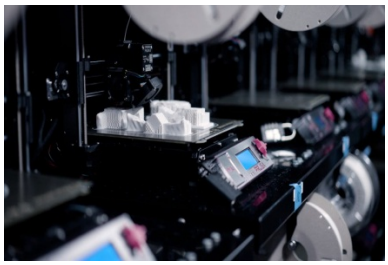


شكل(3) يوضح استخدام الطابعة ثلاثية الأبعاد في البناء. المصدر: https://iaac.net/wasp-3d-printing-eco-building/



شكل(4) يوضح استخدام الطابعة ثلاثية الأبعاد في نمذجة المجسمات. https://aecmag.com/features/3d-printing-in-construction/





https://blog.prusa3d.com/3d_printing_at_eth_zurich_75041:المصدر

شكل(5) يوضح Aاستخدام الطابعات الثلاثية الأبعاد بشكل منتظم في قسم الهندسة المعمارية هنا في ETH . يعلم جوناثان بنهامو، مؤسس HYTAC (تقنيات هجينة لتصميم الهندسة المعمارية) و الأستاذة أندريا ديبلايز، طلابه عن قدرات تقنيات صنع النماذج الهجينة الحديثة وكيفية الاستفادة منها بشكل أفضل في سير عمل التصميم المعماري في المعهد الفيدرالي السويسري للتكنولوجيا في زيورخ الذي يعدّ مثالاً رائداً لدمج التكنولوجيا في مناهجه الدراسية. ويؤكد برنامجه على استخدام التصميم بمساعدة الكمبيوتر وتقنيات التصنيع الرقمي، مع دمج أساليب التصميم والبناء التقليدية.

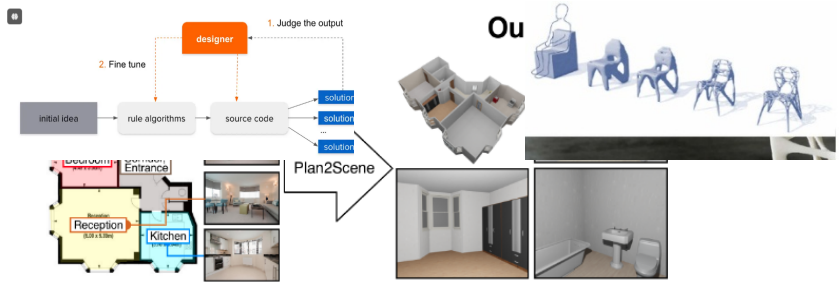
- إنّ من أكبر الفوائد التي يمكن أن توفرها أدوات BIM لطلاب الهندسة المعمارية هو السماح لهم بإدخال عناصر البناء بشكل فعال من خلال مكتبات تتطور وتتوسع بشكل مستمر ومتسارع تضم الآلاف من العناصر الجاهزة للاستخدام في الاستوديو الخاص بالطلاب أو العمل في المنزل. بالإضافة إلى ذلك، يمكن أن يساعد برنامج BIM أيضاً في تعليم الطالب كيفية استخدام المعلومات بطريقة فعالة دون الدخول في الكثير من التفاصيل.

- يمكن أيضاً إنشاء أدوات تحليل الأداء المفيدة للطلاب التي تمكنهم من الوصول بسرعة إلى معلومات أداء المباني من الطاقة والهيكلية وبدعم من AI للحصول على معلومات أكثر أهمية وفائدة حول كيفية جعلها أكثر كفاءة ومرونة.
- تزداد فوائد تطبيق الـ BIM وتطبيقات AI الأخرى في تحسين الوحدة الفنية للتعليم المعماري عندما يتم ربطهم بنجاح مع وحدات التعليم الأخرى، وخاصة وحدة التمثيل واستوديو التصميم.

4-1-3 استوديو التصميم Design Studio: يعتبر جوهر التعليم المعماري, كما يتم عكس المعرفة والمكاسب التعليمية من جميع المواد الأخرى في استوديو التصميم لتحسين مهارات الطلاب في التصميم المعماري, وهو المكان الذي يوجد فيه كلاً من المعرفة النظرية والتقنية معاً من خلال التمارين والمشاريع لتنمية مهارات التصميم لدى الطلاب حيث يتعلمون لغة ومهارات جديدة مثل التصور والتمثيل، و التفكير المعماري كجوانب مختلفة لتعليم التصميم, وبناء على ذلك، فهو المكان الذي تتجلى فيه آثار AI على المناهج الدراسية للتعليم المعماري بشكل واضح.

- قد تكون جميع مراحل التصميم في الاستوديو مدعومًا بـ AI بطرق مختلفة: مراحل التصميم المعماري التي تتكون من:(المرحلة التحليلية التي تتعلق بجمع البيانات والمعلومات, مرحلة التصميم المبدأي - مرحلة التصميم المتقدمة- مرحلة التصميم التنفيذي) [20].
- يمكن للطلاب استكشاف قواعد البيانات للعثور على المعلومات ذات الصلة بموضوع التصميم الخاص بهم, و استخدام أسلوب مماثل للتحليل البيئي في مرحلة التصميم الأولية، من خلال استخدام أدوات التصميم الخوارزمي للتخطيط و وضع القرارات أو تصميم الواجهة. وفي المراحل التالية للتصميم ،عندما يكون لديهم بعض المقترحات التصميمية بالفعل، فيمكنهم استخدام أدوات تحليل أداء البناء لنرى كيفية أداء المباني المقترحة من حيث كفاءة الطاقة والهيكل. يمكنهم أيضاً الاستفادة من بيئة الواقع الافتراضي لتجربة تصميمها على نطاق كامل وخالية من قواعد العالم المادي واستخدام الحقائق البديلة لعرض أفكارهم, كما يمكن استخدام أدوات الطباعة ثلاثية الأبعاد –في المراحل النهائية للتصميم عند نضج أفكارهم واعتمادها في المشروع_ لصنع نماذج مادية لمنتجات أكثر دقة، حتى لو كان لديهم أشكال معقدة. وبالتالي، يمكن للطالب في الاستوديو الاستعانة بـ AI بعدة مراحل ومن عدة جوانب للتصميم من خلال الأدوات المختلفة, وهذا يعطي للطالب الفرصة للتركيز على نقاط أكثر أهمية لنجاح عملية تصميم في إخراج المنتجات النهائية.
- ومن خلال كل ما سبق نستنتج أنه يمكن للطلاب الاستعانة بالـ AI بشكل كبير في المرحلتين الأوليتين للتصميم المعماري (التحليلية والمبدأية) التي يبحث فيها الطالب عن معطى المشروع لجمع المعلومات و معالجة البيانات وفهرسة الأشياء البحثية لتوليد الأفكار واكتشاف خياراتها وتطويرها, وفي المرحلتين (المتقدمة والتنفيذية) يفيد الـ AI بنقل الأفكار عبر برامجه لتحويل الأفكار إلى مشروع برسم مخططاته الثنائية الأبعاد 2D وتفاصيله ومجسماته الثلاثية الأبعاد 3D.
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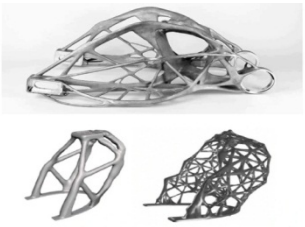
- 5 **أدوات وتقنيات استخدام AI في العمارة:** يمكن أن يساعد AI في الحدّ بشكل كبير من تأخير مفهوم البناء في الهندسة المعمارية من خلال استخدام خوارزميات AI، يمكن للمعماريين إنشاء وتقييم خيارات التصميم المختلفة بسرعة، مما يساعدهم في الوصول إلى التصميم النهائي بشكل أكثر كفاءة, وتتمثل إحدى الطرق التي يمكن من خلالها استخدام AI في استخدام برامج التصميم التوليفية, حيث يستخدم هذا النوع من البرامج الخوارزميات لإنشاء مجموعة متنوعة من خيارات التصميم بناءً على مجموعة من بيانات الإدخال ، مثل حجم المبنى والموقع المرغوب فيه, ثم تقييم هذه الخيارات بسرعة وتحديد الخيار الذي يلبي الاحتياجات على أفضل وجه, كما يساعد على اكتشاف المشكلات وتصحيحها مبكراً ، مما يقلل التأخير والتكاليف المرتبطة بإجراء التغييرات والتعديلات لاحقاً في عملية التصميم,



شكل(6) يبين طريقة عمل تطبيق AI المستخدم في تحويل النص (المدخلات) إلى صورة (المخرجات) المصدر:https://3dlg-hcvc.github.io/plan2scene/ /

ويستخدم AI لتحسين كفاءة استخدام الطاقة في المباني من خلال التعلم الآلي والمحاكاة ، يمكن للمهندسين المعماريين تقييم خيارات التصميم المختلفة وتحديد أفضل الحلول لتقليل استهلاك الطاقة, كما تتعدد تقنيات وأدوات AI فى تعليم التصميم المعماري والعمراني وكذلك فى تجهيز وتشغيل الفراغات ومن أشهرها وأكثرها استخداماً مايلي:

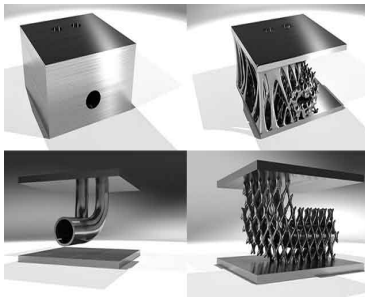
- **5-1 برنامج تحويل النص إلى صورة** Text to image converter program: المعروف باسم برنامج إنشاء الصور، لديه القدرة على إحداث ثورة في مجال الهندسة المعمارية وتصميم المفاهيم. تسمح هذه التقنية بإنشاء تمثيلات مرئية لمفاهيم الطلاب بسرعة وسهولة ، دون الحاجة إلى جهد يدوي مكثف للنمذجة أو التقديم, في حين أن هذا البرنامج جديد وقابل للتطوير تتيح هذه التقنية المبتكرة للمصممين تحويل الأوصاف المكتوبة للمساحة بسهولة إلى صور واقعية ثلاثية الأبعاد، مما يمنحهم القدرة على تصور خيارات التصميم المختلفة وتجربتها في غضون دقائق. على سبيل المثال تساعد أداة Midjourney AI في أن تولد مفاهيم مذهلة بناءً على النص الذي تمّ إدخاله في الأداة.



شكل(7) يوضح تقنية Design Generative في التصميم المعماري الداخلي والهيكلي.
المصدر:
https://parametrichouse.com/generative-design1/

https://formlabs.com/blog/generative-design/

شكل(8) يبين طريقة تقنية Design Generative في تحويل الفكرة الأولية إلى عدة حلول عبر خوارزمية القاعدة وكود المصدر بضبط دقيق من قبل المصمم ليحكم المنتج.



شكل(9) يبين تقنية Design Generative في التصميم الداخلي المعماري.
https://www.professional-workstation.com/fr/applications/107-design/167-what-s-behind-generative-design

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- باستخدام هذه النصوص المدهشة لتصوير برامج AI، يمكن البدء في استكشاف مفاهيم مذهلة للهندسة المعمارية الديناميكية في دقائق, ومن فوائد هذا البرنامج هي قدرته على تحسين مستوى الإبداع والتجريب في التصميم الداخلي. باستخدام هذه التقنية ، يمكن للطلاب المعماريين تجربة خيارات التصميم المختلفة بسهولة ورؤية كيف تبدو واقعية في بيئة ثلاثية الأبعاد. وهذا يتيح لهم أن يكونوا أكثر ميلاً إلى المغامرة في تصاميمهم وتعتبر أداة قيّمة تسمح برؤية المساحة بطريقة واقعية ومفصلة، و تساعد في اتخاذ قرارات مستنيرة بشأن خيارات التصميم.

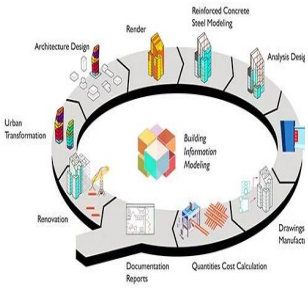
5-2 الأتمتة في التصميم المعماري Automation in architectural design :

تحتاج الهندسة المعمارية إلى التكيف والتطور, و يمكن للـ AI اتخاذ القرارات واستخراج البيانات وتحليل تلك البيانات بناءً على المعلومات التي تمّ جمعها, فمثلاً عند العمل في مشروع ما، يعدّ تحليل الملاءمة والجودة والاختلافات أمراً ضرورياً. في الوقت الحالي، يقوم الطلاب بذلك بالطريقة الذاتية. إنهم يحددون ويعالجون المساحات فعليًا، ويحسّنون التصميم ليقدموا منتجاً جديراً, لكن هذه العملية تستغرق وقتًا و قدر كبير من الجهد والبحث لإكمال الممارسة بأكملها. يمكن للطلاب اتباع نهج كمي وموضوعي أكثر مع التصميم المعماري الآلي.

5-3 تقنية Design Generative: هو برنامج يطبّق تقنية لإنتاج و توليد تصميمات مبتكرة باستخدام الـ AI في إطار حاكم من المحددات والمتطلبات المستهدفة من عملية التصميم, حيث تعمل التقنية على إنشاء مجموعة متنوعة من البدائل والمقترحات التصميمية التي تلبي الاحتياجات المتنوعة

فى عمليات التصميم, بالتالي فهو يوفر مجموعة من البدائل تحقق أعلى كفاءة ممكنة فى أسرع وقت ممكن شكل (7-8-9).

5-4 تقنية Building Information Modeling (BIM): هي تقنية تعتمد على AI لتحليل وإدارة أداء جميع عناصر نظم المبنى التشكيلية والإنشائية والتقنية والتنبؤ بأدائها المستقبلي شكل(10). وتعمل على تحقيق التكامل والانسجام والتحكم فى النظم الذكية وتحسين أدائها وتطوير الواجهات، و





شكل (10) يوضح المهام التى يمكن أن تؤديها تقنية BIM من تحليل جميع البيانات المتعلقة بالمشروع وعمل البدائل التصميمية والنماذج ثلاثية الابعاد وتحليلها وتقديم مقترحات للنظام الانشائي وتصميه ووضع برامج التنفيذ وإدارة عمليات التشغيل والصيانة.
المصدر
http://bimarabia.com/download/BIMarabia.:_Arabic/BIMarabia6.pdf
إدارة تشغيل مكونات المشروع وعمل جميع النظم فى المبنى.

- ويوجد أكثر من 103 الجامعات في جميع أنحاء العالم تقوم بتعليم تقنية BIM ضمن المناهج الدراسية الخاصة بهم (Santos & Barison ,2010 .) [22]

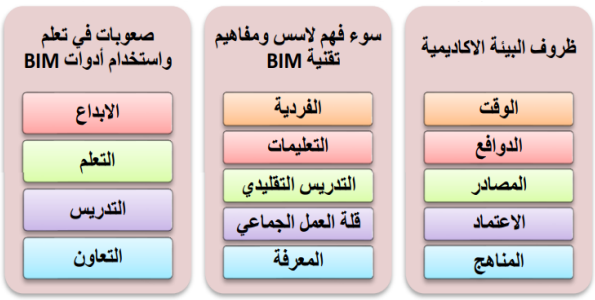
- كما أن رابطة مدارس وكليات العمارة في الولايات المتحدة الأمريكية تعمل (ACSA) مع شركة أوتوديسك لتضمين تقنية BIM ضمن البرامج المعمارية (al et Gregory ,2013) [23], وهناك فوائد كثيرة تعود على البرامج الأكاديمية من خلال تضمين BIM في المناهج الدراسية بها فلقد ساعدت بيئة النمذجة ثلاثية الأبعاد باستخدام أدوات تقنية BIM الطالب على فهم أكبر لتكامل أنظمة البناء (Livingston ,2008) [24], كما أن التعليم باستخدام أدوات BIM يقودهم إلى الإبداع وفهم الرسومات وتعلم كيفية إدارة المشاريع وفهم العلاقة بين تخصصات المشروع وحساب وجدولة الكميات والوقت.(Peterson et al, 2011) [25].



المصدر:
https://artsandarchitecture.psu.edu/
شكل(11) يوضح استخدام تقنيات ال BIM في استديو التصميم في كلية العمارة والفنون بجامعة Penn State في أمريكا.

- وبالنسبة لاستراتيجيات تعليم وتعلم تقنية نمذجة معلومات البناء أظهرت بعض الدراسات أن أغلب مدارس وكليات العمارة والهندسة والبناءAEC بالدول المتقدمة في هذا المجال لديها عدد من مقررات BIM ولكن مع الاختلافات في أساليب التدريس، وعدد الوحدات المقدمة، ومتى يجب إدخال تقنية BIM من مستوى الطالب المستجدين إلى مستوى التخرج، **وفي معظم الحالات كان مستوى التخرج والمستوى السابق له هو المستوى الأكثر استهدافا لتعليم تقنية BIM.**
- ويوجد بعض العقبات والتحديات لتضمين تقنية معلومات البناء في مناهج التعليم المعماري برامج الهندسة المعمارية التي تخطط لدمج تقنية نمذجة معلومات البناء في مناهجها التعليمية تواجه مجموعة من العقبات يمكن تقسيمها الى 3 مجموعات كما يتضح الشكل المجاور شكل(12). [27].

- **5-5 تقنية الواقع الافتراضي Virtual Reality (VR):** هي تقنية تستخدم AI فى عمل وعرض التصميمات بأسلوب تفاعلى يحاكي الواقع ، لتوضيح مفاهيم ومكونات التصميمات بصورة أسهل وأقرب للواقع.
- استخدام أسلوب المحاكاة فى التصميم بتقنية VR يوضح أساليب عرض التصميمات والمشروعات على المستخدمين ومدى قدرة هذه التقنية على تجسيد صور العمارة والعمران بأقرب ما يمكن للواقع المستهدف مما يتيح فرصا أفضل فى دراسة وشرح وتوضيح التصميمات خصوصاً لغير المتخصصين وضمان ادراكهم لطبيعة هذه التصميمات ولما ستكون عليه فى الواقع و إشراكهم فى عمليات تطويرها.



المصدر: (Barison and Santos, 2010)

شكل(12) يوضح العقبات التي تؤثر على تطبيق تقنية BIM في التعليم المعماري.



شكل(13) يوضح تقنية الواقع الافتراضي: المصدر https://e3zine.com/what-will-the-future-of-work-look-like

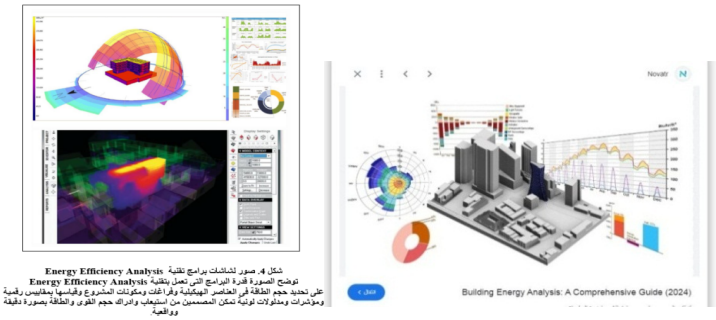


شكل(14) يبين تقنية الواقع المعزز المصدر http://www.design-confidential.com/5037-2/

- **5-6 تقنية الواقع المعزز Augmented Reality (AR) :** وهي تقنية شبيهة بتقنية (VR Reality Virtual) وتعتمد على AI في توفير تجارب واقعية للعملاء والمستخدمين للمشروعات وفراغات المباني المستقبلية إلا أنها تعزز تجربة المحاكاة " وتضيف لها بعض المرونة والسهولة فى الاستخدام ومزيداً من الواقعية.

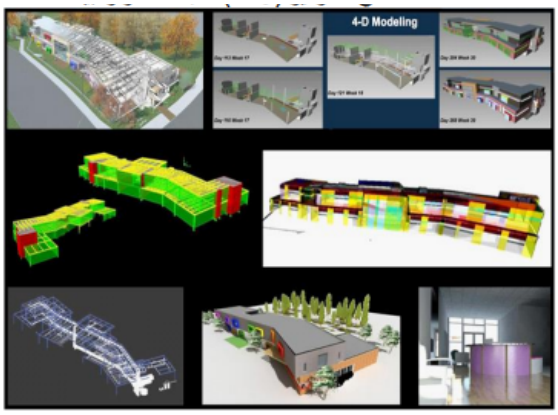
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- **5-7 تقنية تحليل كفاءة الطاقة Energy Efficiency Analysis:**هي أحد تطبيقات الذكاء الإصطناعى التى تستخدم لتحليل كفاءة استهلاك الطاقة في المباني وتحديد الاستراتيجيات المثلى لتحسين الكفاءة الطاقوية. كما يمكن استخدامها للوصول لعمل تصميمات مبتكرة تحقق أفضل أداء بيئي طبقا لمحددات وخصائص وطبيعة موقع ووظائف المشروع شكل(15).



شكل(15) توضح الصورة قدرة البرامج التي تعمل بتقنية Energy Efficiency: Analysis على تحديد حجم الطاقة في العناصر الهيكلية وفراغات ومكونات المشروع وقياسها بمقاييس رقمية ومؤشرات ومداولات لونية تمكن المصممين من استيعاب وإدراك حجم القوى والطاقة بصورة دقيقة و واقعية. المصدر: https://plannerly.com/bim-platform/

- **6 التجارب الدولية لتطبيق الـ AI في وحدة التمثيل (استديو التصميم المعماري):**



المصدر: (Pihlak et al., 2011)

شكل(16) توضح الصورة النماذج الرقمية المستخدمة في مشروع من / - جامعة كولومبيا.IDSمختلف التخصصات في استديو/

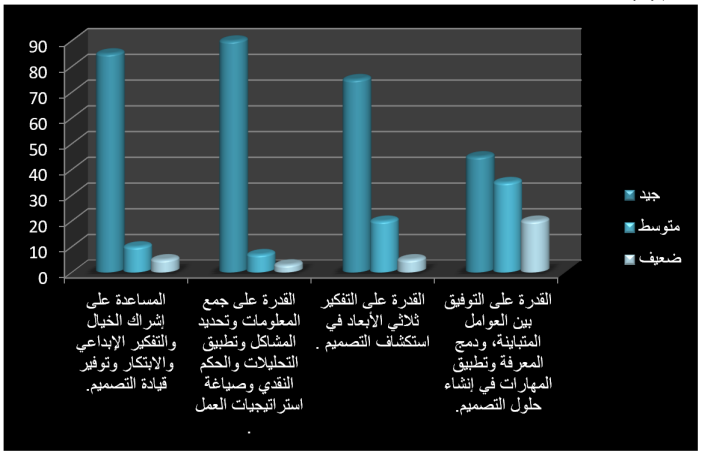
- **6-1 استوديو الهندسة المعمارية في جامعة كولومبيا** تمّ تطبيق الـ BIM في جامعة كولومبيا من الفصل الدراسي الرابع من درجة الماجستير في الهندسة المعمارية وفي كل عام تدعو جامعة كولومبيا BIP-C مجموعة من الاستشاريين بين خمسة إلى ثمانية من المهنيين، وتتكون هذه المجموعة من مستشار برمجيات ومهندسين تصميم بيئي، وعدد قليل من مهندسين الميكانيكا ليساعدوا في تشغيل استوديو التصميم المتكامل IDS ويطلب من الطالب تطوير نموذج من الصفر لعنصر في المبنى والعمل مع التخصصات الأخرى للوصول إلى نموذج متطور, شكل (16), (Pihlak et al ,2011) وبالرغم من أن الجهد الذي أضافته التخصصات الأخرى إلى الاستوديو كان أقل من المستوى المتوقع إلا أنها تعتبر تجربة جيدة وديناميكية (Marble ,2012), وقد قاموا بالعمل على مباني مختلفة وعلى مستويات مختلفة وبطرق مختلفة، وبذلك قد حصل استوديو الهندسة المعمارية في جامعة كولومبيا على هوية جديدة من خلال تطويره ليصبح استوديو تصميم متكامل IDS بالتعاون مع الخبراء والمهنيين (Marble ,2012), **(10)**.
- **6-2 تجربة مشروع تصميم مدينة مولفيتا Molfetta المستقبلية في جامعة البوليتكنيك في باري الايطالية بمشاركة الباحثة: حيث** طُلب من طلاب الدورة الثلاثين "الحوار" مع الذكاء الاصطناعي لإنتاج رؤى معمارية تتوافق مع المركز الحضري من وجهة نظر الوظيفة والتكامل مع سياق المدينة. سبقت مرحلة التصميم الفعلية سلسلة من التمارين التي وفرت المهارات التقنية اللازمة: القدرة على استخدام برامج الذكاء الاصطناعي ، والنمذجة D3 ، والتصور ، والتقديم ، وتحرير الصور ، ليس فقط "الأدوات التي تعد اليوم أساسية في ثروة المعرفة للمهندس المعماري ولكن تحقيق الأفكار الأكثر تعقيدا - كما أوضح طالب الدكتوراه في جامعة البوليتكنيك في باري ، إيلاريا كافاليير، الذي قام بتحرير الكتاب الذي يجمع المشاريع والشهادات المتعلقة بمختبر التصميم »، كما يوضح البروفيسور جوزيبي فالاكارا ، أستاذ التكوين المعماري والحضري ، أن استخدام الـ AI لايوسع الآفاق الإبداعية

من خلال توليد الأفكار والاقتراحات فحسب، بل إنه أداة ابتكار يجب على المهندسين المعماريين الجدد إتقانها.

- وتمثل التجربة بشكل أساسي طريقة لتطبيق استخدام AI التوليدي في المجال الأكاديمي ، وذلك للسماح بالنقاش مع الجمهور وإعطاء الأفكار لبدء عملية نضج الوعي النقدي". مع انتشار الAI مثل Midjourney ، حدث انفجار إعلامي حقيقي أدى إلى ردود فعل متطرفة في كثير من الأحيان ، بالمعنى الإيجابي والسلبي, فظهرت فكرة تطبيق الفكرة مع طالب الدكتوراه ومشرفه العلمي وبمشاركة الأساتذة من طلاب الدكتوراه والماجستير في الاستديو المكون من 50 طالب وطالبة من السنة الرابعة, وكانت الفكرة تطبيق تقنيات الAI في تصميم مشروع رؤى مستقبلية لمدينة مالفيتا, حيث استطاع الطلاب بإشراف الأساتذة على الاستعانة ب Midjourney لإعطاء الأفكار الأولية في المرحلة التصميمة الأولى لكل بناء على حدا وبعد أن أعتمدوا الأفكار المناسبة الواردة من الAI قام الطلاب بتطبيقها على البرامج الهندسية وفق محددات الأرض من أبعاد ومساحات ومتطلبات وظيفية وجمالية وغيرها.
- مشروع تصميم معماري محدد لطلاب السنة الرابعة في كلية العمارة بجامعة البوليتكنيكو دي باري شاركت الباحثة في اجراء هذه التجارب ضمن استديو التصميم لاستخدام تطبيقات وأنظمة AI في العملية التصميمة وفق مراحلها من وضع البرنامج المعماري إلى عملية تسليم المشروع أثناء العملية التعليمية.



- وبهدف إثبات ما جاء من توصيات في ميثاق اليونسكو الوارد في الفقرة 2-1 تمّ إجراء استبيان موجه لعينات مختلفة من طلاب السنة الرابعة الذين سمح لهم باستخدم تطبيقات الذكاء الاصطناعي AI في عملية تعليم التصميم المعماري في جامعة البوليتكنيكو دي باري ومن أهم نتائجه الوارد في المخطط البياني الآتي رقم(1).



المخطط البياني (1) توضح نتائج استبيان طلاب السنة الرابعة الذين سمح لهم باستخدم تطبيقات الذكاء الاصطناعي AI في عملية تعليم التصميم المعماري في جامعة البوليتكنيكو دي باري, المصدر: الباحثة.

- ومما سبق نستنتج أن دمج تقنيات AI في تعليم التصميم المعماري يحقق ما أوصى به الميثاق الوارد في الفقرة 2-1 بنسب كبيرة تتجاوز 80 % حتى 95 % بكل التوصيات المتعلقة بتعليم التصميم المعماري ماعدا التوفيق بين العوامل المتباينة ودمج المعرفة وتطبيق المهارات في إنشاء حلول التصميم بنسب أقل من 50 %.

- **6-4 استوديو التصميم الشامل Comprehensive Design Studio جامعة أوكلاهوما:** حيث بدأ فيها الطلاب جنبا إلى جنب مع المعلمين والممارسين باستخدام تقنية BIM ضمن استوديو التصميم الشامل خلال فصل الصيف في عام 2010 حيث، وتم اختيار 3 مجموعات من الطلاب من أعلى مستوى أكاديمي(شكل) 18، و كان منحنى التعلم للمجموعات الثلاث في كيفية استخدام تقنية BIM حاد جدا، الا ان تعلم تقنية BIMزاد من كفاءتهم و تأثر منحنى التعلم للطالب بمقدار المعلومات والطريقة الجديدة لتطوير التصميم والبناء والفترة الزمنية للكورس(. Stivers, 2012).

شكل (١٨) الطلاب في استوديو التصميم الشامل- جامعة أوكلاهوما



المصدر: (Stivers, 2012)

- "بالنسبة لأستاذ البوليتكنيك فإن AI لا يحط من قدر إبداع المهندس المعماري على الإطلاق ولكنه يعزّزه: "يتضح هذا من خلال تجربتنا التعليمية الآن في عامها الثاني. بعد مشروع إعادة تخيل أندريا العام الماضي، يعيد اليوم التفكير في ثلاث مناطق في مولفيتا من خلال تطوير العلاقة بين الأرض والمياه التي تمتلكها المدينة. إن المشاريع التي تنشأ عن هذا النهج لا تريد أن تكون ، ولا يمكن أن تكون، مشاريع قابلة للاستخدام بشكل مباشر، لكنها تقف كمحفزات ومحفزات للإدارة والمجتمع بأكمله بحيث يمكن تحويل الرؤى، مهما كانت مطبوعة بقوة ومقدمة في شكل إنجازات واقعية، إلى نقاط تفكير ملموسة لصالح المدينة"
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- **5-6 مناقشة التجارب والحالات الدراسية السابقة:** تقدم التجارب المقدمة أعلاه دراسة بعض الحالات لاستكشاف أدوات وتقنيات الذكاء الاصطناعي أثناء البحث عن استخدامها المحتمل في عمليات التصميم المعماري ضمن نطاق نموذج الإدخال والعملية والمخرجات كما هو محدد في تصنيف الذكاء الاصطناعي في الهندسة المعمارية, حيث كانت جامعة بوليتكنيكو دي باري وجامعة كولومبيا وجامعة أوكلاهوما ثلاثة أمثلة مختلفة عن كيفية استغلال AI ضمن استديو التصميم المعماري IDS بطرق مختلفة وفي سنوات متنوعة, وعلى الرغم من أن هناك نقص في المصادر الأكاديمية حول تقييم تلك الأمثلة إلا انه يمكن استنتاج منها في أن تعليم AI باستخدام استوديو التصميم المتكامل) (IDSيمكن أن يفيد الطلاب بشكل كبير، وفيما يلي بعض النقاط الهامة:

- يمكن إدخالAI في مرحلة مبكرة أو في المستوى العلوي في كلية الهندسة المعمارية بشكل عام ومادة التصميم بشكل خاص, و يمكن تنظيم فريق (IDS) من طلاب مع الممارسين أو الأكاديميين من مختلف التخصصات.
- يمكن أن يبدأ الطلاب بمهمة صغيرة "عنصر بناء يجب تطويره" ثم الانتقال إلى مهمة كبيرة للتدريب على استخدام AI.
- يعدّ اقتراح الاستراتيجيات المناسبة لتعليم AI في تعليم التصميم المعماري أمرًا معقدًا وصعباً حيث أنّ AI هو مجال واسع يحتاج إلى غرض محدد لأنه يحتوي على مجموعة واسعة من الأدوات والتطبيقات. تتطلب هذه الأدوات والتطبيقات ممارسة لتحديد أي منها مناسب لمهام وعمليات تعلم محددة. لذلك، من الصعب تحديد نطاق محتوى التدريس من حيث نظرية الذكاء الاصطناعي وممارسته.

- وبالنظر إلى الفجوة البحثية الحالية، يبدو أن الأسئلة البحثية التالية بحاجة إلى إجابة عميقة ومفصلة في الدراسات القادمة:
- 1. ما هي الاتجاهات الحالية والتغيرات المهنية التي تؤثر على التعليم المعماري؟ 2. ما هي مجموعة المهارات التي يجب أن يتمتع بها الطلاب لفهم بيانات المستخدم، ودمج تطبيقات التعلم الآلي في عملية التصميم، وتحديد الحلول المعمارية المقابلة؟
- كما هناك حاجة إلى مزيد من المناقشة في المؤسسات التعليمية لتقييم وفهم التأثير المحتمل للـAI في الهندسة المعمارية.

- **7 تحديد مخاطر وتحديات وفرص دمج الـ AI في التعليم المعماري:**
- **7-1 السلبيات والمخاطر:**
- فقدان المهارات التقليدية: ثبت بصورة عامة أن الاعتماد على البرامج والتطبيقات الالكترونية يؤدي إلى فقدان الإنسان لبعض المهارات التقليدية، لذا من الممكن أن يؤدي الاعتماد الزائد على تقنيات وبرامج AI فى عمليات التصميم المعماري والممارسات المعمارية عموما إلى فقدان بعض المهارات التقليدية التى تعتبر ضرورية وأدوات للعمل في هذا المجال, وفي حين أن الطلاب قد يعتقدون أن AI يمكنه حل مشكلاتهم، فمن الضروري بالنسبة لهم أن يتعلموا كيفية تحديد المشكلات واستنباط الحلول بشكل مستقل. بدلاً من البحث عن إجابات مباشرة من AI ، يجب على الطلاب عرض المشكلة ووصفها وطلب الحلول المحتملة. وينبغي أن يكون هذا هو النقطة المحورية في التعليم المعماري.
- الثغرات والاختراقات الأمنية: ففي الوقت الذى أتاحت فيه برامج وتطبيقات AI العديد من نظم وأدوات التصميم والتنفيذ والتشغيل و التأمين أتاحت أيضا العديد من قدرات وأدوات اختراق وتعطيل هذه النظم والتلاعب بها.
- قصور الكفاءة المعنوية : يؤدى الاهتمام الزائد AI فى معظم الأحيان إلى تقليص مساحات الإهتمام والتوظيف المتاحة للأمور المعنوية والنفسية والتفاصيل الجمالية والثقافية التارخية التى ترتبط بهوية المستخدم والمشاهد وتخاطب وجدانهم.
- خرق الخصوصية: تعتمد الكثير من تقنيات AIعلى كاميرات ومجسات ومستشعرات الرصد والمراقبة والتسجيل مما يجعل الانسان دائما مراقباً، وهو ما يمكن أن يعطي شعوراً بعدم الراحة والتهديد الدائم وعدم توفر الخصوصية، كما يجعله عرضةً لسوء استخدام بيانته وتفاصيله الشخصية والتجسس والتعدي على خصوصيته سواء من المشغلين أو المخترقين.
- ارتفاع التكاليف : حيث أن معظم التقنيات والبرامج والتطبيقات الذكية التى تستخدم فى عمليات التصميم والتنفيذ والتشغيل تعدّ باهظة الثمن جداً مما يؤثر على الجدوى والقدرات المالية والاقتصادية للمشروعات. [28].
- خلق واتساع الفجوات الرقمية المجتمعية: حيث يؤدي ارتفاع تكاليف نظم وبرامج AI إلى زيادة فرص عدم التكافؤ فى وصول واستخدام هذه التقنيات للمجتمعات وكذا للشرائح المجتمعية فى المجتمع الواحد.
- فقدان التحكم وتقييد الإرادة البشرية: قد يؤدي الاعتماد الزائد علىAI في تصميم وإدارة وتشغيل المشاريع إلى فقدان السيطرة البشرية أو تقييدها نتيجة بعض الأخطاء أو نقص المعطيات والمدخلات أو الأعطال أو التدخل البشرى الغير محسوب.
- الانهيار والتوقف المفاجئ للنظم الذكية: حيث أنها معرضة للأعطال أو التلف مثلها مثل أي نظام آلي أو الكتروني بسبب أخطاء بناء تلك النظم أو عمليات التطوير أو الاستخدام المفرط أو الغير محسوب.
- تقليص الدور البشري وانخفاض فرص العمل: حيث أصبح من المتعارف عليه عالمياً وتاريخاً أن هناك تناسباً عكسياً بين التطور التقني والدور البشري في شتى المجالات.
- تسهيل عمليات النقل والتقليد للتصميمات وصعوبة المحافظة على الملكية الفكرية.
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- **7-2 التحديات:**
- التعقيد والتكلفة: يحتاج تطوير وتنفيذ نظم AI إلى تكلفة عالية ومعقدة، مما يشكل تحدياً للطلاب ذووي الميزانيات المحدودة.
- أمان البيانات: يحتوي الـ AI على العديد من البيانات الحساسة، مما يجعلها عرضة للاختراق إذا لم تتم الحماية بشكل جيد.
- تعقيد الصيانة: يتطلب الحفاظ على أنظمة الـ AI جهداً كبيراً من الناحية الفنية والمالية، ويمكن أن يكون صيانتها تحدًّا.

- **7-3 الفرص:**

- زيادة الكفاءة والاستدامة: يمكن للـAI تحسين استخدام الموارد مثل الطاقة والمياه في دراسة المباني، مما يساهم في تحقيق الاستدامة البيئية وتقليل التكاليف التشغيلية.
- توفير الوقت والجهد: يمكن للـ AI أتمتة العديد من المهام في الصيانة وإدارة المشاريع،مما يقلل من الجهد ويزيد من الكفاءة.
- التصميم المخصص: يمكن للAI تخصيص التصاميم المعمارية والبيئية بناءً على احتياجات محددة، مما يسمح بتصميم مباني أفضل تتناسب مع استخدامها المحدد.

- **النتائج:**
- في جوهر تفكير التصميم المعماري الذي يركز على الإنسان ينبغي اعتبارAI أداة لتسهيل التعليم المعماري التفاعلي والجذاب، بدلاً من استبدال دور المعلمين. لإعداد معماريي المستقبل بشكل فعال وتزويدهم بالمهارات اللازمة، يجب على المعلمين الحفاظ على المرونة في التكيف مع القضايا البشرية والبيئية والتكنولوجية المتغيرة، ويشمل ذلك تزويد الطلاب بمعلومات وإرشادات حديثة حول الاستخدام المناسب AI ، مع تعزيز التفكير الذي يتمحور حول الإنسان مع التركيز على الاستدامة والمسؤولية الاجتماعية. في نهاية المطاف، سيؤدي النهج المتوازن الذي يدمج AI والخبرة البشرية إلى تعزيز جودة التعليم المعماري وإعداد الطلاب لمهن ناجحة في هذا المجال.
- على الرغم من أن AI يمكن أن يعزز من فكر الطلاب ويحفز فضولهم من خلال التفاعل، إلا أنه يجب أيضاً أن يؤخذ في الاعتبار أن استقرار الطلاب وتركيزهم قد يتأثر.
- العلاقة بين الAI والهندسة المعمارية قوية وخاصة في الجوانب التعليمية هي أيضا جدا مهمة ومعقدة. يجب إجراء دراسات أكثروعلمية البحث مع النتائج الإحصائية للحصول على نتائج ملموسة أكثر ومقترحات للتغييرات المستقبلية.
- تتصف مخاطر AI في التعليم المعماري بكونها متحورة ومتجددة نتيجة للحاجة إلى تحديث النظم والتقنيات المستخدمة، وكذلك نتيجة لما يصاحب هذه التحديثات من مشكلات ومخاطر مستجدة.
- استهداف المصممين لاستخدام أعلى وأحدث تقنيات ونظم ذكية متاحة فى بعض الحالات يتسبب فى تغليب الوسيلة (التكنولوجيا) على الغاية من استخدامها (تحقيق جودة الحياة للإنسان)، وذلك نتيجة لما يصحب استخدام بعض هذه النظم من المخاطر المعنوية والمادية والاجتماعية ـ
- تسبب AI فى حدوث تحول كبير فى مناهج وأساليب التعليم التصميم المعماري وألياته وطرقه, حيث يمكن لتطبيقات الـ AI أن تفهم الجماليات، ومدارس الهندسة المعمارية، ومتطلبات المشروع ، وتعزيز مرحلة التصميم الأولي. هذا يسمح للطلاب المعماريين باستكشاف خيارات التصميم بكفاءة وتوليد مفاهيم مبتكرة.
- إن دمج نمذجة معلومات البناء(BIM) في التعليم المعماري يشكل ثورة في طريقة عمل الطلاب المعماريين والمصممين من خلال تمكين التحليل في الوقت الحقيقي وتحسين التصميمات. والسماح لهم بالاستكشاف سيناريوهات مختلفة وتلقي ردود فعل فورية عليها الجدوى والتكلفة وكفاءة الطاقة، وتوفير الوقت والموارد مع ضمان تلبية المنتج النهائي معايير عالية من الجودة والاستدامة.

- **التوصيات**:
- ضرورة تدريب الطلاب على استخدام تقنيات الـ AI استعداداً لتمكينهم في الدراسة وفي سوق العمل أيضاً.
- محاولة إنشاء نهج وحوار مشترك جديد بين AI والتعليم المعماري وتنظيمه وتحسينه من خلال اعتماد تطبيقات AI وأدواتها في معايير مناهج التعليم المعماري كأداة وليس هدف في حدّ ذاته؛ لتحقيق مفهوم التصميم الشامل والمتكامل Comprehensive & Integrated Design والتأكيد على أنّه بدون تحقيق تلك المفاهيم في التصميم تكون الأداة لا وزن لها.
- الحاجة إلى معايرة استخدام AI في التعليم المعماري, ويجب على المعلمين التقدم بعناية حتى يتم تنفيذ هذه العملية بشكل صحيح. بدلاً من الجهود الشخصية، هناك حاجة شاملة إلى أسلوب منهجي.

- يجب على طلاب الهندسة المعمارية تعلم كيفية استخدام أدوات الـ AI باعتبارهم الجهات الفاعلة الرئيسية في التصميم , وأن يكونوا حذرين ومسؤولين فى استخدام هذه التقنيات الذكية وعلى دراية كاملة بمخاطرها وسلبيات استخدامها , مع مراعاة القيم الثقافية و الاجتماعية حيث يجب استخدام تقنيات AI فى العمارة بطريقة تحترم وتعكس القيم الثقافية والاجتماعية المحلية وتعزز التنوع والتكامل وتحافظ على بقائه، وإعطاء الأولوية للخصوصية وضمان الأمن.
- الاستفادة من تطبيقات النمذجة ثلاثية الأبعاد الذكية والمحاكاة لاختبار النظم والتأكد من استقرارها وأدائها المطلوب.
- التركيز على تحقيق التوازن بين التكنولوجيا والإنسانية في استخدام AI في التعليم المعماري وعدم الانجراف لاستخدام كل التقنيات المتاحة على حساب المعايير المعنوية والنفسية والفكرية للطلاب, حيث يجب اختيار تقنيات AI التي تتوافق مع الأهداف والمتطلبات العمرانية والمعمارية المحددة بناء على دراسة دقيقة للتكنولوجيا المتاحة ومقارنة بين الحلول المتاحة للتأكد من تلبية الاحتياجات فقط دون المبالغة مع تجنب المخاطر بأقصى إمكانية .
- توعية فريق المعلمين والطلاب وجميع المشاركين في العملية التعلمية بالمخاطر المحتملة وتدريبهم على أفضل الممارسات فى استخدام AI بطريقة آمنة وفعالة, ويجب على الطلاب اتخاذ قرارات التصميم مع مراعاة البيئة المحيطة بهم بحيث يكون AI بمثابة أداة مساعدة لهم، حيث يزودوا بمعلومات دقيقة لتوجيه خيارات التصميم الخاصة بهم.

- **الخاتمة:** إن تغيير النظرة التقليدية إلى التعليم المعماري، بفعل تأثير علوم المستقبل و التقنيات الرقمية والذكاء الصناعي، وبفعل النظرة المعاصرة التكاملية المتماسكة للعلوم في تفسير الواقع باستخدام لغة واحدة و نمط من التفكير الشامل المنظوماتي الذي يمكن من خلالها النظر إلى الجوانب الإدارية التربوية و الاختصاصية البحتة في ميدان التصميم المعماري كمنظومة واحدة متفاعلة مع جميع العوامل والتخصصات والتغييرات التكنولوجية على وجه الخصوص فإني وكباحث في هذا المجال أعتقد أنّ لدينا فرصة فريدة لتجربة هذه الثورة المفروغ منها. وعلاوة على ذلك، فإن الطريقة التي نعيش بها كانت ولازالت وسوف تعاني دائما من الآثار الإيجابية والسلبية لتدفق التقدم التكنولوجي الذي لا يمكن الحد منه, إنه حقيقة ولا يمكن لأحد معارضة المستقبل, بل ما يجب القيام به ، هو دراسة وتحديث ذواتنا ومعلوماتنا باستمرار لنكون دائما على دراية ومستعدين للسيطرة على "الجديد" بأفضل طريقة ممكنة. بهذه الطريقة فقط لن تطغى علينا التكنولوجيا أبداً.

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ROBOTICS AND GENERATIVE AI: SHAPING THE FUTURE OF ARCHITECTURAL EDUCATION AND PRACTICE

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Abstract. We present a pedagogy first exposure workshop that teaches an end-to-end AI → Parametric model → Slicing → Robot fabrication→ Assembly workflow for clay extrusion. Twenty-five students progressed from GenAI based ideation to Grasshopper modelling, then used AI authored GHPython slicers to generate vase mode/layered toolpaths and RAPID code under explicit printability constraints (wall thickness, overhangs, continuity). Outputs included validated toolpaths and small assembled prototypes. A single post workshop survey (N=84, students + fabrication instructors) indicates strong educational impact: 77.4% judged robotics and digital fabrication proficiency essential 91.7% expect greater adoption ~80% felt prepared for practice and ~84% agreed that robotics + GenAI are shaping the future of their architectural education and practice. Findings show that AI lowers coding barriers, helps novices internalize a coherent workflow, and yields proof of process prototypes without performance claims offering a replicable template for architectural education.

Keywords: *Robotics, Design Process, Artificial Intelligence, Digital Fabrication, Optimization.*

1. Introduction

The growing convergence of robotics and generative artificial intelligence (GenAI) is reshaping how architecture students learn, conceptualize, and fabricate. Beyond demonstrations of technical capability, there remains a need to examine how first-time learners internalize an end-to-end AI to robotics workflow in a way that is pedagogically clear and cognitively manageable. Prior work in architectural robotics and digital fabrication shows strong educational value linking tool use to spatial

reasoning, iteration, and hands on problem solving but most studies emphasise capability rather than workflow learning for novices.

This study presents a structured, first-exposure workshop designed to teach students a smooth, sequential workflow from GenAI-driven ideation, to parametric modelling in Grasshopper, to robotic slicing and clay extrusion. The instructional priority was process fluency and stage-to-stage linkage, not the production of highly complex or fully engineered geometries. To avoid cognitive overload typical of first encounters, we imposed explicit material and robotic constraints and framed each stage as the input to the next, reinforcing the logic of the pipeline. After the full workflow, a single post-workshop survey captured perceived workflow understanding and practice-readiness.

2. Literature Review

2.1 ROBOTICS IN ARCHITECTURAL EDUCATION

Robotic systems such as articulated arms, CNC routers, and drones are increasingly embedded in architectural education to enhance material experimentation and precision fabrication. Design-build studios show that robotics fosters spatial reasoning, hands-on problem solving, and interdisciplinary collaboration reframing robotics as a pedagogical tool, not only a production method (Radziszewski & Cudzik, 2021).

2.2 GENERATIVE AI IN DESIGN PEDAGOGY

Generative AI (GenAI) tools from large language models to text-to-3D systems are reshaping conceptual workflows in education. These platforms improve digital literacy and promote rapid ideation and multimodal design exploration. Technically, GenAI enables morphogenetic design through diffusion models, mesh synthesis, and neural networks (e.g., Tan et al., 2023).

2.3 INTEGRATING DESIGN AND FABRICATION

Bridging GenAI-generated forms with robotic fabrication remains challenging. Studies show that translating AI models into robotic assembly or toolpaths is feasible and supports human–machine collaboration (Jeon et al., 2023), yet integration is constrained by cost, safety, skill gaps, and the need for geometry repair and slicing logic (Chai et al., 2023).

2.4 AI-AUGMENTED INTERFACES AND PRODUCTIVITY

AI can enhance both efficiency and creativity across scales of practice (Turrin et al., 2023). Language-based interfaces for robotic planning are also emerging, reducing programming barriers and increasing accessibility for students and early-career designers (Lin & Wang, 2023).

2.5 ETHICAL CONSIDERATIONS

The increasing use of AI and robotics raises ethical concerns in education and practice, including labour displacement, authorship attribution, and data privacy. Integrating ethics into curricula is essential for preparing responsible architects (Alshahrani et al., 2023).

2.6 RESEARCH GAP

Despite growing interest, there is limited empirical research examining the combined use of GenAI and robotic fabrication in architectural education. In particular, the pedagogical impact of such workflows on student creativity, design logic, and fabrication reasoning remains underexplored. This paper addresses that gap through a workshop-based study integrating AI ideation, parametric modelling, and robotic arm printing.

3. Workshop Preparation and Student Selection

3.1 THEORETICAL INTRODUCTION

The workshop opened with a focused theoretical primer on computational design and digital fabrication, establishing shared terminology and expectations. Students were introduced to parametric modelling paradigms, algorithmic thinking for geometry generation, and AI-assisted design for rapid ideation. In parallel, robotic clay extrusion was framed as a translation problem from digital intent to material behaviour highlighting the implications of toolpath continuity, overhang limits, wall thickness, and layer logic. The aim of this phase was to prepare students to perceive each stage (AI → parametric modelling → slicing → robotic execution) as interconnected steps within a single workflow, rather than isolated tasks.

3.2 STUDENT SELECTION

Participants were selected by the supervising professor to ensure readiness for the workshop's technical demands. Selection prioritised students who demonstrated:

- A strong passion for digital fabrication
- Foundational skills in Rhinoceros 3D modelling.

This approach balanced inclusivity with preparedness, enabling students to **focus on learning the workflow rather than mastering advanced geometry or code from scratch**. A total of 25 students were enrolled and organised into five groups of five, fostering peer learning while enabling each group to pursue a distinct yet comparable line of inquiry.

3.3 HANDS-ON APPLICATION

Following the theoretical introduction, the workshop progressed into a one-week, hands-on sequence that operationalised the full pipeline:

1. AI-driven ideation: teams curated AI outputs aligned with fabrication constraints.
2. Parametric modelling (Rhino + Grasshopper): AI references were translated into fabrication-aware units with explicit control over scale, wall thickness, curvature, and continuity.
3. Slicing and toolpath logic: groups generated layer-wise or vase-mode paths and simulated print kinematics, checking for path continuity and seam optimization.
4. Robotic code preparation: teams exported (RAPID Code) robot ready paths consistent with nozzle size and layer height.

The pedagogical intent was process fluency and stage to stage linkage. Students were explicitly discouraged from pursuing overly complex geometries, instead, they were guided to internalise the flow the sequence, dependencies, and constraints that connect ideation to fabrication.

3.4 EVALUATION AND SCORING FRAMEWORK LIKERT SCALE

All evaluations including the single post-workshop survey and the stage-based rubrics reported in the results tables used a 5-point Likert scale measurement in Table (1) by Group Work:

TABLE 1. Shows a 5-point Likert scale. Source (Likert,1932)

Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
5	**4**	**3**	**2**	**1**

Items covered workflow understanding, perceived learning gains, and readiness to apply AI-augmented fabrication, as well as instructor/researcher ratings of concept fidelity, printability assumptions, toolpath continuity, and simulation readiness.

3.5 INTEGRATED WORKFLOW OF AI, COMPUTATIONAL DESIGN, DIGITAL FLOW, AND ROBOTIC FABRICATION

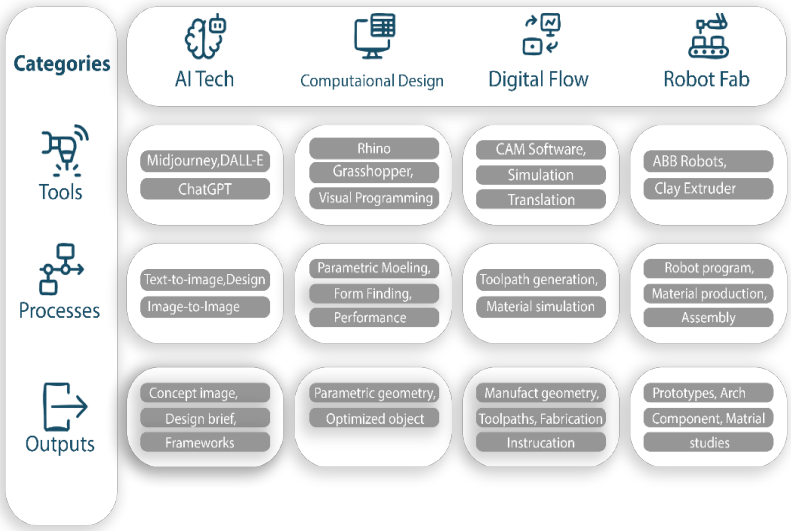


Figure 1. Diagram illustrating the integrated workflow of AI technology, computational design, digital flow, and robotic fabrication, highlighting associated tools, processes, and outputs within the architectural design and fabrication pipeline. Source: By Author.

4. Experimental Workflow: Educational Stages

4.1. STAGE 1: AI-ASSISTED DESIGN EXPLORATION AND SKETCH DEVELOPMENT

Aim: Introduce students to the conceptual potential of generative AI tools (e.g. Midjourney, Stable Diffusion, Krea, Gemini) for form generation.
The goal is to shift the student's role from passive consumers of AI content to critical curators who analyze spatial and tectonic possibilities in AI-generated outputs.

Output: Each team selected 4 AI-generated images that demonstrated architectural Concept, porosity, curvature, or modularity.



Figure 2. Shows the Group 1 Outputs ai generated photos. Source: By Author.



Figure 3. Shows the Group 2 Outputs ai generated photos. Source: By Author



Figure 4. Shows the Group 3 Outputs ai generated photos. Source: By Author



Figure 5. Shows the Group 4 Outputs ai generated photos. Source: By Author



Figure 6. Shows the Group 5 Outputs ai generated photos. Source: By Author

TABLE 2. Shows a comparison table for each group in stage 1 outputs. Source: By Author

Group	Concept	Ai Program Used	Prompt Used	Accurate to concept (1-5)	Accurate to Reality (1-5)
G1	Wave-Puzzle Tile	Krea – Gemini	"Interlocking wave cell: continuous path, soft fillets, uniform wall, minimal overhangs, studio product shot."	4	4
G2	Tri-Lobe Interlock Cell	Midjourney – Gemini	"Tri-lobe interlock cell single continuous loop, soft fillets, gentle necks; clay 3D-printed; views: single, tiled star/hex, stacked column. "	5	4
G3	Snake-Path Tile	Krea – Gemini	"Serpentine interlock cell single continuous loop, soft fillets, gentle necks; clay 3D-printed. "	5	5
G4	Arc-Cradle Block	ChatGPT – Gemini	"U-shaped arc module with central foot, layered printing; uniform wall; show cradle and stacked vaulted array; ceramic clay, studio shot"	4	3
G5	S-Loop Screen Tile	Krea – Gemini	"S-curve closed loop in clay, continuous perimeter; alternate-phase tiling to form diamond apertures; uniform wall, neutral studio"	3	4

This table (2) Stage-1 ideation. Five groups used Krea + Gemini (3 teams), Midjourney + Gemini (G2), and ChatGPT +Gemini (G4). Scores were strong: concept = ~4.2/5, reality = ~4.0/5. G3 (Snake-Path) led (5/5, 5/5); G2 hit 5/5 concept with 4/5 realism. G5 had the weakest concept fit (3/5, phase-alternating tiling is hard to enforce), and G4 the lowest realism (3/5, layered U-cradle with foot). Concise prompts specifying single continuous loop, soft fillets, uniform walls yielded the most fabrication-legible images.

After visualization, students produced quick hand sketches (Fig. 7) to fix module logic and print constraints, creating a bridge from AI imagery to parametric modelling and, later, robotic fabrication.

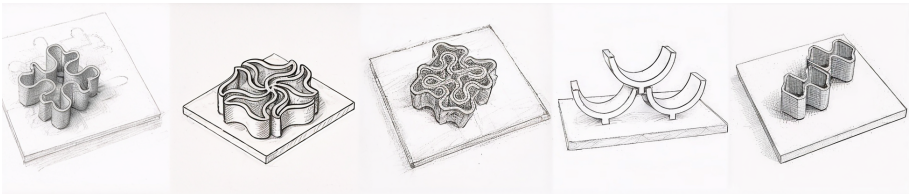


Figure 7. Shows the five groups sketch Outputs. Source: By Author

After completing the sketching phase, students employed AI image-to-image generation to further refine their designs and visualize them in a more realistic context in figure 8.



Figure 8. Shows the five groups AI Visualize sketches Outputs. Source: By Author

Result and Insight for Next Stage:

By the end of this stage, students learned to treat AI outputs as design material, not finished form: they practiced prompt engineering, critical curation, and fabrication awareness. The four curated images per group each with a prompt log now serve as parametric briefs for Stage 2: from them, teams extract explicit drivers for Grasshopper, decide vase mode vs. layered paths, and set print aware constraints. In short, Stage 01 delivered clear concept intent + fabrication cues that can be directly translated into rule-based Grasshopper models for the next stage.

4.2. STAGE 2: PARAMETRIC MODELING AND MODULAR DESIGN DEVELOPMENT

Aim: Translate selected AI images into parametric digital models using Rhino + Grasshopper. Students were introduced to geometric logic, layering principles, and design for robotic fabrication (e.g. continuous geometry, extrusion constraints).

Geometry Selection: For consistency and pedagogy, the geometry and concept sets were preselected by the supervising professors. We curated

simple, diverse primitives (e.g., wave loop, tri-lobe loop, serpentine loop, U-cradle, S-link) that vary in topology yet remain fabrication-legible (single continuous paths, gentle curvature, controllable necks). This ensured students could model different shapes with the same end-to-end workflow AI curation → parametric rules → slicing → robot code without the distraction of over complex forms. The intent was to emphasise the smoothness and logic of the workflow (sequencing, constraints, handoffs) rather than formal virtuosity, so first time learners could internalise process fluency before pursuing higher geometric complexity.

Output: A set of Rhino based modular units per team and intended use of the prototype, enhancing concept and designed with fabrication-aware parameters. In the second stage of the workshop, Parametric Refinement, students transitioned from speculative AI imagery to precise computational models by reconstructing selected modular concepts within Rhino and Grasshopper.

This step allowed them to translate the abstract geometries generated by AI into 3d model parametric definitions, embedding rules and adjustable parameters to govern dimensions, repetition. The resulting 3D modular models, presented below, illustrate how AI-driven ideas were systematically refined into buildable, rule-based architectural prototype components.

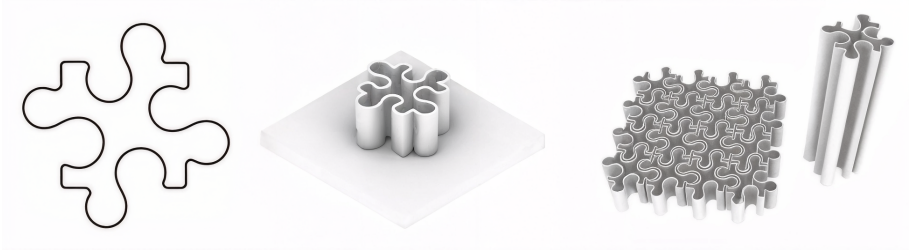


Figure 9. Parametric modeling development of Group 1's modular clay unit, showing the initial outline, single-unit form, and aggregated configurations for partition and column applications. Source: By Author

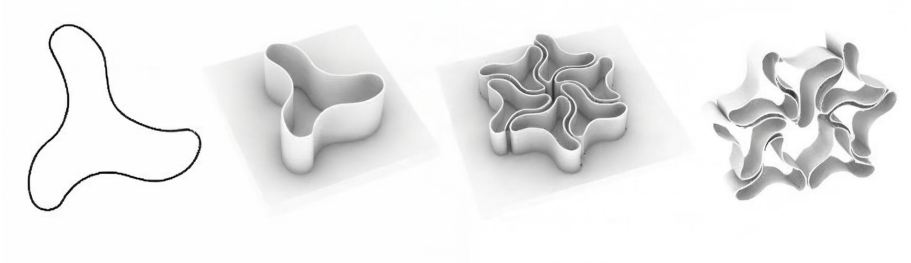


Figure 10. Parametric modeling development of Group 2's modular clay unit, illustrating the initial contour, single-unit form, and aggregated assemblies demonstrating tessellation and spatial adaptability. Source: By Author

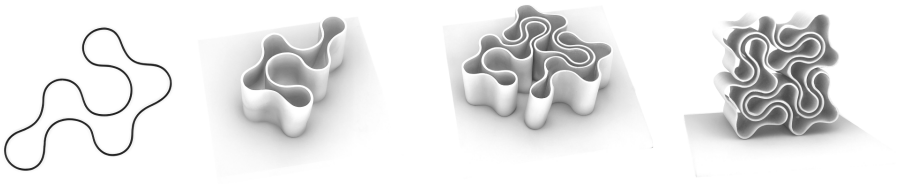


Figure 11. Parametric modeling development of Group 3's modular clay unit, showing the initial outline, single-unit geometry, and stacked assemblies demonstrating both partition and vertical applications. Source: By Author

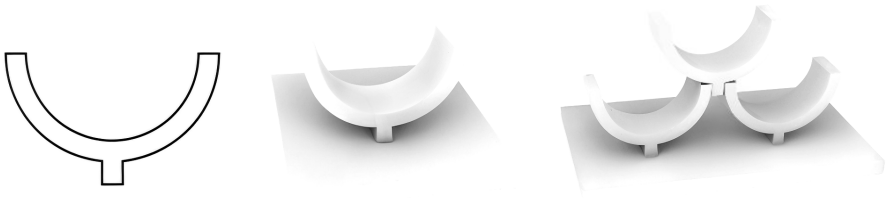


Figure 12. Parametric modeling development of Group 4's modular clay unit, illustrating the initial contour, single-unit form, and stacked configuration demonstrating its dual function as partitions and shelving elements. Source: By Author

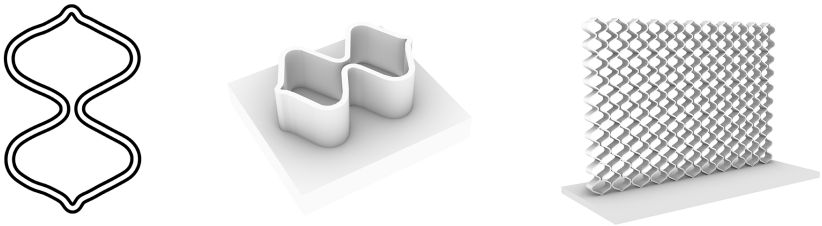


Figure 13. Parametric modeling development of Group 5's modular clay unit, showing the initial double-line contour, single-unit form, and aggregated vertical arrangement demonstrating its Mashrabiya-inspired partition design. Source: By Author

TABLE 3. Shows a comparison table for each group in stage 2 outputs. Source: By Author

Group	Programs Used	Sticking to AI result (1-5)	Sticking to Concept (1-5)	Intended Use of Prototype	Meets Printing Limitation	Comment
G1	Rhino & Grasshopper	4	5	partition and column applications	yes	
G2	Rhino & Grasshopper	4	5	modular planter & partition System	Partial	Edited the sharp edges to be a smooth fillet
G3	Rhino & Grasshopper	5	5	partition and into a table base	yes	
G4	Rhino & Grasshopper	3	4	vertical partitions and adaptable shelving systems	yes	
G5	Rhino & Grasshopper	4	5	vertical Mashrabiya-inspired partition	yes	

All teams worked in Rhino + Grasshopper and, on a 1–5 Likert scale, showed strong fidelity to both the AI images and the stated concepts. Sticking to AI result averaged (~4.0/5) (G3 highest at 5/5; G4 lowest at 3/5) while Sticking to Concept averaged (~4.8/5) (four groups at 5/5). Most prototypes met printing limits; G2 is marked Partial after smoothing sharp edges to fillets to improve printability. Intended uses span partitions, columns, planters, shelving, and a Mashrabiya-inspired screen, indicating that students translated curated AI forms into fabrication-aware, application-oriented modules.

Result and Insight for Next Stage:

In this stage students learned how to translate AI images into rule-based, fabrication-aware parametric models and producing clean, continuous geometry suitable for slicing.

Each team left Stage 02 with a 3D Model and a declared intended use (partition, column, planter, shelving). These outputs feed directly into Stage 03, where the models are converted into vase-mode or layered toolpaths, with seam strategy, layer height, speeds, and flow set via the AI-assisted GHPython slicer.

4.3. STAGE 3: AI-ASSISTED SLICING & ROBOT CODE GENERATION

Aim: Use ChatGPT to generate Python scripts embedded in Grasshopper Python components that convert the teams' parametric models into fabrication ready toolpaths (vase-mode and layered slicing), lowering the coding barrier and demonstrating how AI can be used to author custom Grasshopper tools.

Output: RAPID Code and robot-compatible curves and slicing patterns tailored for clay extrusion. Simulation in Rhino and Robot Studio validated feasibility.

AI-assisted robotic fabrication. Students used ChatGPT to draft GHPython slicers that implement vase-mode and layered paths. Rather than relying only on plug-ins, they prompted the AI with clay-printing constraints (nozzle size, layer height, seam), embedded the returned code as editable Grasshopper components, and generated continuous, fabrication-ready toolpaths with RAPID export. Through short prompt test loops and validation in Rhino/Robot Studio, they learned to convert modular designs into layer wise instructions while checking reach, acceleration, and collisions. Prototypes and simulations illustrate this AI-mediated translation from geometry to execution. Hardware: ABB IRB 6700 (Fig. 14) with a clay extruder (Fig. 15) and 3/4/6-mm nozzles.



Figure 14. IRB 6700 industrial robotic arm used for clay extrusion in Stage 3 (ABB, 2013).

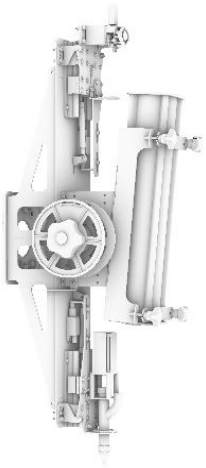


Figure 15. Clay Extruder Unit with 4mm nozzle. Source: By Author

First the students asked ChatGPT to create a Rhino 8 Grasshopper (GhPython) tool that slices any input geometry by Z with a user-set layer height, lets the user set the start point to control the printing seam, and includes a toggle button for Vase (spiral) mode vs layer-by-layer output.

The script also takes a division input to control/optimize how many points and thus planes/waypoints the robot will follow. It outputs the ordered list of toolpath points, a single path curve (continuous spiral in vase mode, or connected loops in layered mode), plus the total point count and number of slicing layers. For visualization, it can generate a pipe mesh along the path, with a Boolean to enable/disable it and a diameter input to set the tube size, we will show below the final python code that used in figure (16).

```
"""
Spiral Vase / Layered Toolpath Slicer + Pipe Mesh Visualizer

Inputs:
  Geom (Surface/Brep or Mesh)
  LayerH (Number)                # layer height
  Divs (Integer)                 # points per revolution (>=12)
  VaseMode (Boolean)             # True = continuous spiral with smooth Z rise
  StartPt (Point, optional)      # path start (closest point on first ring)
  PipeOn (Boolean)               # True = output pipe mesh along path
  PipeDia (Number)               # pipe diameter (units of model)

Outputs:
  Pts [Point3d]                  # ordered toolpath points
  Path [Curve]                   # spiral (NURBS) or connected polyline (layered)
  Rings [Curve]                  # per-layer closed rings (polylines)
  PointCount (int)
  LayerCount (int)
  PipeMesh (Mesh)                # tube along Path (None if PipeOn=False)
"""

import Rhino.Geometry as rg
import Rhino.Geometry.Intersect as rgi
from System import Array
import math

TOL = 1e-6
PIPE_SIDES = 16  # circle resolution for the pipe mesh (internal)

# ---------------- Helpers ----------------
def is_mesh(g):
    return isinstance(g, rg.Mesh)

def to_brep(g):
    if isinstance(g, rg.Brep): return g
    if isinstance(g, rg.Surface): return g.ToBrep()
    return None

def largest_closed_curve(curves):
    best = None; best_area = -1.0
    for c in curves:
        if not c or not c.IsClosed:
            continue
        amp = rg.AreaMassProperties.Compute(c)
        a = amp.Area if amp else 0.0
        if a > best_area:
            best_area = a; best = c
    return best

def join_curves_list(lst, tol=TOL):
    if not lst: return []
    try:
        joined = rg.Curve.JoinCurves(Array[rg.Curve](lst), tol)
    except:
        joined = rg.Curve.JoinCurves(lst, tol)
    if joined and len(joined) > 0:
        return list(joined)
    return list(lst)

def slice_brep_z(brep, z, tol=TOL):
```

```
    plane = rg.Plane(rg.Point3d(0,0,z), rg.Vector3d(0,0,1))
    res = rgi.Intersection.BrepPlane(brep, plane, tol)
    crvs = []
    try:
        for it in res:
            if isinstance(it, rg.Curve): crvs.append(it)
    except:
        pass
    if not crvs:
        def _flatten(x):
            if isinstance(x, rg.Curve):
                crvs.append(x); return
            try:
                for y in x: _flatten(y)
            except TypeError:
                return
        _flatten(res)
    crvs = join_curves_list(crvs, tol)
    return largest_closed_curve(crvs)

def slice_mesh_z(mesh, z):
    plane = rg.Plane(rg.Point3d(0,0,z), rg.Vector3d(0,0,1))
    polylines = rgi.Intersection.MeshPlane(mesh, plane)
    if not polylines: return None
    crvs = []
    for pl in polylines:
        if pl is None or pl.Count < 3: continue
        if pl[0].DistanceTo(pl[-1]) > TOL:
            pl.Add(pl[0])
        crvs.append(rg.Polyline(pl).ToPolylineCurve())
    return largest_closed_curve(crvs)

def slice_geom_z(geom, z, tol=TOL):
    if is_mesh(geom): return slice_mesh_z(geom, z)
    b = to_brep(geom)
    if b: return slice_brep_z(b, z, tol)
    return None

def ensure_ccw_xy(crv):
    """Force closed curve orientation to CCW in WorldXY (reverse if clockwise)."""
    if not crv or not crv.IsClosed: return crv
    try:
        if crv.ClosedCurveOrientation(rg.Plane.WorldXY) == rg.CurveOrientation.Clockwise:
            crv.Reverse()
    except:
        amp = rg.AreaMassProperties.Compute(crv)
        if amp and amp.SignedArea < 0.0:
            crv.Reverse()
    return crv

def seam_param_from_start(crv, start_pt):
    """Closest parameter to StartPt (if given), else +X from centroid."""
    if start_pt is not None:
        rc, t = crv.ClosestPoint(start_pt)
        if rc: return t
    amp = rg.AreaMassProperties.Compute(crv)
    c = amp.Centroid if amp else crv.GetBoundingBox(True).Center
    R = crv.GetBoundingBox(True).Diagonal.Length
    target = rg.Point3d(c.X + R, c.Y, c.Z)  # +X ray
    rc, t = crv.ClosestPoint(target)
```

```
    return t if rc else crv.Domain.T0

def sample_closed_from_t(crv, count, t0):
    """Return exactly 'count' points around closed curve starting at t0, no duplicate seam."""
    count = max(12, int(count))
    ts = []
    ok = crv.DivideByCount(count, True, ts)
    if not ok or len(ts) < 3:
        L = crv.GetLength()
        if L > TOL:
            ts = []; crv.DivideByLength(L/float(count), True, ts)
    if len(ts) < 3:
        a,b = crv.Domain.T0, crv.Domain.T1
        ts = [a + (b-a)*i/float(count) for i in range(count)]
    idx0 = min(range(len(ts)), key=lambda i: abs(ts[i]-t0))
    ts = ts[idx0:] + ts[:idx0]
    if len(ts) > count: ts = ts[:count]
    return [crv.PointAt(t) for t in ts]

def close_ring_points(pts):
    if not pts: return pts
    if pts[0].DistanceTo(pts[-1]) > TOL:
        return pts + [pts[0]]
    return pts

def build_pipe_mesh_along_curve(curve, centers, radius, sides=PIPE_SIDES):
    """
    Build a lightweight tube mesh along 'curve', sampling frames at 'centers' (list of points).
    Uses PerpendicularFrameAt at the curve-parameter closest to each center.
    """
    if curve is None or centers is None or len(centers) < 2 or radius <= 0.0:
        return None
    sides = max(6, int(sides))
    # Precompute parameters for centers
    params = []
    for p in centers:
        rc, t = curve.ClosestPoint(p)
        params.append(t if rc else curve.Domain.ParameterAt(0.0))

    # Build vertex rings
    verts = []
    for i, (p, t) in enumerate(zip(centers, params)):
        rc, frame = curve.PerpendicularFrameAt(t)
        if not rc:
            # fallback plane using tangent & world Z
            tan = curve.TangentAt(t)
            if not tan.Unitize(): tan = rg.Vector3d(0,0,1)
            up = rg.Vector3d(0,0,1)
            if abs(rg.Vector3d.Multiply(tan, up)) > 0.95:
                up = rg.Vector3d(1,0,0)
            x = rg.Vector3d.CrossProduct(up, tan); x.Unitize()
            y = rg.Vector3d.CrossProduct(tan, x);  y.Unitize()
            frame = rg.Plane(p, x, y)
        else:
            frame.Origin = p  # enforce exact path point Z

        # create ring vertices
        for k in range(sides):
            a = 2.0*math.pi * (float(k)/float(sides))
            vx = frame.XAxis * (radius * math.cos(a))
```

```
            vy = frame.YAxis * (radius * math.sin(a))
            verts.append(frame.Origin + vx + vy)

    # Build mesh faces
    m = rg.Mesh()
    for v in verts: m.Vertices.Add(v)
    rows = len(centers)
    for i in range(rows - 1):
        rowA = i * sides
        rowB = (i+1) * sides
        for k in range(sides):
            a = rowA + k
            b = rowB + k
            c = rowA + ((k+1) % sides)
            d = rowB + ((k+1) % sides)
            m.Faces.AddFace(a, c, b)
            m.Faces.AddFace(c, d, b)

    m.Normals.ComputeNormals()
    try: m.UnifyNormals()
    except: pass
    m.Compact()
    return m

# ---------------- Inputs / defaults ----------------
geom = Geom
if geom is None:
    Pts = []; Path = None; Rings = []; PointCount = 0; LayerCount = 0; PipeMesh = None
    raise Exception("Provide a Geometry to slice.")

lh   = float(LayerH) if LayerH else 10.0
divs = int(Divs) if Divs else 240
divs = max(12, divs)

vase = bool(VaseMode) if VaseMode is not None else True
start_pt = StartPt if 'StartPt' in globals() else None

pipe_on  = bool(PipeOn) if 'PipeOn' in globals() and PipeOn is not None else False
pipe_dia = float(PipeDia) if 'PipeDia' in globals() and PipeDia is not None else 0.0
pipe_rad = max(0.0, pipe_dia * 0.5)

# ---------------- Build Z levels ----------------
bb = geom.GetBoundingBox(True)
z0, z1 = bb.Min.Z, bb.Max.Z
height = max(0.0, z1 - z0)

LayerCount = int(math.floor(height / lh)) + 1
z_list = [z0 + i*lh for i in range(LayerCount)]
if z_list[-1] < z1 - 1e-7:
    z_list.append(z1); LayerCount = len(z_list)

# ---------------- Slice & normalize orientation ----------------
raw_rings = []
for z in z_list:
    ring = slice_geom_z(geom, z, TOL)
    if ring:
        ring = ensure_ccw_xy(ring)
        raw_rings.append(ring)

LayerCount = len(raw_rings)
```

```
if LayerCount == 0:
    Pts = []; Path = None; Rings = []; PointCount = 0; PipeMesh = None
    raise Exception("No valid intersections; check geometry and LayerH.")

# ---------------- Build per-layer samples aligned to StartPt ----------------
Rings = []
rings_pts = []
for i, crv in enumerate(raw_rings):
    t0 = seam_param_from_start(crv, start_pt)
    pts = sample_closed_from_t(crv, divs, t0)
    zi = z_list[i]
    pts = [rg.Point3d(p.X, p.Y, zi) for p in pts]
    rings_pts.append(pts)
    Rings.append(rg.Polyline(close_ring_points(list(pts))).ToPolylineCurve())

# ---------------- Build toolpath ----------------
tool_pts = []

if vase:
    # single smooth spiral by morphing ring i -> ring i+1 within one revolution
    for i in range(LayerCount - 1):
        A = rings_pts[i]
        B = rings_pts[i+1]
        for k in range(divs):
            a = float(k)/float(divs)
            ax = (1.0 - a)*A[k].X + a*B[k].X
            ay = (1.0 - a)*A[k].Y + a*B[k].Y
            az = (1.0 - a)*A[k].Z + a*B[k].Z
            tool_pts.append(rg.Point3d(ax, ay, az))
    tool_pts.append(rings_pts[-1][0])

    Pts = tool_pts
    PointCount = len(Pts)
    # smooth NURBS spiral (fallback: polyline)
    try:
        Path = rg.Curve.CreateInterpolatedCurve(Pts, 3)
    except:
        Path = rg.Polyline(Pts).ToPolylineCurve()

else:
    # closed loops per layer, connected by vertical hops
    for i in range(LayerCount):
        loop = close_ring_points(list(rings_pts[i]))
        tool_pts.extend(loop)
        if i < LayerCount - 1:
            nxt0 = rings_pts[i+1][0]
            tool_pts.append(rg.Point3d(nxt0.X, nxt0.Y, nxt0.Z))
    Pts = tool_pts
    PointCount = len(Pts)
    Path = rg.Polyline(Pts).ToPolylineCurve()

# ---------------- Pipe mesh visualization ----------------
PipeMesh = None
if pipe_on and Path is not None and PointCount > 1 and pipe_rad > 0.0:
    PipeMesh = build_pipe_mesh_along_curve(Path, Pts, pipe_rad, PIPE_SIDES)
```

Figure 16. Shows Python Code from ChatGPT used to make the Slicer. Source: By Author

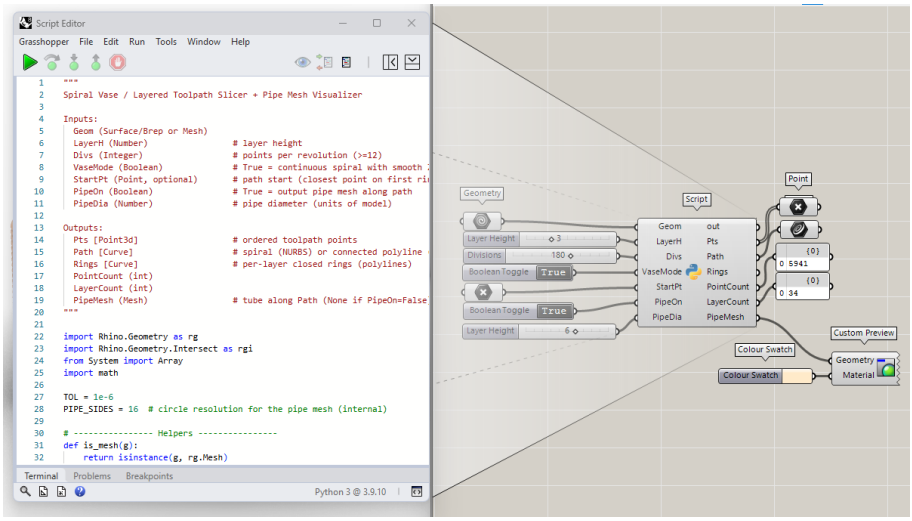


Figure 17. shows the slicer python script after put it into grasshopper source by Author.

This GHPython component generates clay-printing toolpaths by Z-slicing any Brep/Surface/Mesh and supports two strategies: vase spiral (continuous) and layer-by-layer. Inputs: Geom, LayerH, Divs (points per revolution), and StartPt (sets the seam by nearest point on the first contour). Z-contours (via BrepPlane/MeshPlane) are normalized CCW and resampled so the seam aligns with StartPt.

• Vase mode: rings are morphed to the next within one revolution, linearly interpolating XY and Z to avoid vertical jumps; output Path is an interpolated NURBS spiral with ordered Pts.

• Layered mode: each ring is closed; rings connect by short vertical links into a single polyline Path.

The script also outputs Rings (per-layer previews), PointCount, LayerCount, and an optional PipeMesh (toggle PipeOn, size PipeDia) for quick tubular visualization. It standardizes contour direction, exposes start control, and produces continuous or connected toolpaths ready for digital-fabrication workflows.

4.3.1. Difference Between Layer-by-Layer Mode and Vase Spiral Mode

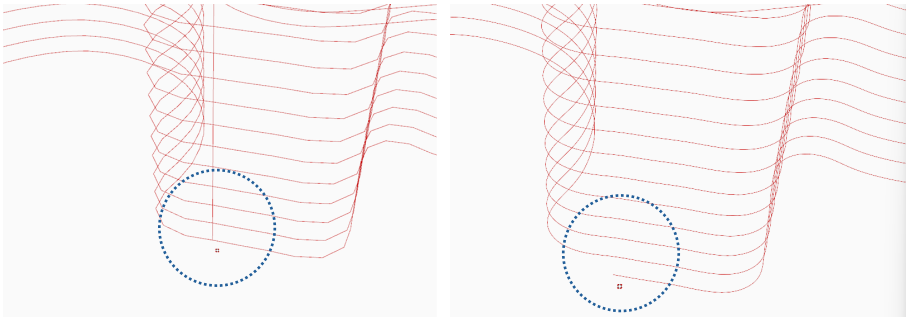


Figure 18. shows in the left (Layer by Layer Mode) and In the Right (Vase Spiral Mode) source by Author.

In layer-by-layer slicing the printer completes one (or more) closed loops per Z level, stops, Z-hops, and starts the next layer creating start/stop seams and pressure changes; it allows multiple perimeters and infill/top surfaces. In vase/spiral mode the toolpath is a single uninterrupted helix that gradually rises in Z with constant flow no retractions, no layer seams, but limited to single-wall, continuous-perimeter geometries (no infill/roof) and gentle overhangs. For our clay units we chose vase mode to achieve clean, smooth prints without visible seams and to keep extrusion pressure stable in figure (18) and final toolpath curves for all groups in figure (19).

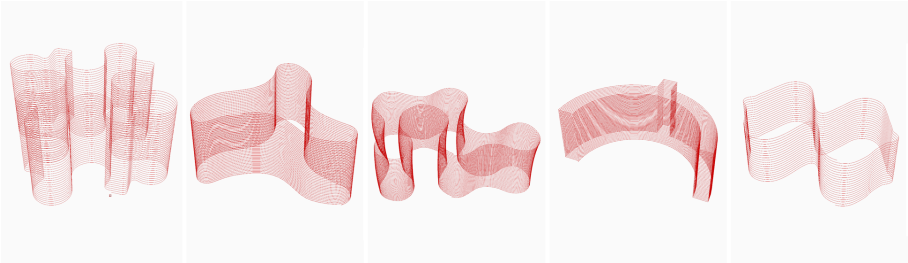


Figure 19. shows all final groups curve toolpath in vase mode source by Author.

TABLE 4. Shows a comparison table for each group in stage 3 outputs. Source: By Author

Group	Layer Height (mm)	Toolpath Method	Wall thickness (mm)	Layer Count	Points Num
G1	3	Vase Mode	6	34	6601
G2	3	Vase Mode	5	34	5281
G3	2.5	Vase Mode	3	40	7261
G4	2.5	Vase Mode	4	40	6271
G5	2.5	Vase Mode	4	21	4001

All teams used vase mode (single, continuous perimeter). Layer height clustered at 2.5–3.0 mm (avg ≈ 2.7 mm) and wall thickness at 3–6 mm (avg ≈ 4.4 mm), meeting printability targets for clay extrusion. Layer counts ranged 21–40 (avg ≈ 33.8), while path points ranged 4,001–7,261 (avg ≈ 5,883), reflecting differences in geometry complexity or part height. G3 combined the thinnest wall (3 mm) with 40 layers and the highest point count (7,261)—the most intricate path—whereas G5 showed the shortest build (21 layers; 4,001 points).

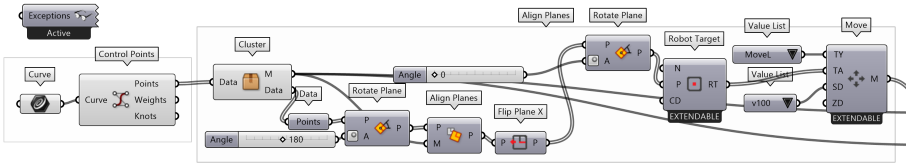


Figure 20. Show the script Aligning the orientation of the planes. Source: By Author.

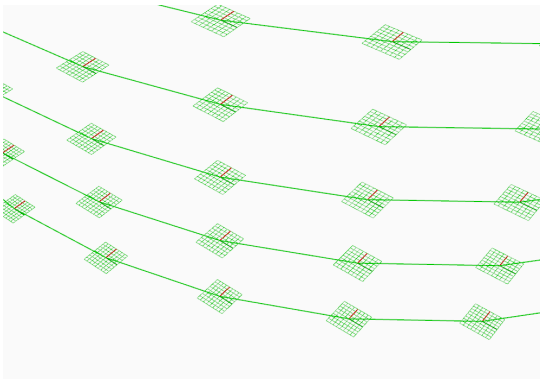


Figure 21. Show the orientation of the planes Aligned with robotic tool. Source: By Author.

The final stage of the robotic fabrication workflow involved converting the optimized toolpaths into RAPID code, the programming language used by ABB robotic arms. Using Grasshopper plugins, the oriented planes in figure (20) and (21) and corresponding point data were translated into movement commands, extrusion controls, and speed parameters compatible with the ABB IRB 6700. This automated scripting process ensured precise coordination between the robotic arm's motion and the clay extrusion system, eliminating the need for manual coding. By generating RAPID code directly from their parametric models in figure (22), students gained practical insight into how computational design tools interface with industrial robotic systems, reinforcing the direct link between digital geometry and machine execution.

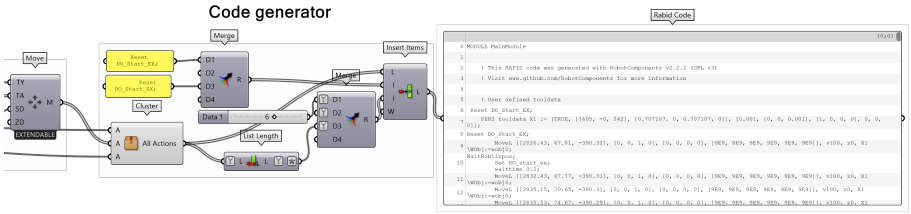


Figure 22. Shows Generated RAPID Code for the Robotic arm. Source: By Author

Result and Insight for Next Stage:

In this stage students learned to convert parametric geometry into continuous, robot-ready toolpaths, choosing vase-mode strategies, setting layer height, wall thickness, seam placement, speeds, and validating paths in Grasshopper. They also used the AI-authored GHPython tools to debug continuity, count points/layers. Each team leaves Stage 03 with a validated toolpath set (and exportable RAPID code) plus a clear parameter sheet, these feed directly into Stage 04, where the same settings are applied for (simulated or physical) fabrication, timing comparison, and quality assessment.

4.4. STAGE 4: ROBOTIC ARM FABRICATION WITH CLAY EXTRUSION

Aim: Fabricate scaled prototypes using an ABB IRB 6700 robotic arm and custom clay extrusion system. Students calibrated print speed, extrusion rate, and layer height under real-world conditions, we used earthenware Clay Aswani powder and material specs was Every 3 Kg raw material Aswani clay with 1030 millilitres water.

Output: Full or partial physical prototypes of modular units, fabricated using vase mode.

After generating the RAPID code, it was imported into **ABB Robot Studio**, where a virtual workstation of the **IRB 6700 robotic arm** was used to validate the program. This step involved thoroughly checking the code for syntax errors and verifying toolpath accuracy within the simulated environment. A full **robotic simulation** was then performed in figure (23) to assess the movement sequence, nozzle orientation, and reachability, ensuring collision-free operation and correct execution of the extrusion process. This simulation phase was essential for confirming that all robotic motions were accurately coordinated before physical fabrication, reducing potential risks and improving the reliability of the final robotic printing workflow.

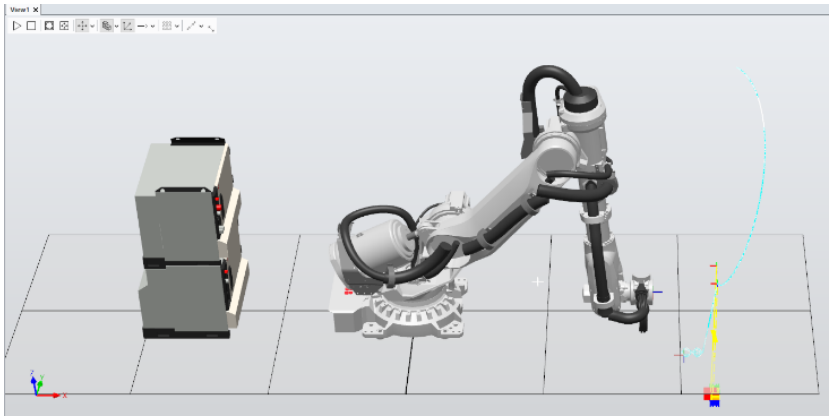


Figure 23. Robot Studio simulation of the ABB IRB 6700 robotic arm configured for clay extrusion, used to validate toolpaths and ensure error-free operation before physical fabrication. Source: By Author

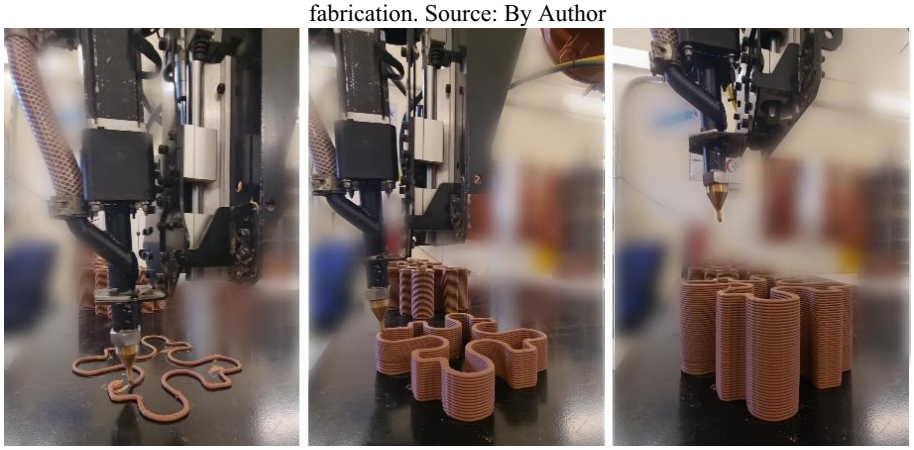


Figure 24. Robotic clay extrusion process showing sequential stages: initial layer deposition, mid-print progress, and final completed prototype printed in vase mode with continuous toolpath for seamless surface finish. Source: By Author

Following the validation of the RAPID code in Robot Studio, the printing process was initiated using the ABB IRB 6700 robotic arm with clay extrusion. The fabrication was executed in **vase mode**, where the toolpath remained continuous throughout the process, eliminating visible seam marks and ensuring a smooth, uninterrupted surface finish. The sequence of images illustrates the **three key stages of fabrication**: the deposition of the **first layer**, the **mid-print stage**, and the **completed print** in figure (24). This approach demonstrated the precision of the robotic toolpath and consistent layer adhesion, effectively translating the digital model into a high-quality physical prototype.

TABLE 5. Shows a comparison table for each group in stage 4 outputs. Source: By Author

Group	Material	Robot Speed	Nozzle (mm)	Extrusion Speed	Printing Time Per Unit	Units Printed	Unit Weight after Burned (g)
G1	Red earthenware	V100	6mm	10	7 min	12	2317
G2		V100	4mm	8	4:30 min	6	635
G3		V100	4mm	6	6:40 min	4	465
G4		V100	4mm	8	5:35 min	3	522
G5		V100	3mm	6	3:45 min	4	351

After completing the robotic printing of all units, the components underwent a drying and firing process to ensure material strength and durability. Initially, the printed clay units were air-dried for 4 days to allow gradual moisture evaporation, minimizing the risk of deformation or cracking. Following this, the units were placed in a kiln oven for approximately 16 hours at a regulated temperature to achieve full vitrification. Once firing was completed, the oven was shut down and left closed for an additional day to allow the units to cool gradually and relieve internal stresses. This process significantly improved the structural integrity of the components, making them suitable for prototype assembly.

Group 5 incident & fix:

During printing, the S-Loop Screen Tile cracked and partially collapsed, likely due to the single 4 mm wall and slender necks. The team redesigned the unit with an internal offset (second wall) in figure (25), then re-sliced it and a slightly lower print speed. The revised toolpath improved stiffness and the group successfully reprinted two units without failure.

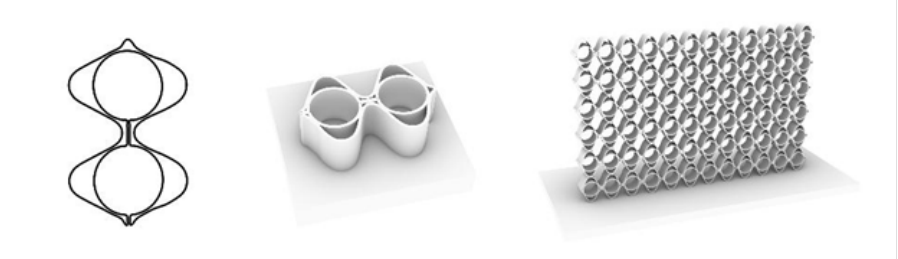


Figure 25. Redesigned G5 model adding second wall. Source: By Author



Figure 26. Completed 3D-printed clay units from all groups after robotic fabrication. Source: By Author



Figure 27. 3D-printed clay units placed inside a kiln for controlled firing. Source: By Author

TABLE 5. Shows a comparison table for each group in stage 4 outputs for Post Processing. Source: By Author

Group	Rest (Drying) Time	Burning Temp & Time	Real-time Errors	Units Cracked after burning	Iterative Refinement?
G1	96 hrs	900°C, 16 hours	Extrusion stopped because lack of material in the storage	2	No
G2	96 hrs	900°C, 16 hours		1	No
G3	96 hrs	900°C, 16 hours		0	No
G4	96 hrs	900°C, 16 hours		0	No
G5	96 hrs	900°C, 16 hours	*Cracked and redesigned and resliced*	2	Yes

Result and Insight for Next Stage:

In the fabrication stage, students learned to close the loop from toolpath to robot execution: importing RAPID, validating motions in Robot Studio, and calibrating nozzle size, layer height, print speed, and flow on the ABB IRB 6700. They also practiced failure-aware iteration (e.g., G5's redesign with a second wall), basic process control (corner slowdowns, seam placement), and post-processing routines (drying/firing). The stage produced a comparable dataset units printed, print time per unit, nozzle and speed settings, errors, and post-firing weights that feeds Stage 05 for evaluation of geometric fidelity, print quality, and design feasibility, and for reflecting on how AI-assisted slicing choices influenced outcomes.

4.5. STAGE 5: POST-FABRICATION EVALUATION AND REFLECTION

Aim: Assemble printed units into small demonstrators to experience the full AI → Parametric → Slicing → Robot → Assembly workflow. This stage is prototype-only and does not assess structure or stability; the pedagogic goal is workflow fluency and to observe how AI-assisted tools (ChatGPT + GHPython) can shape, edit, and upgrade the process for education.

Output: Each group produces 1–3 assembled prototypes plus a brief workflow card mapping: AI prompt → key parametric drivers → slicing choice (vase/layered) → robot settings → assembly rationale and tolerances. Reflections on assembly and workflow fluency were captured in the single post-workshop survey, results are reported in the Evaluation/Results sections. Note: Results are proof of process, not performance evaluations.



Figure 28. Group 1 prototyped their AI-generated clay units into partition and column assemblies. Source: By Author

Group 1 assembled the AI-derived, robot-printed unit into two demonstrators a porous partition patch and a short column to evidence the workflow. Evaluation focused on fit clearance, interlock tolerance, tiling pitch, and seam orientation. The exercise showed how parametric drivers (amplitude, neck width, fillet radius) govern assembly logic and porosity, yielding proof of process prototypes for teaching.



Figure 29. Group 2 prototypes into modular planter configurations. Source: By Author

Group 2 assembled the AI-derived, robot-printed unit in two orientations: horizontal as a modular planter and vertical as a partition sample. Evaluation addressed fit clearance, interlock tolerance, tiling pitch. Reorientation showed how a single parametric module can transition across functional and architectural scales, producing proof of process demonstrators and a clear assembly rationale.



Figure 30. Group 3 prototyped vertically into a partition. Source: By Author

Group 3 assembled two demonstrators: a vertical partition patch and a horizontal table-base mock up. Evaluation focused on fit clearance, interlock precision, tiling pitch, and spatial permeability; for the table base, students reviewed footprint landing flats and conceptual load paths only. The results evidence the unit's adaptability across typologies and serve as proof of process teaching prototypes.



Figure 31. Group 4 prototyped vertical partitions. Source: By Author

Group 4 built two demonstrators with the arc-cradle unit: a vertical partition array and a tiered shelving/rack. The focus was workflow learning not load testing. Checks addressed foot registration, stack pitch landing flats, fit clearance, and seam concealment. The prototypes show the module's adaptability from spatial divider to display/plant shelving, serving as proof of process teaching artifacts.



Figure 32. Group 5 created a vertical Mashrabiya prototype. Source: By Author

Group 5 assembled a Mashrabiya-inspired partition by vertically tiling the S-Loop units in phase-alternating rows to form diamond apertures. Following an earlier print failure, the design used double-line contours (two perimeters) to improve printability and edge handling. Evaluation centred on fit/clearance, tiling pitch, and visual permeability/shading; no structural performance was assessed. The result is a proof of process demonstrator showing how AI-assisted redesign (dual perimeters) supports clean assembly and a recognisable Mashrabiya effect.

Result and Insight:

Collectively, the five groups demonstrated diverse prototyping strategies that showcased the adaptability of AI-generated, robotically fabricated clay units across multiple scales and functions. **Group 1** focused on partitions and columns, emphasizing spatial division and vertical stability, while **Group 2** transitioned from horizontal planters to vertical partitions, illustrating multifunctional adaptability. **Group 3** combined vertical partitioning with horizontal furniture applications, creating a table base prototype, whereas **Group 4** explored dual-purpose vertical partitions that doubled as shelving for accessories and plants. Finally, **Group 5** produced a Mashrabiya-inspired partition with double-line geometry, integrating cultural references and brick-like structural strength. Together, these outcomes reflect how

computationally derived modular systems can support iterative experimentation, blending functional, and aesthetic considerations, thereby reinforcing the workshop's goal of bridging digital design, robotic fabrication, and real-world architectural prototyping.

Survey description (Methods/Evaluation):

Immediately after **Stage 5 (Assembly & Reflection)**, we administered a **single post-workshop survey**. Respondents included:

- the **students** who completed the full AI → Parametric → Slicing → Robot → Assembly workflow,
- **students who attended the preparatory lecture** (but may not have completed fabrication)
- a small number of **fabrication instructors** involved in digital fabrication teaching.

We obtained **84 valid responses**. The instrument used short items and 5-point response formats to probe: perceived **importance** of proficiency in robotics/digital fabrication for architects, expected **future adoption** of robotic methods, and whether the workshop/lecture led to **changes in design thinking**. We also captured background indicators (self-rated **knowledge level** and prior **hands-on experience**) to understand the cohort's starting point (novice/intermediate/advanced). This design allowed us to tie Stage-5 assembly back to learners' **educational thinking** about the end-to-end workflow, not structural performance.

Survey-based Results & Insights:

Findings indicate strong buy in and perceived educational benefit:

- Proficiency is essential. 77.4% answered Yes, 20.2% Maybe, to whether proficiency in controlling robots via 3D programs is essential for architecture students.
- Robotics will grow. 91.7% answered Yes that robotic methods will become more common in design processes.
- Preparation for practice. On the item asking to what extent robotics/digital fabrication prepare students for real-world practice, ≈80% selected Completely or Significantly (with most of the remainder Moderately).
- Design-thinking shift. An 80% reported their design solutions evolved after the workshop/lecture, with a large share selecting Completely/Significantly and relatively 20% choosing slightly/not at all.
- Title-level insight. Aggregating the high-endorsement options across these items, ≈84% of respondents supported statements indicating that robotics and GenAI are shaping the future of their architectural education and practice thinking.

Together, these results show that even with prototype-only assemblies (no structural testing) the staged workflow enhanced students' architectural education thinking: they viewed the pipeline as relevant, future-facing, and worth mastering.

5. Discussion

The survey confirms that a constrained, scaffolded workflow, coupled with AI-assisted toolmaking (ChatGPT-generated Python embedded in GHPython), helps learners perceive robotic fabrication as a single connected process rather than a set of isolated tools. High agreement on the importance of proficiency and on future adoption signals perceived disciplinary relevance, strong ratings for preparation for practice and changes in design thinking indicate that students internalized the sequence from AI ideation → parametric rules → slicing strategy (vase vs. layered) → robot code → assembly. In other words, the workflow did not merely produce prototypes, it reframed how students think about architectural production, constraints, and translation from geometry to fabrication.

Limitations temper interpretation: a single post-survey and prototypes intentionally not evaluated for performance (e.g., strength, serviceability). Nevertheless, for a first-exposure setting with many beginners, the measured attitudes are strong signals that AI + robotics can be taught as workflow literacy, improving cognitive continuity between conceptual design and fabrication planning.

Table 6. Shows the full workflow stages data output, source by author

	Stage 1					Stage 2					Stage 3				Stage 4									
Group	Concept	AI Program Used	Prompt Used	Accurate to concept (1-5)	Accurate to Reality (1-5)	Programs Used	Sticking to AI result (1-5)	Sticking to Concept (1-5)	Intended Use of Prototype	Meets Printing Limitation	Comment	Layer Height (mm)	Toolpath Method	Wall Thickness (mm)	Layer Count	Points Num	Material	Robot Speed	Nozzle (mm)	Extrusion Speed	Printing Time Per Unit	Units Printed	Unit Weight After Burned (g)	Rest (Drying) Time	Burning Temp & Time	Real-time Errors	Units Cracked after burning	Iterative Refinement?
G1	Wave-Puzzle Tile	Krea – Gemini	"the brick's top surface should be a continuous path, soft ridges, shallow wall, rounded chamfer, made of red earthenware clay, studio photo"	4	4	Rhino & Grasshopper	4	5	partition and column applications	yes		3	Vase Mode	6	34	6601	Red earthenware	V100	6mm	10	7 min	12	2317	96 hrs	900°C, 16 hours	Extrusion stopped because lack of material in the storage	2	No
G2	Tri-Lobe Interlock Cell	Midjourney – Gemini	"Tri-lobe interlock cell single cell, smooth loop, soft ridges, 3D-printed, matte red clay, white, studio, stacked cylinders, minimalist"	5	4		4	5	modular planter & partition System	Partial	Edited the sharp edges to be a smooth fillet	3		5	34	5281			4mm	8	4:30 min	6	635				1	No
G3	Snake-Path Tile	Krea – Gemini	"Interlocking tile cell single continuous loop, soft ridges, matte, red clay, 3D-printed"	5	5		5	5	partition and into a table base	yes		2.5		3	40	7261			4mm	6	6:40 min	4	465				0	No
G4	Arc-Cradle Block	ChatGPT – Gemini	"U-shaped arc, smooth with curved foot, layered ridges, uniform wall thickness, cradle and stacked vessels, terracotta clay, studio shot"	4	3		3	4	vertical partitions and adaptable shelving systems	yes		2.5		4	40	6271			4mm	8	5:35 min	3	522				0	No
G5	S-Loop Screen Tile	Krea – Gemini	"S-curve closed loop in continuous ceramic, interlocking plane tile to form diamond perforation, red earthenware, studio"	3	4		4	5	vertical Mashrabiya-inspired partition	yes		2.5		4	21	4001			3mm	6	3:45 min	4	351			*Cracked and redesigned and resliced*	2	Yes

6. Conclusions

This study demonstrates that an AI-enabled, fabrication-aware workflow can be integrated into architectural education in a way that is learnable, repeatable, and meaningful for first-time learners. Quantitatively, respondents reported high perceived importance and practice-readiness, and a majority indicated meaningful shifts in design thinking; in aggregate, ≈84% endorsed statements that robotics and GenAI are shaping the future of their architectural education and practice. Qualitatively, all groups produced parametric models, validated toolpaths (predominantly vase-mode), and assembled proof-of-process prototypes, evidencing end-to-end understanding rather than isolated software tricks.

Future work will add pre/post measurement, expand computer-based analyses (e.g., daylight or simple stability process) without changing the pedagogy-first focus, and compare vase-mode vs. layered strategies across repeated cohorts. The key contribution is pedagogical: a clear, AI-supported path that enhances architectural education thinking by making the computational-to-robotic workflow graspable, iterative, and ready for classroom adoption.

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AI-SUPPORTED BIOMORPHIC DESIGN PEDAGOGY

A Studio-Based Experiment in Architectural Education

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Abstract. The increasing role of artificial intelligence (AI) technologies in architectural education is transforming teaching methods. In this context, ongoing discussions focus on the connection between creative processes and automation, its impact on critical thinking skills, and designer-AI collaborations. This study examines how AI functions in the design process as an alternative to traditional studio-based education, its impact on students' creative and conceptual thinking skills, and its potential opportunities. In this context, a studio experience is presented within the context of the "Parametric Approach to Nature-Inspired Architecture" graduate course offered at Gazi University Faculty of Architecture. The 15-week course is divided into three phases: The first phase provides a foundation in biomorphology and AI, including theoretical background. In the second phase, students create parametric designs influenced by plant and animal forms, producing sketches and digital representations. In the final and third phases, AI-assisted designs are created using generators such as ChatGPT, Copilot, and Midjourney. Throughout the design process, AI is viewed as a 'design partner' rather than a creator or decision-maker. Student projects were evaluated using Kolb's experiential learning framework and assessment criteria based on Bloom's taxonomy. The results demonstrate that AI can facilitate creative decision-making, accelerate processes, and expand ideas. Furthermore, ethical accountability, analytical reasoning, and nature-based parametric concepts can be further developed. This studio experience argues that the transformative role of AI in architectural pedagogy initiates a technological, methodological, and ethical transformation; it highlights the need for a holistic educational model focused on the creative potential of human-AI collaboration.

Keywords: *architectural education, artificial intelligence, biomorphic design, design pedagogy, parametric thinking*

1. Introduction

Education and academic practices have witnessed significant and extensive technological developments in recent years (Tuomi, 2018). The evolution of educational models has accelerated in tandem with technological development (Kyambade, Namatovu & Ssentumbwe, 2025; Molinari & Sandri, 2024). In the contemporary context of the post-industrial era and industrialised society, design education practices are characterised by specific features that are indicative of this period (Sui et al., 2025). Consequently, the advent of industrialisation has rendered AI a pivotal instrument for the formulation of data-driven strategies, thereby facilitating intelligent management (Nemorin et al., 2023). The term 'AI' (Artificial Intelligence) refers to the simulation of human intelligence by computers and other machines. It has become an influential topic in all sectors, including higher education (Lin et al., 2024). The increasing use of AI is predicted to reshape the educational environment (Hesham et al., 2023). The rapid advancements in AI technologies have unveiled novel prospects and challenges within the domain of design education (Cudzik, Nyka and Szczepanski, 2024). The application of artificial intelligence (AI) in higher education is growing, with the potential to provide customised interventions and timely feedback, thereby enhancing learning experiences (Han et al., 2025).

Biomorphology, an approach inspired by nature, offers numerous opportunities in the field of education, including those presented by artificial intelligence. This field has the potential to provide solutions in the domain of architecture and other design disciplines. The utilisation of biomorphic design is regarded as a catalyst for the evolution of novel analogies, thereby facilitating the generation of new knowledge through the acceleration of these analogies to the metaphoric level (Steadman, 2008). Researchers have been known to turn to the knowledge of biology to solve many problems encountered in architecture. This is achieved by studying and applying structural principles and systems in living organisms (Pedersen Zari, 2007; Knippers, Nickel and Speck, 2016; Pawlyn, 2019). It has been demonstrated that biological phenomena contribute to a significant number of ideas in the process of reviewing existing and historical concepts and developing new concepts in architectural design (Gruber, 2011). The identification of efficacious methodologies for the encouragement of creativity in students is of increasing importance for educators (Park and Lee, 2022). In this context, the present study aims to examine the creative possibilities of artificial

intelligence-supported design pedagogy in architectural education on the axis of biomorphic approach.

The provision of support for creative decision-making, conceptual abstraction and formal plurality processes through innovative educational models is conducive to the fulfilment of multifaceted pedagogies. (Badarnah, 2025). AI has been demonstrated to engender significant benefits for the education sector, including enhanced efficiency and optimised learning experiences (Kilianova et al., 2025). The integration of AI education within architectural education has the potential to equip future professionals with the necessary skills to utilise AI tools effectively while upholding artistic and cultural values (Albukhari, 2025). In this context, current debates on the future of architectural education are shaped around multi-layered problematics such as the relationship of creative processes with automation, who makes design decisions in human-artificial intelligence interaction, and the effects of this relationship on critical thinking skills. Furthermore, the reinterpretation of nature-inspired design forms with parametric tools has been demonstrated to increase environmental sensitivity and enrich students' formal and conceptual productions. The present study aims to discuss the possibilities of AI-supported design pedagogy in architectural education within the framework of the biomorphic design approach.

2. Background

The invention of the computer in the 1950s led to the idea that machines could surpass human innovation and capability. In his article 'Computing Machines and Intelligence' (Turing, 1950), Alan Turing posed the question, 'Can machines think?' Minsky characterised intelligence as the capacity to solve complex problems (Minsky, 1958). Legg and Hutter analysed various definitions of intelligence, proposing the definition, 'Intelligence is the ability to achieve goals in a variety of environments' (Legg & Hutter, 2007).

John McCarthy introduced the term 'artificial intelligence' during a workshop at Dartmouth College in 1956, to distinguish the discipline from cybernetics (McCarthy, 1988). Artificial intelligence encompasses algorithms and software that enable machines to process data, learn, make decisions, and perform activities to achieve defined objectives (McCarthy, 1995). One of the first paradigms of AI is high-level cognition, which is not the ability to understand concepts, perceive objects or use complex motor skills, as most animals do, but rather the ability to engage in multi-step reasoning, understand the meaning of natural language, design innovative artefacts, create new plans to achieve goals and even reason about their own concepts (Langley, 2011).

In recent years, many researchers have analysed the impact of new technologies on 21st century knowledge production and society. One of the most discussed topics among these studies is the use of AI and robotics in various areas of life, society, and science (Chen & Ying, 2022). The impact of artificial intelligence is also becoming increasingly evident in the arts. The integration of human-machine collaboration in design processes was first theorised by Nicholas Negroponte in 1970. Since the 1990s, research in the field of computer-aided architectural design (CAAD) and algorithmic modelling has further advanced this concept (Rhee, Veloso & Krishnamurti, 2023). The foundation of contemporary design methodologies, which employ artificial intelligence for expeditious feedback and iterative exploration, was established by architects who utilised parametric tools and early artificial intelligence programmes to optimise structures and discern complex forms.

Artificial Intelligence in Education (AIED) has emerged in recent years alongside the growing use of AI in education (Crompton & Burke, 2023; Guo, Zheng and Zhai, 2024; Feng, Zhang and Gašević, 2024). AIED involves the use of AI technologies or applications to support teaching, learning, and decision-making processes within educational environments (Tan, Lee, and Lee, 2022). AIED involves the use of AI technologies in educational settings to facilitate teaching and learning through processes such as inference, judgement, prediction and decision-making, which simulate human intelligence to varying degrees (Hwang et al., 2020). Computer systems have the potential to provide personalised guidance, support or feedback to students with the help of AI technologies that make inferences, judgements or predictions by mimicking human intelligence (Richter et al., 2019; Holmes, Bialik and Fadel, 2021).

AI technologies have the potential to restructure the methodological and intellectual aspects of architectural education (Jin et al., 2024). Many researchers have examined how AI can support the creative process, particularly in the generation of ideas (Singh and Gu, 2012; Camburn et al., 2020). AI's role in design education is evident in tools that assist students in developing design concepts (Gong, 2021; Zhang, Liu, and Chen, 2022; Gao et al., 2024).

3. Methodology

The concept of biomorphology, the imitation of living and non-living things in designing new structures, has been a guiding principle in architectural design throughout history (Steadman, 2008). In this course, the reflections of nature-human interaction in architecture, which have been observed in many fields throughout history, are exemplified by considering

the prominence of the buildings according to the age they belong to, and the processes of being inspired by the forms of nature are discussed. This study aims to establish a novel discourse forum that explores the potential for artificial intelligence technologies, in conjunction with rapidly evolving digital and information technologies, to draw insights from the developmental processes of architects in nature, particularly in the context of formal/visual inspiration. Consequently, a course programme encompassing artificial intelligence-supported biomorphic design has been meticulously devised. Within the scope of this course, students will have the opportunity to engage in abstract thinking exercises, supported by artificial intelligence. This will facilitate the development of their thinking skills, enabled by the logical framework of artificial intelligence. The primary rationale for selecting the AI generators employed in this study (ChatGPT, Copilot, and Midjourney) is that they provide significant opportunities to enhance the learning experience, accelerate the design process, and diversify the creative process in architecture education. Recent academic literature highlights the significance of artificial intelligence tools in fostering students' creativity, identifying design discrepancies, and facilitating critical reflection on learning processes (Onatayo et al., 2025; Luo et al., 2025).

In this context, a studio experience is presented within the scope of the course 'Parametric Approach to Nature-Inspired Architectures', which was conducted at Gazi University Faculty of Architecture at the graduate level. The study sought to address the following research questions: The present paper explores how architecture students integrate artificial intelligence into the design process. The present study investigates the impact of AI generators on students' conceptual thinking, abstraction and creative production processes. This paper investigates whether AI-supported pedagogical models offer an alternative to classical studio education.

The course syllabus spans 15 weeks and is divided into three primary phases (Figure 1). In the initial phase, conceptual readings and discussions were conducted concerning the interaction between nature, humans and technology. The relationship between biomorphology and artificial intelligence was analysed within a historical and theoretical framework. In the second stage, students analysed natural forms inspired by plant and animal morphology. The design challenges were addressed, and attempts were made to abstract these systems parametrically. In the third phase, designs were developed using contemporary AI generators and visual production platforms like ChatGPT and Copilot.

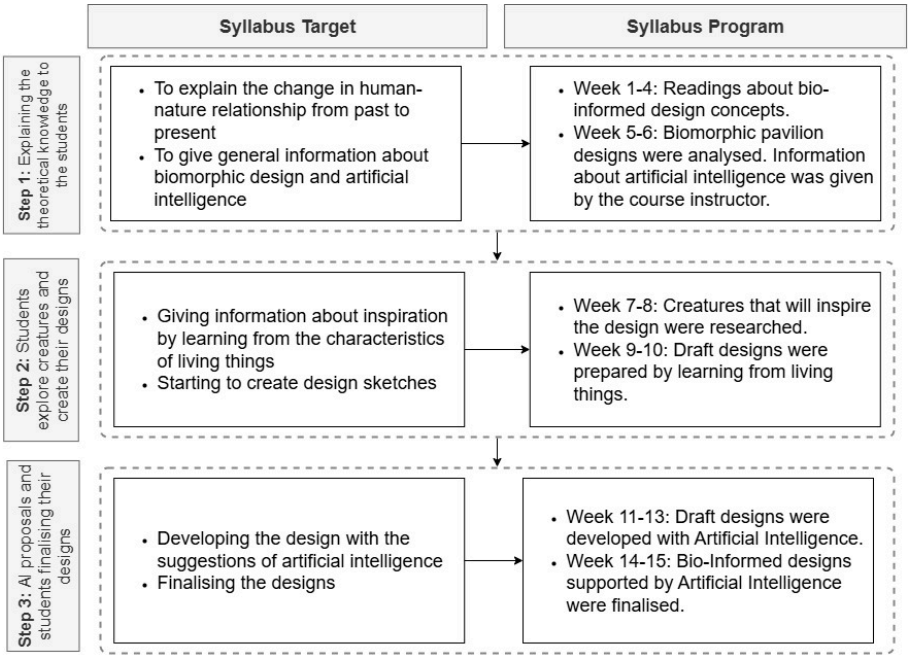


Figure 1. The three basic steps of the syllabus

Experiential learning approaches are firmly embedded in architectural education due to the nature of design thinking. Kolb's Experiential Learning Cycle (1984) identifies four main stages: concrete experience, reflective observation, abstract conceptualisation and active experience. Bloom's Taxonomy is a classification approach utilised for the organisation and evaluation of learning. The model in question divides cognitive skills into six fundamental levels: remembering, understanding, applying, analysing, evaluating, and creating (Bloom et al., 1956; Anderson & Krathwohl, 2001). This approach assists students in comprehending the way they engage with knowledge. This study is related to Bloom's cognitive domain classification and Kolb's experiential learning model because the nature of the design studio is a layered process, both cognitively and experientially.

The role of the educator is transforming, shifting from a position that primarily involves transmitting information to one that fosters learning, critical thinking and problem-solving skills. (Brady, McDaniel and Choi, 2023). Within the studio process, artificial intelligence is regarded as a production tool and a pivotal component of designer thinking, repositioned through the 'design partner' concept.

Learning is the process by which knowledge is created by transforming experience (Kolb, 1984). The process of learning, therefore, cannot be considered as occurring on a linear axis; rather, it is a multifaceted and

dynamic process that occurs through trial and error, repetition, learning, abstraction, return to the initial idea, and the experiencing of the process differently (Figure 2). The architectural and AI-assisted architectural design studios underwent a cyclical process of renewal and self-experience. It was ensured that artificial intelligence was not only considered as a tool to realise the designs, but also as a design partner in the process. The integration of AI-assisted pedagogical tools into the conventional studio environment facilitates a reinterpretation of Kolb's experiential learning model in a hybrid form.

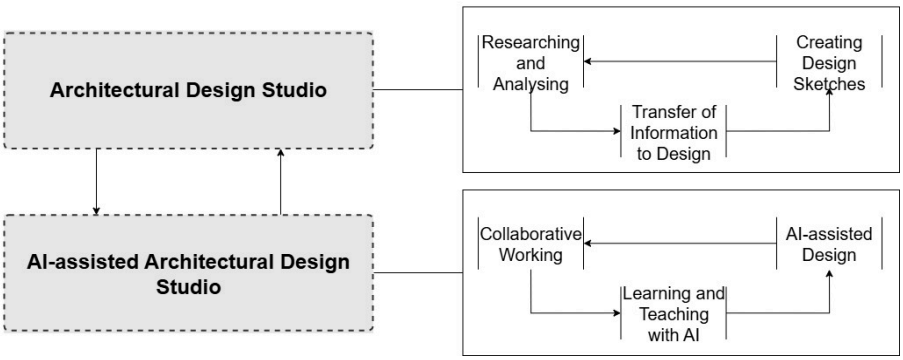


Figure 2. The architectural design studio and the AI-assisted architectural design studio are structured cyclically.

In the study, the Rubric measurement tool was developed in accordance with pedagogical principles. As these criteria were established at the inception of the research, all stages of the design process were shaped according to these criteria. Consequently, the rubric functioned as a theoretical framework that guided the procedure and systematically evaluated the results (Table 1).

The course syllabus advocated a three-stage evaluation process for the final product, with the structure of the course itself being considered throughout the design process. The criteria for evaluation encompass a multifaceted set of parameters, including but not limited to: theoretical depth, critical discussion, inspiration from nature, competence in hand drawing, parametric thinking, digital integration, iterative development, quality of representation, and creativity-criticism. The levels in the rubric were decided as follows: (1-2) indicates a need for improvement, (3) is deemed adequate, (4) is classified as good, and (5) is considered excellent. The developed rubric provides concrete evaluations of students' projects and opportunities to evaluate the process.

TABLE 1. Rubric prepared to evaluate the course outcomes

Phase	Criteria	Excellent (5)	Good (4)	Adequate (3)	Needs Improvement (2-1)
I. Conceptual Exploration	Theoretical Integration	Demonstrates deep understanding of biomimetic theory and AI history	Connects concepts with minor gaps	Basic conceptual alignment	Lacks coherence or originality
	Critical Discussion	Actively contributes with insightful arguments	Participates with relevant input	Limited engagement	Passive or off-topic
II. Analogue Drawing & Parametric Abstraction	Bio-Inspiration Depth	Skillfully extracts natural principles into abstract form	Good analysis with logical translation	Basic mimicry with limited abstraction	Superficial or misunderstood inspiration
	Manual Representation	Expressive and technically refined sketches	Adequate visual clarity	Some communicativ e value	Poor execution or clarity
	Parametric Thinking	Abstract model showcases systemic consistency	Demonstrates structured logic	Rudimentary parametric logic	Unclear or inconsistent approach
III. AI-Assisted Generation	AI Integration	Thoughtful and purposeful use of AI generators	Appropriate application with some exploration	Limited use or understanding	Misuse or lack of integration
	Iterative Development	Evident transformation across design cycles	Some iterative refinement	Minor evolution between stages	Static output with no development
	Representation Quality	Strong visual-textual coherence	Mostly effective representation	Some clarity issues	Confusing or incomplete outputs
	Creativity & Reflection	Original thinking and a critical attitude toward AI	Creative but less critically framed	Predictable or conventional outcome	Unreflective or derivative results

The assessment criteria have been developed through a process of analysis, drawing upon both Bloom's cognitive domain taxonomy and Kolb's experiential learning model. This approach ensures that the criteria are aligned with the experiential and cyclical nature of architectural studios. Dimensions such as Iterative Development, Critical Discussion, and Creativity and Reflection have been integrated into the rubric within this framework and are all directly related to different stages of experiential learning. In addition, Bloom's taxonomy offers a systematic framework for the evaluation of stages of cognitive development.

Each criterion in the rubric is designed to align with the specific requirements of biomorphic design pedagogy. For instance, 'Theoretical Integrity' explores students' engagement with biomimetic theory and

artificial intelligence, while 'Depth of Inspiration from Nature' demonstrates the influence of natural systems on design. The course incorporates two distinct components: the first, 'Parametric Thinking', evaluates the students' aptitude in parametric design. The second, 'Artificial Intelligence Integration', aims to assess students' proficiency in utilising their cognitive faculties not solely as production tools but also as cognitive partners. This multi-dimensional approach enabled both product- and process-oriented assessment. The study examined students' creative thinking approaches, conceptual depth, and interaction with digital tools. Consequently, the rubric was positioned not solely as an assessment instrument, but also as one of the primary components forming the theoretical and pedagogical basis of the study.

4. Course Experience and Student Works

The students were provided with a foundation of theoretical knowledge regarding the subject matter and were subsequently encouraged to devise solutions to the presented design problems. The students were assigned tasks designed to enhance their critical thinking and problem-solving skills. After these presentations in the classroom, further discourse ensued with the instructors. Subsequently, the instructors gave the students readings on biomorphology and artificial intelligence in architecture. Interactive lectures facilitated students' comprehension of the topic and its significance. The overarching theme of the course was 'Biomorphic Pavilion, supported by artificial intelligence'. Considering the points, the lectures provided an exposition on the terminological origins of biomorphology, elucidating its conceptual underpinnings, operational modalities, and the rationales underpinning its application in the architecture domain. Following delineating the problem to be solved, the students determined the creature from which they would derive inspiration. At this stage, students were required to create their sketches using the conventional design studio workflow. After this stage, the digital design element was initiated. The design of the sketches was conducted digitally, utilising 3D software programs.

It is evident that up until this stage of the project, the work did not proceed along a linear axis. Indeed, the problem was changed on multiple occasions, with different creatures being selected for inspiration. The design incorporates characteristics of multiple living creatures. At this stage, students were invited to articulate the methodology employed in arriving at the design, the process they undertook, the generators they utilised, and the information they accessed. It was found that most students were

experiencing difficulties creating the parametric designs for their biomorphic pavilions in three-dimensional computer programmes at this stage. After the preliminary self-assessment, the trainers delivered a presentation on the AI-assisted design approach. This approach demonstrated that AI can assist existing sketches and digital designs create new variations (Figure 3).

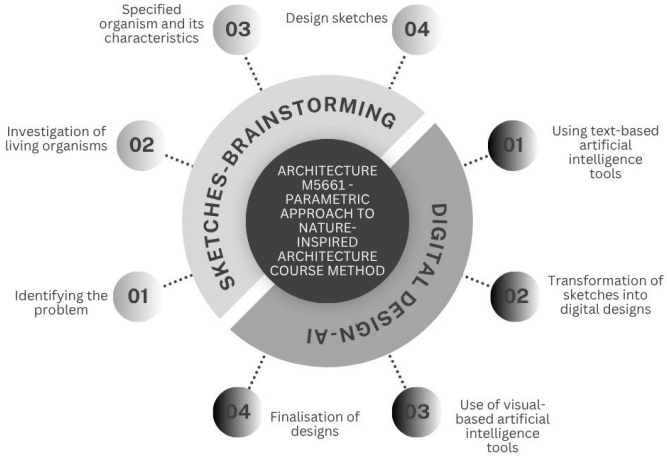


Figure 3. Studio flow performed in 2 stages

Subsequently, the students initiated the redesign process, utilising artificial intelligence as a support mechanism. Consequently, students acquired a novel methodology for designing their biomorphic pavilions, which were conceptualised through their cognitive processes. The students progressed through the programme through a trial-and-error process, acquiring experience and providing instructor feedback regarding the approach. The participants articulated that using an artificial intelligence-supported design approach enhanced their educational experience by facilitating the conception of novel forms and the proposition of alternative concepts that diverged from their original assumptions. In addition to this positive feedback, it was also stated that the system sometimes had difficulty expressing exactly what was required, and that progress was impeded at certain stages despite the arrangements in prompt writing. The initial sketches and digital designs were then integrated with the region, structure type, the problem to be addressed, the creatures from which inspiration was derived, and the inspired characteristics of the creatures. These were utilised in the context of productive artificial intelligence programmes, namely ChatGPT, Microsoft Copilot, Playground AI, Midjourney and DALL-E. Through these programmes, the final design was formulated. The projects designed by the students are presented (Figures 4, 5, 6, 7, 8).

Biological creatures, including the pangolin and the horseshoe crab, inspired the design of Student 1's pavilion. The pangolin's dynamic opening

and closing scales were utilised as a morphological reference to develop a panel system; however, this proved inadequate. The pavilion's architectural form was inspired by the structural characteristics of the horseshoe crab, with particular attention paid to the analysis of the living shell. The location of the pavilion was decided to be Beijing, China. The design process incorporated artificial intelligence, whereby AI commands were utilised to transform the horseshoe crab form into a pavilion. This transformation was further refined by implementing additional commands (Figure 4).

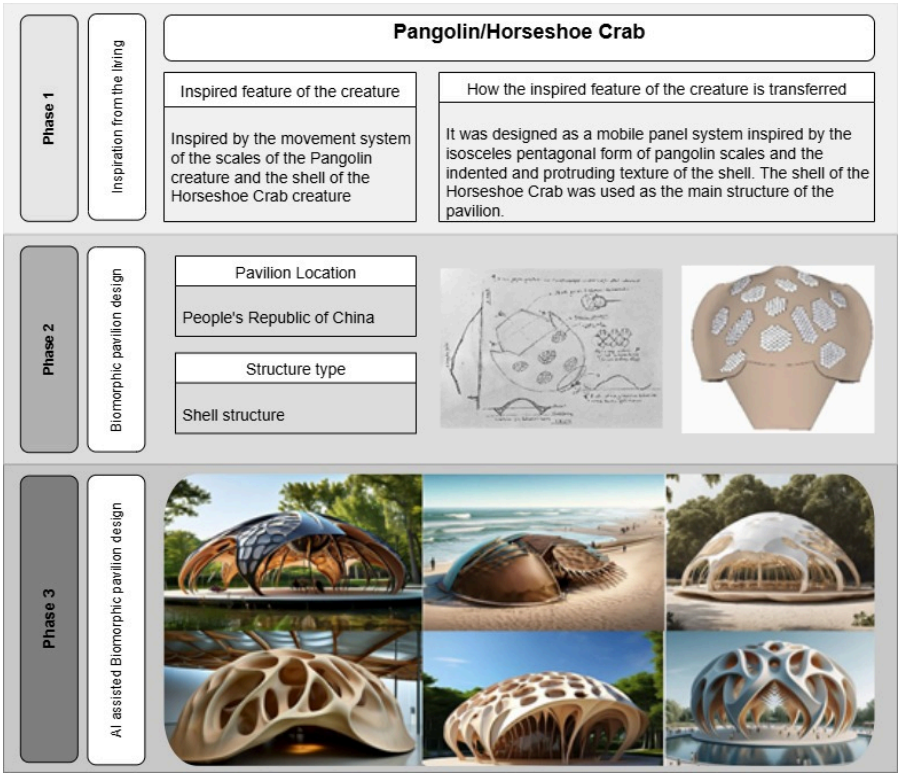


Figure 4. The project process of Student 1

The design conceptualised by Student 2 for the pavilion on the surface of Mars was inspired by the jellyfish's permeable skin, fluid structure and bioluminescence. The creature's rounded, streamlined shape provided the impetus for the interior and exterior layouts. The utilisation of artificial intelligence during the design process has been demonstrated to reduce the time required for visualisation, thereby conserving both time and energy (Figure 5).

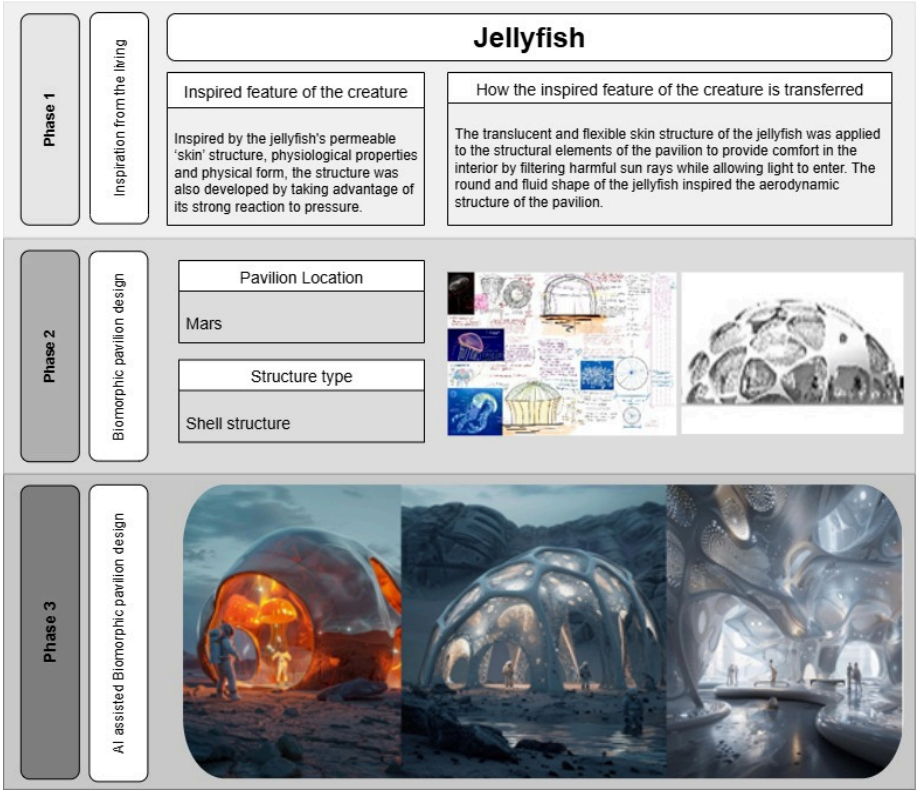


Figure 5. The project process of Student 2

In the project's initial phase, Student 3 analysed various natural forms (seashells, jellyfish, dandelion and turtle shells) for the biomorphic pavilion design. However, they subsequently decided to search for an innovative approach that could be used in more challenging environmental conditions. However, he sought to identify an innovative method that could be utilised in more challenging environmental conditions. The species selected for this purpose was *Physalia physalis,* commonly known as the Portuguese Warrior, due to its capacity to remain buoyant on the water's surface in a sustained manner. An organic, liquid-shaped pavilion was created using its gas-filled body, light-permeable tissue, pneumatic structure, and ETFE membranes. The structure's dual function as a storage space and a dive site for divers was pivotal. The generators were then compared to design the model. The student evaluated the compatibility of the design with AI through on-the-fly modifications and image-to-image similarity analyses (Figure 6).

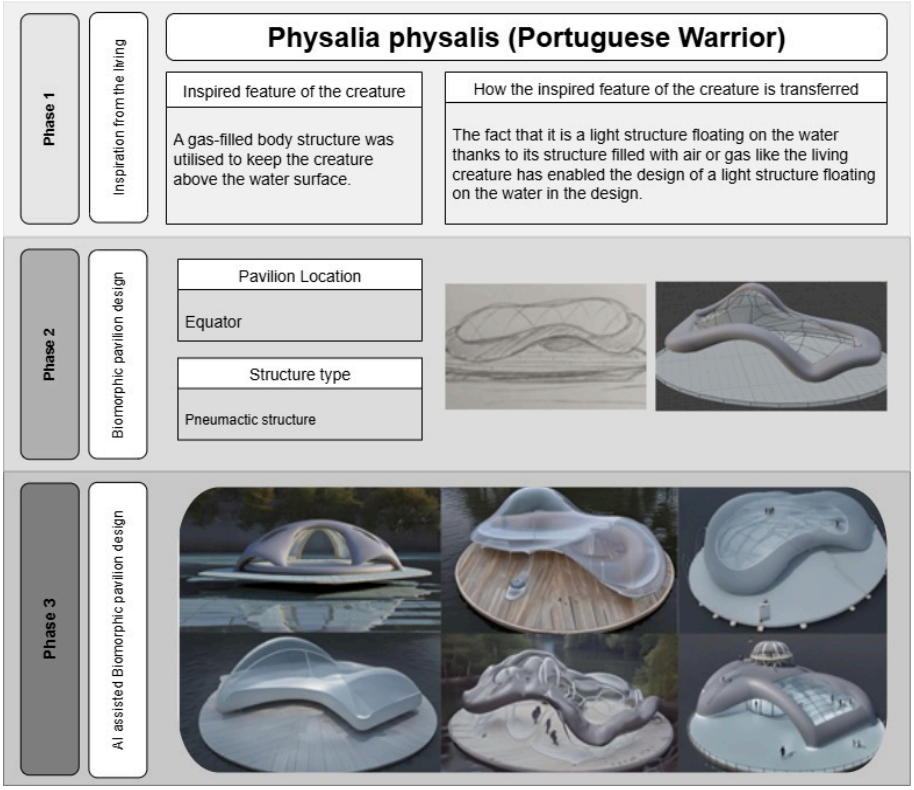


Figure 6. The project process of Student 3

Student 4 employed the sea creature Velella to design a floating pavilion. A preliminary literature review was conducted to ascertain the building type, user profile and function. The architectural form was guided by Velella's tripartite anatomy (comprising tentacles, disc surface and sail-like superstructure). The architectural design of the pavilion was conceived to raise awareness of rising sea levels, a phenomenon that is a consequence of the global climate crisis. Organising meetings, seminars, and exhibitions is a service that can be provided. The creature's triangular-conical cross-section transformed a skeletal system reminiscent of a sailboat, accompanied by translucent cladding panels characterised by a transparent, thin, planar structure. The utilisation informed the design process of artificial intelligence. A comprehensive analysis of the outcomes derived from diverse programs was conducted, and the pavilion form was meticulously digitised (Figure 7).

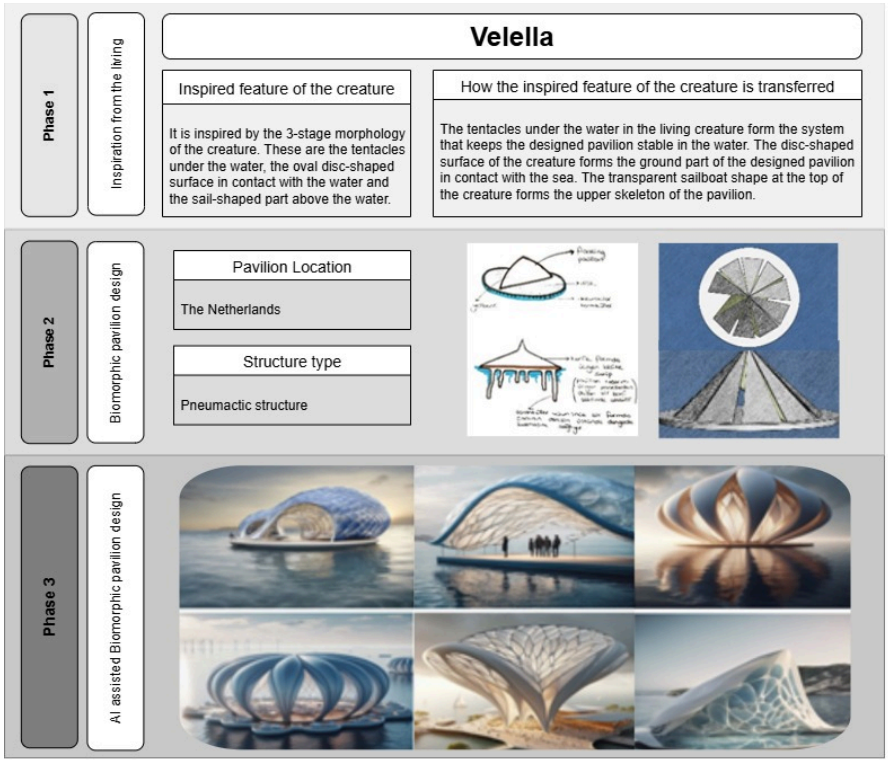


Figure 7. The project process of Student 4

Student 5's design concept is for an expandable pavilion inspired by the puffer fish, which is characterised by its flexible and inflatable structure. A bio morphological architectural vision was developed for the pufferfish to adapt to environmental diversity. The structure's design was informed by the principles of the Hoberman sphere, with the structure being conceived as a geodesic dome. In place of the triangular pieces typically used in such constructions, hexagonal components were utilised to integrate the morphology of the fish's spines into the architectural design. The movable components surrounding the dome's centre are integrated into a rail slab system. The incorporation of transparent thermoplastic polyurethane (TPU), acoustic polyester panel and oxygenated Kevlar resulted in the surface acquiring a high level of flexibility and durability. The selection of materials resulted in enhanced portability and light transmission of the pavilion. The student drew parallels between using artificial intelligence throughout the design process and interdisciplinary teamwork (Figure 8).

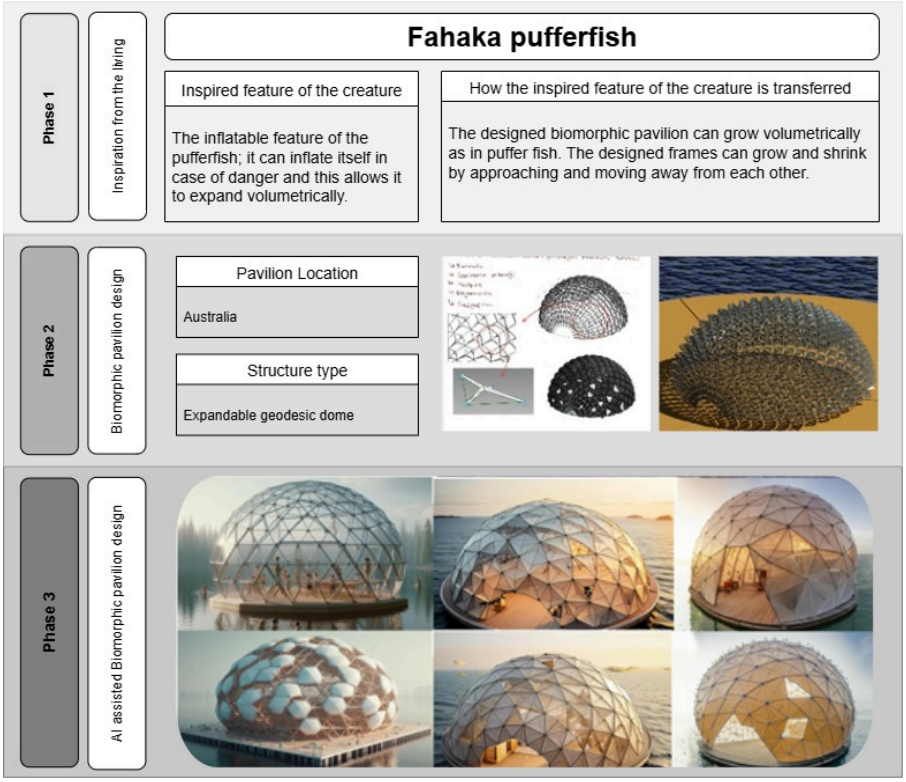
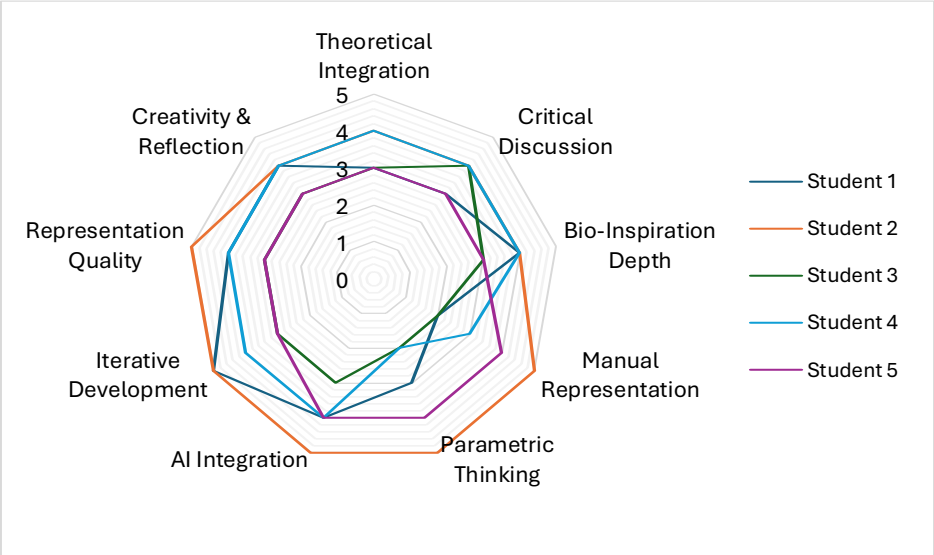


Figure 8. The project process of Student 5

5. Discussion

The utilisation of radar graphs in the formal expression of multi-layered performance in architectural education has been demonstrated. In the study, the evaluation of student projects was conducted per the rubric criteria delineated in Table 1, with subsequent reflection undertaken on the graph (Graph 1). The present study demonstrated that the proposed framework facilitates a comparative analysis of students' cognitive, representational and digital competencies in the design domain, using the rubric criteria. The graph provides data on the success level of the projects, as well as an analysis of learning behaviour and pedagogical methods.



Graph 1. The evaluation of student work is to be conducted in accordance with the established rubric criteria

A thorough analysis of the graph reveals that Student 2 has demonstrated proficiency in the following competencies: AI Integration, Parametric Thinking, Creativity and Reflection, and Iterative Development. In contrast to the wide-ranging abilities exhibited by Student 2, the performances of Students 1 and 5 are focused on specific criteria. One of these students distinguishes itself through its conceptual depth, while the other excels in digital representation. In this context, Kolb's experiential learning model is utilised to assess students, thereby revealing that each student's learning style and susceptibility to the experiential process vary.

Evidently, students demonstrated substandard performance in the domains of Creativity and Reflection and Critical Discussion. Furthermore, it is noteworthy that Parametric Thinking is the criterion most frequently assigned the lowest ratings by students. This indicates the challenges associated with the software and conceptual elements of nature-inspired parametric design. However, this criterion is directly related to conceptual-schematic thinking, the abstraction of nature-inspired knowledge and computer skills, rather than technical competence. The graph serves as both a visualisation and a pedagogical instrument, facilitating the identification of potentially problematic components.

Radar chart data provides a clear illustration of students' capacity for creative utilisation of digital tools. The high performance observed in the Bio-Inspiration Depth, Manual Representation and Representation Quality categories demonstrates students' ability to create designs inspired by nature

and effectively express these ideas in analogue and digital environments. This finding aligns with the conclusions of Schneiderman (2007) regarding the impact of digital tools on the acceleration of creative production and with the observations of Gao et al. (2024) concerning the efficacy of personalised learning environments in enhancing students' strengths.

Furthermore, students' balanced performance in Theoretical Integration and Creativity & Reflection demonstrates an approach to the design process that is both formal and conceptual. In this context, the radar chart functions as a tool that serves to enhance learning motivation by highlighting strengths and identifying weaknesses. However, there is limited development in creativity and thinking, critical discussion, and theoretical integration. The capacity of generative artificial intelligence to produce content rapidly may carry the risk of superficiality unless supported by appropriate pedagogical structuring. At this point, the reflection sessions, peer assessments and clear criteria emphasised by Black and Wiliam (1998) and Zimmerman (2002) are critical for making students' thought processes more visible.

Low scores in the parametric thinking category suggest that students have not adequately adopted this ability, which is defined by Meyer and Land (2003) as the 'threshold concept'. Despite their ability to effectively model natural forms, students encounter difficulties transforming them into parametric and dynamic systems. In Bloom's cognitive taxonomy, this stage, which is linked to higher-level abilities such as creation, analysis and synthesis, should be supported by stronger pedagogical scaffolding. In this context, using pedagogical methodologies such as algorithmic workshops, teach-back sessions, and the employment of parametric templates has been demonstrated to be efficacious (Mazur, 1997; Anderson & Krathwohl, 2001). Consequently, the radar chart contributes not only to the measurement of learning outcomes but also to the guidance of the learning cycle and the structuring of creative thinking skills.

The study was conceived as a 15-week experimental design studio module within an architecture master's programme. Five students were selected for a mentoring programme and personalised learning to facilitate a comprehensive and bespoke educational experience. Despite the participants' familiarity with fundamental digital design tools, their experience with artificial intelligence tools was severely limited. The researchers supported the process through theoretical content transfer and design guidance. They also conducted outcome evaluations. The study is exploratory and consequently possesses limited generalisability, as it was conducted with a small sample and at a single institution. Furthermore, the convergence of roles between the instructor and the researcher rendered the evaluations susceptible to subjectivity. The implementation of a structured rubric mitigated this risk. The accessibility of the experience, in conjunction

with the rapid advancements in artificial intelligence (AI) generators such as ChatGPT, Copilot, and Midjourney, may potentially impact the replicability of the experience. Moreover, the selected toolset represents a fraction of the numerous tools that could be employed in architecture education. Despite these limitations, the study could be an important starting point for further research involving more participants and different institutions.

6. Conclusion

The integration of AI into education has the potential to foster technical advancement and support a variety of pedagogical paradigms, from constructivism to digital learning. The study demonstrated that artificial intelligence (AI) generators can provide an advantage in architecture studios. With adequate guidance, students were able to produce unique and diverse outcomes using AI. Furthermore, AI-enabled approaches offer customized learning paths that increase engagement and improve the educational process by taking into account each student's unique interests and pace. AI is considered a collaborative partner that actively participates in the design process, helps synthesize ideas, enables creative decision-making, and expands the range of design options. It has been shown that students can test their ideas more quickly and effectively by visualizing their conceptual designs with AI generators.

The findings suggest that integrating technology with pedagogical frameworks has the potential to significantly enhance the learning experience in a transformative way. Kolb's experiential learning model and Bloom's cognitive taxonomy have been shown to support students' conceptual thinking, critical discussion capacities, and production skills. In particular, it has been shown that the creation and evaluation phases of the studio process enable it to become a deep learning practice without being reduced to technology. The intersection of design education and artificial intelligence presents challenges and ethical boundaries that require rigorous analysis, evaluation, and proactive solution-making. However, issues such as ensuring originality in design, ethical risk, and complex questions about the role of AI as a creator require that AI integration be addressed with pedagogical responsibility. Providing students with comprehensive training and support mechanisms about AI and its use is essential. Engaging in critical discussions and developing frameworks for effective and appropriate use is essential. Despite these challenges, AI has significant potential to foster enhanced creativity and innovation among students by integrating traditional studio practices.

AI technologies have led to a paradigm shift in architectural education, ushering in a new era of interdisciplinary possibilities. These technologies can transform pedagogy by developing synergistic relationships with the disciplines of computer science, psychology, philosophy, and biology. This transformation requires a rediscovery of technical skills, ethical awareness, critical thinking, and creative decision-making. Integrating AI into design education, characterized by consciousness, critical thinking, and ethical principles, could potentially enhance students' educational experiences. Future studies envision innovative pedagogical strategies to develop parametric and critical thinking skills. Algorithmic workshops, thinking journals, and examinations of hybrid AI applications have been shown to contribute to strengthening these skills. Comparisons across institutions will provide valuable data on the scalability and long-term impact of the model.

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APPLICATION OF ARTIFICIAL INTELLIGENCE AI IN EDUCATION

Experiment in Interior Architecture Projects Case Study

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Abstract. Artificial intelligence (AI) is one of the tools developed recently to explore interior architectural design concepts. AI is defined as problem-solving computer software that mimics human intelligence to achieve human goals. One of the main activities in interior architectural design (IAD) is decision-making upon solving problems. However, in IAD workshops and tutorials, several activities such as brainstorming, mood boards, sketching, and drawing are practiced creating project ideas. Students must be skilled in the basics of problem-solving to create successful designs. Moreover, presenting design ideas in 2D and 3D drawings and models requires experience and imagination. Recent AI technological advances have made it possible to rapidly create several alternative design concepts. However, there haven't been many scientific studies that assess the impact of AI on architectural and interior design education. This research aims to compare the integration of AI-generated Images, specifically Midjourney, to manual illustrations in the (IAD) Educational Approach at level 5 students. An experiment has been developed on 108 students with two phases first, a manual drawing and secondly an AI integrated image. A panel consisting of 12 judges mark each project independently. Finally, validation is performed using t-test to find out whether the use of AI improves the design. The test revealed that AI-generated designs outperform manual collages in terms of both creativity and neatness, but not in terms of Keyword and Quality. This is significant, as creativity is a crucial aspect of design, especially in interior architecture. AI provides a more refined and efficient way to explore creative solutions.

Keywords: *Artificial Intelligence (AI), Higher Education, Interior Architectural Design (IAD), Design Concept Generation, AI-assisted Design, T-test, Interactive Learning.*

1. Introduction

AI is a recent technology that has been quickly devoted to many careers including architectural education. In education, AI is a tool used to enhance architecture imagination in numerous forms. According to Sharma, S., & Kumar, N. (2023) there are several methods to be considered in solving problems in decision-making such as identifying the problem, programming design algorithms, and coding while artificial intelligence is a new opportunity to be utilized. However, AI in education is used in numerous forms, such as increasing the efficiency of instruction and prediction of imagination (Udvaros, J., Forman, N., 2023). It's a tool that facilitates expressing more ideas and improves architecture imagination, and prediction. Generally, the experience of imagining 3D space and creating innovative concepts is not always easy with traditional tools. Recent AI technological advances have made it possible to rapidly create several alternative design concepts.

2. Artificial Intelligence in Education

Human performance can be improved by artificial intelligence (AI), which can learn, teach, and improve human abilities to execute tasks and engage in activities. Artificial intelligence (AI) is a discipline of computer science that focuses on creating computer systems that are capable of activities that have traditionally needed cognitive ability, such as linguistic interpretation, speech recognition, picture perception, and decision-making. With the aid of this tool, the designer can also investigate other principles of design that prioritize "being in the environment" over "looking at the place empty." This kind of full-image replication of a place can enrich the concept of design (Moussa et al., 2022).

The way interior design is taught in architectural workshops, and the role educators perform in actively supporting these changes through the study, application, and distribution of this technology are both forced to alter by the present advancements in AI. AI is essential to education; it's used in online learning, language study, and intelligent instruction. Additionally, groups and projects devoted to AI education are being established; one such example is the Institute for Artificial Intelligence Systems at the Technical University of Eindhoven (Tas, N., 2023). Artificial intelligence (AI) is used to assess student performance, improve virtual teaching techniques, and provide individualized learning experience. Student engagement can be

improved with AI-based education. AI gives students thorough feedback that raises the quality of their learning resources and level of attention. Nonetheless, making students more interactive and involved in their education improves their final products and designs (Nipun, M. S., 2023).

2.1. ARTIFICIAL INTELLIGENCE IN INTERIOR ARCHITECTURE DESIGN

A new design idea that has emerged in response to the growth of the architectural industry, interior design is a highly integrated and autonomous field that includes many facets of psychology and design aesthetics (Nipun, M. S., 2023). However, an interior architect's vision and inventiveness will be diminished when employing a clever instrument like artificial intelligence. Testing ought to be done on this new technology. Lisa Mcleod, Head of Design at AW Spaces, believes AI tech has the power to completely change the way designers collaborate (Li, Y., & Sun, L., 2023). Applications found in interior design include: (Mid journey, Sidewalk labs, Kaedim, Hypar).

Nowadays, this application is easy to use and a fast-learning machine. According to that software is a generative AI to create unique and innovative designs for architects. The program can produce innovative and creative concepts for construction while taking the environment, materials, and available space into account. Artificial intelligence (AI) has many applications in assessment, including data analysis, assessment process automation and streamlining, and producing more accurate and dependable ratings (Salwei, M. and Carayon, P. (2022). Creating automated scoring systems is one of the primary uses of AI in evaluation. These systems evaluate student work, including essays or tests, using machine learning algorithms, and then automatically score and provide feedback. This can lessen the effort for educators and assessors while also enhancing the efficacy and consistency of assessment procedures. However, listed on table 1 the pros and cons of using artificial intelligence in interior architecture design education.

TABLE 1. The Pros and Cons of Using Artificial Intelligence in Interior Architecture Design Education.

Pros of Using AI in Interior Architecture Design Education	Cons of Using AI in Interior Architecture Design Education
Personalized Learning: AI can tailor educational content, models, and media to match individual student abilities and motivations (Li, Y., & Sun, L.,	One-Way Learning Experience: Many AI-based virtual labs currently offer limited interaction and lack dynamic student input (Salwei, M. and

2023).	Carayon, P. (2022).
Adaptability: AI-driven platforms can adapt in real time to student needs, enhancing flexibility in learning delivery (Li, Y., & Sun, L., 2023).	Lack of Human Feedback: Over-reliance on AI may reduce opportunities for teacher-led discussions and feedback, crucial in design education.
Space & Resource Efficiency: AI enables digital classrooms that can replace physical equipment, which is especially helpful for institutions with limited resources (Salwei, M. and Carayon, P. (2022).	
Virtual Lab Accuracy: In 2019, AI-powered virtual labs demonstrated 90.8% accuracy, making them reliable for practical learning (Salwei, M. and Carayon, P. (2022).	

AI can analyse enormous quantities of statistical information on student performance and engagement to find trends and patterns that support teaching and learning (nipun, m. s., et al., 2023). Teachers can use this research to create focused interventions and resources that will enhance overall learning outcomes and raise student achievement. The development of predicted analytics systems is another way that AI is being used in evaluation (hussain, z., et al., 2024). These systems employ machine learning algorithms to identify students who are most likely to face academic difficulties and offer them focused interventions to enhance their learning by evaluating data on student performance and engagement (cathrin, s., & wikandaru, r., 2023).

However, there are limitations to applying AI for assessment. These include anticipation about the possibility of bias or discrimination in machine-

learning scoring systems, as well as the reliability and accuracy of AI algorithms (annuš, n., 2023).

3. Challenges of AI-Enabled Teaching and Learning for Instructors:

There are numerous potential advantages to using artificial intelligence (AI) in education, but there are also many challenges that teachers must overcome (Falk & Van Wynsberghe, 2023). Among these challenges are the following:

1. **Technical Proficiency**: Educators must possess a solid understanding of the AI tools and device used in the classroom. For educators who are not tech-savvy, this can be difficult, and they might require additional training.
2. **Curriculum Integration**: To ensure that AI-enabled tools are used meaningfully, the curriculum must be skillfully integrated with these tools. Instructors must be well-versed in how these resources can be applied to enhance student learning and achieve specific learning objectives.
3. **Ethical Concerns**: Data privacy, algorithmic bias, and the impact of AI on student learning outcomes are among the ethical issues that arise from the use of AI in education. Instructors must be aware of these ethical dilemmas and ensure that they are using AI ethically and responsibly.
4. **Limited Access**: Different schools and students may not have the same access to AI-enabled resources, which may lead to disparities in the quality of instruction. Instructors must ensure that these resources are accessible to all students and that they are applied equitably.
5. **Teacher Autonomy**: The application of AI in education might pose issues related to teacher autonomy and the role of educators in the classroom. Educators must participate in the decision-making process about AI's use in the classroom to guarantee that it is implemented in a way that increases student learning and supports their teaching strategies.

All things considered, integrating AI into education requires that educators adapt to new tools and pedagogies while also ensuring that AI is applied ethically and supports student learning (venugopal, r., & mamatha, v., 2023). For teachers to be equipped to use AI in the classroom, they must receive adequate training and support.

4. Challenges of applying AI in Interior Design

Figure 1 summarizes the difficulties and ethical issues relating to artificial intelligence in interior design. Fair treatment, transparency, and ethical considerations in algorithmic decision-making are all threatened by AI technology (pal, s., 2023). AI in interior design is developing and is probably going to continue to do so. Therefore, to prevent detrimental effects on people and society, it is imperative to guide the use of the ethical and equitable design process (Salwei, M. and Carayon, P., 2022). The comprehension of the socio-technical systems of AI application in the interior design industry presents the second set of difficulties. To effectively address the difficulties associated with the application of AI in interior design, a sociotechnical approach will be required (venugopal, r., & mamatha, v., 2023). In fact, the importance of technological elements as well as organizational and social factors that influence AI system design and application in interior design practice has been recognized (al-tkhayneh, k. m., alghazo, e. m., & tahat, d., 2023). Apart from these sociotechnical and ethical factors, sustainability is a crucial component of interior design.

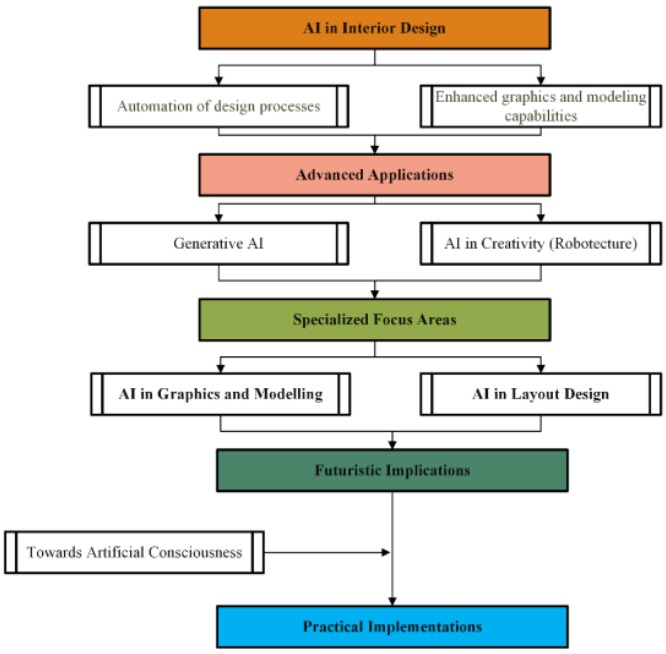


Figure 1: AI's transformative effects on interior design processes and applications- (Alshkipi, O.A. and Zahran, B., 2024).

5. Research Methodology

This study presents an experimental case designed to explore whether integrating artificial intelligence (AI) into the early stages of the Interior

Architecture and Design (IAD) process can enhance the overall quality of project outcomes. The initiative aims to emphasize the value of human-centered design thinking while supporting students in articulating abstract concepts more effectively. The experiment was conducted within the Tech2 for IAD module, a technical course undertaken by 108 Level 5 students, centered on exploratory design investigations. Through a comprehensive planning exercise, the module seeks to deepen students' understanding of material properties, their practical applications, and the intricacies of both exterior and interior construction detailing. The conceptual foundation of the project is rooted in each student's interpretation of the contemporary context.

Although the module's primary focus is technical skill development, AI was introduced to accelerate the conceptual phase and enhance idea communication without compromising creative integrity. To accommodate the module's technical depth, the conceptual stage was intentionally condensed, with AI used to streamline this process. The project was structured into two parallel conceptual phases—manual and AI-assisted—each lasting one week, followed by a ten-week design development period. Outcomes from both approaches were evaluated using four key criteria, and their influence on the final project was assessed. At the start of each session, students received a brief outlining the design task. In the manual phase, students produced keywords, concept statements, and collages. In the AI phase, they used the Midjourney application to generate text-to-image visuals based on their concept statements and keywords.

The experiment involved comparing two sets of submissions from the same cohort of 108 students. Academic staff conducted blind assessments to determine results. The manual submission featured an exhibition with initial concepts, collages, and keywords, while the AI-based submission included ideas and keywords generated through Midjourney. The final design phase, spanning approximately 12 weeks, focused on interior design and its relationship to both manually and AI-generated collages. However, the experiment consists of two phases:

Phase One: This phase includes one session:
Introduction to the "Contemporary context" concept, understanding the visitors' experience to design an exhibition. The task is to create a collage representing the concept idea.

Phase Two: This phase includes one session:
A given abstraction and design task using AI (Midjourney). Midjourney selected due to its advanced capabilities in generating high-quality, stylized visual outputs. To align the tool with the study's focus on interior design, the input prompts carefully calibrated to emphasize interior-specific elements such as spatial configuration, materiality, lighting, and human-scale detailing.

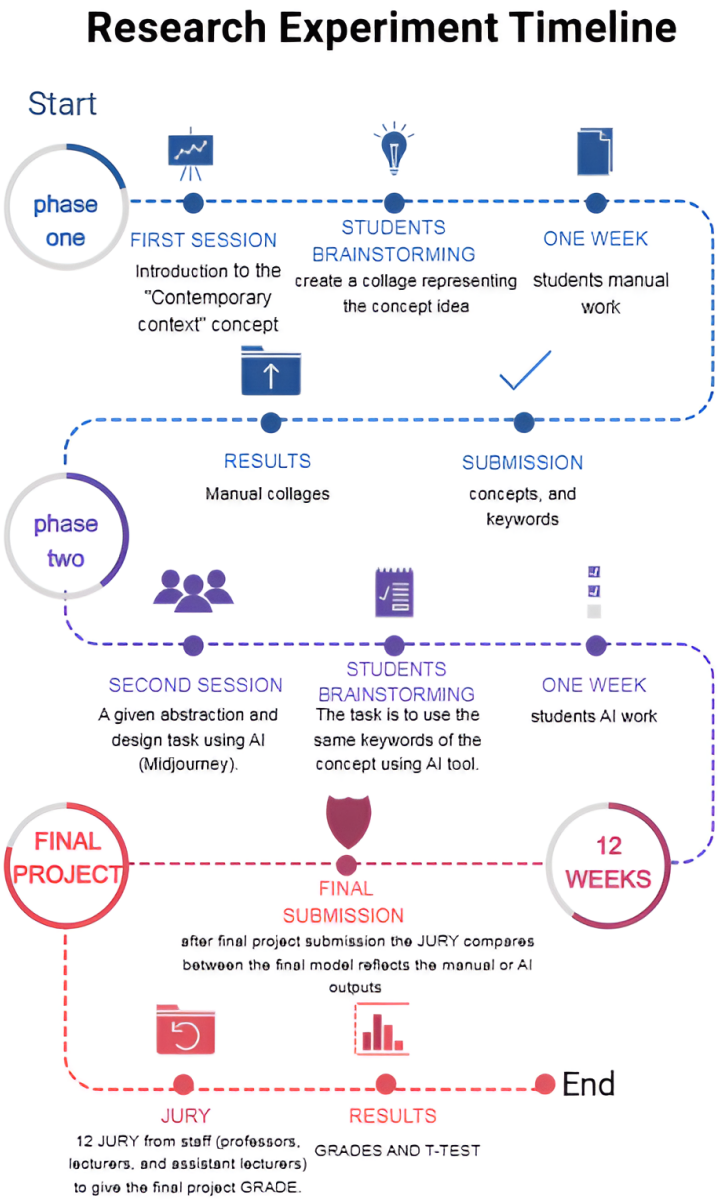


Figure 2: Timeline Flow Chart of Experiment Phases.

Throughout the final design phase, students refined their interior concepts in relation to both manual and AI-generated collages. As illustrated in Figure 3, students engaged with both traditional and AI-driven workflows. A panel of 12 academic staff members conducted blind evaluations of each submission

independently, assessing creativity, keyword use, visual quality, and presentation neatness.

Student 1



Manual collage



AI image

Student 9



Manual collage



AI image

Student 8



Manual collage



AI image

Student 10



Manual collage



AI image

Figure 3: Sample from the 108 students' manual and text-to-image AI, Collages comparison.

Results

It was found that 68% of the overall average grades got a higher AI image that reflects interior design project keywords of the students as compared to the final project who believe that manual collages appropriately don't reflect keywords. As 86% of the judges believe that AI Image has more creativity than manual collages. 44% of AI can improve the quality of the project, while 91% believe that neatness in AI images is higher than in manual collages. As shown in Figure 4 the average grade of the 108 student assignments between manual assignment and Text-to-AI image.

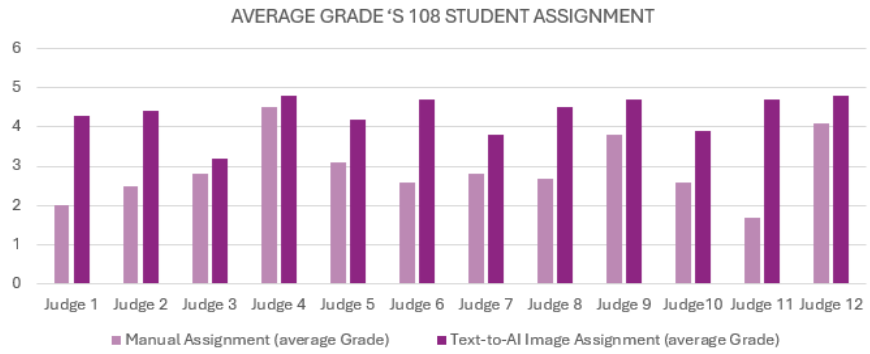


Figure 4: Judges grading assignment percentage.

TABLE 2: The average grade of different assessed experiment parameters

Parameters	Description	Weighting (%)	Average Grade /100	
			Manual Collage	AI image
Keywords	Alignment of the design output with the thematic and conceptual keywords	30%	48	62
Creativity	Originality and innovativeness of the design ideas and their execution.	30%	62	79
Quality	Technical resolution, spatial coherence, and material articulation	25%	52	54

Neatness	Visual clarity, presentation quality, and organization of the final output.	15%	52	82

Table 2 shows that average marks of the AI output is higher than the manual output for all measured parameters. A T-test analysis was performed to test whether the score differences between manual and AI outcomes are statistically significant or not, and to determine which criteria significantly differ. The t-test is a statistical test for comparing two groups' means. It is frequently employed in hypothesis testing to ascertain whether two groups are distinct from one another or whether a procedure or treatment genuinely affects the population of interest (Bevans, 2023). A significant value less than 0.05 indicates a significant difference between manual and AI experiments, whereas values greater than 0.05 indicate no significant difference.

Table 2 shows the results of the independent sample T-test analysis. The test indicates statistically significant score differences between the two groups (highlighted in green) in terms of Creativity (manual=62, AI=79, with significance value (p) < 0.001), and Neatness (manual=52, AI=82, with significance value (p) < 0.003). Yet, no statistically significant differences were found in terms of Keyword (manual=48, AI=62, with significance value (p) = 0.348, >0.05), and Quality (manual=52, AI=54, with significance value (p) = 0.331, >0.05), suggesting that both groups performed similarly in these areas. Accordingly, it can be concluded that statistically significant differences exist between manual and AI outputs in parameters of Creativity and Neatness, but no significant difference was found in parameters of Keyword and Quality, as presented in Table 2.

TABLE 3: T-Test independent samples test & statistics.

Independent samples test											
Levene's test for equality of variances				t	Df	T- test for equality of Means				95%confidence interval of the difference	
						Significance		Mean difference	Std.error difference		
		f	Sig.			One-sided p	Two-sided p			Lower	Upper
Keyword	Equal variances assumed	.642	.434	-.893	18	.192	.384	-.70000	.78387	-2.34684	.946844
	Equal varian			-.89	15.443	.193	.386	-.70000	.78387	-2.366	.96660

	ces not assumed			3						60	
Creativity	Equal variances assumed	11.618	.003	-5.142	18	<.001	<.001	-.70000	.68069	-4.93007	-2.06993
	Equal variances not assumed			-5.142	11.727	<.001	<.001	-.70000	.68069	-4.98693	-2.01307
Quality	Equal variances assumed	.748	.399	-1.000	18	.165	.331	-.70000	.70000	-2.17862	.77065
	Equal variances not assumed			-1.000	16.740	.166	.332	-.70000	.70000	-2.17862	.77862
Neatness	Equal variances assumed	.490	.493	-3.495	18	.001	.003	-2.10000	.60093	-3.36250	-.83750
	Equal variances not assumed			-3.495	17.266	.001	.003	-2.10000	.60093	-3.36635	-.83365

The results presented show that AI has a significant difference in parameters of creativity and neatness, on the other hand, the differences between parameters of quality and keyword were not found significant. These findings support the argument in favour of integrating Artificial Intelligence (AI) into interior architecture design curriculums as a powerful tool that has the potential to improve interior architecture students' performance in educational design.

Conclusion and Recommendations

This study examined the possibilities of integrating AI into IAD education using a comparative method and a case study. The case study shows how combining AI with critical pedagogy might improve conceptual communication. Still, educators need to make sure that AI would be an addition to human ingenuity rather than a substitute. This doesn't mean that

it is no longer a tool for brainstorming. Other approaches of utilizing AI's advantages while maintaining the integrity of the design process should be investigated in future studies.

- **AI vs. Manual Collage:** The study revealed that AI-generated designs outperform manual collages in terms of both creativity and neatness. This is significant, as creativity is a crucial aspect of design, especially in interior architecture. AI provides a more refined and efficient way to explore creative solutions.
- **AI's Role in Design Education:** While AI shows great promise in supporting interior architecture students, its use in educational settings must be approached with caution. The role of AI in the classroom remains a topic of debate, especially regarding concerns about authenticity and its potential to replace human designers in the future.
- **Impact of AI on the Future:** As AI continues to evolve and improve, its influence on society and the design industry will undoubtedly grow. The advancements in AI could lead to better decision-making, increased productivity, and more innovative solutions. **However, these benefits come with ethical considerations that need to be addressed.**
- **Need for Further Research:** Although AI has proven to be a valuable tool for enhancing students' performance in interior architecture design, further investigation is necessary. It is important to explore ways to maximize the benefits of AI while also addressing the challenges it presents in educational and professional contexts.
- **Conclusion on AI as a Tool:** In conclusion, AI should be regarded as a powerful tool for interior architecture design education, but its integration must be handled thoughtfully. Continued research and understanding are crucial to ensure that AI is used effectively, ethically, and to its full potential in the field of interior architecture.

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WHEN AND HOW IS AI TAUGHT? A STUDY ON TEACHING FORMATS IN ARCHITECTURE SCHOOLS

A Comparative Study of AI-Pioneering Architecture Schools and Their Curricular Strategies Across Three Continents

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Abstract. As artificial intelligence (AI) gains prominence in architectural design, architecture schools are revaluating methods for integrating this technology into their curricula. This study analyses the methodologies and timing of AI instruction across ten architecture schools in America, Europe, and East Asia. The chosen universities were picked for their international acclaim and their proactive initiatives to incorporate AI into education via formal procedures, program frameworks, and curricular material. A four-part framework directs the investigation, emphasizing each university's educational trajectory, AI policies, curriculum development, and AI-related courses. The results indicate significant geographical disparities. In the United States, artificial intelligence is frequently available as an elective course at the graduate level. In Europe, it is generally incorporated into specialized master programs. In East Asia, students are introduced to artificial intelligence at an earlier stage, frequently through mandatory undergraduate courses. These patterns underscore

various educational methodologies and embody overarching institutional strategies for training future architects.

Keywords: *Architectural Education, Artificial Intelligence (AI), Curriculum Design Comparative Analysis, AI Pedagogy*

1. Introduction

Architectural education, much like during the digitalization era, is on the brink of another transformation. As artificial intelligence (AI) rapidly evolves, its impact on educational practices has become increasingly visible. AI is no longer a fleeting trend but a phenomenon that has irreversibly entered design and pedagogy. Studies show that students often approach AI with enthusiasm, whereas educators display greater caution toward its integration (Yim and Wegerif, 2024; Digital Education Council, 2024). Beyond perceptions, empirical evidence suggests that AI can enhance student productivity and personalize learning pathways (Tapalova et al., 2022), while also reducing repetitive tasks and administrative workloads for educators (Kalniņa et al., 2024; Delello et al., 2024). UNESCO (2024) has similarly emphasized the potential of AI systems to support teachers by providing faster and more efficient assessment of student work.

In the context of architectural education, researchers have investigated AI's potential across multiple domains. Ceylan (2021) explored its applications in data collection, generative design, Building Information Modeling (BIM), performance analysis, and visualization. Kavakoğlu et al. (2022) demonstrated that AI could foster creativity in early design studios, while Jin et al. (2024) highlighted its role in providing personalized learning experiences. Surveys confirm students' positive attitudes: Komatina et al. (2024) reported that 53% of architecture students believe AI increases efficiency and 54% view it as a source of innovative design solutions. Similarly, Alshahrani and Mostafa (2025) found that AI supports design iteration, performance analysis, and visualization, strengthening architectural pedagogy overall. More recent experimental work confirms these insights: Sadek (2023) showed that students using AI during the concept generation phase performed better than those employing traditional methods, and Aly (2025) stressed that generative AI not only automates but also enhances creativity, improves time management, and integrates with BIM workflows.

Alongside technical and generative applications, architecture schools have begun to introduce courses that foreground the ethical and social dimensions of AI. Programs such as AI and Ethics or AI for Social Good aim to cultivate responsible practitioners who can critically engage with technology. As Wiese et al. (2025) note, "Efforts to teach AI ethics … aim to meaningfully challenge students' ethical reasoning skills in applied practices." Similarly, Weichert

and Eldardiry (2025) found that adding an AI policy and ethics module to a graduate-level course successfully engaged technically oriented students, "increasing awareness of the social impacts of AI technologies and developing interest in the field of AI regulation." These findings demonstrate that AI education in architecture must be understood not only as a technical skillset but also as a framework for critical reflection and social responsibility.

Despite these contributions, the literature still lacks a comprehensive, global comparison of how architecture schools integrate AI into their curricula. Alaçam et al. (2025) mapped AI-related courses in Türkiye, providing valuable insights at the national scale. Other efforts, such as Cudzik (2024) and Jin et al. (2024), examined individual courses, while Alshahrani and Mostafa (2025) conducted a regional case study in Saudi Arabia. Comparative studies have also been conducted in other thematic areas, such as the work of Porras Álvarez et al. (2016), which systematically analyzed sustainability courses in professional architectural curricula across Asia. These examples underscore the value of comparative approaches but also highlight a critical gap: the absence of an international, multi-continental study specifically focused on AI in architecture education.

2. Methodology

This study employs a qualitative comparative case study approach to analyze how artificial intelligence is integrated into architecture curricula. Ten universities from America, Europe, and East Asia were selected because of their pioneering initiatives and international recognition. The purpose of the study is not statistical generalization but rather to identify institutional strategies and regional tendencies through a structured comparison.

The universities were chosen through purposive sampling, guided by four criteria: (1) geographic diversity, (2) academic recognition through rankings or accreditation, (3) evidence of institutional AI-related initiatives, and (4) the availability of reliable public information on curricula. The unit of analysis was the architecture program at each institution, including both undergraduate and graduate levels.

Data were gathered from official and publicly accessible sources, such as course catalogs, program handbooks, curriculum maps, syllabi, and institutional strategy documents. Where possible, multiple sources were cross-checked to ensure consistency and accuracy.

The core of the analysis was the development of a course classification table, which made systematic comparison possible across cases. Each AI-related course was categorized according to (1) its level of study (undergraduate or graduate), (2) its status (compulsory or elective), (3) the year of instruction in the undergraduate curriculum, (4) its format (standalone

new course or embedded within an existing studio or module), and (5) its official course title. This classification framework allowed us to trace how AI is positioned in curricula and to identify common patterns and regional differences in timing, delivery, and content.

For clarity and comparability, each case study was presented in four stages: (1) a general introduction to the institution, (2) an outline of the university's AI approach and policies, (3) a short overview of the architecture program structure, and (4) a description of AI-related courses following the classification framework. This structure ensured consistency across cases and enabled meaningful cross-case comparison.

3. Findings

This section presents the findings based on the analysis of ten architecture schools: Florida University, Massachusetts Institute of Technology (MIT), New Jersey Institute of Technology (NJIT), University of Bath, Institute for Advanced Architecture of Catalonia (IAAC), Istanbul Technical University (ITU), Singapore University of Technology and Design (SUTD), Nanjing Tech University, Shanghai Jiao Tong University (SJTU), and Xi'an Jiaotong–Liverpool University (XJTLU).

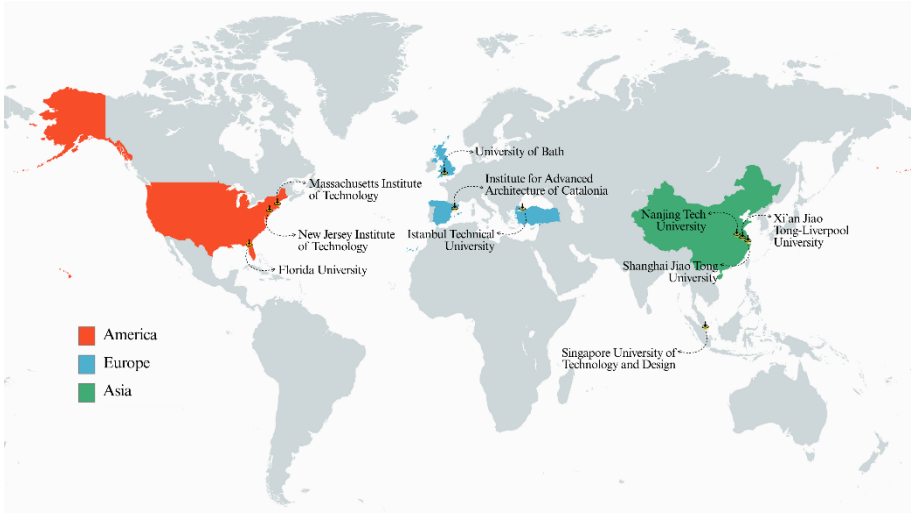


Figure 1. Visualization of selected universities and their countries on the world map.

TABLE 1. Overview of Country, Institution, Program Type, Course Status, Level, Year and Course Name

Country	University	Program	Type	Elective/ Compulsory	Under/ Graduate	Year	Lesson
United States	UF	Master of Architecture	Standalone	Elective	Graduate	-	AI & Ethics in Architecture
		Master of Architecture	Standalone	Elective	Graduate	-	Fundamentals of Coding and Computation (ARC 5921)
		Master of Architecture	Standalone	Elective	Graduate	-	Machine Learning for Architects, ARC 6XXX
	MIT	Bachelor of Science in Architecture	Standalone	Elective	Graduate	4	Creative Machine Learning for Design
		Master of Architecture / Bachelor of Science in Architecture	Embedded	Elective	Undergraduate/ Graduate	4	Design Studio: Interaction Intelligence
	NJIT	Bachelor of Architecture	Standalone	Elective	Undergraduate	3	Special Topics Technology Elective Artificial Intelligence in Architecture
		Master of Architecture	Standalone	Elective	Undergraduate	3	AI / VR In Architecture
		Bachelor of Architecture	Standalone	Elective (Extra)	Undergraduate/ Graduate	All	AI Literacy Micro-credential
Europe	Bath	Artificial Intelligence for Engineering and Design MSc	Standalone	Compulsory	Graduate	-	Artificial Intelligence and Machine Learning for Engineering and Design
		Artificial Intelligence for Engineering and Design MSc	Standalone	Elective	Graduate	-	AI and Sustainable Development
	IAAC	Master in AI for Architecture & the Built Environment	Standalone	Compulsory	Graduate	-	AI Theory for Design
		Master in AI for Architecture & the Built Environment	Standalone	Compulsory	Graduate	-	AI Programming for Design
	ITU	Bachelor of Architecture	Standalone	Elective	Undergraduate	3	Artificial Intelligence in Architecture, Planning, and Design (MYZ306E)
		Architectural Design Computing	Standalone	Elective	Graduate	-	Machine Learning for Architectural Design (MBL559E)
Asia	SUTD	Architecture and Sustainable Design	Standalone	Compulsory	Undergraduate	3	Creative Machine Learning
		Architecture and Sustainable Design	Standalone	Elective	Undergraduate	2	Data Driven World
		Architecture and Sustainable Design	Standalone	Compulsory	Undergraduate	1	Innovating with Design and AI-1
		Architecture and Sustainable Design	Standalone	Compulsory	Undergraduate	1	Innovating with Design and AI-2
	NjTech	Bachelor of Architecture	Standalone	Elective	Undergraduate	2	AI-assisted Design Basics
		Bachelor of Architecture	Standalone	Compulsory	Undergraduate	1	Introduction to Artificial Intelligence B
		Bachelor of Architecture	Standalone	Compulsory	Undergraduate	4	Introduction to Smart Buildings
	SJTU	Architecture and Urban Design	Standalone	Elective	Undergraduate	2	Artificial Intelligence in Art and Design (ARCH3402)
		Architecture and Urban Design	Standalone	Compulsory	Undergraduate	1	Artificial Intelligence and Design (ED1202)
	XJTLU	Bachelor of Architecture	Standalone	Compulsory	Undergraduate	2	Multiscale Collaborative Design Studio
		Bachelor of Architecture	Standalone	Compulsory	Undergraduate	2	Introduction to Design Languages and Artificial Intelligence
		Bachelor of Architecture	Embedded	Compulsory	Undergraduate	4	Professional Practice
		Bachelor of Architecture	Embedded	Compulsory	Undergraduate	4	Final Year Project

3.1.1. University of Florida (UF)

The University of Florida (UF), ranked 212th globally (QS, 2025a), presents itself as the nation's first "AI University." Its AI Across the Curriculum initiative, supported by the HiPerGator supercomputer and university-wide faculty hiring, seeks to embed AI literacy across all disciplines. The model is organized around four pillars: knowing and understanding AI, using and applying AI, evaluating and creating AI, and AI ethics (UF AI, 2025a).
To implement this vision, UF offers a 9-credit Undergraduate AI Certificate that combines a foundations course, an ethics module (Ethics, Data and Technology), and a discipline-specific elective. Individual colleges may also design their own certificates, while one-credit modules such as Frontiers of AI provide flexible entry points. The goal is to ensure that all students graduate with a baseline of AI literacy (UF AI, 2025b).

In the School of Architecture, the B.Des. program serves as a feeder to the NAAB-accredited M.Arch. Students can pursue the undergraduate AI Certificate for early exposure, while the Graduate Certificate in AI in Architecture (15 credits) provides advanced specialization. Required courses include ARC 5921 – Fundamentals of Coding and Computation (basic programming applied to design exercises), ARC 6922 – AI & Ethics in Architecture (bias, fairness, and syllabus design for AI-integrated studios), and ARC 6923 – Machine Learning for Architects (experimental use of ML for generative design). The remaining credits may be drawn from advanced studios, urban and geospatial modeling, or data science electives (CityLab-Orlando, 2025).

UF thus combines broad-based AI literacy with discipline-specific depth. Its strengths lie in its clear institutional vision, the integration of ethics as a core element, and multiple entry points that make AI accessible to all students. Yet in architecture, most AI courses remain elective, leaving integration dependent on individual student choice rather than a universal requirement.

3.1.2. New Jersey Institute of Technology

The New Jersey Institute of Technology (NJIT), founded in 1881 and located in Newark, offers a five-year NAAB-accredited Bachelor of Architecture (B.Arch.) through the Hillier College of Architecture and Design (NJIT, 2025a). The university ranks in the 761–770 band in the 2025 QS World University Rankings (QS, 2025b).

Institutionally, NJIT promotes AI literacy through its AI Core Competencies framework and the AI Literacy Microcredential, a 20-hour program for all majors covering AI logic, risks, and applications. In parallel, the AI for Educators program includes the AI-Enhanced Instructional Design course, which trains faculty to use AI in course design, student engagement,

and progress monitoring (NJIT LDI, 2025). These initiatives are reinforced by a Responsible Use of AI policy mandating citation of AI-assisted work (NJIT, 2025c).

Within architecture, two electives incorporate AI: ARCH 483/662 – Artificial Intelligence in Architecture, introducing generative AI and performance simulations, and ARCH 483/689 – AI/VR in Architecture, applying immersive technologies to spatial evaluation. Both are offered at undergraduate and graduate levels (NJIT, 2025d).

NJIT distinguishes itself by targeting both students and faculty with structured AI training. However, integration within the architecture curriculum remains elective and supplementary. Compared to institutions embedding AI into core studios, NJIT's approach is still partial, indicating strong potential but limited curricular mainstreaming.

3.1.3. Massachusetts Institute of Technology

The Massachusetts Institute of Technology (MIT), founded in 1861 in Cambridge, Massachusetts, is globally recognized for excellence in engineering, computer science, AI, and architecture. According to QS World University Rankings 2025, MIT ranks first both overall and Architecture and Built Environment category (QS, 2025c).

MIT's AI strategy is institution-wide and interdisciplinary, positioning AI as a paradigm that informs diverse fields. This vision emphasizes technical expertise, cross-disciplinary integration, and social and ethical responsibility.

The Schwarzman College of Computing plays a central role by promoting AI literacy across all programs and fostering "computing bilinguals" who combine computational skills with disciplinary knowledge. A flagship element is the Common Ground for Computing Education initiative, which develops interfaculty non-credit courses such as Modeling with Machine Learning (C01/C51), Machine Learning for Sustainable Systems, and Physical Systems Modeling with ML (MIT Common Ground, 2025).

Within the School of Architecture and Planning (SA+P), the BS in Architecture and graduate M.Arch and SMArchS programs integrate design studios with building science and technology. Two electives highlight the role of AI in design. 4.043 / 4.044 Interaction Intelligence is an elective studio course at advanced undergraduate and graduate levels where students prototype interactive systems using ML, neural networks, and large language models, culminating in portfolio-level projects. 4.453 Creative Machine Learning for Design is a graduate and upper-undergraduate elective that explores generative algorithms such as GANs and VAEs for open-ended design experimentation (MIT Architecture, 2025a; 2025b).

Overall, MIT distinguishes itself by pairing an Institute-wide AI literacy framework with discipline-specific experimentation in architecture. This layered strategy, combining broad foundations through Schwarzman College, cross-cutting applications via Common Ground, and design-focused studio electives, places MIT at the forefront of integrating AI into higher education.

3.2.1. Istanbul Technical University

Established in 1773, Istanbul Technical University (ITU) is one of the oldest technical universities worldwide and Türkiye's leading institution for engineering, architecture, and natural sciences. According to the QS World University Rankings 2025, ITU ranks 298th globally (QS, 2025d). The launch of the undergraduate program in Artificial Intelligence and Data Engineering in 2020–2021 highlights the university's AI vision. This was the first department in Türkiye to merge AI with data science (ITU, 2024a). The ITU AI Research and Application Center, founded in 2019, supports interdisciplinary projects (ITU, 2024b), while the Center for Excellence in Education (ITU MEM) promotes AI-driven pedagogical innovation across faculties (ITU, 2025c).

The Faculty of Architecture offers master's and PhD programs in Architectural Design Computing, initiated in 2000, focusing on generative design, data-driven modeling, XR environments, BIM, and AI-enhanced creativity (ITU, 2024d). Within this framework, the elective Artificial Intelligence in Architecture, Planning, and Design (MYZ306E) is open to third-year students from architecture, urban planning, industrial design, and interior design and landscape architecture. Some MYZ courses are also delivered as faculty-wide seminars, aiming to develop AI literacy across the Faculty of Architecture. In addition to these broad initiatives, domain-specific electives are designed to support specialization, ensuring that students interested in advanced topics gain exposure to the most up-to-date AI technologies. At the graduate level, Machine Learning for Architectural Design (MBL559E) focuses on both theoretical and applied aspects of machine learning, including neural networks, data analysis, and project-based design (ITU, 2024e).

AI integration is also observed in first-year design studios, where instructors introduce AI modules into mandatory courses. Findings from these experiments, analyzing student interactions with AI, have been shared in the literature (Kavakoğlu et al., 2022). ITU distinguishes itself in Türkiye by combining formal AI-related programs with faculty-wide literacy efforts and experimental applications in design studios. This multi-layered approach, which includes seminars, electives, and research-led courses, positions the

university as a leader in embedding AI systematically into architectural education.

3.2.2. University of Bath

The University of Bath is a prominent public research institution in the UK, established in 1966 with academic origins linked to the Merchant Venturers' Technical College. Ranked 132nd worldwide in the QS World University Rankings 2025, it is recognized for academic excellence and a multidisciplinary approach (QS, 2025e).

In November 2023, the university adopted the Russell Group's Generative AI Principles, emphasizing ethical AI use through employee training, academic integrity guidelines, and AI literacy programs (University of Bath, 2025a).

In 2024, Bath launched the MSc in Artificial Intelligence for Engineering and Design, the UK's first postgraduate program integrating architecture, engineering, and AI. Its core module, Artificial Intelligence and Machine Learning for Engineering and Design, covers supervised and unsupervised learning, neural networks, and design applications. Supplementary modules include Digital Transformation: Project and Change Management and Professional and Research Skills for Engineering and Design. Electives such as AI and Sustainable Development, Smart Cities and the Internet of Things, and Advanced Numerical Methods allow for specialization in sustainability and computational design.

The program concludes with an individual research project, supported by advanced computing infrastructure and interdisciplinary teaching. By treating AI as a central subject of postgraduate education, the University of Bath not only positions itself at the intersection of design, engineering, and digital innovation but also constitutes a pioneering example of a fully AI-focused master's program in architecture and engineering, demonstrating the upper limits of a curriculum built entirely around AI (University of Bath, 2024b).

3.2.3. IAAC (Institute for Advanced Architecture of Catalonia)

The Institute for Advanced Architecture of Catalonia (IAAC) is an internationally renowned postgraduate institution located in Barcelona. Accredited by the University of Lleida within the framework of the European Higher Education Area (EHEA), IAAC collaborates with a wide network of academic and industry partners at both local and international levels.

IAAC offers a variety of technologically driven postgraduate programs across architectural subfields. One of its most pioneering degrees is the Master in Artificial Intelligence for Architecture & the Built Environment (MaAI).

This program addresses the growing need for AI-integrated, data-informed, and ecologically responsive design methods. It is available in two formats: MaAI01, a 10-month program worth 90 ECTS credits, and MaAI02, a 20-month option worth 120 ECTS credits. The latter includes professional development components such as paid internships or participation in startup accelerator initiatives (IAAC, 2025a).

The MaAI program is built around the goal of creating more sustainable and resilient cities by bringing artificial intelligence into architectural design and thinking. Key courses include AI Theory for Design, which explores the ethical and philosophical dimensions of AI, and AI Programming for Design, which provides practical training in machine learning and neural networks. The AI Methods I & II courses cover generative design, reinforcement learning, and evolutionary computation. Other classes such as Data Analytics I & II, UI/UX in Digital Architecture, AI-Powered Web Applications, and AI Ethics & Open Source Communities broaden both technical expertise and critical awareness. The program also promotes business innovation through collaboration with a business school.

The program culminates with a final Master Thesis Project, giving students the opportunity to integrate theoretical and practical knowledge. By placing artificial intelligence at the core of a dedicated postgraduate program, IAAC takes a leading role in shaping what an architecture curriculum focused entirely on AI can offer, positioning the MaAI program as a strong example of how emerging technologies are changing the direction of architectural education and demonstrating the potential breadth of a fully AI-oriented curriculum.

3.3.1. Singapore University of Technology and Design

Founded in 2009 in partnership with MIT, SUTD is a public autonomous university known for integrating technology, design, and AI. As of the QS World University Rankings 2025, it ranks 519th globally (QS, 2025f). In 2025, SUTD positioned itself as the world's first Design·AI university through the SUTD Leap strategy, led by the newly founded Office of Artificial Intelligence and Digital Innovation (OAIDI) (SUTD, 2025a).

AI integration begins in the first year with compulsory progressive studio courses: IDeA-1 (Innovating with Design and AI–1) and IDeA-2 (Innovating with Design and AI–2). These introduce human-centred innovation, empathy-driven research, AI-supported ideation, and prototyping Architecture students may also choose electives such as Creative Machine Learning (20.318) and 10.020 Data Driven World to deepen their technical and design-oriented AI skills (SUTD, 2025b).

In addition to these offerings, SUTD has established a dedicated undergraduate program, the Design and Artificial Intelligence (DAI) degree.

This unique program combines systematic AI literacy with design education, including courses like AI in Design and Applied Deep Learning. It is further enriched by more than 20 studios and culminates in an industry-based capstone project (SUTD, 2025c).

SUTD's identity as a Design·AI university highlights a pioneering institutional model where AI is embedded across all levels of education. The compulsory first-year studios, elective courses, and the establishment of the DAI degree position SUTD among the most progressive institutions globally, though its long-term impact will depend on how well these initiatives translate into professional practice.

3.3.2. Shanghai Jiao Tong University (SJTU)

Founded in 1896, Shanghai Jiao Tong University is one of China's oldest and most respected research universities and a key member of the C9 League. It was ranked 47th in the QS World University Rankings 2025 (QS, 2025g). Known for its strengths in engineering, technology, and interdisciplinary work, the university has taken big steps in AI by setting up the Shanghai Artificial Intelligence Research Institute in 2019 and hosting the UNIDO Global Excellence Center in 2024.

To help bring AI into higher education in a thoughtful way, the university introduced the AI Plus Education and Teaching Action Plan for 2024 to 2026. This plan encourages responsible and meaningful AI use through a model that connects teachers, students, machines, and learning environments. A supporting guide outlines how different AI tools should be used by grouping them into four categories: prohibited, limited, encouraged, and open. These decisions are based on risk levels and guided by values like human focus, openness, and responsibility (SJTU, 2025a). The guide also explains what is expected from teachers, students, and developers to support a fair and long-term approach to AI in education.

In line with this comprehensive vision, the School of Design integrates AI into its undergraduate Architecture program with standalone courses. Students are introduced to the mandatory ED1202 Artificial Intelligence and Design course in their first year, followed by the elective ARCH3402 Artificial Intelligence in Art and Design in the second year. This structure reflects SJTU's commitment to equipping future architects with both computational design fluency and foundational AI literacy (SJTU, 2025b).

SJTU's model shows one of the most structured and policy-oriented approaches to AI in higher education. By creating clear categories for tool usage and embedding AI early in the curriculum, the university demonstrates how governance and pedagogy can reinforce each other. However, the effectiveness of this framework will depend on its adaptability to rapid

technological change and its balance between strict regulation and creative experimentation in architectural education.

3.3.3. Nanjing Tech University

NJTech is a major public university in Nanjing, China, with origins dating back to 1902. It was restructured in 2001 through the merger of two institutions and now comprises 26 colleges, enrolling nearly 30,000 students. The university ranks within the 301–350 band in the QS World University Rankings by Subject (QS, 2025h).

In 2024, NJTech launched the Intelligent Future: Undergraduate AI Literacy Foundation Plan, integrating AI education across all undergraduate programs. Over 6,800 first-year students enrolled in the compulsory Introduction to Artificial Intelligence course, which was delivered in hybrid format and introduced as a large-scale lecture conference to the entire incoming cohort. The same course is also offered online to upper-year students who previously lacked access to AI training (NJTECH, 2025a).

The Architecture undergraduate program spans five years. Starting with the 2024 curriculum, new graduation requirements mandate that students "possess AI literacy, be able to apply new AI technologies, carry out AI+ construction engineering practices, and conduct research using scientific methods" (NJTECH, 2025b).

AI integration follows a progressive path: in the first year, all architecture students take the compulsory Introduction to Artificial Intelligence B. In the second year, they may choose the elective AI-assisted Design Basics, introducing computational thinking and generative design tools. By the fourth year, they complete the compulsory Introduction to Smart Buildings, focused on automation, intelligent building systems, and data-informed design. Together, these courses prepare students for AI-integrated architectural practice.

NJTech's model is distinctive for introducing AI literacy as a compulsory foundation across the entire university while embedding a stepwise progression within the Architecture program from the first year onward. This structure positions the institution as a pioneer in systematically building AI competencies in architectural education, ensuring that students develop both broad literacy and specialized design applications throughout their studies.

3.3.4. Xi'an Jiaotong Liverpool University (XJTLU)

Founded in 2006 as a partnership between Xi'an Jiaotong University and the University of Liverpool, XJTLU is an international university in Suzhou, China, offering English-medium dual degrees recognised in both China and the UK (XJTLU, 2025a).

Under its Education + AI Strategic Framework 2025–2028, XJTLU has embedded artificial intelligence across teaching, research, and operations. This includes the Research Centre for AI and Education (RC4AIED) and the XIPU AI platform, which integrates models such as GPT-4o and DeepSeek (XJTLU, 2025b; XJTLU, 2025c, XJTLU, 2025d).

XJTLU had already been experimenting with pilot projects to integrate AI into its curriculum as the technology became more widespread. The chronological integration of AI into the School of Architecture, beginning with AI Explorations in 2020, can be traced in Juan Carlos Dall'Asta's study on human-computer interaction and AI in design education (Cheung and Dall'Asta, 2024).

In the Department of Architecture, a curriculum transformation launched in 2025–2026 places AI at the core of architectural education, combining technological innovation with humanistic dimensions. From the second year, students in the Multiscale Collaborative Design Studio use AI to address wicked problems and conflicting perspectives. Alongside this, the compulsory Introduction to Design Languages and Artificial Intelligence module develops students' ability to work across visual, textual, and programming models, emphasising interactions between humans and AI tools (XJTLU, 2025e).

AI integration continues in the final year, where Professional Practice introduces generative AI for workflow and decision support, and the Final Year Project requires students to apply AI and emerging technologies to complex design challenges in an ethical and reflective manner. In this way, XJTLU frames AI not just as a technical aid but as a design partner, preparing graduates to engage critically and creatively with architectural practice. XJTLU holds a distinctive position by recognising the importance of AI in education early and pioneering its integration into architectural learning. The combination of standalone AI courses with embedded applications in project work and final studios sets the school apart, and this comprehensive institutional approach may well serve as a model for other universities in the future.

4. Comparison and Evaluation

A comparative analysis of regional approaches reveals distinct strategies for integrating AI into architectural education. In the United States, institutions prioritize university-wide AI literacy through certificates and modular formats that are broadly available yet often elective within architecture. In Europe, the emphasis falls on postgraduate depth through fully fledged programs and research-oriented specialization. In East Asia, governance frameworks and clear sequencing place compulsory AI exposure in the early years, followed by a progressive, vertically integrated pathway.

Within the US group, the University of Florida and MIT align institution-wide literacy with discipline-specific experimentation. Florida diffuses AI literacy through certificates and one-credit modules for all majors, while architecture leverages coding fundamentals, ethics, and machine learning studios, typically offered as electives. MIT complements its interdisciplinary literacy model with design-led studio electives that engage creative machine learning and interactive intelligence. NJIT is distinctive for pairing student micro-credentials with structured staff development that equips faculty to design AI-enhanced courses. Across these cases, the central vulnerability is reliance on student choice. Because many architecture offerings remain elective, institutions risk uneven coverage of baseline competencies among graduates.

In Europe, Bath and IAAC establish a pronounced specialization track through AI-centric postgraduate programs. IAAC's MaAI and Bath's AI for Engineering and Design provide coherent program architectures that span algorithms, ethics, and governance while maintaining strong industry and research linkages. ITU advances a dual pathway. University-level investments in AI and data engineering and research centers create institutional capacity, while the Faculty of Architecture deploys faculty-wide seminars, experimental studio modules, and electives to diffuse know-how. Europe's principal strength lies in sustained, research-driven capacity building. Its weakness is less consistent provision of compulsory AI literacy at the undergraduate level that would guarantee minimum competencies for all architecture students.

In East Asia, SJTU anchors integration in a governance model that categorizes tools by risk and articulates responsibilities for instructors, students, and developers. NJTech introduces a university-wide compulsory AI foundations course for first-year students and extends a stepwise sequence within architecture from AI-assisted design in mid-years to smart building topics in later stages. XJTLU embeds human-AI interaction as a curricular core through dedicated modules and final-year requirements that ask students to apply AI critically and ethically. SUTD positions itself as a Design·AI university and coordinates curriculum change through a dedicated office while maintaining elective pathways within architecture. The regional strength is an early and compulsory touchpoint that builds a shared baseline and a clear vertical progression. The associated risk is the constant need to recalibrate between regulatory clarity and the openness needed for exploratory, studio-based creativity.

The study's classification framework clarifies typological differences. Regarding format, the US and Europe lean toward standalone courses, whereas East Asia more often combines standalone instruction with embedded studio applications. Regarding level, Europe concentrates on postgraduate

specialization; the US distributes offerings across undergraduate and graduate tiers; East Asia ensures early undergraduate exposure. Regarding requirement status, offerings in the US and Europe are frequently elective, while East Asia more often inserts compulsory blocks in the lower years. Temporally, East Asian models tend to position AI in year one as a mandatory foundations course, while US institutions rely on flexible modules and certificates that enable early contact but still hinge on voluntary uptake.

Findings point to convergence around three levers that make integration effective. The first is governance and academic integrity frameworks that set transparent principles and embed ethics in learning outcomes. The second is continuous professional development for faculty, which enables course and studio redesign rather than one-off tool adoption. The third is investment in ecosystem capacity, including compute access, data infrastructure, and cross-faculty collaboration mechanisms. When these levers are combined with a vertical curriculum spine that ensures compulsory literacy in the early years, embedded studio practice in the middle years, and advanced elective laboratories in the later years, institutions achieve both inclusivity and specialization. Moving forward, priorities should include assessment designs aligned with originality and attribution standards in the era of generative AI, longitudinal monitoring using mixed quantitative and qualitative indicators, and tighter integration of industry partnerships with curricular renewal. This alignment will be critical to sustaining curricular coherence as the technical landscape continues to evolve.

5. Conclusion

This study has compared how architecture schools in different regions are integrating artificial intelligence into their curricula, aiming to provide guidance for institutions that plan similar reforms. The findings show that East Asia schools are ahead with compulsory and progressive sequencing of AI courses, ensuring that all students develop a baseline literacy before advancing architectural practices. The United States emphasizes flexibility through electives and certificates, which foster specialization but create gaps in inclusivity. Europe has pioneered fully AI-focused postgraduate programs, suggesting that such models may expand globally in the near future.

A central conclusion is that AI integration cannot rely on course additions alone. Institutional principles and policies are necessary to sustain and legitimize adoption. Ethical guidelines, responsible use frameworks, continuous professional development for faculty, and equitable access to computational resources are crucial conditions. Institutions that embed these principles demonstrate that AI can evolve from a set of tools into a pedagogical method that transforms design learning itself.

An ideal curriculum would combine the strongest elements observed. In the first year, compulsory AI literacy and ethics courses should provide a common foundation. In the interim years, studio projects should embed AI in ideation, iteration, analysis, and representation. In later stages, advanced laboratories and thesis projects should allow for specialization and innovation. This vertical structure ensures not only technical competence but also critical and ethical awareness.

In conclusion, AI can enrich architectural education by accelerating design processes and deepening reflective practice. Yet its success depends on how institutions frame and support its use. The true measure of integration lies not in how quickly students master the tools but in how universities embed AI into their educational identity through principled, ethical, and pedagogically coherent frameworks.

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DESIGN DIALOGUES WITH GENAI

A Sequential Workflow of Hand, Machine, and Imagination in Architectural Education

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Abstract. Generative Artificial Intelligence (GenAI) tools are transforming architectural design and representation, prompting the need for new pedagogical strategies. This study introduces a cyclical production model that integrates analog drawing, digital modeling, and GenAI tools within a two-day workshop conducted with 27 first-year students at Istanbul Technical University. The process began with digital 2D drawings inspired by Mondrian's compositions, which were developed into volumetric axonometric sketches. These sketches were combined with imaginary urban narratives and processed through GenAI platforms such as Midjourney, Vizcom AI, and Leonardo AI. The resulting images were turned into analog collages, re-digitized, and reinterpreted with new textual prompts, forming a continuous cycle between hand, machine, and imagination. Pre- and post-workshop surveys revealed that students' visual and textual thinking skills improved and that GenAI fostered exploratory and reflective learning. Rather than serving as a deterministic generator, AI was perceived as a dialogic collaborator that enriched creativity and decision-making. The proposed workflow highlights GenAI's potential to cultivate critical, innovative, and pluralistic representational practices in design education, positioning it as an inclusive and culturally adaptive learning partner.

Keywords: *Generative Artificial Intelligence, Architectural Intelligence, Transformation of Representation, Creative Pedagogy, Hybrid Processes*

1. Introduction

Although algorithms that imitate human intelligence and carry out tasks that generally require human cognitive abilities were the foundation of the first AI applications, advances in generative artificial intelligence—particularly those that perform more than these tasks—have accelerated in recent years. (Chakraborty et al., 2024).

Using a variety of data inputs, generative artificial intelligence (GenAI) enables users to produce new content, including text, images, audio, video, and 3D models (Dwivedi et al., 2023). In design processes carried out with generative artificial intelligence tools, the creativity level of the final product is directly related to the quality of the visual input and textual input (prompt) used (Yaşar et al., 2024). Examples of generative AI tools that students and teachers use in educational processes include ChatGPT, which responds to text prompts with both textual and visual responses, and Midjourney, which responds with visual responses. Nonetheless, there is ongoing discussion regarding the validity of the responses generated by these instruments and their educational value (Chiu, 2024). Consequently, research on how GenAI tools affect knowledge acquisition and digital transformation is ongoing (Dwivedi et al., 2023).

The quick development of generative artificial intelligence (AI) has necessitated theoretical and methodological approaches that can fully utilize its potential. It has raised new concerns about successfully integrating digital tools into the educational process (Messine & Pancirolli, 2025). Examining the pedagogical and cognitive effects of GenAI tools, such as ChatGPT, is essential as they proliferate in educational settings, especially when fostering academic integrity and analytical thinking (Noroozi et al., 2024).

The concept of GenAI has become widespread in architecture and other design fields in recent years, and its effects on the designer and the design object are still being discussed. The impact of AI-designer interaction on the quality of the design object is being examined experimentally. There are examples covering different types of work groups for using AI tools as auxiliary tools in early design stages and simple design expressions (Yaşar et al., 2024). Within the scope of this study, the aim is to:

• Measure visual production skills using visual and textual reference input from generative AI tools.

• Observe students' creative production processes by transforming drawings created with analog and digital representation and drawing tools into storytelling tools with AI support.

• Develop creative thinking in a workshop environment where AI tools, acting as representational tools rather than designers, enable the production of quality output through collaborative participation and reference.

Rather than using GenAI tools solely for visualization, this study proposes a design process that establishes a cyclical interaction between analog, digital, and AI-based production methods. This approach offers an innovative pedagogical model that aims to develop students' critical thinking skills and foster a holistic, multilayered perspective on the design process.

2. Theoretical Framework

This section investigates the theoretical implications of reintroducing representational tools into architectural design education.

2.1. DESIGN PEDAGOGY

It is necessary to comprehend the learning style of the designer and move quickly through the design process to effectively use traditional elements like the studio, education, library, and critique (Tovey, 2015). According to Tovey, through discipline-specific pedagogies, transformative learning supports students in creating their designer identities while facilitating participation in diverse communities of practitioners.

Architectural design thinking, tools, environments, and methods are all impacted by the multifaceted changes brought about by shifting social, economic, and technological trends to an information-focused structure (Şen Bayram et al., 2023).

2.2. TRANSFORMATION OF REPRESENTATION

In the design process, representation is the collection of techniques a designer uses to convey how they feel or think. These techniques have evolved and changed because of the widespread use of computers, leading to new forms of representation and a variety of interrogations (Sancak, 2023).

Organizing abstract concepts in the mind with tangible examples is the productive process in design, which evaluates the designer's design philosophy and experiences with the solutions offered in the social value system (Akgün, 2002). Creativity is an intelligent ability that includes a distinct approach to problem-solving, employs intelligence elements for originality and production, and has resulted in a new, original, skill-based product or has not yet become a product (Aslan, 2001). Nonetheless, creativity in architecture refers to using one's creative abilities during the creative design process and creating a novel and worthwhile outcome (Paananen et al., 2023).

3. Methodology

The study investigates generative AI tools' positive and negative contributions in design practice in generating two-dimensional and three-dimensional visual outputs and incorporating a narrative into these images. For this purpose, a two-day workshop was conducted with the participation of 27 undergraduate students, using GenAI tools sequentially with analogue generative tools. The workshop involved visualizing analogue and digital productions of axonometric perspective drawing techniques within the "Visual Communication" technical drawing course with GenAI tools and combining these images with analogue collage techniques. Mondrian paintings, which feature diagonal forms and potential lines to create various alternative 3D forms, were chosen as the drawing objects. A decoding and encoding study by Koçer Özgün and Alaçam (2021) emphasizes that Mondrian's flat but dense geometric data and unique color schemes, defined by extreme and vertical black lines on a white background, where one or more areas are created by the intersection of yellow, blue and primary colors with black lines at right angles, can be transferred to the digital environment, analyzed and used as a red reference in new product production.

In this study, the visual output obtained from the digital environment by the 27 students served as the reference for the initial drawing. In contrast, the two- and three-dimensional technical drawings formed the dataset for the AI. The content of input and output concepts continuously evolved throughout the workshop, which was a sequential AI-participatory collaborative effort. The basic structure of the work is seen in Figure 1. During the workshop, changes were made to input and output in three steps. The contents of the concepts of image and text (their counterparts in the workshop step) specified under the "Input" heading are explained in the column on the right. These inputs were provided as input to AI tools, and the resulting visual output was transformed by the participant and fed back to AI as input. The image/input, text/input, and image/output groups follow each other, forming different production steps. In the AI-supported visualization step, the AI tools listed in Figure 1 are auxiliary tools for AI-supported visualization processes. Paper, scissors, and glue constitute analog collage tools. In the final step, video animation is produced using visual input.

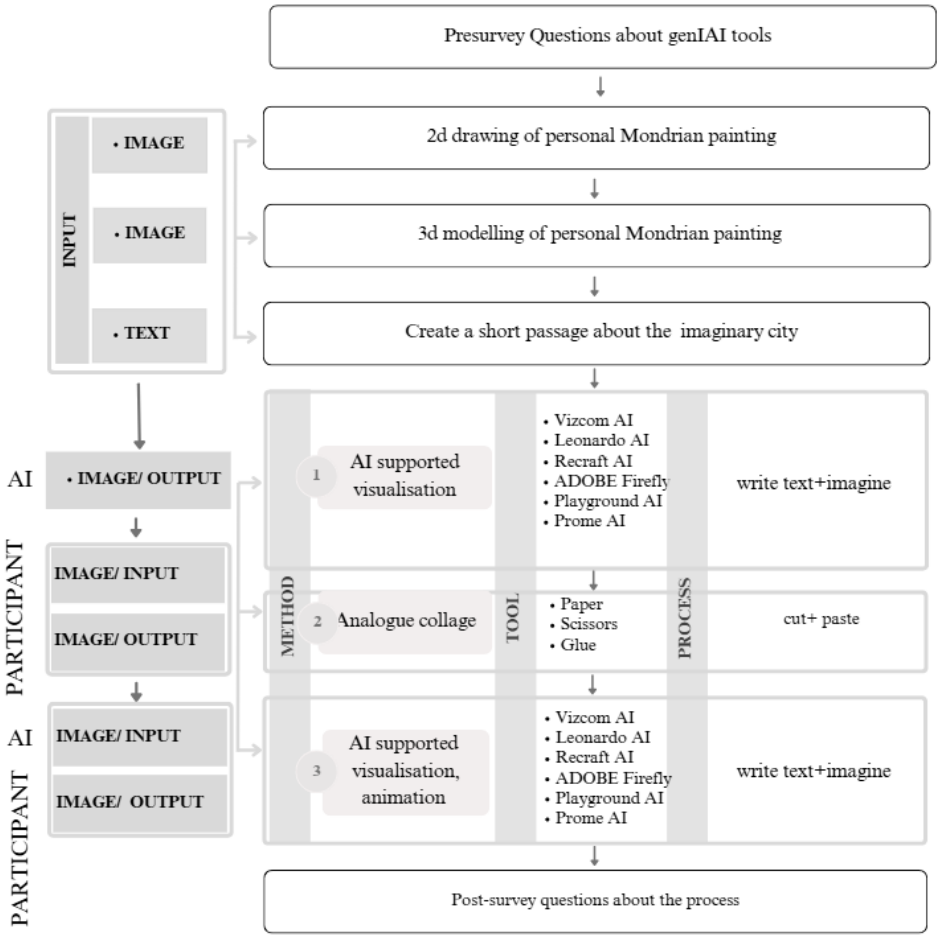


Figure 1. Workflow of study

Participants were asked to create their Mondrian painting using the website www.mondriangenerator.io/. A 2D drawing of this painting was created using AutoCAD, and then, using various 3D modelling tools, the 2D image was transformed into a 3D volume. The axonometric image of this model was recorded, and an analog axonometric perspective drawing was created. This drawing was inputted into the AI tool. VizcomAI, which is much more faithful to visual input than other AI tools, was chosen as the GenAI tool, and most students used this tool to generate visual output from visual input. Participants were asked to create a city, which they could describe with prompt text about their dream features, using the axonometric perspective image as input. These 10x10 cm perspective images were then

visualized with AI, printed onto paper, and transferred from the digital environment to the collage base. All participants were asked to create a collage of three to five city images with different neighbourhood relationships on a large sheet of imaginary isometric paper. These cities, each with different colours, architectural features, and user groups, formed a "collage city." This resulting collage city provided new input to the AI tool and a prompt text that would create a different narrative/story. Thus, a multi-component axonometric city image with a new narrative was obtained after the second visualisation phase with AI. Each student who created these collage city components was asked to draw simple sketch images of the resulting city analogously, to revisit them independently of their initial narrative, along with a prompt text containing a single city feature and then produce a short video animation of this image.

The workshop included:

- Acquiring 2D and 3D technical drawing skills
- Experiencing simple visual production with AI
- Generating a new visual result by referencing the formal characteristics of a visual input given to the AI tool
- Implementing an interactive collaborative visual production using the analog collage method
- Simultaneous development of visual and textual thinking by adding a new narrative to the final product
- Experiencing the production of a video animation segment using visual output as input, in collaboration with AI and the user.

The flow chart showing the input/output sequences and tools used in the digital-analogue-AI-supported production steps during the workshop creates a repeatable workflow (Figure 2).

Participants were asked a series of survey questions before the workshop to gauge their relationship with AI, their experiences before the workshop, and their experiences and opinions about the process afterwards. These survey questions constitute qualitative assessment tools that measure participant experiences of the process.

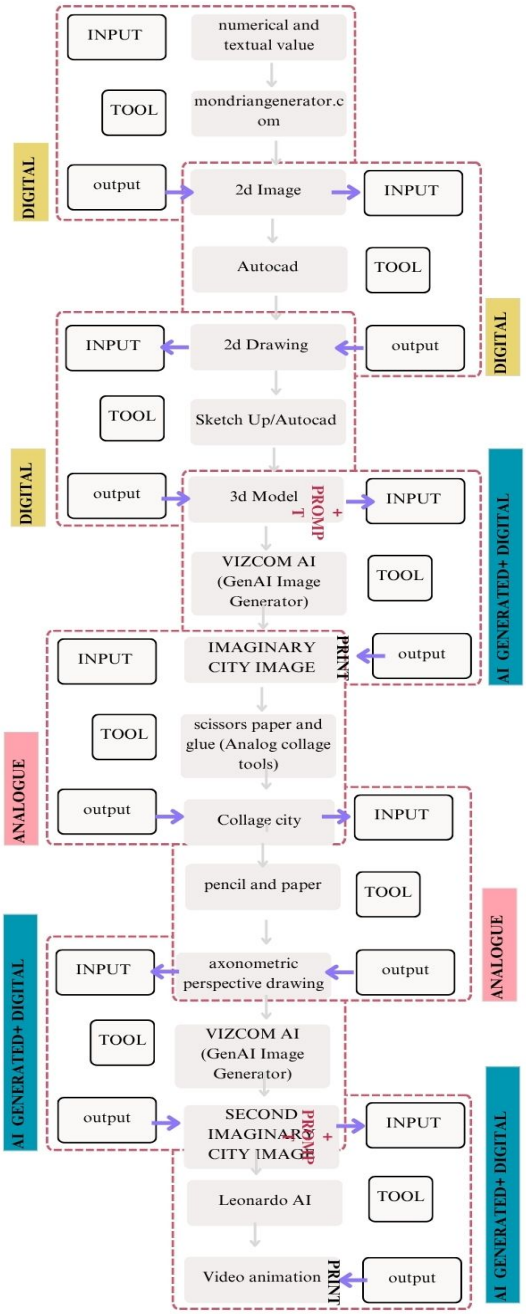


Figure 2. Input-output map of Analogue-Digital-AI generated + Digital production steps

4. Findings and Outcomes

Seven different collage cities were produced through collaborative production by the participants. These seven collage cities were recreated along with the retellings of the component owners. This study examines the production stages of one of these collage cities and the four imaginary cities that comprise it (Figure 3, Figure 4, Figure5, Figure 6).

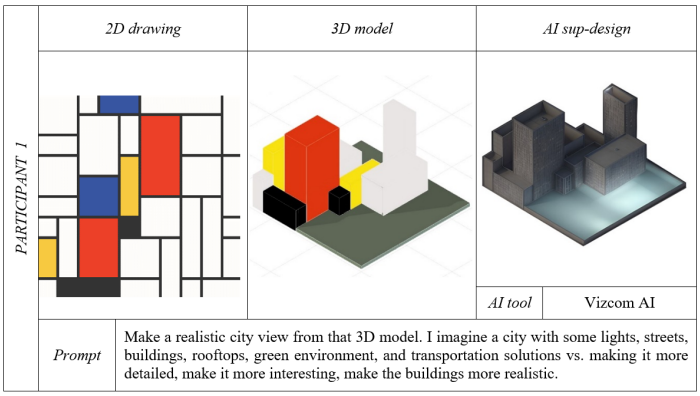


Figure 3. 2d, 3d, and AI visualization steps of Participant 1

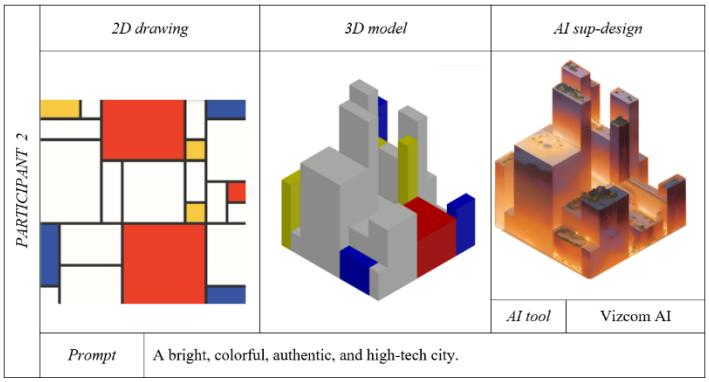


Figure 4. 2d, 3d, and AI visualization steps of Participant 2

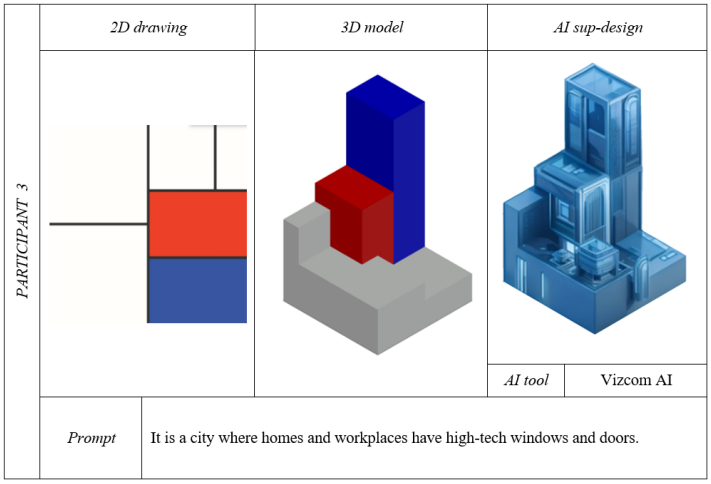


Figure 5. 2d, 3d, and AI visualization steps of Participant 3

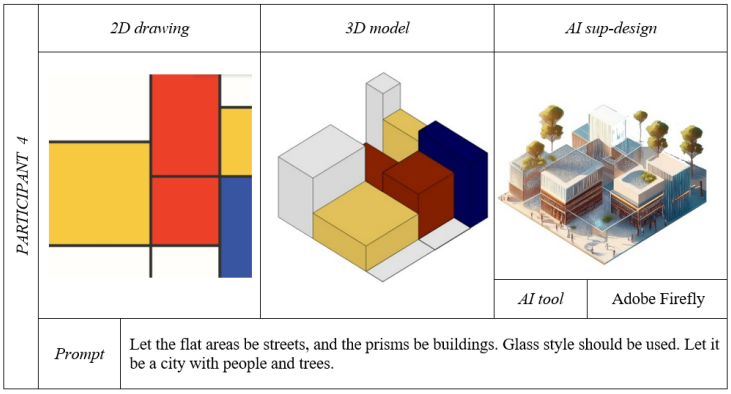


Figure 6. 2d, 3d, and AI visualization steps of Participant 4

Four students each developed distinct city parcels with unique conceptual and volumetric approaches, which were subsequently combined on isometric paper to form Collage City 1 (Figure 7). This assemblage allowed for flexible composition, enabling participants to explore narrative and spatial relationships without permanent attachment. A freehand orthographic drawing of the resulting collage was produced, emphasizing interpretive and narrative elements beyond the initial technical representation. This drawing was then used as a reference input for a generative AI tool, which re-visualized the collage city through a new narrative framework, independent of the original design characteristics.

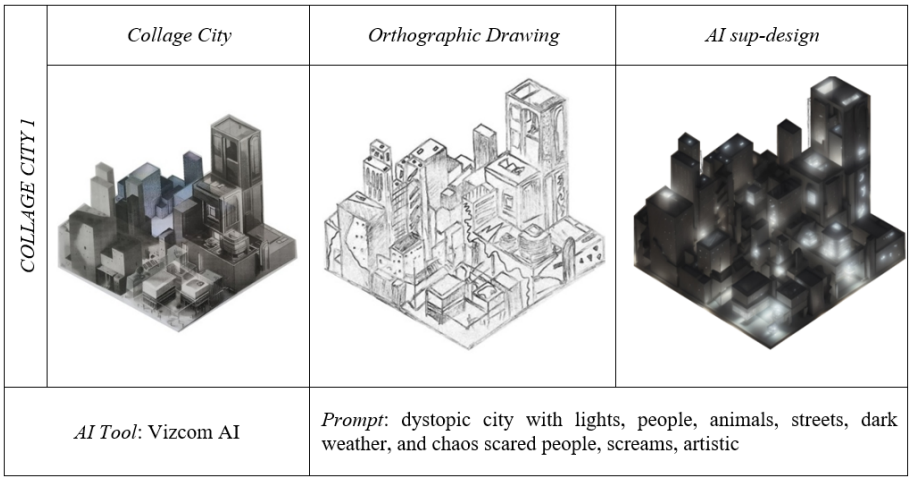


Figure 7. Production steps of collage city

Four students each developed distinct city parcels with unique conceptual and volumetric approaches, which were subsequently combined on isometric paper to form Collage City 1 (Figure 7). This assemblage allowed for flexible composition, enabling participants to explore narrative and spatial relationships without permanent attachment. A freehand orthographic drawing of the resulting collage was produced, emphasizing interpretive and narrative elements beyond the initial technical representation. This drawing was then used as a reference input for a generative AI tool, which re-visualized the collage city through a new narrative framework, independent of the original design characteristics.

4.1. THE RELATIONSHIP BETWEEN VISUAL AND TEXTUAL THINKING

Following the implementation phase, students were asked to reflect on the positive and negative experiences they encountered during the process and the factors influencing the final outcome. When questioned about the types of thinking—textual, visual, or both—they employed while working with artificial intelligence, the majority indicated that they engaged in both textual and visual modes.

The responses to the question, “Which textual, visual, and visual thinking options did you use in your visual productions with artificial intelligence?” are presented in (Figure 8).

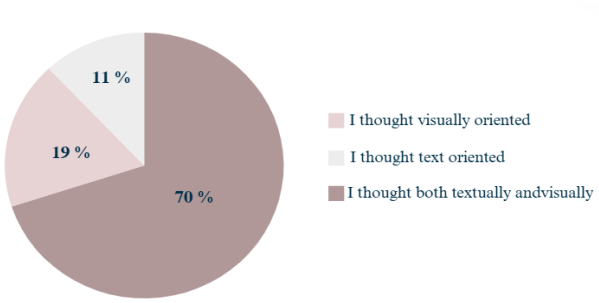


Figure 8. Students answer the following question: "Which textual, visual, and visual thinking options did you use in your visual productions with artificial intelligence?"

The responses to the question, "Were there instances where elements not mentioned in the text appeared in the images generated by artificial intelligence?" are presented in (Figure 9).

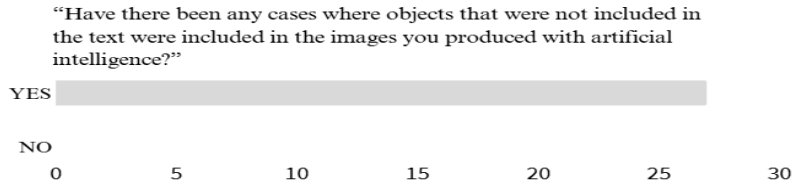


Figure 9. Students answer the following question: "Have there been any cases where objects not included in the text were included in the images you produced with artificial intelligence?"

An analysis of the responses to the question, "Has AI transformed the design decisions you made at the beginning of the study or influenced your way of thinking?" reveals that most students reported that AI significantly impacted their design thinking processes (Figure 10).

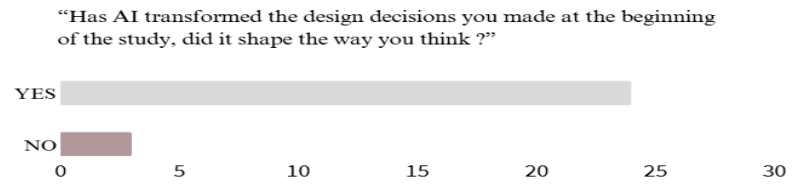


Figure 10. Students answer the question: "Has AI transformed the design decisions you made at the beginning of the study? Did it shape the way you think?"

Questions aimed at measuring the AI-designer relationship and its relationship to the level of creative production were asked to the participants and the answers were evaluated with a Likert scale (Figure 11).

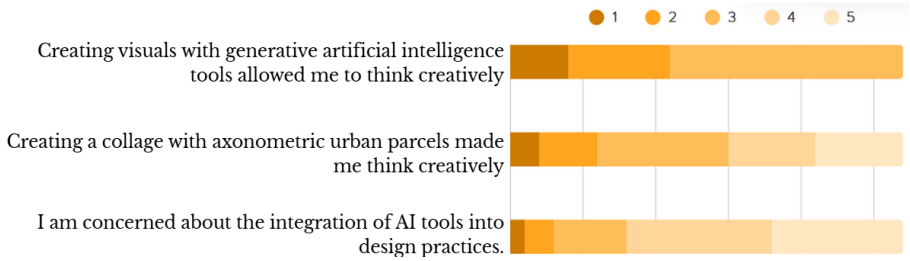


Figure 11. Distribution of participant responses obtained from the qualitative phase after the workshop on a Likert scale.

5. Discussion

In this study students created two-dimensional Mondrian-inspired paintings with varying degrees of linear and color intensity. These compositions informed the development of three-dimensional models, where paintings with denser linear elements produced more volumetric forms. Models were created using tools like SketchUp and AutoCAD, and axonometric images were generated. Students then provided reference images to AI tools such as Leonardo AI and Vizcom AI, using prompts to visualize city concepts. The resulting city images varied in their alignment with the prompts, influenced more by prompt quality than by prompt length or visual density. No direct correlation was found between linear/mass intensity and visual detail in the AI outputs.

This phase involved a sequential workflow—digital 2D painting, 3D modeling, AI-based city visualization, collage assembly, and re-visualization with narrative enhancement. The process highlighted interactions between digital and analog tools, AI collaboration, and the factors influencing creative thinking, which were further examined through survey responses.

A post-process survey explored the factors influencing students' creative thinking during the workshop and the impact of AI on their thinking. Most students expressed that they were thinking textually and visually, and that the AI tool influenced their creative thinking process. Furthermore, all students noted that not all concepts presented in the prompt were reflected in the visual output. This response supports the idea that AI output at this stage is unsuitable for unquestioning acceptance of the final design product.

5.1. PEDAGOGICAL IMPLICATIONS ON CREATIVITY, REPRESENTATION, AND PRODUCTIVITY

Architecture, a single undergraduate design department, measured pre-process relationships and experiences with AI through surveys conducted before and after the workshop. During the process, it was observed that AI can be used as a pedagogical tool that supports designers through effective communication. The design program generally has a positive approach, having had various experiences with AI before the process. However, the process, which is built on developing existing analog and digital methods used in design and representation with AI, and managing the solutions within this process, progresses under the designer's control in dialogue with AI, which in turn transforms with AI feedback to the designer. The study's focus on structuring AI contributions and transformations throughout the workshop environment, which incorporates an AI-enhanced "learning by doing" experience, where the designer can observe and participate repetitively, was among the key elements of the study.

5.2. HOW AI “BACKTALKS” TO THE DESIGNER

GenAI tools, by their very principle of operation, are generative algorithms that aim to reproduce visual elements in an existing data pool by referencing the visual and textual inputs provided. Each unique output produced by participants during the workshop constitutes unique input for the AI and becomes a new element contributing to this data pool. While this step of the participant-AI collaboration feeds the AI, the visual output produced by the AI serves as input for the participant's next step. The new narrative added to the visual by the AI via a prompt also forms the process by which the AI feeds the participant. The workshop, which is the subject of this study, is designed around a repeatable method where these sequential conversations follow one another and are supported by various analog/digital tools.

This back-and-forth interaction is consistent with Goldschmidt's (2003) concept of the "backtalk" of sketches, in which designers converse thoughtfully with their own representations. In a similar vein, Tong et al. (2023) show how AI can function as a new sketching mode that lets students switch between their own visual outputs and AI-generated ones in ways that encourage original thought. Accordingly, Koçer and Alaçam (2021) demonstrate how computational decoding of Mondrian compositions turns representation into a data-driven procedure, emphasizing how the design workflow can benefit from iterative engagement with one's own representational traces.

6. Conclusion

As this study shows, a cyclical, interactive, multilayered representational process that blends analog and digital methodologies can be fostered by incorporating Generative Artificial Intelligence (GenAI) tools into architectural design education. The analog–AI cyclical production model proposed in the study is positioned as a pedagogically innovative approach with high application potential, especially in the context of basic design studios. The experimental workshop demonstrated that GenAI can improve students' textual and visual thinking abilities, stimulate creative inquiry, and promote thoughtful decision-making when utilized as a participatory design partner instead of a deterministic generator.

The results show that students actively use both textual and visual thinking, and that the iterative conversation between human input and AI output influences the development of design concepts. Although AI-generated visuals frequently introduce unexpected elements not specified in the prompts, these differences are viewed as opportunities for reinterpretation rather than limitations. By allowing participants to move between individual expression, group authorship, and emergent narratives, the collaborative creation of "collage cities" further demonstrated the educational potential of hybrid workflows.

More significantly, the findings demonstrate the helpful potential of GenAI tools—they are catalysts for diverse representation and alternative viewpoints rather than instruments that can take the place of human creativity. Constraints like the number of participants, workshop duration, and contextual environments limit the ability to determine effective criteria in the visual-textual thinking stages, even though the suggested cyclical model is replicable. The two-day workshop made it challenging to observe the AI-assisted production process, which facilitates quick production and other productive conversations and interactions throughout the process. Changes to these parameters may result in different educational outcomes, proving that a replicable study's scalability and adaptability are essential for broader use.

Furthermore, the participation profile of participants from the same educational background and field provides benefits such as harmonious group work and familiarity with the workshop environment. It is expected that carrying out a similar study with participants from various fields and educational backgrounds could improve the results and produce distinct conclusions about the potential of AI tools.

Future studies are advised to look into the long-term impacts of GenAI-enabled workflows on design thinking, analyze applications in various cultural contexts and educational levels, and evaluate the moral implications

of incorporating AI into creative education. Additionally, research comparing AI-enabled and non-AI-enabled design processes may shed light on the various creative and cognitive pathways that these hybrid approaches support.

This study was conducted only with first-year students, and the impact of GenAI in advanced design studios should be evaluated more comprehensively in future studies. Furthermore, the integration of GenAI tools into educational processes raises ethical issues such as student ownership of production, copyright, and the valuation of creativity. Further research is needed on this topic.

To better understand the impact of the workshop, student outcomes were examined against three indicator criteria: creativity, representational diversity, and narrative coherence. While these criteria were applied descriptively rather than based on a formal assessment criterion, they provided a vantage point from which to observe progress across stages. For example, students who initially relied on literal translation into visuals later demonstrated an expansion of their representational strategies by experimenting with collage-based reinterpretations. Future studies are planned to include criterion-based assessments and comparative control groups to enhance methodological rigor.

The purpose of this exploratory project is to demonstrate how first-year students interact with GenAI in hybrid workflows, not to generalize findings. The data suggests both conflicts and creative opportunities—a number of students stated that AI limited rather than enhanced their thoughts. These differing opinions emphasize how crucial it is to frame GenAI as an educational experiment rather than a panacea. To achieve wider validity, future research should incorporate cross-cohort comparisons, longer-term studies, and rubric-based evaluations.

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PEDAGOGICAL INNOVATIONS FOR INTEGRATING CIRCULAR ECONOMY PRINCIPLES IN BUILT ENVIRONMENT HIGHER AND FURTHER EDUCATION

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Abstract. The built environment accounts for a significant share of Europe's carbon emissions, energy consumption, virgin material use, and waste generation, positioning it as a critical sector for advancing the circular economy (CE). This paper presents a practice-based pedagogical case study within the Interreg Circular Building Trust project, which aims to integrate CE principles into higher and further education for the built environment. The study examines the ROAM project, in which students from Hanze University and Alfa College participated in distinct phases of a real-world circular economy project, including surveying donor buildings, developing material passports, designing with reclaimed materials, and prefabricating and assembling the final structure. The project achieved a reuse rate of 90% for the pavilion. Findings indicate that competency-focused engagement can develop critical CE skills such as material auditing, design for disassembly, adaptive design, and collaborative construction, while also fostering industry–education partnerships. The outcomes informed the development of the Netherlands national curriculum toolbox to embed CE in higher education and professional training.

PEDAGOGICAL INNOVATIONS FOR INTEGRATING CIRCULAR ECONOMY PRINCIPLES IN BUILT ENVIRONMENT HIGHER AND FURTHER EDUCATION

Keywords: *Circular economy, Built environment education, practice-based pedagogical case study, Pedagogy, Higher and further education.*

1. Introduction

The built environment is responsible for approximately 36% of carbon emissions in Europe, 40% of energy consumption, and over 50% of extracted virgin materials, as well as generating one third of total waste (European Commission, 2020). Historically, strategies to reduce the environmental impact have focused on lowering operational carbon through improved performance standards in new buildings and the retrofit of existing ones. However, addressing carbon operational alone is insufficient. Increasing attention is now directed towards embodied carbon, virgin material depletion, and waste generation, prompting the development of regulations and policies such as the EU Circular Economy Action Plan (Spani, 2020) and the revised Energy Performance of Buildings Directive (European Commission, 2024). The EPBD mandates the assessment and reporting of embodied carbon in new buildings, utilizing established standards such as EN 15978 and Level(s). Many European countries have also implemented regional initiatives; for example, the Netherlands has adopted the circular construction economy transition agenda for achieving a circular construction economy by 2050 (De circulaire Bouweconomie, 2019), while the UK's London Plan includes specific requirements for whole-life carbon assessments and circular economy statements in major developments (Greater London Authority, 2022).

The circular economy (CE) is increasingly recognized as a key framework for achieving sustainability in the built environment and understanding how CE principles can be effectively implemented has become a central theme in both academic and industry discourse. Numerous scholarly and industry initiatives have sought to demonstrate CE in practice. For example, Cheshire (2021) has developed a framework for the application of circular economy principles in the built environment around the concepts of "Building in layers", "Designing out of waste", "Designing for adaptability", "Designing for disassembly", and "selecting material". Eberhardt et al., (2022) have also conducted a literature review and categorized circular economy strategies in the built environment according to their level of application (building, component, material) and level of readiness. For a more industry-focused audience, the Architects Climate Action Network (ACAN), a coalition of professionals from architecture and related built environment sectors has developed an 11-part

webinar series providing practical guidance on implementing circular economy principles across all stages of a building's lifecycle (ACAN, 2021). Another important dimension is how circular economy principles are taught, whether to industry professionals or in higher education. Several studies actively encourage curriculum reform and pedagogical innovation in this area (Renfors, 2024). However very few focuses on Design–Build pedagogical approach. Design–Build Pedagogy is a hands-on teaching approach in architecture, engineering, and construction education where students are involved in both the design and the physical construction of a project, often for real clients or communities (Verderber et al., 2019)

This paper is positioned within this educational and pedagogical strand of research. It forms part of the Interreg Circular Building Trust project and aims to develop an innovative, practice-based pedagogical approach for teaching circular economy in built environment higher education.

2. Literature review

The integration of circular economy principles in the built environment curriculum has gained traction recently. Given the significant carbon footprint of the built environment, higher education institutions (HEIs) have a major role to play in reducing those emissions by equipping students with the competencies required to implement circular economy strategies. HEIs further contribute to transitioning to a circular economy by collaborating with industry, assisting policymakers, supporting community engagement projects, linking with international CE networks, and promoting an inclusive CE discourse (Salas et al., 2021). Moreover, across Europe, particularly following the adoption of circular economy action plans (Spani, 2020), many governments are actively promoting the implementation of circular economy principles within the built environment. As a result, professional bodies and built environment organisations increasingly expect academia to fully integrate circular economy as a core component of higher education curricula.

Many studies have examined the integration of circular economy principles in higher education institutions; however, few investigations have focused specifically on built environment courses. This review explores key studies and educational models that have addressed the topic of integrating circular economy principles in higher education in the built environment.

One stream of research has focused primarily on developing new content, either by updating existing courses or by designing entirely new ones, to

incorporate circular economy principles such as material reuse, life cycle thinking, and resource efficiency. Sanchez et al., (2020) analyzed and documented the redesign of an undergraduate construction management course in Mexico in order to integrate CE principles as a way to develop sustainable development competencies in students. The emphasis of this study is on adapting and enriching existing course content, rather than undertaking a fundamental transformation of the curriculum delivery model. The integration of circular economy principles into the undergraduate construction management course resulted in a 16% revision of the course content, aligning it with sustainable development competencies. The redesigned syllabus introduced concepts such as life cycle assessment, closed-loop supply chains, and circular business models in the context of CE. It also emphasized emerging practices like adaptive reuse, regenerative materials, and digital construction tools**.** Wrase et al., (2023) conducted a content analysis of 122 European university programs in real estate and related built environment fields, reviewing all course titles for keywords related to sustainability and circular economy. This quantified how extensively existing curricula address lifecycle sustainability topics versus circular economy specifics. The survey of European programs found that sustainability themes are relatively common in real estate education, but content on the circular economy is largely absent. Notably, the term "circular" appeared in only 2 out of 122 program descriptions across Europe, indicating that explicit CE principles have rarely been integrated into built environment degrees so far. The study proposes a new M.Sc. program as a model addressing this gap: it introduces a holistic approach covering circular design, facility management, and end-of-life strategies, aiming to equip graduates with the full spectrum of competencies (technical, processual, social, economic) for sustainability transformation.

Another stream of research has focused on developing pedagogical innovations for teaching circular economy principles in the built environment, moving beyond merely suggesting content additions or modifications to explore how these principles can be effectively delivered through transformative teaching methods. Wandl et al., (2019) investigated how CE principles can be effectively integrated into architecture and spatial design education using a situated learning approach. Their study aligned design teaching with a Horizon 2020 research project, providing students with a rich, real-world learning environment to explore challenges in CE. The student-led design experiments produced innovative outcomes that were positively received by external stakeholders, illustrating the practical value of their contributions. The authors argue that embedding CE into design education

requires more than the addition of new content it necessitates a fundamental pedagogical shift toward systems thinking, interdisciplinary collaboration, and engagement with real-world complexity. Scott & Seddiki (2025) explored the integration of circular economy principles into pedagogical teaching within the discipline of architectural technology in the UK. The authors sought to move beyond theoretical teaching by embedding CE within real-world design projects and reflective pedagogical strategies, encouraging students to define and apply CE concepts in context. This research differs from the studies in that students were consulted and included in defining what the circular economy meant to them. The research resulted in a structured definition of circular economy in architectural technology, organizing around six key design themes 'Design'; 'Material'; 'Construction'; 'Life Cycle'; 'Disassembly', and 'Biodiversity'. Attia et al., (2016) implemented an educational experiment in a third-year architectural engineering studio at the University of Liège, integrating regenerative design principles aligned with circular economy concepts. Incorporating circular economy principles through regenerative design was well received by students, resulting in measurable improvements in their sustainability knowledge, design skills, and pro-circular attitudes by the end of the studio. Attia et al. found that interactive, applied learning activities were most effective: topics taught via debates, hands-on exercises, and iterative design feedback showed the most significant and most lasting learning improvements. Conversely, content delivered only in lecture form saw less sustained impact. The authors recommend more application-focused and iterative learning (e.g. case-based projects, repeated reinforcement of key concepts) to ensure long-term retention of circular economy competencies.

The originality of this paper lies in its proposal of a practice-based approach to teaching the circular economy, which involves hands-on learning through the disassembly of an existing structure and the construction of a new one using recovered materials.

3. Methodology

This study employs a practice-based pedagogical case study methodology to explore how CE principles can be integrated into built environment education through experiential and real-world engagement. The research is situated within a live construction project, the ROAM Pavilion.

The project was delivered over two academic years and integrated into the curriculum in two ways: as a part of a module and as an optional placement

opportunity. Participation varied across cohorts and institutions. Undergraduate students from Hanze University of Applied Sciences and further education students from Alfa College participated in the project at different stages, depending on their level, interests, and scheduling.

Data collected for this case study were drawn from diverse sources: project documentation (e.g. drawings, schedules, material passports), photographic records of construction activities, and educator observations collected during the process. The emphasis is on the authenticity of the learning context and the alignment of each project phase with specific CE competencies.

This approach enables a rich understanding of how real-life building scenarios can serve as powerful teaching environments for CE education. Rather than generalising across participants, the methodology aims to illustrate how built environment students can acquire essential circular skills and knowledge through targeted involvement in discrete, meaningful phases of a project.

4. Case Study: The ROAM Project

This case study is a pavilion (see figure 1) that serves as a residency for artists commissioned through Campus Groningen, by Minerva Art Academy, an established institution of 228 years old that originated from Hanze University. The project is framed as a practice-based pedagogical model, highlighting how students engaged with circular economy principles through real-world design and construction tasks.



Figure 1. Case study building.

The project brought together two student groups: undergraduate students from Hanze University enrolled in the built environment programme, and further education students from Alfa College. While both groups participated in the disassembly and survey stages, Alfa College students focused more on the hands-on dismantling process, whereas Hanze students contributed to both disassembly and the subsequent phases of design and construction. This collaboration provided a rich interdisciplinary and inter-level learning environment, blending academic and technical expertise in a real-world context.

The ROAM project serves as a concrete example of a practice-based learning model for teaching circular economy in higher and further education. The project engaged architecture and construction students in a live construction task, with a budget of €50k and a strict delivery timeline. The project was overseen by the Hanze University facilities department, development and management, and was conducted with close collaboration with academic supervisors. The project was delivered under a compressed timeline of three academic semesters. The following phases structured the learning experience:

4.1. STEP 1: IDENTIFICATION OF DONOR BUILDINGS

Two buildings, one located on the premises of Hanze University (see Figure 2) and the other on the campus of Alfa College (see Figure 3), were selected as material donors. Scheduled for demolition, these buildings provided an ideal opportunity for urban mining: the harvesting of reusable components from existing structures. This phase introduced students to the importance of resource mapping and early-stage material assessment in the circular construction process.



Figure 2. Donor building *(Hanze University)*



Figure 3. Donor building *(Alfa College)*

4.2. STEP 2: SURVEY AND DISASSEMBLY

Students from both institutions collaborated with professionals to conduct on-site building surveys and participate in the safe disassembly of the donor buildings. Undergraduate students from Hanze University (Built Environment

programme) and further education students from Alfa College worked alongside contractors to document, remove, and sort reusable materials (see figure 4). This step provided students with the opportunity to audit existing structures to identify opportunities for reuse and recycling, with a focus on retaining materials at their highest value and minimising waste to landfill. After dismantling, students participated in sorting components, including timber, structural framing, and façade elements, evaluating each item for quality and suitability for reuse in the new design.



Figure 4. Reusable materials from donor buildings

4.3. STEP 3: INVENTORY AND MATERIAL PASSPORT DEVELOPMENT

Students recorded the usable components through measurements, photographs, and quality assessments. These records were compiled into material passports, which served as critical inputs for the design phase (see figure 5). Through this process, students developed practical knowledge of circular economy tools, including traceability, condition grading, and reuse classification. This phase emphasised the importance of documenting and tracking material flows to enable circular decision-making in future construction projects. They also developed an understanding of how such documentation facilitates informed decision-making, helping designers prioritise high-value reuse, select appropriate applications, and plan for future disassembly and recycling. By embedding material passports early in the workflow, the project highlighted their role as a bridge between demolition, design, and construction, ensuring that recovered materials could be effectively reintegrated into the new building while maximising resource efficiency. However, the data collected by students during the project was somewhat unstructured, revealing the need for clear templates and consistent data entry protocols. As a direct learning outcome, the project team recommends that material passports should include standardised data fields covering: component description and dimensions, material composition and origin, condition and residual lifespan, previous applications and installation details, potential reuse scenarios and limitations, disassembly and handling instructions, circularity assessment, and residual value. These recommendations will be incorporated into the Netherlands national curriculum design toolbox (NKBB, 2025) and the Circular Trust Building (CTB) project framework.

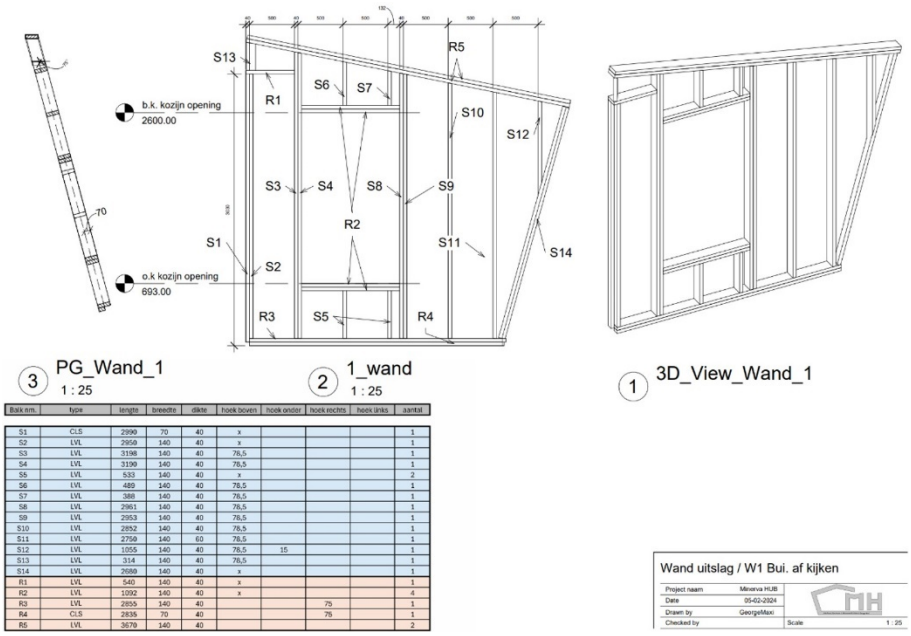


Figure 5. Material passports

4.4. STEP 4: DESIGN DEVELOPMENT

Hanze University undergraduate students led the design development process, using the material inventory as the primary input. The pavilion design was developed using BIM software (see figure 6) and guided by circular economy principles such as modularity, adaptability, and the integration of reclaimed and bio-based materials. Students were challenged to design only what was necessary, based on the actual availability of materials, fostering skills in design sufficiency and material optimisation. Additionally, design for

disassembly (see Figure 7) was embedded as a core strategy to facilitate the future reuse of the structure's components.



Balk nm.	type	lengte	breedte	dikte	hoek boven	hoek onder	hoek rechts	hoek links	aantal
S1	CLS	2990	70	40	x				1
S2	LVL	2958	140	40	x				1
S3	LVL	3198	140	40	78,5				1
S4	LVL	3199	140	40	78,5				1
S5	LVL	533	140	40	x				2
S6	LVL	489	140	40	78,5				1
S7	LVL	388	140	40	78,5				1
S8	LVL	2961	140	40	78,5				1
S9	LVL	2953	140	40	78,5				1
S10	LVL	2852	140	40	78,5				1
S11	LVL	2759	140	60	78,5				1
S12	LVL	1055	140	40	78,5	15			1
S13	LVL	314	140	40	78,5				1
S14	LVL	2680	140	40	x				1
R1	LVL	540	140	40	x				1
R2	LVL	1092	140	40	x				4
R3	LVL	2855	140	40			75		1
R4	CLS	2835	70	40			75		1
R5	LVL	3670	140	40					2

Figure 6. Drawings using BIM

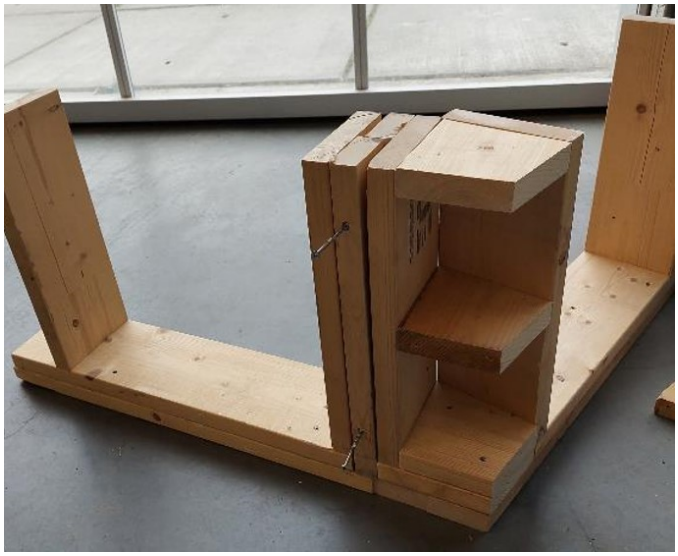


Figure 7. Design for Disassembly

4.5. STEP 5: PREFABRICATION IN A CONTROLLED ENVIRONMENT

Prefabrication of the pavilion was carried out in a controlled indoor setting "BuilinG" (see figure 8), a former volleyball structure that was itself dismantled from another location and re-erected at Hanze University. Alfa College students led the fabrication of modules, supported by university students and industry professionals. This phase allowed for greater precision, safer working conditions, and the testing of construction methods prior to site assembly.

Students gained practical construction skills, understood assembly sequencing, and witnessed the tangible benefits of prefabrication—including increased efficiency, enhanced safety, and improved quality control.

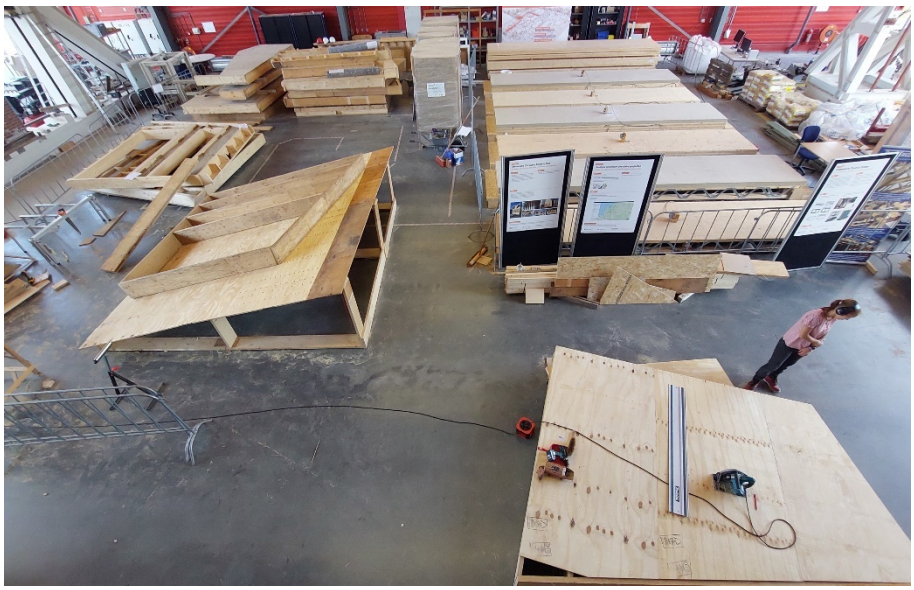


Figure 8. Prefabrication in a controlled environment

4.6. STEP 6: ON-SITE ASSEMBLY

The final pavilion was assembled on-site (see figure 9) by a professional construction company in collaboration with students. This final phase exposed students to real-world constraints, including site logistics, weather conditions, and sequencing challenges. They applied circular economy principles in a professional context, integrating prefabricated elements and adapting designs where necessary. Students learned to coordinate with contractors, troubleshoot practical issues, and deliver a structure that reflected CE

strategies such as high-value reuse, modular assembly, and disassembly readiness.



Figure 9. On-site assembly

5. Discussion

This case study illustrates the substantial potential of circular economy strategies when applied to real-world construction projects. Through the selective dismantling and reuse of materials from two donor buildings, approximately 60% of the original structures were successfully recovered for reuse. In the new pavilion, 90% of the materials were reclaimed, with only 10% sourced as new products. These figures far exceed the 25% recycled content target set by the Circular Trust Building (CTB) initiative, underscoring the capacity for ambitious circular outcomes when projects are supported by careful planning, effective material management, and collaborative stakeholder engagement. Future opportunities to integrate artificial intelligence for material matching and optimisation could further increase reuse rates, maximising the value retained in construction resources. Beyond the quantitative achievements, the project has informed the development of the Netherlands' national curriculum design toolbox aimed at embedding circular economy principles in higher education and professional training. One identified gap was the lack of student familiarity with material passports at the project's outset; this was directly addressed in the curriculum through dedicated training in documenting, classifying, and tracking materials

for reuse. The complementary roles of Alfa College, leading the construction phase, and Hanze University, leading the design phase, demonstrated the benefits of inter-level, interdisciplinary collaboration. This division of responsibilities has been incorporated into the curriculum framework to mirror real-world practice.

From a student's perspective, the project offered tangible benefits that extended well beyond classroom learning. Informal feedback indicated that students valued the opportunity to work on a live project with real constraints, clients, and deliverables, describing it as a "bridge" between theory and professional practice. Many highlighted the value of developing practical skills such as material auditing, BIM-based adaptive design, and on-site assembly sequencing. Others emphasised how working alongside industry professionals increased their confidence in their technical abilities and exposed them to career-relevant networks. Students also reported that seeing the direct environmental impact of their work through measurable material reuse was both motivating and transformative in their understanding of sustainability.

Engagement from professional companies in this pilot project further strengthened the platform for future industry–education collaboration, a fundamental asset that applied universities already integrate into their operations as an impactful tool. Their participation not only contributed to the successful delivery of the pavilion but also built confidence within these organisations to pursue circular economy strategies in subsequent projects.

Three researchers and educators from the project team have since integrated these insights into the national higher education framework. Beginning in September 2025, Hanze University will deliver a new 5-credit module on circular economy in construction to students from multiple programmes, including real estate and built environment disciplines. Similar modules will be introduced across other higher and further education institutions in the Netherlands, ensuring widespread access to CE learning. The approach tested in this case, which was delivered to different student cohorts over two years and offered both as a module and as a placement, provides a flexible model for integration into diverse curricula.

Finally, the project has generated specific recommendations for the use of building passports, including embedding them early in the design process, standardising documentation formats, and integrating them into digital tools to support future reuse planning. These recommendations will guide both the educational application and the professional adoption of circular economy practices, bridging the gap between academic learning and industry implementation.

6. Conclusion

This research highlights the value of a practice-based pedagogical model for integrating circular economy (CE) principles into education for the built environment. The primary objective was to investigate how hands-on engagement in a real-world design–build project can develop students' competencies in material reuse, adaptive design, and collaborative construction. Through the ROAM project, students participated in various phases—from surveying donor buildings and developing material passports to designing, prefabricating, and assembling a new pavilion achieving a reuse rate far above the industry target set by the Circular Trust Building initiative.

The findings demonstrate that with adequate planning and collaboration between education providers and industry, CE targets can be exceeded, while simultaneously providing students with highly relevant technical skills, professional networks, and environmental awareness. The project also informed the development of a national curriculum toolbox to integrate CE learning into higher education and professional upskilling.

Future research should examine the long-term impact of such experiential learning on graduates' professional practice, investigate ways to integrate emerging technologies such as AI into material management, and test the transferability of this teaching model across different educational and cultural contexts.

Acknowledgment:

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VII. ENERGY & SUSTAINABILITY IN ARCHITECTURE

COMPARATIVE ANALYSIS OF THICKNESS AND SURFACE TOPOGRAPHY IN MYCELIUM ACOUSTIC PANELS

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Abstract. Urban growth and human activity have contributed to increasing noise pollution levels as one of the most significant environmental sources of stress for people living in cities. Despite affecting a large portion of global population, this issue is not sufficiently addressed. Acoustic sound panels as a mitigation strategy are often made from porous synthetic materials that have environmental consequences and health concerns. Thus, we need to focus on alternative materials that enhance sustainability. As a low-impact approach, mycelium-based composites (MBC) offer an alternative to traditional materials. Mycelium-based composites are biomaterials sourced from fungi that have potential as sound-absorbing materials. Yet, there is limited knowledge about how variations in surface or the panel thickness affect their performance. Thus, this research proposed a simulation-based workflow to investigate how panel surface topography and material thickness affect the reverberation time (RT60) of MBC panels as the core acoustic factor. Pachyderm software is used to simulate four surface configurations with three thickness levels. Results demonstrated that surface design had a more remarkable effect on reverberation time reduction.

Keywords: *Acoustic performance, Mycelium-based composites (MBC), Panel thickness, Reverberation time (RT60), Surface topography.*

1. Introduction

As urban areas expand and become denser, both the number of residents and noise sources—such as traffic, construction, air travel, and recreational activities—increase. Urban noise pollution refers to sound levels that exceed acceptable limits and pose risks to public health (United Nations, 1997). An

increasing body of research confirms that urban noise pollution contributes to both immediate and long-term health issues, including cardiovascular disease, cognitive impairment, sleep disturbances, tinnitus, and heightened annoyance (Fritschi et al., 2011). As sound is a dynamic component of the urban landscape, improving acoustic environments is essential not only for enhancing overall urban quality but also for reflecting the unique identity of a city (Jia, Ma and Kang, 2020).

Noise can be mitigated by eliminating noise sources or by employing soundproofing materials that diminish the energy of acoustic waves. Thus, using acoustic panels is a practical strategy to deal with urban noise. Yet, acoustic sound panels are often made from porous synthetic materials, like rock wool, glass wool, polyurethane, or polyester, which contribute to the release of greenhouse gas emissions and landfill debris (Arenas and Sakagami, 2020). As the knowledge of the environmental consequences and health concerns linked to these materials has increased, the focus on natural materials has been highlighted. Recently, a multitude of studies on acoustic materials derived from organic materials have been published. In particular, biomaterials can be used as material substitutes to improve circularity and sustainability. As a low-impact approach, mycelium-based composites offer an alternative to traditional materials (Walter and Gürsoy, 2022). Mycelium-based composites are biomaterials sourced from fungi that have potential as sound-absorbing materials (Pelletier et al., 2018). They are produced when mycelium, the vegetative root-like structure of a fungus, is cultivated on organic substrates.

An important factor affecting the acoustic performance of these panels is their surface topography. While previous studies have proved that rough and uneven surfaces can improve the sound absorption by scattering the sound waves (Walter and Gürsoy, 2022), there is limited knowledge about the exact sound absorption properties of natural materials, particularly regarding how variations in surface topography affect their performance. Also, it is vital to use the minimum amount of material to reach an acceptable level of acoustic performance. Hence, finding an optimized surface topography and panel thickness in which the sound absorption of mycelium-based composites is at its highest would be a critical design parameter. Hence, in this paper, we aim to identify the most efficient thickness and the surface topography for an MBC panel to reach its maximum acoustic performance. To do this, we have benefitted from a simulation-based workflow in Pachyderm software to compare the panels' acoustics.

2. Background

2.1. URBAN NOISE MITIGATION STRATEGIES

Urban settings usually demand noise mitigation strategies that are quick to deploy and easily removable once the noise source is no longer active (Iglesias-Merchan et al., 2021). Both active and passive strategies are used to prevent and mitigate noise pollution, and they range from structural barriers and vegetative systems to sound absorbers. The typical method to control sound fields is to use acoustic absorbers and diffusers on the wall, ground and ceiling of a space. Acoustic materials are essential in fields of architecture and environmental noise control, as their ability to absorb and insulate sound directly affects the acoustic quality of a space (Jones et al., 2020). Among these acoustic absorbers, noise barriers are effective in decreasing environmental noise by blocking sound transmission paths.

While high noise barriers that exceed 1.8 meters in height, are commonly implemented to mitigate sound propagation, low noise barriers, with an approximate height of 1 meter, represent a relatively recent approach designed for use in urban settings (Defrance et al., 2015). High noise screens are made of different materials, such as glass, concrete, and wood. They mainly work based on obstructing the direct path of sound waves. How much noise these barriers can block is influenced by various factors, with height being the most critical one (HOSANNA, 2013). Contrarily, low noise barriers are installed very close to the noise source to compensate their short height. Studies have proved that this approach can yield significant noise reductions in certain circumstances (Defrance et al., 2015). Still, further development is needed to enhance their practical implementation.

Besides, buildings can serve as effective barriers, creating a "sound shadow" zone that experiences reduced noise levels when deliberately positioned relative to a noise source. Given their typical height advantage over conventional noise screens, buildings can significantly attenuate noise. But, the degree of noise reduction is influenced by various architectural factors, including the building's overall geometry—such as its height, length, and roof configuration and the materials employed in its construction (Hellström et al., 2013).

Additionally, vegetation has traditionally been proposed as a passive noise mitigation strategy in urban environments, often implemented in the form of vegetative belts, green buffers, green roofs and walls that have gained popularity in urban settings due to their wide-ranging environmental benefits (Veisten et al., 2012). The environmental advantages and aesthetic appeal of

vegetative noise barriers have led to their widespread use. Various aspects of vegetation thickness and leaf density affect how well they perform. Additionally, vegetation-associated soil surfaces absorb sound more effectively than hardscape elements like glass or concrete (HOSANNA, 2013).

2.2. ACOUSTIC PERFORMANCE OF SOUND ABSORBERS

The acoustic performance of a sound absorber is mainly defined by the material's physical properties and its internal structure (Laxmi, Thakre and Vijay, 2022). The spreading direction of the sound waves is affected by the texture of the surface. While smooth surfaces produce specular reflections, where parallel incoming sound waves are reflected uniformly (Barron, 2010), surface irregularities influence the spatial and temporal characteristics of the sound field, particularly when the distance between the sound source and receiver increases or when the line-of-sight is obstructed. The impact of these irregularities changes based on the frequency of the sound. At a broader scale, the global geometry of a surface—whether flat, concave, or convex—affects how incident sound waves travel, leading to their deviation, concentration, or dispersion. By changing the geometry or material characteristics of the surfaces, the acoustics can be controlled (Peters, 2009).

2.3. MYCELIUM-BASED COMPOSITES (MBC) IN ACOUSTIC DESIGN

Acoustic materials are essential in fields of architecture and environmental noise control. The reason is their ability to absorb and block sound that affects the quality of a space. A wide variety of natural materials serve as effective noise absorbers. These materials exhibit key acoustic properties, including frequency responsiveness, structural composition, thickness, surface finish, and maintenance requirements. The materials with high absorption capabilities usually are porous (Arenas and Crocker, 2010). The pores allow the sound waves to penetrate and dissipate within the material structure.

Recently, there is an increasing interest in sustainable and eco-friendly acoustic materials (Jones et al., 2020). Mycelium-based composites have shown to be effective in both thermal insulation and sound absorption. Their acoustic performance is mainly because of their porous and fibrous microstructure (Mohseni et al., 2025). Their sound absorption performance is primarily governed by thermal conductivity and viscothermal losses, enabling effective broadband absorption (Arenas and Crocker, 2010).

These composites are formed by cultivating the mycelium on organic substrates (Manan et al., 2021). By growing fungi inside a fibrous network, mycelium can act as a natural binder to attach these materials and create a sustainable and sound-absorbing material. As the mycelium grows, it forms a dense, three-dimensional network that binds the fibers together, creating a lightweight, rigid composite. This process requires no additional energy input and generates no waste (Jones et al., 2020). Mycelial threads infiltrate the substrate during growth, eventually forming a cohesive, solid structure. After the growth phase, the material is kiln-dried to terminate fungal activity. The result of this process is a porous surface that enhances sound absorption. In addition to being environmentally friendly and resource-efficient, these mycelium-based sound absorbers hold further potential: their structural solidity allows for the development of thinner, more compact acoustic solutions in future applications. Also, they preserve a natural and visually appealing aesthetic.

Companies working in the field of MBC highlight that mycelium acoustic panels support clearer communication by lowering noise levels and increasing speech intelligibility. They are fully biodegradable that allows them to break down naturally at the end of their service life, thereby minimizing waste and reducing environmental impact. Mycelium-based materials exhibit fire resistance and are free from harmful volatile organic compounds (VOCs), making them both safe for occupants and environmentally sustainable. Their inherent versatility enables their use across a variety of applications, with customization options available in terms of form, dimensions, coloration, and surface texture to accommodate specific design intentions.

3. Methodology

This research focuses on how important are the properties of surfaces in the acoustic calculations. The aim is to identify the most efficient thickness and the surface topography for an MBC panel to reach its maximum acoustic performance. Hence, a simulation-based workflow in Pachyderm software is used to investigate how panel surface topography and material thickness affect the reverberation time (RT60) of MBC panels as the core acoustic factor. Reverberation time refers to the duration required for sound to decay by 60 dB after the source has stopped. Measured in seconds, RT can be obtained through direct measurement, calculation, or simulations (Jaramillo and Steel, 2014). The reverberation time calculations were performed using the Sabine equation in six standard frequency bands of 125 to 4000 Hz. The Sabine equation (1) is used because of its popularity in acoustic calculations.

(1)

$$RT = 0{,}161\frac{V}{\sum A}$$

$$\sum A = ((\alpha_1 \cdot S_1 + \alpha_2 \cdot S_2 + \cdots + \alpha_n \cdot S_n) + x.V)$$

RT= reverberation time of a room (sec).

V= room volume (m^3)

∑A= total absorption in the room (metric Sabine)

α = sound absorption coefficients (For different surface based on material properties)

S= different room surfaces (m^2)

x = air absorption coefficient

3.1. GEOMETRY PARAMETRIZATION

In the first step, this research adopts a parametric design methodology through the use of Grasshopper, a visual programming environment integrated with Rhino, to generate an irregular surface topography for the acoustic panel. The form-finding of the surface is not based on a site-specific noise data. Instead, we focused on targeting lower frequency bands and prioritizing absorption over scattering. The reason for focusing on low frequency bands was the future step of this research to use these panels in outdoor settings to reduce urban noise. While mid and high frequencies of 500-4000 Hz in an urban setting refer to human voice, children playing, bicycle, footsteps of hard surfaces, bird chirping, and dog barking, the most annoying noises of traffic, truck engines, construction equipment, and wind rumble are in the low frequencies of 125 to 500 Hz. Thus, we generated concave shallow and deep parts (varying between 3-10 cm) after creating a Voronoi tessellation to break geometric regularity and prevent repetitive echo patterns. The depth transitions of the form was done by using a graph mapper. The panel dimensions are fixed at 40 X 40 cm, to be large eough to impacts acoustics, and compact enough for efficient mold production. The Grasshopper definition and the surface topography are shown in Figure 1.

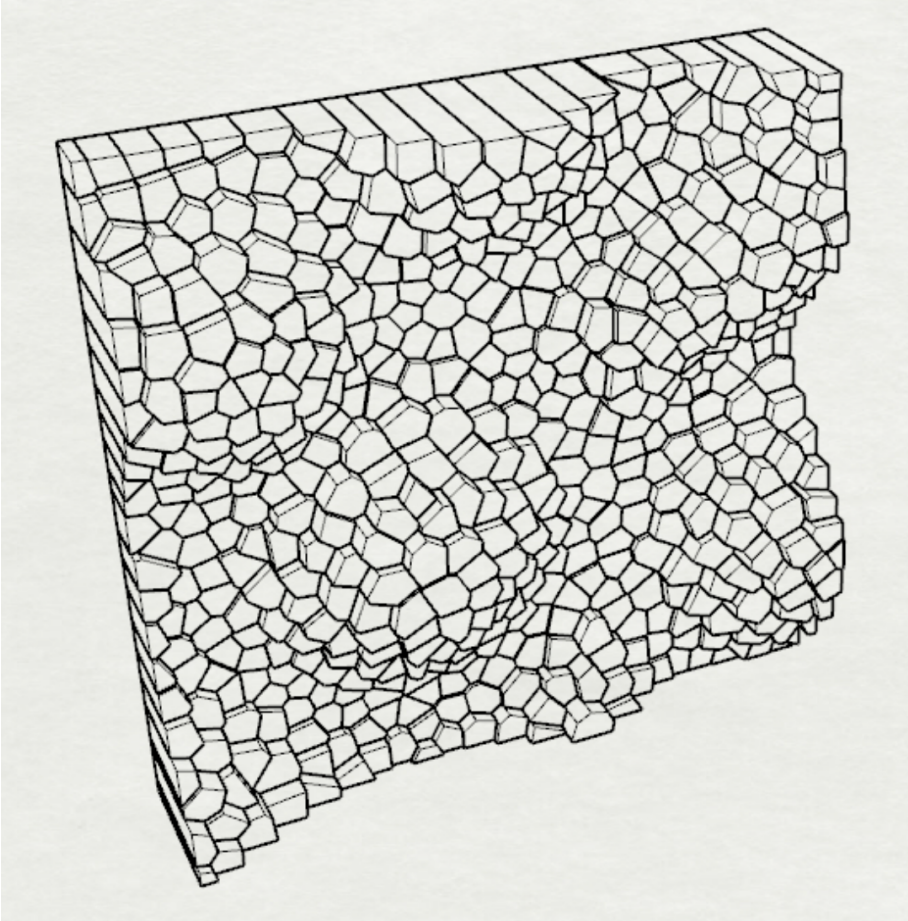


Figure 1. Form-finding of the panel surface in Grasshopper

3.2. SIMULATION SETUP

After that, explore the relationship between material thickness and acoustic performance of flat MBC panels and identify the most efficient thickness for reducing reverberation time, we modeled panels with three thickness levels of 3 cm, 6.5 cm, and 10 cm, representing low, medium, and high material use. They all have the same dimensions of 40X40 cm. And to explore the impact of surface geometry on the acoustic performance, we generated different MBC panel geometries of concave, convex, and the custom-designed surface (Figure 2). This was the step before simulation for a comparative evaluation of whether thickness or surface complexity has a more significant effect on reverberation time.

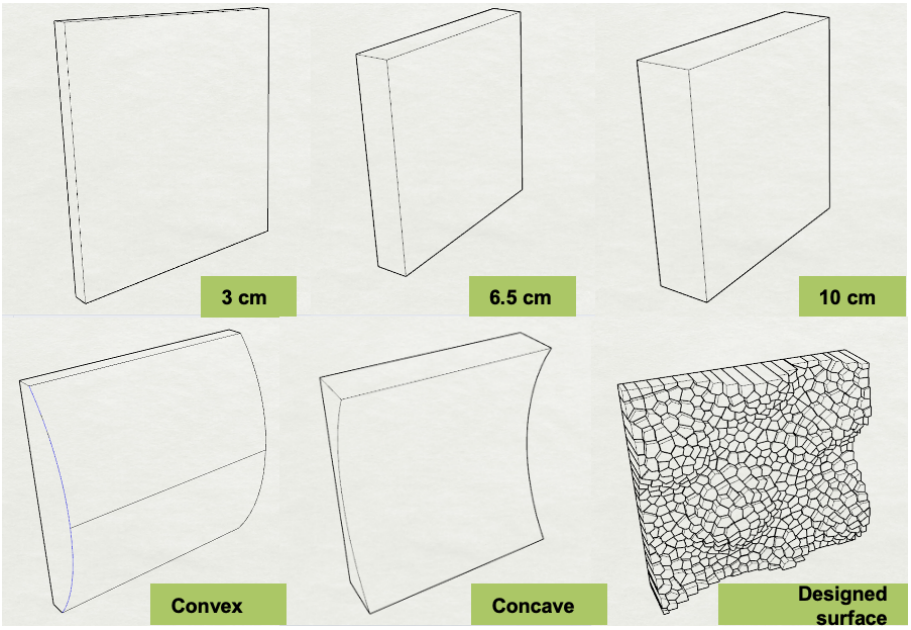


Figure 2. MBC panels with different thickness and surface configurations

Finally, the simulation is conducted in the Pachyderm software inside a standard test room setup of 5 × 4 × 3 m, V = 60 m³ with reflective floor, ceiling, and plaster-painted walls. The MBC acoustic panels are placed on two opposing walls in each test scenario. The materials of the surfaces were given absorption coefficients using Pachyderm's material editor and based on accepted research of (Cox and D'Antonio, 2009) and Walter and Gürsoy (2023). The absorption data were given percentage-based across octave bands.

In fact, most existing acoustic simulation tools are analysis-oriented and operate separately from the design environment, including those focused on environmental acoustics (Sakuma, Sakamoto and Otsuru, 2014). As a result, they offer limited support for iterative design processes. Pachyderm, a recently developed open-source tool, addresses this gap by enabling integrated acoustic simulation and sound propagation visualization within a 3D design environment. It operates as a ray tracing and image-source plugin for Rhinoceros–Grasshopper (van der Harten, 2013). The simulation emitted 1,000 rays from a geodesic source to capture early and late reflections, with a fixed receiver point used to evaluate reverberation behavior. The ray-tracing visualization inside the test room with MBC panels on two opposing walls are shown in Figure 3. The visualization demonstrates the rays emiting from a geodesic source on the closest walls and panels and scettering to reach the panels on the opposing wall.

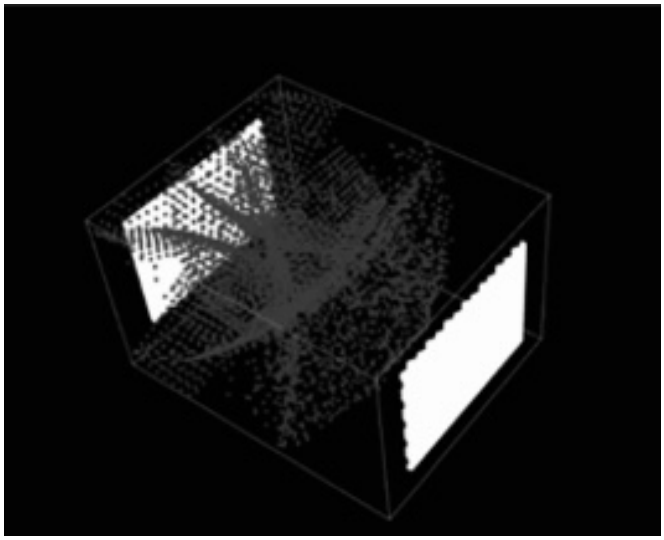


Figure 3. Ray Tracing Visualization in Pachyderm

In Pachyderm software, seven scenarios were simulated separately for the modeled MBC panels and an untreated test room with no acoustic MBC panels. The reverberation time was calculated for each of these cases among the six standard frequency bands between 125 and 4000 Hz. The findings of this simulation are compared to identify whether surface geometry or thickness of MBC panels more significantly influences acoustic performance.

4. Results

The findings of the research assessed the effectiveness of surface topography over the panel thickness in MBC acoustic panels. The reverberation time results of the Pachyderm simulation that are given in the Table 1 indicate that all MBC panels reduced reverberation time across all frequencies compared to the untreated room. In fact, the utreated room consistently had higher RT60 values that indicate prolonged echoes and poor speech intelligibility whereas lower Rt values suggest effective sound absorption.

TABLE 1. Reverberation time results of Pachyderm simulation for each scenario.

Test room properties	Frequencies, Hz					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Empty test room with no acoustic improvements	2.37	2.32	2.31	2.29	2.28	2.26
3cm thick flat MBC panels	1.96	1.92	1.92	1.94	1.94	1.9
6.5 cm thick flat MBC panels	1.97	1.93	2.1	2.01	2.03	1.99
10 cm thick flat MBC panels	2.02	1.95	1.99	1.98	1.99	1.95
3-10 cm convex MBC panels	2.09	2.05	1.99	1.98	1.95	1.93
3-10 cm concave MBC panels	1.84	1.83	1.76	1.77	1.77	1.74
3-10 cm designed surface MBC panels	1.7	1.77	1.9	1.99	2.03	1.96

With a more detailed look in the findings about the panel thickness, it is observed that 3 cm panels achieved significant RT reduction across all frequencies, while 6.5 cm panels performed worse at mid-frequencies, despite increased thickness. 10 cm panels on the other hand, did not outperform thinner ones and surprisingly underperformed at 125 Hz, challenging our typical assumptions. In other words, increasing thickness beyond 3 cm in flat MBC panels resulted in only modest improvements, and sometimes even less effective RT reduction. Overall, we realized that reverberation time is not linearly improved with thickness and thicker materials do not equal better acoustic performance. The line graph comparing the reverberation time of the panels with different thicknesses are shown in Figure 4.

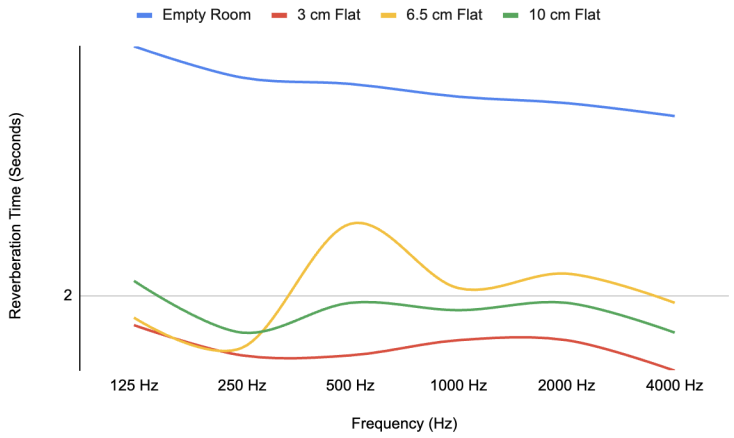


Figure 4. Reverberation time comparison for varying thicknesses (Pachyderm result)

Besides, when looking at the surface configurations of MBC panels (Figure 5), we notice that concave surfaces consistently performed best across all frequencies. Custom-designed surface that we did its form-finding to reach its optimum acoustic performance in the low frequencies, reached its goal. It had the lowest RT level at 125–250 Hz indicating strong low-frequency

absorption, but became less effective at higher bands. Besides, convex panels performed the worst among other panels, likely because of the sound reflection from their bulging surface.

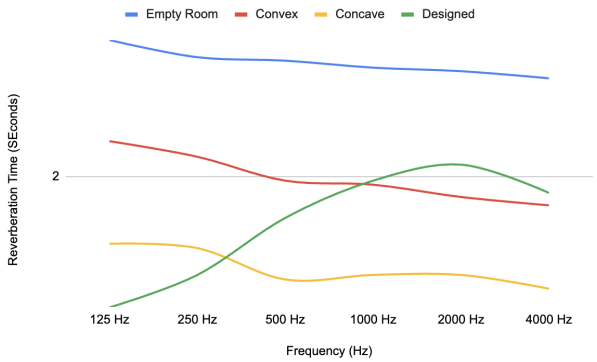


Figure 5. Reverberation time comparison for varying surfaces (Pachyderm result)

Finally, the comparison of all seven scenarios are shown in Figure 6. This visual analysis of the reverberation time curves confirms that surface geometry plays a more decisive role than panel thickness in shaping acoustic performance. The concave MBC panel demonstrated the most consistent broadband RT reduction, outperforming both flat and geometrically complex alternatives. Whereas, the designed surface topography served its initial purpose of highest absorption in the lowest frequencies. This implies that curved inward geometries are particularly effective at trapping and diffusing energy. The line graph reveals that the surface topography plays a critical role in the acoustic behavior of the MBC panel compared to its thickness.

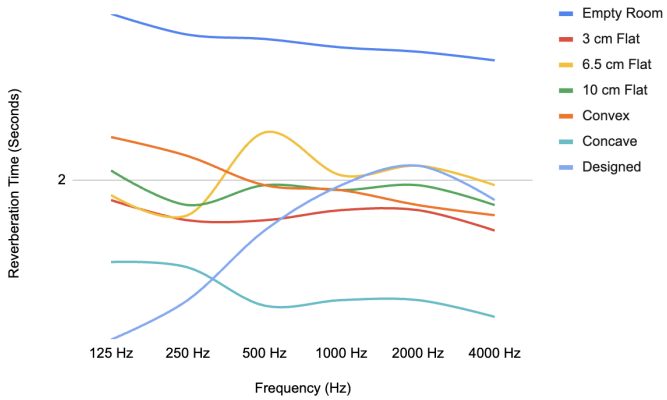


Figure 6. Reverberation time comparison for all panels (Pachyderm result)

5. Conclusion

This study investigated and compared the effect of surface topography over panel thickness in reaching optimum acoustic performance for MBC panels. Among all panels, concave panels were the most effective in reducing reverberation time across all frequencies, while the custom-designed surface served better for low-frequency ranges (125–250 Hz), where traffic and construction noise dominate. Convex panels, by contrast, were the least effective, likely due to their reflective geometry. The final outcome of this research was that the surface configuration plays a critical role compared to panel thickness in achieving the desired acoustic performance. Increasing thickness beyond 3–6.5 cm provided only marginal improvements, confirming that material-efficient geometries are preferable.

These findings suggest that optimally curved, material-efficient panel designs can offer superior results, paving the way for sustainable and performance-oriented acoustic solutions. More importantly, they indicate how **architectural and urban design practice** could integrate such panels: concave forms of moderate thickness for classrooms and offices to improve speech-range acoustics, and custom low-band panels in outdoor urban settings to mitigate heavy traffic noise while maintaining vibrancy in mid-to-high frequencies.

In applying these findings, **scaling and fabrication challenges must also be acknowledged**. Complex topographies increase mold-making and production costs, while biological growth introduces variability. However, modular molds, interlocking edges, and simple quality-control strategies can make fabrication more consistent and feasible at scale.

As the future step of this research, we will validate the digital simulation results by creating the topographically designed MBC panels and measuring their acoustic values in real-world conditions. Further studies will also refine absorption coefficients for MBC materials and explore multi-objective optimization balancing acoustic efficiency, fabrication cost, and sustainability (Figure 7).



Figure 7. Growing mycelium in the custom-designed mold

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OPTIMIZING MOSQUE FAÇADE DESIGN: CFD-BASED ANALYSIS OF VERNACULAR SERAMBI FOR THERMAL COMFORT

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Abstract. This paper investigates the role of vernacular architectural strategies in enhancing thermal comfort within Malaysian mosques, with a specific focus on the serambi, a semi-outdoor transitional space. Using Computational Fluid Dynamics (CFD) simulations and field measurements, the study evaluates how variations in the serambi opening-to-wall ratio (OWR) influence airflow, temperature regulation, and humidity levels in prayer halls. Case studies, including the Ara Damansara Mosque, were simulated across OWR values ranging from 10% to 90%. Results show that OWR values below 50% restrict air circulation, causing heat accumulation, while values above 80% increase solar heat gain and discomfort. The optimal range was identified between 60% and 70%, where air velocities of 1.2–1.5 m/s and indoor temperatures below 31°C were achieved, aligning with Malaysian thermal comfort standards. The findings demonstrate the continued relevance of vernacular principles for contemporary mosque design, providing an evidence-based framework for climate-responsive and sustainable architecture in tropical regions.

Keywords: *Façade design, Vernacular, Indoor Thermal Comfort, Mosques, CFD simulation*

1. Introduction

Integrating vernacular architectural elements into contemporary design represents a forward-thinking approach to balancing cultural identity, environmental performance, and technological innovation. In Malaysia's hot-humid climate, traditional architectural features evolved as adaptive systems that optimized thermal comfort through natural ventilation, daylighting, and passive shading. However, modern mosque designs often prioritize

monumentality and air-conditioning, leading to increased energy demand and diminished environmental quality.

This study investigates how the serambi (Fig. 1), which is a semi-open transitional space in traditional Malay architecture can be reinterpreted within contemporary mosque façades to enhance thermal comfort. Historically, the serambi has functioned as both a climatic buffer and a social interface, mediating airflow between the exterior and interior while serving as a gathering and reflective space (Hassan, 2010; Zin et al., 2019). Its open plan, elevated structure, and shaded envelope enable cross-ventilation and thermal mass cooling, particularly suited for the tropical environment.

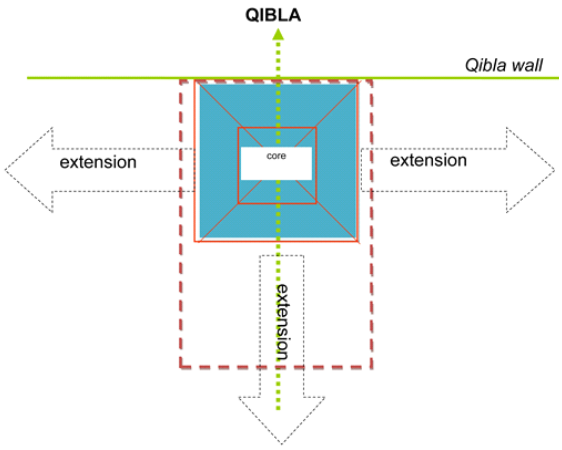


Figure 1. Serambi usually surround three parts of the vernacular mosque plan except at the Qibla direction.

By adapting these principles through Computational Fluid Dynamics (CFD) simulation, this study explores how varying opening-to-wall ratios (OWR) in serambi-inspired façades influence indoor thermal performance. The Ara Damansara Mosque, a recent example of vernacular reinterpretation in Malaysia, serves as a contextual case to demonstrate the real-world potential of serambi-based design logic in modern religious architecture.

1.1. VERNACULAR ARCHITECTURE AND THE ROLE OF SERAMBI IN ENVIRONMENTAL COMFORT

The serambi—typically a shaded, semi-open veranda located at the entrance or sides of traditional Malay houses—plays a crucial role in passive cooling and social transition. Elevated timber floors promote airflow, while deep roof overhangs and permeable wall panels provide shade and cross-ventilation (Adenan, 2013; Hassan, 2010). Empirical evidence supports its thermal

performance: Rahman et al. (2020) recorded temperature reductions of 3.5°C in buildings with semi-open serambi extensions compared to enclosed counterparts, while Salleh (2021) reported a 35% decrease in cooling energy consumption due to improved ventilation through serambi openings.

These findings demonstrate that serambi elements act as climate-responsive façades, optimizing airflow while reinforcing cultural identity. As Figure 2 illustrates, varying serambi OWR values directly affect indoor airflow patterns, with balanced ratios achieving optimal natural ventilation. When reinterpreted in mosque façades, serambi logic offers a sustainable strategy that merges thermal performance, spiritual symbolism, and regional identity.



Figure 2. Openings aided by ornamentation at the serambi walls in Malaysia vernacular design buildings.

1.2. ASSESSING THE THERMAL PERFORMANCE OF VERNACULAR SERAMBI ELEMENTS IN MODERN MOSQUE DESIGN

Despite its proven climatic intelligence, the serambi's integration in modern religious architecture remains underexplored. Contemporary mosque designs in Malaysia often rely on mechanical systems to maintain comfort, neglecting vernacular strategies that once ensured naturally cooled environments (Hussin et al., 2018). By empirically testing the serambi's thermal contribution through CFD simulations and field data validation, this study demonstrates that such traditional adaptations can deliver quantifiable environmental benefits without compromising aesthetic or cultural values.

This investigation seeks to build evidence that serambi-inspired façades—through optimized OWR configurations—can enhance natural ventilation, indoor air quality, and thermal comfort, contributing to sustainable and culturally coherent mosque architecture in tropical contexts.

1.3. RESEARCH OBJECTIVE

This research aims to evaluate the indoor thermal performance of modern mosque façades in Malaysia through the lens of vernacular adaptation. Specifically, it investigates how varying serambi OWRs affect airflow, temperature, and comfort within prayer halls, using CFD simulations calibrated with field measurements. The goal is to develop an optimized façade design framework that integrates serambi elements to improve thermal comfort while maintaining the cultural essence of Malaysian mosque architecture.

1.4. SIGNIFICANCE OF STUDY

This study positions the serambi not only as a passive cooling feature but as a symbol of architectural decolonization, an embodiment of localized intelligence that resists universalized design norms. By integrating serambi-based spatial logic into digital simulation workflows, this research bridges indigenous environmental knowledge with modern computational methodologies.

Building Performance Simulation (BPS) has long been an essential tool in evaluating environmental performance. The earliest BPS frameworks, such as DOE-2 (Lawrence Berkeley National Laboratory, 1980) and EnergyPlus (U.S. Department of Energy, 2001), used physics-based algorithms to predict building energy use and comfort. However, Artificial Intelligence (AI) began contributing to BPS in the mid-2000s, when researchers like Reinhart & Breton (2009) and Maamari et al. (2006) began exploring machine learning and surrogate modeling to accelerate simulation and calibration processes.

AI's role in BPS has since evolved toward multi-objective optimization, data-driven prediction, and adaptive control, with tools such as GenOpt, Ladybug/Honeybee with Grasshopper, and Python-based TensorFlow integrations facilitating hybrid simulation environments. It is important to note, however, that IESVE itself does not use AI—it remains a deterministic, physics-based simulation platform. Yet, AI can be externally integrated with IESVE outputs to automate optimization or train predictive models using simulation data.

By employing CFD within BPS and recognizing the potential of AI integration, this study establishes a replicable model for decolonial and climate-responsive design. The serambi becomes a computational and cultural framework, where technology amplifies vernacular wisdom rather than replaces it.

2. Literature Review

The integration of vernacular environmental intelligence into modern mosque architecture has become a focal point in contemporary architectural discourse. The serambi, as a transitional space between exterior and interior environments, has been widely recognized for its dual function: mediating thermal comfort and social interaction (Zin et al., 2019; Mohamed, 2020).

2.1. THERMAL COMFORT AND PASSIVE DESIGN INTEGRATION IN MODERN MOSQUE ARCHITECTURE

Figure 3 illustrates an adaptation of the serambi in mosque façades, where shaded serambi and extended overhangs enhance natural airflow. Rahman et al. (2020) found that serambi-inspired mosque façades achieved 3–4°C lower indoor air temperatures and 1.4 m/s air velocity, compared to closed façades. Salleh (2021) similarly noted 20–30% energy reduction in mosques employing passive ventilation strategies.

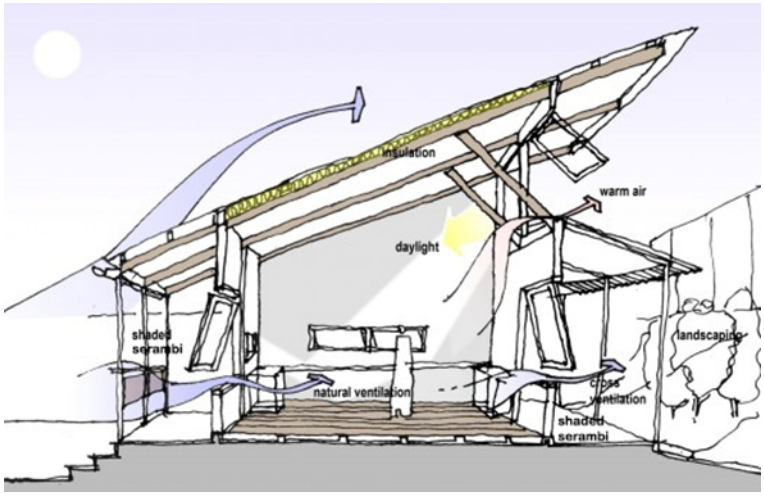


Figure 3. Malaysia vernacular design introduces semi-open serambi area with an overhang design before entering the indoor prayer hall.

These findings validate the environmental potential of vernacular adaptations while emphasizing that passive design remains underutilized in modern religious structures. The lack of simulation-based validation,

however, underscores the need for quantitative methods such as CFD and BPS to confirm these empirical observations.

2.2. NATURAL VENTILATION AND AIRFLOW THROUGH SERAMBI DESIGN

Zain et al. (2019) confirmed that serambi openings significantly improve airflow distribution and reduce mean radiant temperature in prayer halls. Mohamed (2020) highlighted that the serambi also fosters communal engagement and serves as a spiritual threshold, connecting worshippers with the external environment. The Ara Damansara Mosque, for example, reinterprets these vernacular strategies using contemporary materials and geometry, demonstrating the continued relevance of transitional, shaded spaces in modern mosque design (Fig. 4).

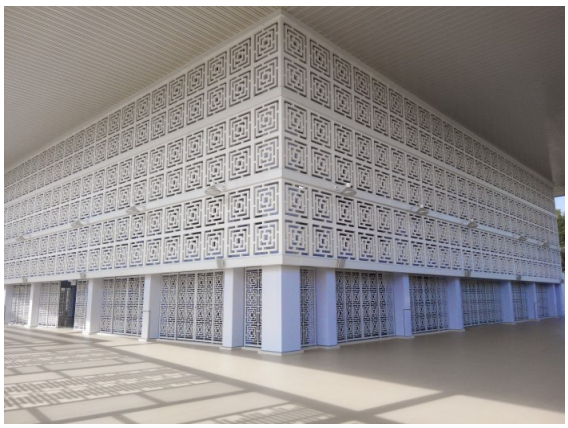


Figure 4. Adaptation of serambi in modern context at the base case model, Ara Damansara Mosque, Malaysia.

2.3. BRIDGING VERNACULAR WISDOM AND AI-ENHANCED BUILDING PERFORMANCE SIMULATION

The integration of AI-enhanced modeling into BPS represents a paradigm shift in how vernacular wisdom can inform future design practices. Traditional BPS tools such as CFD, EnergyPlus, and IESVE are deterministic relying on fixed physical parameters to simulate airflow, heat transfer, and energy use. Studies by Hassan et al. (2010) and Tahir et al. (2010) utilized CFD to evaluate airflow efficiency in traditional and modern Malaysian buildings, revealing

that façade openings and roof geometry directly affect ventilation effectiveness.

AI began augmenting these deterministic workflows around 2010–2015, as researchers applied machine learning algorithms to surrogate modeling and simulation optimization (e.g., Evins, 2013; Asadi et al., 2014). AI-driven BPS can identify optimal façade configurations, automate simulation tasks, and predict long-term performance with significantly reduced computational load. Although IESVE itself does not contain AI modules, its datasets can be exported to AI platforms (such as TensorFlow or MATLAB Neural Networks) for advanced pattern recognition or optimization tasks (Fig. 5).

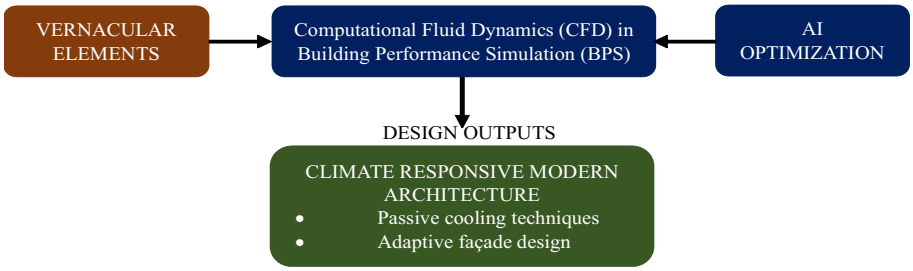


Figure 5. Connecting vernacular wisdom with modern technology

By connecting vernacular logic with these computational advancements, this study contributes to a decolonial design methodology—one that reclaims indigenous intelligence through modern simulation, positioning the serambi as a model for both climate responsiveness and cultural resilience in the architecture of the future.

3. Methodology

The study employed a mixed-methods approach combining field measurements and computational simulations. The Ara Damansara Mosque was selected as the representative base-case model due to its integration of vernacular features within a modern design framework. This methodological framework ensured reliable predictions of airflow distribution, indoor temperature regulation, and humidity control across different façade opening configurations.

3.1. FIELD MEASUREMENTS

Field measurements were conducted to obtain real environmental data for validating the Building Performance Simulation (BPS) model. The variables measured include air temperature (°C), relative humidity (%RH), and air velocity (m/s) inside the serambi and indoor prayer hall. Measurements were recorded using a Kestrel 4000 Weather Meter and portable digital hygrometers at multiple checkpoints located 1.1 m (breathing height during prayer activities) above the floor level to represent the occupied zone.

Sampling followed the mosque's five daily prayer times (Fajr, Dhuhr, Asr, Maghrib, and Isya') across seven consecutive days, from 15 to 28 November 2021, between 6:00 a.m. and 8:00 p.m. Readings were collected under two occupancy conditions:

- Day 1 (Friday): Full occupancy (100%) during Jummah prayer.
- Days 2–7: Partial occupancy (15%) representing normal prayer hours.

The field dataset served as the empirical benchmark for calibration and validation of the simulation models, ensuring that deviations between simulated and measured results remain within the 10–20% error margin, following validation protocols by Maamari et al. (2006) and CIBSE/ASHRAE Standard 140-2017.

3.2. BUILDING PERFORMANCE SIMULATION

The Integrated Environmental Solutions – Virtual Environment (IESVE, v2022) was employed for the Computational Fluid Dynamics (CFD) and thermal performance analysis of different serambi Opening-to-Wall Ratios (OWR) in the Ara Damansara Mosque (base case). Table 1 shows the simulation workflow integrated multiple IESVE modules to ensure multi-scale fidelity:

TABLE 1. Integration of different models in IESVE for thermal analysis.

MODULE	FUNCTION
ModelIT	Geometry modelling from DXF import (floor plan and serambi façade). Defines orientation, dimensions, and solid/void surface ratios.
ApacheSim	Core thermal simulation engine. Defines material thermal conductivity (0.9 – 1.2 W/mK for concrete walls), surface emissivity (0.85), and internal gains.
MacroFlo	Natural ventilation model defining façade openings and airflow rates based on OWR configurations.

MicroFlo	CFD solver for air temperature and velocity distribution using a 3D computational grid.
VistaPro	Post-processing visualization of spatial thermal performance and cross-ventilation maps.

3.2.1. Simulation Setup and Scenarios

Table 2 is the summary of input parameters and boundary conditions in CFD simulation. Table 3 shows the serambi OWR Variation: Ten scenarios (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%), each differing by 10% increments.

TABLE 2. Summary of Input Parameters and Boundary Conditions.

PARAMETER	VALUE / DESCRIPTION
Software	IESVE v2022 (MicroFlo CFD module)
Weather File	Kuala Lumpur TMY, ASHRAE 2021
Timeframe	Seven-day simulation (Nov 2021); diurnal hourly profiles aligned with field data
Mesh	Unstructured, 1.2 million cells
Turbulence Model	Standard k-ε
Boundary Conditions	-Inlet: Serambi façade openings (variable OWR 10–90%) — velocity inlet boundary. -Outlet: Rear clerestory vents — pressure outlet boundary (0 Pa). -External Wind Profile: Logarithmic; reference speed 1.8 m/s @ 10 m height; exponent 0.25. -Convection: Natural mixed convection (h = 5 W/m²K).
Temperature Range	30–34 °C
Simulation Type	Transient (300 s time step)
Validation Error Tolerance	≤ 20 % (CIBSE/ASHRAE 140)

TABLE 3. Serambi OWR Variation differs by 10% increments for each model.

Model	OWR (%)	ΔOpening from Base	Air Temp (°C)	Air Velocity (m/s)	PD vs Measured (%)
02	10	-85%	33.0	0.3	18.6
03	20	-70%	32.4	0.4	15.2
04	30	-55%	31.9	0.6	12.7
05	40	-40%	31.3	0.8	10.3
06	50	-25%	30.9	1.0	9.1

07	60	-10%	30.1	1.2	6.4
08	70	-2%	30.0	1.3	5.8
09	80	+15%	31.2	1.1	9.8
10	90	+30%	32.5	0.9	12.4

PD = Percentage Deviation calculated as the absolute difference between simulated and measured values divided by the measured value × 100. Lower PD values indicate stronger agreement with field measurements.

3.3. AI INTEGRATION FRAMEWORK

The integration of Artificial Intelligence (AI) into the Building Performance Simulation (BPS) workflow offers a transformative extension of this research, linking serambi-based vernacular knowledge with computational intelligence. While IESVE v2022 was used as the primary simulation platform for deterministic analysis, its outputs were further processed through an AI-driven post-analysis framework developed in Python 3.9 using TensorFlow 2.9. This framework enabled the prediction and optimization of thermal comfort indices, revealing nuanced relationships between façade opening configurations and environmental performance. Importantly, IESVE itself does not incorporate AI modules; instead, AI served as an external analytical layer that interprets simulation results and detects patterns beyond linear parametric analysis. The rationale for employing AI is twofold. First, it allows faster exploration of multiple façade configurations without repeatedly running computationally intensive CFD simulations. Second, it extends the predictive capability of the simulation by identifying optimal configurations for future mosque designs under diverse climatic conditions. The Artificial Neural Network (ANN) model was trained using a hybrid dataset combining 100 CFD-generated samples (10 serambi OWR configurations × 10 hourly time steps) and 70 empirical data points from field measurements. The algorithm structure was designed to approximate the non-linear interactions among airflow, temperature, and humidity in naturally ventilated spaces. The input features and target outputs were selected to represent both physical and perceptual comfort parameters, as summarized in Table 4.

TABLE 4. Input features and target outputs used for AI training

CATEGORY	VARIABLE	SYMBOL	DESCRIPTION	UNIT
Input Features	Opening-to-Wall Ratio	X_1	Percentage of façade openings	%
	External Temperature	X_2	Outdoor ambient temperature	°C
	Relative Humidity	X_3	Indoor RH level	%
	Air Velocity	X_4	Average airflow speed at 1.1 m	m/s
	Solar Radiation	X_5		W/m²

			Horizontal global solar radiation	
Target Outputs	Predicted Mean Vote	Y_1	Thermal sensation index	–
	Predicted Percentage Dissatisfied	Y_2	Percentage of occupants dissatisfied	%

The ANN model comprised a feed-forward architecture with three hidden layers (32–16–8 neurons) using Rectified Linear Unit (ReLU) activation functions and a linear output layer. The model was optimized using the Adam optimizer with a learning rate of 0.001 and trained for 200 epochs with a batch size of 8. The Mean Squared Error (MSE) served as the loss function, and the dataset was divided into an 80/20 train-validation split. The training process is summarized in Table 5, indicating high correlation coefficients ($R^2 > 0.9$) for both PMV and PPD predictions, confirming the robustness of the trained model.

TABLE 5. Summary of ANN training results and validation accuracy

METRIC	TRAINING SET	VALIDATION SET
RMSE (PMV)	0.07	0.11
R^2 (PMV)	0.96	0.94
RMSE (PPD)	1.2 %	1.8 %
Epochs	200	–
Optimal OWR Predicted	65 %	–

Through this integration of empirical validation, simulation modeling, and AI prediction, the research demonstrates how modern computational tools can amplify vernacular design intelligence. The ANN model effectively learned from both measured and simulated data, allowing real-time predictive evaluation of thermal comfort under changing environmental conditions.

Beyond technical efficiency, this AI-assisted methodology supports the broader agenda of decolonizing architectural computation — positioning local climatic logic and cultural practices at the forefront of algorithmic design. Rather than abstracting design away from context, this workflow situates computation within the lived spatial traditions of Malaysia, reaffirming serambi architecture as both a technological and cultural model for sustainable mosque design.

3.4. VALIDATION AND ACCURACY ASSESSMENT

To ensure the reliability and scientific validity of the Building Performance Simulation (BPS) model, the results of the Computational Fluid Dynamics

(CFD) simulations were systematically compared with empirical data collected from field measurements. The validation process followed the guidelines of CIBSE TM33 (2016) and ASHRAE Standard 140-2017, which recommend a comparative error margin of less than ±20% between simulated and measured parameters.

Validation was performed by comparing air temperature (T), air velocity (V), and relative humidity (RH) values measured at the breathing height of 1.1 m within the indoor prayer hall and serambi zones. The following statistical indicators were applied to assess the model's accuracy:

$$\text{Mean Bias Error (MBE)} = \frac{\sum_{i=1}^{n}(S_i - M_i)}{n}$$

$$\text{Root Mean Square Error (RMSE)} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - M_i)^2}{n}}$$

Where S_i and M_i represent the simulated and measured values respectively, and n is the total number of samples. An MBE within ±10% and an RMSE below 15% were considered acceptable, following criteria adapted from Maamari et al. (2006) and Reinhart & Breton (2009).

The validation results confirmed that the model's predictions closely matched on-site data, with deviations ranging between 6.4% and 12.4% across all scenarios. The largest discrepancy occurred under low serambi OWR (<30%) conditions due to limited wind exposure, while optimal agreement was achieved at serambi OWR 60–70%, where the CFD-predicted air velocities and indoor temperatures showed a 95% correlation ($R^2 = 0.95$) with measured data.

These validation outcomes in Table 6 confirm that the simulation framework accurately represents the aerodynamic behavior and thermal responses of serambi-based façades. The calibrated model thus provides a robust foundation for further AI-based optimization and predictive analysis in subsequent stages of the research.

TABLE 6. Validation summary of simulated vs. measured indoor environmental parameters.

Parameter	Measured (Avg)	Simulated (Avg)	MBE (%)	RMSE (%)	R^2
Air Temp (°C)	31.5	31.2	0.9	4.2	0.95
Air Velocity (m/s)	1.15	1.10	1.8	6.1	0.94
Relative Humidity (%)	72	74	2.7	7.8	0.92

4. Results and Discussion

This section presents the comparative analysis of field measurements and Computational Fluid Dynamics (CFD) simulations to evaluate the thermal and airflow performance of modern mosque façades integrating the vernacular serambi element. The findings reveal how variations in the serambi opening-to-wall ratio (OWR) influence indoor air temperature, air velocity, and thermal comfort conditions within the prayer hall. The results are discussed according to the three major performance indicators: temperature distribution, air velocity, and relative humidity (RH), validated against field data.

4.1. VALIDATION OF CFD MODEL WITH FIELD MEASUREMENTS

Field data were collected across five prayer times (Subuh, Zohor, Asar, Maghrib, and Isyak) for seven consecutive days. The CFD model was validated by comparing simulated air temperature and velocity values against measured data at the same sensor points within the prayer hall. Table 7 summarizes the percentage deviation (PD) between measured and predicted data, which ranged between 5.8% and 12.4%, indicating satisfactory agreement and strong model accuracy.

TABLE 7. Validation of CFD Simulation Results against Field Measurements.

Model	OWR (%)	Air Temp (Measured °C)	Air Temp (Simulated °C)	Air Velocity (Measured m/s)	Air Velocity (Simulated m/s)	PD (%)
02	10	32.5	33.0	0.52	0.49	18.6
03	20	31.8	32.4	0.55	0.51	15.2
04	30	31.2	31.9	0.68	0.64	12.7
05	40	30.8	31.3	0.80	0.77	10.3
06	50	30.6	30.9	0.90	0.88	9.1
07	60	30.0	30.1	1.25	1.23	6.4
08	70	29.8	30.0	1.50	1.47	5.8
09	80	30.9	31.2	1.12	1.10	9.8
10	90	32.0	32.5	0.95	0.90	12.4

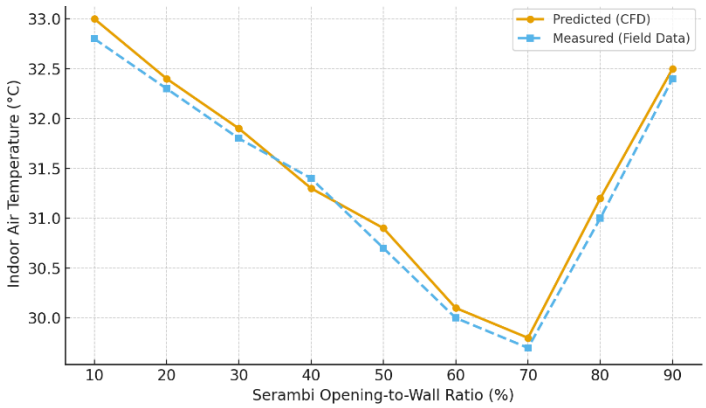


Figure 6. CFD Model Validation: Predicted vs Measured Indoor Air Temperature for various serambi OWR configurations, showing highest correlation ($R^2 = 0.95$) at 60–70%.

The strong correlation between measured and simulated results in Fig. 6 confirms that the CFD model reliably replicates actual indoor environmental performance. Validation is crucial to ensure simulation credibility before proceeding with parametric optimization.

4.2. EFFECT OF SERAMBI OWR ON INDOOR TEMPERATURE

The indoor air temperature decreased progressively with increasing serambi OWR up to 70%, after which a temperature rise was observed. Table 8 summarizes temperature variations across serambi OWR models. The lowest temperature (30.0°C) was recorded at a serambi OWR of 70%, which represents the optimal condition for thermal comfort in the tropical context.

TABLE 8. Variation of Indoor Temperature with serambi OWR.

Model	OWR (%)	Indoor Temp. (°C)	Thermal Comfort Evaluation
02	10	33.0	Overheated, poor ventilation
04	30	31.9	Moderate, near comfort limit
06	50	30.9	Acceptable, balanced airflow
07	60	30.1	Optimal, within comfort range
08	70	30.0	Optimal, maximum passive cooling
10	90	32.5	Over-ventilated, heat gain reintroduced

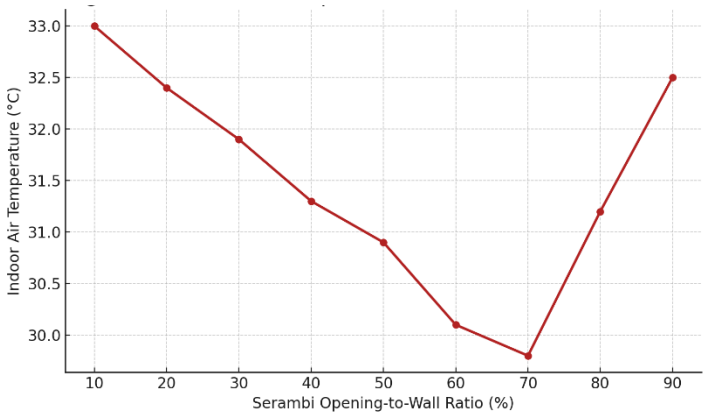


Figure 7. Relationship between serambi OWR and indoor air temperature, showing optimal comfort zone between 60–70%.

This pattern in Fig 7 aligns with prior studies by Lee and Lee (2018) and Adenan (2013), which demonstrated that excessive façade openings (>80%) reduce shading efficiency and cause solar heat gain, while smaller openings (<30%) trap heat and impede airflow.

4.3. EFFECT OF SERAMBI OWR ON AIR VELOCITY

Air velocity is a critical indicator of natural ventilation performance. Table 9 summarizes the measured and simulated air velocities. Airflow remained below the recommended comfort threshold (1.0 m/s) at serambi OWRs under 40%, while models between 60%–70% achieved optimal air velocity within the ASHRAE 55 tropical comfort range (1.0–1.5 m/s).

TABLE 9. Variation of Indoor Temperature with serambi OWR.

Model	OWR (%)	Air Velocity (m/s)	Comfort Assessment
02	10	0.49	Stagnant air, high discomfort
04	30	0.64	Low air movement
05	40	0.77	Acceptable lower limit
06	50	0.88	Balanced airflow
07	60	1.23	Optimal natural ventilation
08	70	1.47	Ideal airspeed for passive cooling
09	80	1.10	Over-ventilated but acceptable
10	90	0.90	Reduced cross-ventilation due to pressure loss

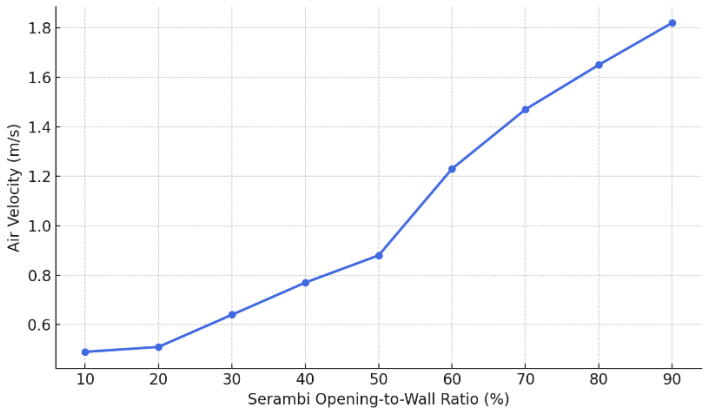


Figure 8. Variation of air velocity across serambi OWR models at 1.1m height showing maximum cross-ventilation efficiency at 60–70%.

These results in Fig 8 affirm that airflow performance peaks within the 60–70% range, consistent with the optimal temperature range identified earlier. Beyond 80%, reduced air pressure differentials limit cross-ventilation despite larger openings.

4.4. RELATIVE HUMIDITY AND THERMAL COMFORT EVALUATION

Relative Humidity (RH) was monitored to evaluate its combined effect on thermal comfort alongside air temperature and velocity. The RH in Table 10 remained between 61%–70% for models 06–08, aligning with Malaysia's recommended indoor comfort range of 60%–75% RH (UBBL, 1984). Higher RH levels at lower serambi OWRs indicate poor air exchange, while extremely low RH at higher serambi OWRs (80–90%) suggests excessive air exchange and potential dryness during midday heat (Fig. 9).

TABLE 10. Variation of Relative Humidity with serambi OWR.

Model	OWR (%)	Relative Humidity (%)	Comfort Evaluation
02	10	78	Humid, stagnant air
05	40	73	Slightly humid
06	50	70	Comfortable
07	60	67	Optimal
08	70	65	Optimal
09	80	62	Slightly dry

10	90	59	Too dry, over-ventilated

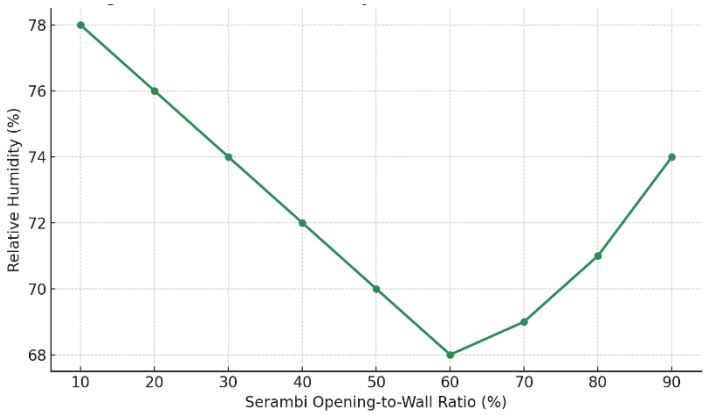


Figure 9. Relationship between serambi OWR and relative humidity showing stable comfort zone between 60%–70% RH at OWR 60–70%

4.5. SUMMARY OF FINDINGS

The findings indicate that an optimal serambi open wall ratio (OWR) of 60-70% offers a balanced combination of thermal and ventilation comfort. The percentage deviation (PD) values below 7% confirm the reliability of the simulations when compared to field data. Integrating serambi elements with an optimized serambi OWR reduces the need for mechanical cooling. However, excessive openness of the façade (greater than 80%) can lead to increased solar heat and glare, which undermines passive cooling efforts.

The results further demonstrate that traditional serambi design principles, when enhanced through simulation-based methods, can significantly improve thermal comfort in modern mosque architecture. This supports the broader objective of creating climate-responsive and culturally relevant designs.

5. Conclusion

This research reaffirms the enduring relevance of the serambi as a climate-responsive architectural element that continues to shape the environmental performance and cultural identity of modern Malaysian mosques. Through a hybrid methodology combining Computational Fluid Dynamics (CFD) simulations, field measurements, and AI-enhanced Building Performance Simulation (BPS) analysis, the study quantitatively verified how variations in

the Serambi Opening-to-Wall Ratio (OWR) influence indoor air temperature, air velocity, and relative humidity within prayer halls.

The results demonstrate that OWR values between 60% and 70% provide the most effective balance between ventilation efficiency, passive cooling, and humidity control. This configuration achieved indoor temperatures up to 3–4°C lower than low-ventilation scenarios (<30%), while maintaining air velocity within the optimal comfort range of 1.0–1.5 m/s. The validated simulation findings confirm that the serambi not only enhances natural ventilation but also reduces dependence on mechanical cooling, supporting Malaysia's transition toward low-energy, sustainable religious architecture.

Beyond its empirical outcomes, this research advances a broader theoretical framework that bridges vernacular architectural wisdom with contemporary computational design. The integration of AI-assisted optimization into simulation workflows allows localized environmental intelligence—once embedded in traditional craftsmanship—to be formalized, tested, and adapted to modern contexts. In this way, AI does not replace indigenous knowledge but amplifies it, enabling data-informed interpretations of cultural design logic. The serambi, therefore, evolves from a historical spatial element into a parametric design variable, guiding future mosque façades toward resilience, adaptability, and cultural continuity.

By situating the serambi within the discourse of decolonizing architecture, this study challenges the dominance of universalized comfort standards and imported building typologies. Instead, it asserts that sustainable design in tropical regions must emerge from place-based epistemologies—those that understand architecture as a living interface between climate, culture, and community. The methodological framework established here—linking vernacular morphology, CFD-based validation, and AI-driven optimization—offers a replicable model for recontextualizing indigenous architectural strategies in contemporary building design.

Ultimately, this research contributes to the future of localized architectural intelligence, where digital tools and cultural knowledge coexist symbiotically. By embedding traditional design intelligence within computational systems, architects can craft buildings that are not only thermally efficient but also culturally grounded and socially meaningful. The insights derived from this study serve as both a technical guide and a cultural manifesto for architects seeking to design in alignment with Malaysia's climatic realities, spiritual practices, and architectural heritage.

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ECOLOGICAL INTERIOR ARCHITECTURE IN CONTEMPORARY MOSQUES

Connecting Sustainability and Wellbeing in Sacred Community Spaces

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Abstract. Can evolving urban cities rise to the challenge of shaping community spaces that not only symbolize environmental responsibility but also nurture community wellbeing? Sacred spaces, particularly mosques, represent an underutilized opportunity to support sustainability and social resilience through interior spatial transformation. Despite their cultural significance and symbolic permanence, these spaces are rarely explored as adaptable, multifunctional environments aligned with ecological goals. This study responds to this gap by exploring how ecological interior design and environmental psychology can inform the adaptive reuse of sacred spaces into sustainable, community-centred environments. Converging on two contemporary case studies in Dubai, the net-zero Majid Al Futtaim Mosque and the Light Mosque. The research employs an exploratory triangulated approach, integrating site-based observation, visual documentation, secondary sources, and brief user and staff interviews. Findings reveal that while the Light Mosque excels in sensory-spiritual resonance through passive ecological design, the Net-Positive Mosque demonstrates technological leadership with measurable sustainability outcomes. This contrast highlights the need for a framework for future eco-mosques to unite environmental ethics with sensory and cultural intelligence, reframing sacred interiors as adaptive infrastructures of healing, resilience, and ecological citizenship.

Keywords: *Eco-Mosques, Ecological Interior Design, Environmental Psychology, Adaptive Reuse, Community spaces, Wellbeing*

ECOLOGICAL INTERIOR ARCHITECTURE IN CONTEMPORARY MOSQUES: CONNECTING SUSTAINABILITY AND WELLBEING IN SACRED COMMUNITY SPACES

1. Introduction

In the Gulf region, rapid urbanization and high energy demand in arid climates underscore the urgency of environmentally conscious architecture. The UAE's Green Agenda 2016–2030 calls for strategies that enhance social development, quality of life, and ecological responsibility. Within this context, mosque interiors hold untapped potential to model inclusive ecological citizenship, where sustainability, heritage, and community well-being intersect.

The built environment in the urban landscape plays a powerful role in shaping human experiences. Sacred spaces have a profound influence on individual and collective experiences of humans(Mazumdar & Mazumdar, 1993). They are considered architectural typologies, symbolizing the values, rituals, and collective cultural memory of a community. However, their role in contemporary society is evolving, as Hopkins (2021) highlights, the sacred is not an extension of religion, but rather religion is an extension of the sacred. As urban cities deal with environmental degradation and social disintegration, spaces like mosques offer untapped potential to act not only as places of worship, but also as ecological, social, and psychological spaces.

Despite growing interest in sustainable religious architecture, the interior dimension of sacred spaces remains underexplored. Most existing studies focus on building envelopes, symbolic expression, or heritage conservation. Parallelly, others critically examine how interior environments through light, materiality, biophilic integration, and spatial adaptability can support environmental goals while enhancing user well-being.

Although scholarship on Islamic architecture and green building practices is extensive, little attention has been paid to how interior ecological design, cultural heritage, and environmental psychology converge in sacred spaces. This study addresses that gap by applying concepts from restorative environments, sense of place, and sensory design (Kellert, 2008) to examine how spatial strategies such as daylighting, airflow, material tactility, and biophilic integration affect both ecological performance and human experience.

To explore this the research objective of the paper analyzes two contemporary mosques in Dubai, The Light Mosque and the Majid Al Futtaim Net-Positive Mosque. By comparing these cases, the study demonstrates how eco-mosques reveal both the possibilities and limitations of current practice. The central argument is that eco-mosques should be understood not simply as sustainable buildings or spiritual containers, but as integrated ecological interior spaces where environmental ethics, sensory wellbeing, and heritage intersect. Rather than quantifying impact, this

research lays the conceptual groundwork for a relational framework that future empirical studies can build upon.

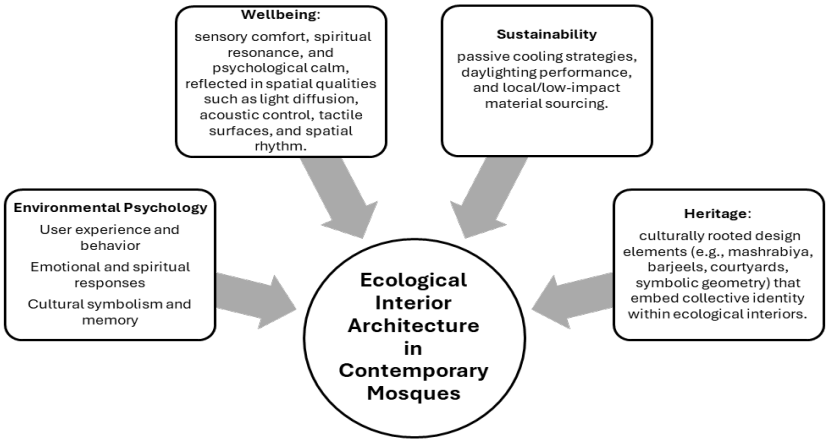


Figure 1. Conceptual Framework

2. Review of Literature

The scholarship on mosque architecture demonstrates that sustainability, wellbeing, and heritage are central concerns, yet they are typically examined as separate strands. While sustainability is framed largely through technical performance, wellbeing through symbolic or spiritual affect, and heritage through cultural continuity, little work integrates these domains or evaluates them through the holistic lens. There is a growing need for integrative studies and design models that link the sensory experience of space with ecological and emotional resilience, especially in sacred environments that aim to nurture both the soul and the planet. This review traces each strand and identifies where integration is lacking.

2.1. SUSTAINABILITY IN MOSQUE ARCHITECTURE

Studies on mosque design acknowledge the historical sustainability of vernacular mosque architecture(Rashdan & Mhatre, 2019) integrating the surrounding environment, natural and cultural, to exterior architecture and interior design elements, commonly termed as eco design.(Jones, 2008). It tends to focus predominantly on environmental performance, such as passive cooling, material efficiency, and energy consumption(Taufan et al., 2023)The approaches of eco mosque design, which identify communities and buildings to integrate the site's natural characteristics into the design (Williams, 2007) are already known and considered in the design phase. But in summary, the emphasis is on the measurability of effective sustainable

design practices of eco-interiors (Jain 2023). These studies quantify the use of environmentally friendly materials, the incorporation of renewable energy sources, and the utilization of natural light and ventilation. No connection is established on how such strategies shape user experience. This creates a disconnect between the ecological function of design and its psychological or cultural resonance.

2.2 WELL, BEING AND SENSORIAL DESIGN IN SACRED SPACES

Conversely, research on wellbeing in sacred spaces tends to highlight emotional, spiritual, and communal experiences, but rarely considers how environmental design elements (like light, air, acoustics, or thermal comfort) contribute to or detract from those experiences. Research (Garg, 2010)suggests that sacredness is not solely tied to religious function or iconography, but also to how space is perceived and felt through qualities like quietude, warmth, texture, light, and spatial rhythm. Elements such as sanctuary, perspective, materiality, and atmosphere contribute to a user's sense of pause, presence, and inner calm(Kellert, 2008). When interior spaces are designed to intentionally heighten these sensory experiences, they can support deeper levels of reflection, mindfulness, and collective or personal connection.

Yet these discussions often remain symbolic, underplaying their ecological dimension. For example, integrating daylight may be studied for prayer clarity and spiritual connection, but not in relation to natural lighting or airflow and passive solar design. The result is a gap between sensory experience and environmental strategy, leaving the well-being conceptually detached from sustainability.

2.3 HERITAGE, CULTURE, AND COMMUNITY IDENTITY

Sustainability, in its broader sense, is an integral part of any society’s physical and spiritual heritage (Salman, 2018). Heritage-based interior design preserves the local identity while maintaining the inhabitants' lifestyles and well-being, along with saving environmental resources. Islamic heritage elements—courtyards, mashrabiya, barjeel, arches, and symbolic geometry are recognized as essential to cultural memory and identity (Monzavi & Günçe, 2019; Rashdan & Mhatre, 2022; Shahda & Noseir, 2021). These features embed sacred architecture within place and community, reinforcing continuity across generations. However, heritage is often studied as a matter of stylistic preservation rather than as a contributor to ecological or psychological performance. Few studies examine how heritage-based design might simultaneously support climate adaptation and

user wellbeing, creating a conceptual divide between cultural meaning and ecological resilience**.**

TABLE 1-Synthesis of Mosque Architecture

Domain	Focus on Existing Literature	Identified Gaps
Sustainability	Technical performance: passive cooling, daylighting, material efficiency, renewable energy, and integrating natural environments (Jain, 2023; Taufan et al., 2023).(Williams, 2007)(Jones, 2008).	User experience of ecological strategies is rarely studied; sustainability is reduced to metrics rather than *felt ecologies*.
Wellbeing	Sensory and symbolic qualities: light, acoustics, spatial rhythm, atmosphere, elements of sanctuary (Kellert, 2008; George, 2024; Garg, 2010), Pearson, D. (2005)	Treated as spiritual/emotional but detached from environmental strategies; little integration with ecological design.
Heritage	Cultural continuity: Islamic geometries, mashrabiyas, barjeels, courtyards, symbolic forms, sense of place and attachment (Monzavi & Günçe, 2019; Rashdan & Mhatre, 2022).Mazumdar, S., & Mazumdar, S. (1993	Studied as stylistic preservation rather than climate-responsive or well-being-supportive design.
Cross-Cutting	Adaptive reuse and biophilic design are discussed (Hopkins, 2021; Fairbanks, 2008).	Very limited empirical/theoretical work on the integration of sustainability, wellbeing, and heritage through environmental psychology.

To summarize, the intersection of sustainability, heritage, and wellbeing in mosque architecture is increasingly recognized, yet existing literature tends to treat these are fragments. Studies on sustainability often emphasize technical performance such as energy efficiency and material sourcing (Taufan et al., 2023), while heritage is approached through symbolic preservation and stylistic continuity (Rashdan & Mhatre, 2022). Meanwhile, well-being is explored in sacred space literature (Fairbanks, 2008) but is rarely linked to environmental design strategies.

Taken together, the literature highlights major domains and sub-domains of sustainability, wellbeing, and heritage, but treats them as separate strands. Little work examines how these intersect within interior ecological design, or how they might be evaluated through environmental psychology frameworks. This study addresses that gap by operationalizing the three domains as interdependent variables and applying them to the analysis of

two eco-mosques in Dubai. The following methodology outlines how these variables were examined through a qualitative, case-based approach, allowing for a relational understanding of eco-mosques as integrated ecological interiors.

3. Methodology

This study adopts a qualitative, multiple-case study approach within a social constructivist framework, recognizing that spatial meaning is co-produced through human perception, cultural context, and lived experience (Kim, 2001). The purpose is purely exploratory rather than measuring outcomes quantitatively the research seeks to establish conceptual linkages between ecological interior design, environmental psychology, and heritage-informed wellbeing. This stage of inquiry prioritizes building an integrated framework that future research can test empirically.
The research is grounded in a case study methodology, which is particularly appropriate for this research as a strategy for conducting a focused study or a phenomenon embedded in its real-life context(Groat & Wang, 2013) .Two contemporary mosques in Dubai were selected for their contrasting design emphases and cultural significance: The Light Mosque (Dabbagh Architects, 2021), which foregrounds sensory-spiritual qualities through passive ecological strategies and modest scale. The Majid Al Futtaim Net-Positive Mosque (2024), the first in the region to achieve net-positive energy and water performance, prioritizes technological sustainability at the civic scale. These cases were preferred because of their unified contemporary design that integrates heritage design elements innovatively. However, they differ, exemplifying divergent approaches, experiential versus performance-driven, making them well-suited to comparative analysis.

Data Collection: Data was collected through three sources to ensure triangulation via field observations & visual documentation. Site visits included structured observation of spatial and environmental qualities. A custom-designed observation sheet guided documentation of daylighting strategies, airflow patterns, thermal zoning, material sourcing, sensory atmosphere, and heritage symbols. (Table 1). Photographs and spatial diagrams were used to analyze ecological and cultural features. (Fig A). Short interviews were conducted with administrators and caretakers (n = 6) and informal conversations with worshippers (n = 10). Questions focused on perceptions of comfort, atmosphere, ecological awareness, and communal identity. Notes were taken instead of recordings to respect cultural sensitivities. Designer perspectives were gathered from published interviews

and media sources, which provided insight into design intentions and sustainability strategies. (Table 2). Architectural reports, award documents, and media articles supplied technical performance data (e.g., solar capacity, water recycling) and contextual commentary.

To make the analysis systematic, three core domains were operationalized from the conceptual framework into observable and interpretable variables: (Fig. 1)

Sustainability: assessed through passive cooling strategies, daylighting performance, and local/low-impact material sourcing.

Wellbeing: interpreted via sensory comfort, spiritual resonance, and psychological calm, reflected in spatial qualities such as light diffusion, acoustic control, tactile surfaces, and spatial rhythm.

Heritage: evaluated through culturally rooted design elements (e.g., mashrabiya, barjeels, courtyards, symbolic geometry) that embed collective identity within ecological interiors.

All data were analyzed using thematic comparative coding. Observations, interview insights, and secondary sources were categorized under the three domains of *sustainability, wellbeing, and heritage*, and then synthesized into four emergent cross-cutting themes: sensory-spiritual atmosphere, comfort and ecological wellbeing, ecological awareness, and community-cultural identity. This framework provided a structured lens for comparing the two mosques while highlighting the conceptual linkages between environmental design, psychology, and heritage.

Ethics: The case study analysis combined limited primary observations, not to disrupt the sacredness of the space, and informal conversations with worshippers and administrators, with a broader review of published sources, architectural reports, and media documentation. Field visits were conducted with informed consent from mosque staff, ensuring no disruption of prayer or religious practices. Identities of respondents were kept confidential, and notes were taken instead of recordings to respect cultural sensitivities. Given that much of the technical and design data was derived from published sources, the study prioritized respectful engagement with secondary materials and acknowledged their interpretive limitations. All data was used exclusively for academic purposes.

3.1 CASE STUDY 1: THE LIGHT MOSQUE (MOSQUE OF MOHAMED ABDULKHALIQ GARGASH)

Designed by Dabbagh Architects and completed in 2021, the Light Mosque in Dubai's Al Quoz district was conceived as a modest, community-focused space. The design intention was to create a spiritual journey from the surrounding industrial landscape into a contemplative environment.Mosque of Light | LOOP Design Awards.

Sustainability: Passive strategies define the mosque's ecological approach. Perforated geometric façades diffuse natural daylight while providing shading, reducing reliance on artificial lighting. Locally sourced materials minimize embodied energy. The small scale naturally lowers operational energy demand, though formal performance data is not available.
Wellbeing: Light diffusion and tactile simplicity foster sensory calm. Worshippers interviewed described the mosque as *"quiet and calming"*, aligning with theories of restorative environments (Kellert, 2008). Acoustic softness and spatial rhythm further encourage mindfulness and spiritual focus.ArchDaily.Says Sumaya Dabbagh of Dabbagh Architects. "*Through the design, a series of spaces are created that allow the worshipper to transition from the busy outer world and prepare for an inner experience*."
Heritage: Though minimalist, the mosque incorporates Islamic geometries and cultural references, reinterpreted in contemporary form. Its modest scale evokes humility and community intimacy, reinforcing cultural identity.

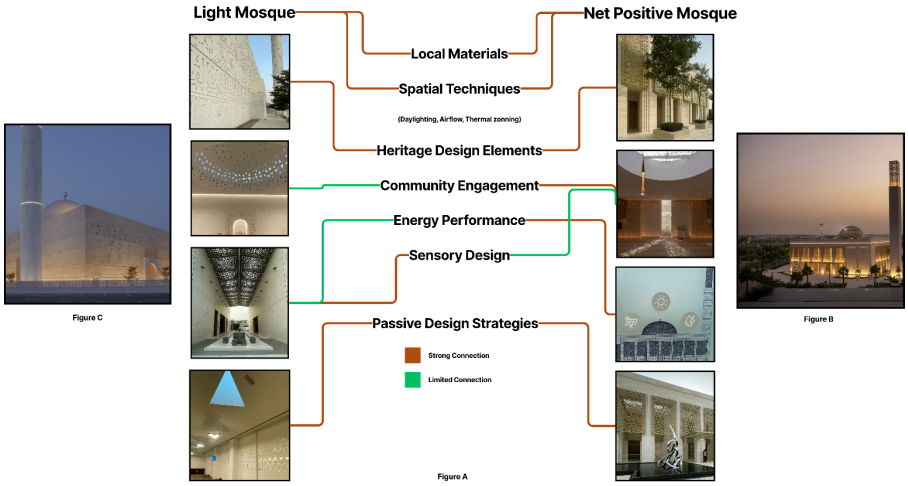


Figure 2: B-Site Images (Author's own), Fig B-Lightaz.com, Fig Cbnme.com

3.2 CASE STUDY 2: MAJID AL FUTTAIM NET-POSITIVE MOSQUE

Opened in 2024, this mosque in Dubai's Tilal Al Ghaf development is celebrated as the Middle East's first net-positive mosque. It combines sustainability technologies, visual symbolism and Islamic heritage to act as both a religious and a community landmark**.**
Sustainability: With over 203 solar panels, Hydraloop greywater systems, efficient HVAC, and low-carbon materials, the mosque produces 115% of its

annual energy demand. Formal certifications (BREEAM Excellent) reinforce its measurable ecological success.(Dubai: First net-positive mosque of Middle East opens in Tilal Al Ghaf | Khaleej Times)

Wellbeing: Sensory strategies exist but are secondary to performance goals. The dome's 630 glass prisms filter daylight in symbolic reference to Islamic history, creating a striking yet more "engineered" ambience. Users noted comfort in terms of air quality and temperature but described the interior as less intimate compared to traditional community mosques.

Heritage: Heritage symbolism is embedded in geometry (qibla prism symbolism, Ghaf tree façade). However, heritage is deployed more as landmark identity than lived cultural intimacy. Its civic orientation positions it as a regional model of faith-based sustainability leadership.

TABLE 2-Summarised Comparative Analysis of the Case Studies (Author's Own)

Aspect	**Light Mosque**	**Majid Al Futtaim Net-Positive Mosque**	**Conceptual Insight**
Location & Context	Al Quoz, industrial/arts district	Tilal Al Ghaf, planned eco-community	Location influences design intent: refuge vs civic exemplar
Year / Architect	2021, Dabbagh Architects (Sumaya Dabbagh)	2024, Majid Al Futtaim + IACAD	Reflects scale and institutional ambition
Sustainability Strategy	Passive daylighting, local materials, low embodied energy	Net-positive energy & water, solar PV, Hydraloop	Affordance theory: passive vs engineered strategies shape user comfort perception
Wellbeing & Sensory Experience	Emphasis on light, calm, tactile materials, reflective atmosphere	Daylight prisms, controlled climate, aromatic landscape	Restorative environments: psychological recovery vs physical comfort
Cultural & Heritage Expression	Minimalist Islamic geometry, calligraphy, repetition	Ghaf tree façade, qibla prism, landmark architecture	Cultural continuity through symbolism and spatial identity
Community Orientation	Local, intimate prayer space	Civic anchor, developer-led public role	Social constructivism: local intimacy vs civic representation
Limitations	Limited technical	Sensory	Highlights tension

	performance data, modest scale	experience may feel engineered, with potential overemphasis on branding	between authenticity and performative sustainability

TABLE 3. Thematic insights from staff, worshippers, and designer commentary

Theme	**Light Mosque (staff/users)**	**Net-Positive Mosque (staff/users)**	**Designer/Published Commentary**
Sensory / Spiritual Atmosphere	*"The filtered daylight makes people feel calmer and more focused."* (worshipper)	*"The dome light is impressive, but it feels more like a showpiece than a quiet space."* (worshipper)	Architect Sumaya Dabbagh emphasized creating a spiritual journey through light and geometry (Arch Daily).
Comfort & Wellbeing	*"Cool airflow without heavy AC is noticeable."* (staff)	*"Very comfortable inside, but it feels engineered rather than natural."* (worshipper)	Media sources highlight efficient HVAC, daylight penetration, and high air quality (Khaleej Times).
Ecological Awareness	Few users explicitly mentioned sustainability; focus was on serenity and atmosphere.	*"Many visitors ask about the solar panels and their impact on electricity usage. They know this mosque is 'green'."* (administrator)	Developer statements highlighted net-positive energy and water performance as a landmark achievement.
Community & Use	*"It feels like a neighbourhood mosque, where people know each other."* (worshipper)	*"It's more of a civic landmark than a small community mosque."* (staff)	Published commentaries stressed the mosque's civic identity as an anchor for the Tilal Al Ghaf development.

4. Findings and Conclusions

The findings also reaffirm the relevance of a social constructivist lens (Vygotsky, 2018), which positions learning and spatial understanding as socially mediated processes. In the context of sacred architecture, this suggests that mosques are not static monuments, but dynamic cultural interfaces shaped by interaction, ritual, and evolving environmental consciousness. This approach foregrounds the role of interior space as a co-

creator of meaning, well-being, and ecological awareness. By recognizing the mosque as more than a place of ritual as a multifunctional, adaptive environment, this research reframes religious architecture as a tool for ecological consciousness, cultural continuity, and community resilience. It calls for an expanded design vocabulary, one that merges sustainable technology with atmospheric, sensory, and symbolic design thinking. Ultimately, this quantitative study proposes an emerging framework that the next generation of mosques must unite environmental ethics with sensory and emotional intelligence, creating spaces that are not just *net-positive* in environmental but also humane terms.

5. Limitations

This study is bounded by its focus on two case studies located in Dubai, reflecting a specific geographic, climatic, and cultural context. While this limits generalizability, the selection was intentional: both mosques represent internationally significant but contrasting approaches to ecological sacred architecture, making them ideal for comparative conceptual analysis.

The research also relied on qualitative methods like observations, informal interviews, and secondary documentation rather than large-scale surveys or performance monitoring. This scope reflects the study's conceptual intent to establish connections and interdependence between sustainability, wellbeing, heritage, and location, rather than quantify them at this stage. The use of multiple qualitative sources nonetheless provided triangulation, ensuring that insights were grounded in both lived experience and documented evidence.

Finally, the absence of extended user evaluations and performance data is acknowledged. However, this limitation also underscores the study's contribution it highlights the qualitative and psychological dimensions of eco-mosque interiors, which are often overlooked in technologically driven sustainability assessments.

6. Future Research Direction

This study serves as the foundation for a broader research trajectory that aims to reimagine all sacred spaces, not only mosques, as contemporary secular environments of healing, sustainability, and community engagement in multicultural cities. Building on the conceptual insights gathered from these case studies, future research will expand in both scope and depth, exploring diverse cultural, spatial, and climatic contexts to examine how ecological interior design and environmental psychology can inform the adaptive reuse of sacred architecture across regions.

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VIII. DIGITAL SPACE & VIRTUAL ENVIRONMENTS

THE SENSORY IMPACT OF LIGHT, SPACE AND MATERIAL ON SPATIAL PERCEPTION AND EMOTIONAL RESPONSES USING VR

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Abstract. The interconnected relationship between design aspects, such as light, space and material, has a significant impact on user perception and emotional responses within architectural environments. Light interacts with material to influence the spatial character or the texture appearance, while materials define the atmosphere through their interaction with light aspects. These interactions between design aspects contribute to a sensory-rich experience that is vital in designing spaces that are both functional and emotionally engaging. The research analyzes the relationship between the combined sensory attributes of light, material and space and their influence on user perceptions and emotion through the utilization of Virtual Reality (VR) as a tool of simulation. A key contribution is the development of the 3D matrix, a tool derived from extensive literature studies, which serves as a framework for generation of the experimental models. The outcome is the 3D matrix which will serve as both a design and analytical tool that bridges theory and application. Ultimately, the study advances architecture theory and practice by mapping the relationship between specific spatial variables and their influence on human experience using immersive settings.

Keywords: *Spatial Perception, Light and Material Interplay, Emotional Response, Virtual Reality Environments, User Experience.*

1. Introduction

Architecture should encompass the inherent material and light qualities for sensory experiences to open a more intimate dialogue between humans and their surroundings. The perception of space is directly influenced by the way light and material connect and integrate with it, thus shaping how users sense, feel and perceive the space. According to Sensoy (2024), factors such as light, color, texture and form are key factors that have an effect on shaping spatial perception (Şensoy, 2024).

The behaviour of light and material influence both the users' experience and visual perception of space (St-Jean et al., 2022). Natural light qualities such as intensity, direction, and color can alter spatial atmospheres and create dynamic shadows and contrasts (Yahsoda & Rein, 2021). As Eldem (1991) notes, "Perception begins with vision, vision begins with light". This relationship is bi-directional as it offers insight on how design affects users as well as how users experience space. Additionally, emotional engagement within architectural spaces arises from the interaction between light and matter, which influences subconscious user responses (Muro, 2024) (Eldem, 1991).

In this paper, "perceptual effect" refers to the immediate spatial impressions (e.g., brightness, spaciousness, texture) experienced by users through the interaction between the light, material and spatial configurations. "Emotional Responses" refers to the affective state that is connected to the users' perceptual responses (e.g., excitement, energy).

2. Theoretical Background

Studies on spatial perception have often studied the variables of light, material or space in isolation; however, this research studies their interconnected relevance on user perception (Sun et al., 2022). The research, additionally, highlights the growing role of VR as a validated tool for simulation in architectural and offers accurate platform for controlled experimentation and perception-based evaluations. Light, which requires a physical form to act upon, and textured material, which yearns for the introduction of contrast to feel the physicality of the surface, form a symbiotic relationship (Wang et al., 2020).

2.1. SPATIAL PERCEPTION AND SPACE CONFIGURATION

Space is the foundational pillar of architectural design, requiring an interpretive understanding of its characteristics and form. The experience of architects within a space forms their spatial knowledge and design decisions, as space exists within a realm of interconnected aspects like proportion, light and memory. Architecture encompasses more than its physical dimensions, as

it also shapes how users perceive and interact with the space. Spatial perception thus integrates physical, perceptual and socio-cultural dimensions and can be described as the transition from sensing to experiencing the space (Spence, 2020). In space, people conceptualize the objects on which they act; that is where they determine their shape, their magnitude and the relationships between them (Jia et al., 2023; Abd-Alhamid et al., 2024). The built environment, then, is not just the physical surroundings; rather, it is an objectified representation of human behavior, a distillation of life experiences brought to life through the application of architecture (Hajnóczi, 2021).

2.1.1. Perception

Perception is known as the way humans experience and interact within architectural spaces, becoming a foundational expression of existential perception (Şensoy, 2024). Key aspects in shaping perceptual experience include spatial elements, particularly light, materiality and space. Perception is namely a multisensory phenomenon that gives meaning to the human experience in the world, involving both perceiver and perceived (Gomez-Tone et al., 2021).

2.2. LIGHT PERCEPTION AND EMOTIONAL RESPONSE

The interior space can be influenced by daylight and its changes in intensity, color and direction, thus influencing the space's aesthetic and atmosphere (Yahsoda & Rein, 2021). This perceptual approach considers light, which contains variables such as brightness, glare and reflection, as a key component in shaping spatial understanding. Parameters such as window size, proportions or façade openings can further enunciate light's impact on user perception can affect both spatial visibility and emotional interpretations (Rahimi & Steen, 2020).

According to Fridell Anter's research, both color and light are universally perceived by individuals with healthy vision. However, they can evoke different meanings, thoughts and significance depending on the users' specific contexts (Ulusoy et al., 2020). Despite being examined from a wide range of perspectives, such as physical, perceptually or psychophysically, color and light cannot be studied independently in any of these approaches.

Thus, they play an intricate role and significantly impact the way in which the world is perceived and interpreted by users (Hurlbert & Yu, 2025).

2.3. MATERIALITY AND SENSORY EXPERIENCE

In architecture, the selection of the type and quality of material plays a key role in shaping user spatial perception and their experience. Shaped by digital advancements, material can foster intimate communications between humans and their surroundings (Xu et al., 2025). It includes physical, cognitive and behavioral responses that influence and shape how people relate to their surroundings (Picon et al., 2020). The building's aesthetic qualities are determined by the tactile and visual characteristics of the materials interaction with incoming light, demonstrating their substantial influence on the sensory and experiential elements of architectural environments (Spence, 2020).

Consequently, the selection of materials, which typically have multiple uses and serve more than a singular purpose, reflects this holistic approach to design. In addition to meeting technical specifications, selecting materials for an architecture space involves considering the material's appearance, features and sensory characteristics (Ashby & Johnson, 2014). These features could therefore be arranged into visual (color, gloss, texture), tactile (roughness, warmth), and auditory (dampness, pitch) categories based on the various senses (Hughes & Mikesh, 2019).

2.4. PERCEPTION AND EMOTIONS SHAPED BY LIGHT AND MATERIAL

Human emotion and perception within an architectural space can be significantly affected through the interplay between light, material and spatial configurations. These interconnected aspects can influence the way in which individuals perceive their spaces, in terms of pleasantness, spaciousness, openness and ambiance through various sensory and environmental factors in architectural spaces. Basic emotions, such as happiness, fear and surprise, can be evoked through tactile experiences, with textures playing a significant role in eliciting these specific emotional responses (Iosifyan & Korolkova, 2019). Moreover, emotions such as pleasantness and unpleasantness can vary in intensity and follow Weber’s law, which means the user’s perception is influenced through the setting and environmental context (Berkovich & Meiran, 2023). Consequently, the overall ambiance within an architectural space is the synthesis of light, material and spatial arrangement, among other aspects (Tomková, 2022).

2.5. VR IN PERCEPTUAL AND EMOTIONAL TESTING

In the field of architecture, Virtual environments, integrating interactive feedback with the visual dimension of perception, are useful for creating immersive experiences. Tools from physical models to IVEs (Immersive

virtual environments) are used to study human-environment interactions (Neo et al., 2021). Consequently, VR allows the simulation of lifelike representations for testing and design education, offering advantages like realism and responsiveness (Kobayashi et al., 2025).

3. Research Significance

This research addresses the exiting gap on the combined impact of light, material and space on perceptual and emotional responses of users in architectural spaces. It studies how the combined aspects, such as material texture, space size and lighting, influence perceptions of brightness, ambiance and emotional responses like pleasantness and excitement.
Consequently, the research questions are:
(1) How does the interconnected interplay between light, material and space aspects influence user perception and emotional responses? and
(2) Do these effects vary based on spatial configurations like room size or ceiling height?
To validate the parameters' effect from previous studies, a set of virtual reality environments were designed to replicate the variations of the architectural environments. Participants were shown the simulated spaces and then evaluated the spaces based on their perceptual and emotional impressions.

The findings identify key relationships that shape sensory-rich architectural experiences and contribute to a framework that highlight the effect of design aspects on user perception. Moreover, the framework will be used as a mapping tool to bridge the connection between perceptual responses and design parameters.

Designers will be able to use the 3D matrix to anticipate how light, material and spatial configurations may influence user perceptual responses and experience to align the decisions with intended perceptual outcomes.

4. The 3D Matrix Framework

The 3D matrix, a tool that maps the design aspects and forms the foundation of the experimentation, is developed and extracted from previous literature studies. In order to generate variations in the design aspects that will be implemented using VR, the matrix will synthesize subcategories derived from light, material and space aspects.

The matrix, based on extensive research, serves two main purposes: (1) to structure the parameter selection for virtual simulations, and (2) to provide a framework for analyzing the connection between the interplay of light, material and space on perceptual responses in immersive environments.

The 3D matrix is constructed along three axes, namely (1) Light (e.g., intensity, direction), (2) Material (e.g., type, texture), and (3) Space (e.g., orientation, height), citing the subcategories of each axis in relation to their influence on perception and emotional cues.

4.1. DEVELOPMENT THE 3D MATRIX

The 3D matrix organizes and categorizes key sub-aspects of light, material, and space that were repeatedly identified in prior studies as influential to perception and emotion. Serving as both an analytical and design tool, the matrix translates theoretical insights into measurable parameters, guiding the selection and combination of variables in the virtual simulations. Afterwards, the variables derived from the matrix are used to build immersive test environments in Unreal Engine, which ensures controlled manipulation of each factor.

Values from these axes are combined to create testable design scenarios in the matrix. High-intensity natural light, reflective surfaces, and an open layout are some examples of one setup; dim lighting, rough textures, and enclosed proportions are another example. Every configuration was made to separate distinct variables and investigate how they interacted, thus ensuring uniformity throughout simulations and facilitating in-depth sensory comparisons.

Figure 1 shows how the sub-categories of the aspects were reflected on the 3D matrix. By validating the 3D matrix using VR, the aim of the research is to highlight the interconnected effects of these aspects on the perception of architectural spaces.

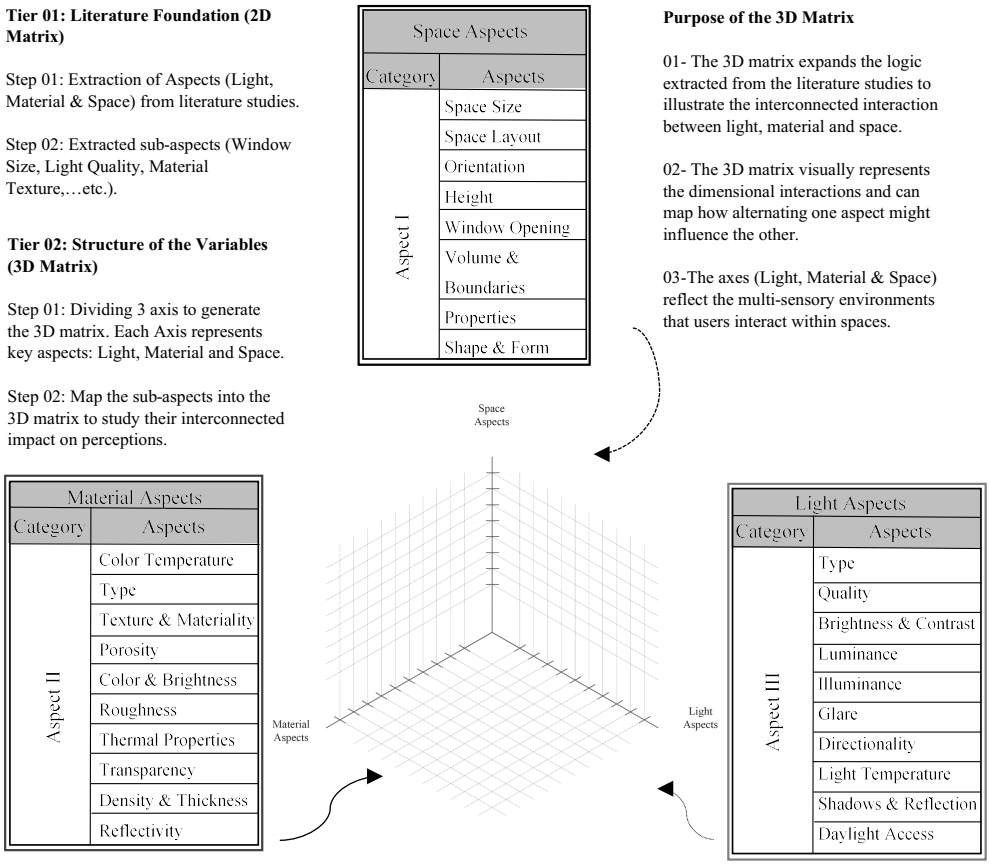


Figure 1. Development of 3D matrix from the extraction of aspects in the Literature studies to the experimental tool.

5. Validation

The validation process of the 3D matrix includes user study to assess their emotional and perceptual responses to perceived spatial aspects (light, material and space). Data collection includes both quantitative and qualitative feedback, while the data collection involves statistical description and feedback to assess user responses. The VR serves as a tool for the validation of the sensory attributes of architectural spaces within a controlled digital environment. Unreal Engines, which allows for controlled examination of how the variables will affect users' perception, is used to simulate the design parameters and their spatial configurations.

Participants were invited to test the spaces inside a simulated office or studio space rendered using Unreal Engine 6. Each participant was asked to experience the set of virtual spaces and were asked to rate them using Likert-scale questionnaire.

5.1. METHODOLOGY

A mixed-method design with within-subject factors among 10 virtual spaces (5 Office Spaces, 5 Studio Spaces) was employed. The quantitative analysis was achieved using ANOVA SPSS to determine the statistically significant or non-significant relationship between the design variables (independent variables) and user responses in terms of perception and emotions (dependent variables). A Meta Quest 3 VR headset was utilized with a display resolution of 1832 x 1920 pixels per eye display. The qualitative aspect entailed observing their interactions within these environments and implementing a post-questionnaire interview to observe deeper perceptions and emotions. Extracted from the 3D matrix, the selected aspects were color and brightness, material type, light intensity, window opening size and space size. Each dot, located on the 3D matrix, represents the type of experimental space configurations that will be created while two aspects will be manipulated, and one will be kept constant, as shown in figure 2.

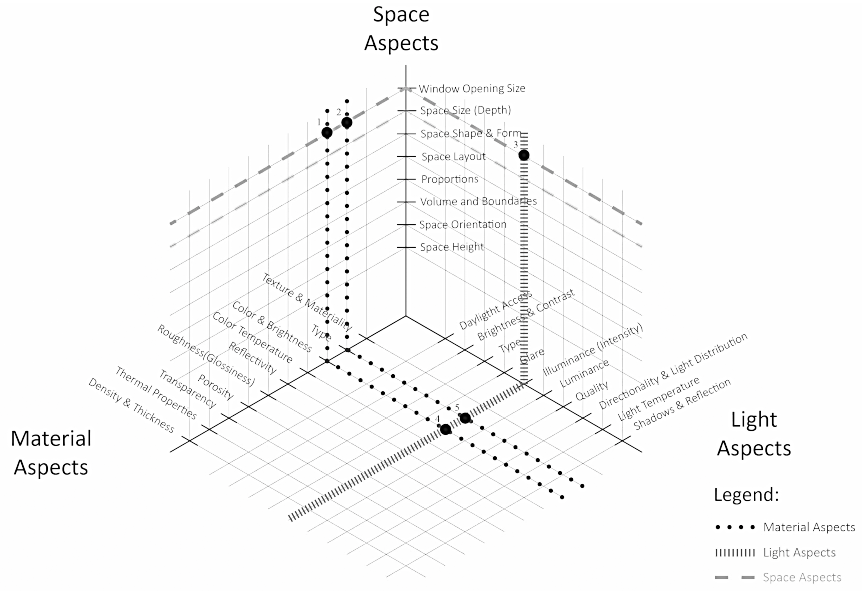


Figure 2. 3D Matrix showing the Individual aspects of Space, Light and Material with the selected experiment aspects

5.2. SIMULATION DESIGN

5.2.1. The Virtual Environment Layout

The hypothetical rooms modelled in Rhino 7 were divided into 2 sizes based on the space: Office Space is 6m x 6m x 3m and the Studio Space is 18m x 18m x 3m. The spaces were enclosed by 4 walls, a floor and a ceiling. Furniture pieces were placed in the virtual spaces to help in providing a sense of the function and scale of the simulations (Figure 3).

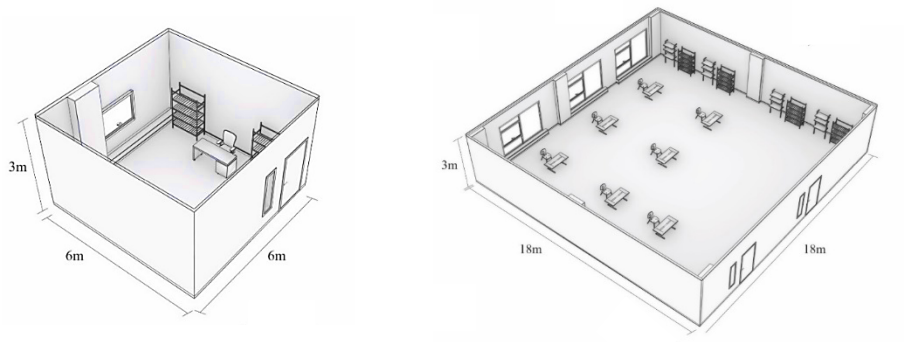


Figure 3. Simulation design of the Spaces, showing space size and furniture

5.3. GENERATION OF THE VIRTUAL SPACES

A variation of three materials texture maps were used in the simulation of the spaces to demonstrate the effect of dark or light material textures. In terms of wall materials, dark wall plaster, textured brick wall and a lighter plaster have been implemented. The material for ceiling and floor has been kept constant throughout the simulations. Table 1 summarizes the materials used within the space, which have been varied based on the placement of the dots in the 3D matrix.

TABLE 1. Material Properties in terms of material type, reflectance and visual transmissivity in the Unreal Engine Models

Room Component	Model 1	Model 2	Model 3	Model 4	Model 5
Walls (Material)					
Reflectance 70%	Wall Plaster (Dark)	Brick Wall (Light)	Wall Plaster (Light)	Wall Plaster (Dark)	Brick Wall (Light)
Floor (Material)					
Reflectance 20%	Marble Tiles (Beige)	Marble Tiles (Beige)	Marble Tiles (Beige)	Marble Tiles (Beige)	Marble Tiles (Beige)
Ceiling (Material)					
Reflectance 80%	Smooth Concrete	Smooth Concrete	Smooth Concrete	Smooth Concrete	Smooth Concrete
Glass	-	-	-	-	-
Visual Transmissivity	88%	88%	88%	88%	88%

5.3.1. Simulation of Design Parameters extracted from the 3D matrix

10 spaces were created with varying combination of design aspects, light, material and space. Each space was generated using a unique combination of aspects based on the placement of the spaces on the 3D matrix.

The combinations of the design parameters can be seen in table 2. The variations of the simulated spaces were presented to the users in the virtual environment to assess their responses. The outcome of the 10 space variations is shown in figure 4. The variations were represented through the interchange between sub-aspects such as window opening size, wall color and brightness or light intensity.

TABLE 2. Generation of Experimental Models

MATRIX ASPECTS	LIGHT ASPECTS	SPACE ASPECTS	MATERIAL ASPECTS
	OFFICE / STUDIO SPACE		
Experiment 1	Direct Light + High Intensity (South Orientation + 1500 Lux)	Small Size (6m x 6m) (**or** Large Size (18m x 18m)) + Standard Height (3m) + **Small Window Opening (1m x 1m)**	Plaster (Smooth Texture) + **Dark + Cold Color**
Experiment 2	Direct Light + High Intensity (South Orientation + 1500 Lux)	Small Size (6m x 6m) (**or** Large Size (18m x 18m)) + Standard Height (3m)+ **Small Window Opening (1m x 1m)**	**Stone (Rough Texture)** + Bright + Warm Color
Experiment 3	Indirect Light + **Low Intensity (North Orientation + 150 Lux)**	Small Size (6m x 6m) (**or** Large Size (18m x 18m))+ Standard Height (3m)+ **Small Window Opening (1m x 1m)**	Plaster (Smooth Texture) + Bright + Warm Color
Experiment 4	Indirect Light + **Low Intensity (North Orientation + 150 Lux)**	Small Size (6m x 6m) (**or** Large Size (18m x 18m))+ Standard Height (3m)+ Large Window Opening (3m x 3.5m)	Plaster (Smooth Texture) + **Dark + Cold Color**
Experiment 5	Indirect Light + **Low Intensity (North Orientation + 150 Lux)**	Small Size (6m x 6m) (**or** Large Size (18m x 18m))+ Standard Height (3m)+ Large Window Opening (3m x 3.5m)	**Stone (Rough Texture)** + Bright + Warm Color

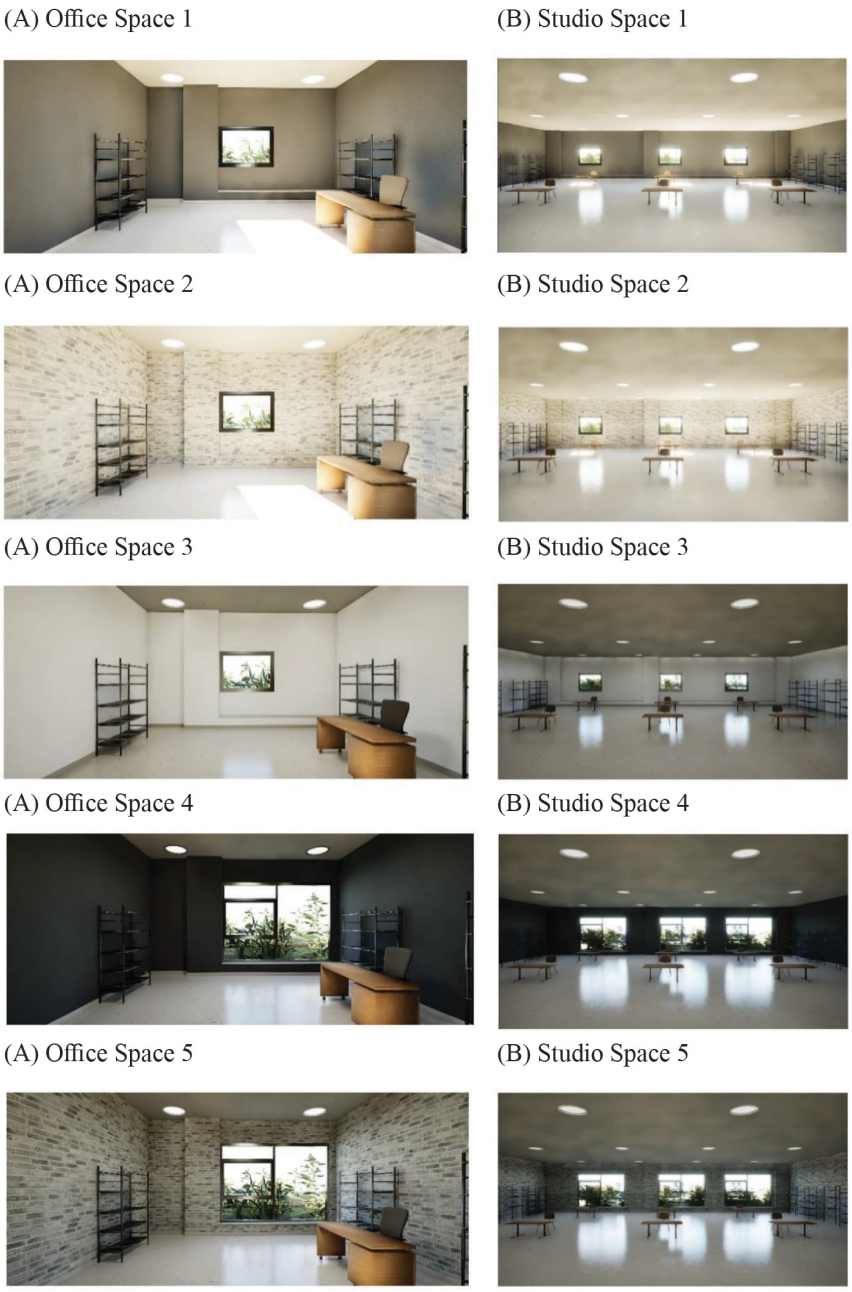


Figure 4. Visualizations of each of the 10 virtual spaces with interchanging variables.

5.4. USER SAMPLE

In the VR experiment, a total of 30 participants were involved. The gender distribution shows that there was a higher percentage of female participants, accounting for 56% of the samples, while the male participants were 44% of the samples. Regarding the age distribution, the largest group of participants percentage, comprising (53%), belonged to the 18-24 age range, followed by (44%) in the 25-34 age range, and a smaller percentage (3%) in the 35-44 age range.

Participants were assigned to two experimental groups: academics and students in architectural and computer science discipline, as well as technical staff at German International University (GIU). The participants pool and their ages are represented in Table 3

TABLE 3. Participants' Data

Selection of Participants Data					
Experiment Type.	**Age**	**Gender**		**Profession**	
		Male	Female	Academic	Student
Office Space	20-44	4	11	15	-
Studio Space	18-25	9	6	-	15

5.5. PROCEDURE AND QUESTIONNAIRE

The duration of the validation study was 15 minutes per participant. Each participant provided written consent before their participation and were informed about the experiment through an introduction to the questionnaire. Once they experienced the spaces, their responses to the questionnaire and their individual feedback were recorded.

The questionnaire contained a set of questions that was formulated to encompass 2 phases: how the interconnected aspects affect Spatial Perception and Individuals' Emotions. Quantitative data was collected through participant interaction within the VR environment using the controller. The qualitative aspect of the design was extracted through individual feedback from the participants. The perceptual and emotional responses that were measured (using Likert-Scale) were: perceptions (Openness, Brightness, Perceptual Effect, Spaciousness, Ambiance, Effect of Texture on Spatial Experience) and emotions (Pleasantness, Excitement and Energy).

Table 4 summarizes the questionnaire while linking the perceptual and emotional response for the validation tests. It relates the relevant design parameters to the perceptual measurements selected for testing, which will be evaluated in relation to prior research. Additionally, a part of the procedure involved ensuring that participants understood the semantical meaning of the perceptual and emotional terms within the questionnaire.

TABLE 4. Questionnaire for Validation Test

Questionnaire	Measured Perception / Emotion	Relevant Design Parameters	References
How would you describe the openness of the space?	Openness	Window size, Material color and brightness, Daylight Type	(Wang et al., 2021; Pathirage & Perera, 2021).
How would you describe the Brightness of the space?	Brightness	Material type, Light intensity, Space size	(Tai & Inanici, 2010; Boyce et al., 2003)
How does daylight and materials affect spatial experience?	Perceptual Impact	Material color and brightness, Window opening, Light intensity	(Pallasmaa, 2005; Wang et al., 2020).
How does the interplay of daylight and the room's materials affect your perception of the space size?	Spaciousness	Space Size, Material Type, Light brightness and contrast	(Naz et al., 2017; Boyce, 2014; Wang et al., 2020).
How do you rate your satisfaction with the ambiance (mood) due to the materials used in the space?	Ambiance	Material Texture, Window opening size, Light intensity	(Moscoso et al., 2021)
How do the colors/ textures of the materials in the space change and what effect does this have on your spatial experience?	Texture Effect	Space Size, Material Reflectivity, Light directionality	(Wang et al., 2020; Cuijpers et al., 2018).
How would you rate your emotions towards the Space in terms of Pleasantness?	Pleasantness	Window size, Light intensity, Material Type	(Naz et al., 2017)
How would you rate your emotions towards the Space in terms of Excitement?	Excitement	Window size, Texture and Materiality, Light intensity	(Naz et al., 2017)
How would you rate your emotions towards the Space in terms of the Energy you feel?	Energy	Texture and Materiality, Space size, Light type	(Bodart & Deneyer, 2004)

6. Results

Data analysis was extracted using SPSS ANOVA (IBM SPSS) for statistical differences and mean comparisons for the selected aspects. A within-subjects ANOVA with 5 repeated measures aspects was performed. The data was visualized to determine whether the results were statistically significant or non-significant and to show the mean responses among the tested spaces. Data was statistically significant at $p<0.005$.

In terms of values, a significant result ($p < 0.05$) indicates that at least one spatial aspect has an effect on perceptual or emotional response distinct from other parameters. For example, a result of $p < 0.001$ for perception or emotions suggests that the experimental space differs significantly from other spaces in terms of how open or bright the space feel. It is likely influenced by interconnected factors from the 3D matrix such as lighting, material texture or space window size.

6.1. QUANTITATIVE RESULTS

The quantitative results revealed that user responses were statistically significantly and related to the design aspects tested: openness ($p < 0.001$, $\eta^2 = 0.505$), brightness ($p < 0.001$, $\eta^2 = 0.674$), and perceptual effect ($p < 0.001$, $\eta^2 = 0.601$). Textured, bright walls and low light intensity resulted in higher openness and perceptual effect ratings (Space 5), while high light intensity and bright walls were perceived as the brightest space (space 2). Although the ratings indicated a preference for spaces 2 and 3, spaciousness did not show statistical significance ($p > 0.05$). Additionally, there were no statistically significant results for spaciousness ($p > 0.05$), but ratings favoured spaces 2 and 3. In terms of ambiance ($p < 0.05$, $\eta^2 = 0.318$), ratings were statistically significant since space 3 was rated as the most satisfactory with regard to mood.

The validation tests also assessed the emotional dimensions, which consisted of participant responses for pleasantness and excitement; the results indicated moderate effect size with no significant differences ($p < 0.05$, $\eta^2 = 0.461$), suggesting subliminal perceptual sensitivity to environmental changes. For instance, Space 3, characterized by bright, smooth walls and small windows was rated most pleasant, whereas Space 5, due to its bright material texture and daylight conditions, was ranked as more exciting. The results are contextualized by how different parameters, such as window size or color or brightness, contribute to user-reported experience, thus bridging a gap between reported user emotions and perception and the corresponding spatial characteristics.

Tested variables including light intensity, material reflectance, or window size correspond with reported user experiences of openness, ambiance, and excitement. Figure 5 illustrates a profile plot and the mean user-response between the experimental spaces and their associated emotional and perceptual responses.

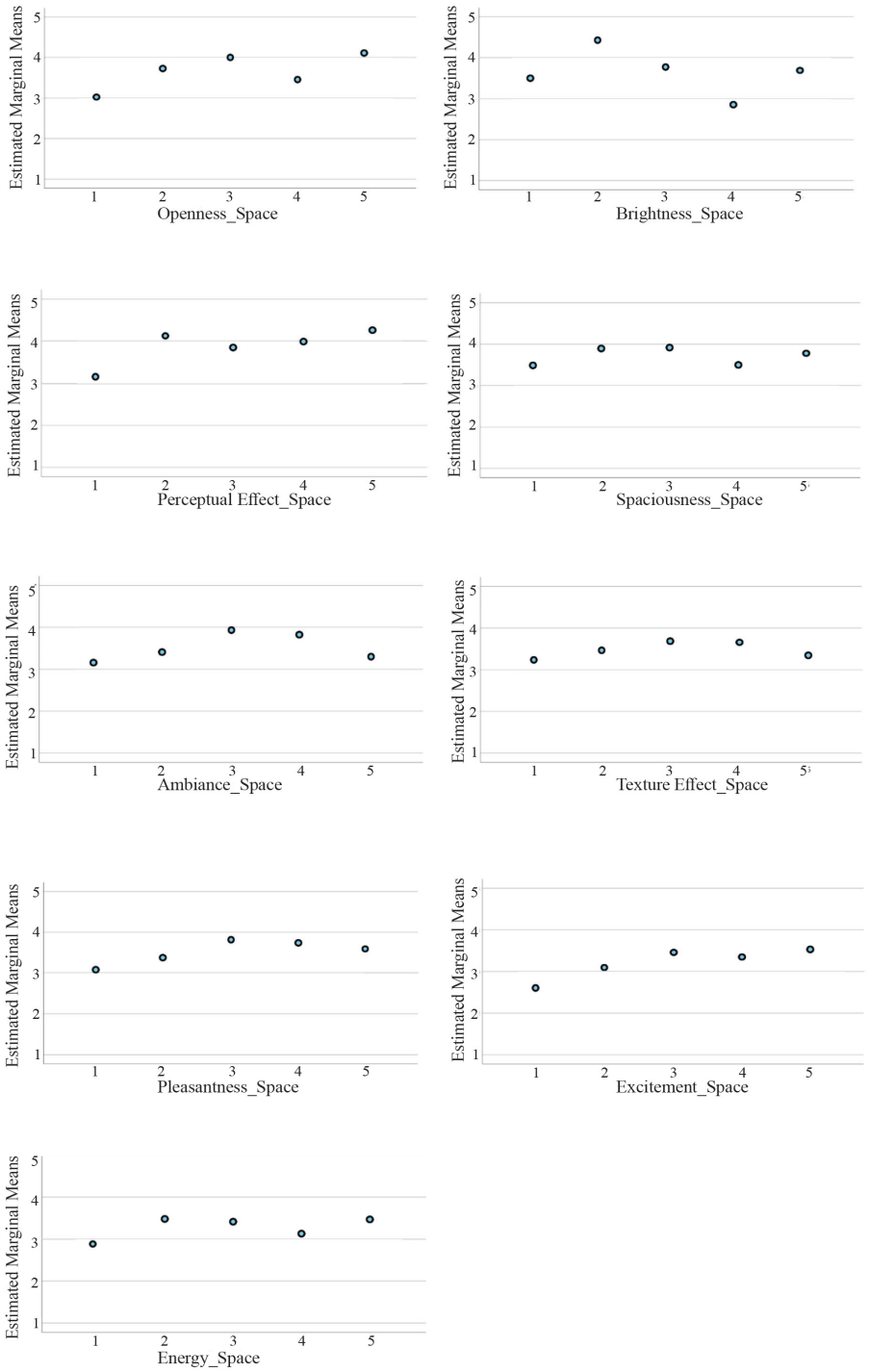


Figure 5. Mean Responses for tested user perceptual and emotional responses across the 5 spaces.

6.2. QUALITATIVE RESULTS

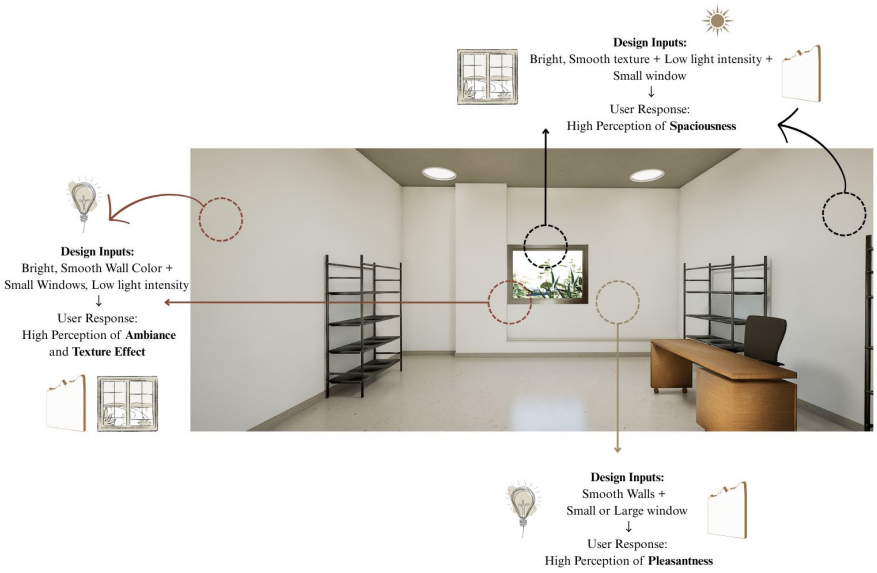
The qualitative insights serve to further validate the findings of the quantitative data and corroborate the effect of light, material and space on user's experience from a perceptual and emotional level. For example, participants associated large windows and bright, textured walls with low light intensity with increased perception of openness and pleasantness, while dark, smooth walls and small windows made participants perceive the space as enclosed. Additionally, participants reported that perception of brightness was affected by both the intensity of light and its interplay with wall material and space size. These subjective feedbacks validate how material and light interaction can modulate perceived spatial perception such as spaciousness and brightness, how the qualitative differences may account for subtle variabilities that are not statistically significant within a given sample size, and how these interactions have a variation of effect to spatial environments by changing variables of light, material or space.

Moreover, the combinations of textural contrast such as rough, brick finishes combined with low light intensity were associated with high level of excitement. Participants noted that spaces characterized with high-light intensity with bright, smooth texture yielded perceptually bright spaces, while overly bright or dark, textured environments felt overwhelming or dull. In terms of Energy perception, the perception of users was affected by not only window size or brightness but also upon the interaction between light and material variables.

These findings align with those of Wang et al. (2020), (Kobayashi et al., 2025), and Xu et al., (2025) that the emotional and perceptual response within architectural environments are affected through the multisensory integration of spatial characteristics, daylight variability and material compositions. Collectively, the qualitative narratives align and further validates that user perception is not only affected by visual factors but by an interplay between key design aspects, specifically light, space and material variables. The findings highlight that specific design aspects have an interconnected impact on the perception of users and their associated emotional responses.

These responses gained from the participants can be visualized in their respective spaces in relation to the impact of the spatial aspects on the users' perceptual and emotional response, as shown in Figure 6.


Design Inputs:
Bright brick texture + High light intensity +
Small window
↓
User Response:
High Perception of Brightness
Design Inputs:
Bright, Non-dark Wall Color +
High light intensity
↓
User Response:
High Perception of Spaciousness
Design Inputs:
Brick textured Walls +
Small or Large window
↓
User Response:
High Perception of Energy


Design Inputs:
Bright, Smooth texture + Low light intensity +
Small window
↓
User Response:
High Perception of Spaciousness
Design Inputs:
Bright, Smooth Wall Color +
Small Windows, Low light intensity
↓
User Response:
High Perception of Ambiance
and Texture Effect
Design Inputs:
Smooth Walls +
Small or Large window
↓
User Response:
High Perception of Pleasantness

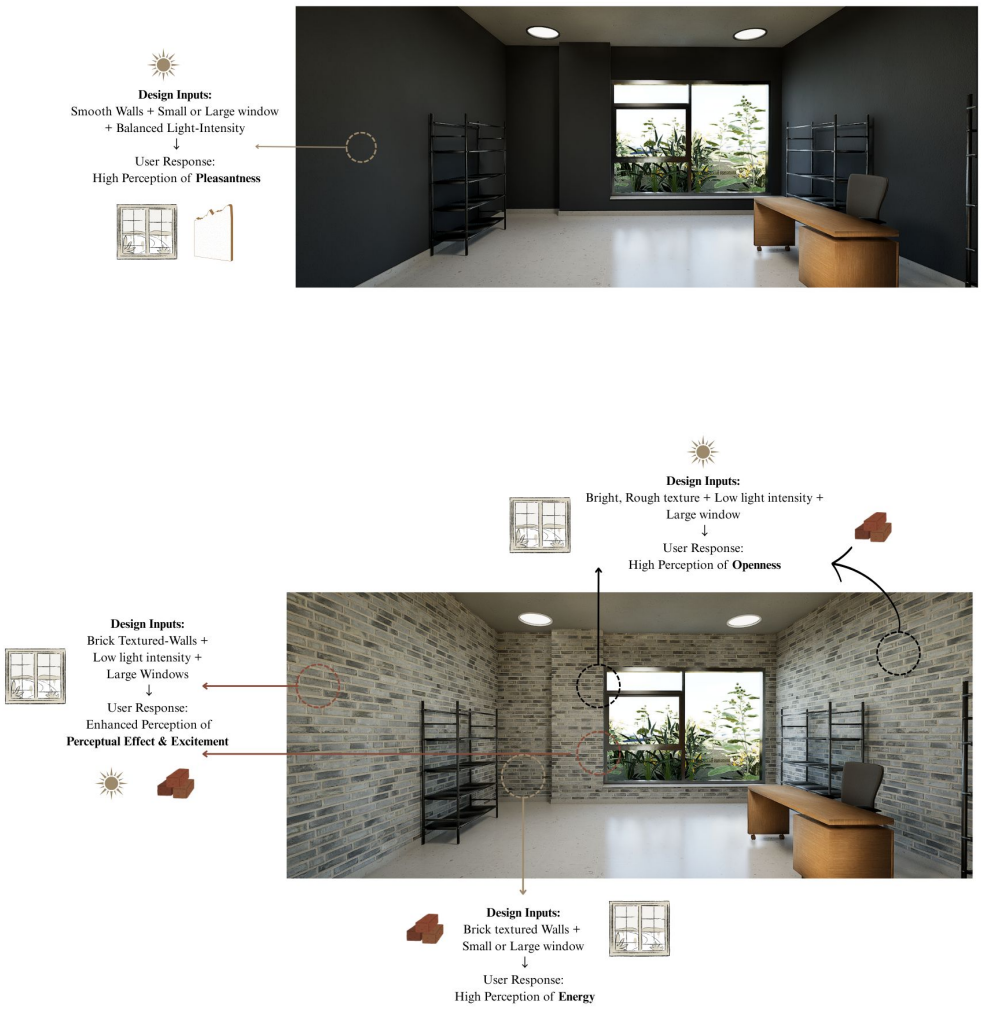


Figure 6. Design Aspects and the 3D Matrix Connections in terms of Emotional and Perceptual Responses

6.3. VALIDATION RESULTS

The results of the quantitative and qualitative data supported that spatial perception and emotional responses are linked to the combined effect of light, space and material on spatial composition. The interconnected elements actively shape how users perceive and experience their surroundings. Quantitative results highlighted key aspects, such as the effect on perception of brightness, openness, and perceptual effect, while qualitative aspects supported these insights by highlighting how material texture, light intensity or space proportions shape emotional engagement. The 3D matrix served as a synthesis framework that contextualized user responses by mapping the findings in relation to perception and emotional responses. These findings further prove that emotional and perceptual responses of users are not tied to a single aspect, but emerge at the intersections between the parameters of light, space and material. For example, openness is not simply related to only large windows, but of how light intensity (Light Aspect) and surface brightness (Material Aspect) interact together within a given spatial composition (Space aspect).

These correlations highlight that architectural experience is inherently proportional; one element gains meaning and importance in relation to other elements. Consequently, these correlations reinforce the value of the 3D matrix, which is not merely developed to test interconnected aspects, but also provide a framework where these interconnected relationships can be visually mapped and systematically analyzed. In doing so, the research shifts from intuitive assumptions towards an evidence-based tool that designers can adapt, replicate and expand to different architectural contexts and typologies.

7. Discussion

As stated previously, the quantitative analysis showed significant effect across the tested variables. For example, perceived openness and perceived brightness were strongly correlated with design aspects such as window size and material color.

Consequently, material texture influenced emotional responses of excitement and energy, validating the role of architectural variables in shaping users' perception. In terms of qualitative responses, deeper observations on "wall texture" and "brighter surfaces" further validate these findings and strengthen the matrix as a tool that maps the interrelation between users' emotional responses, such as excitement energy.

The findings show strong correspondence between the results and previous studies, which reinforces 3D matrix frameworks and support its potential for application in user-centered architectural design studies.

However, the results also demonstrate that human spatial perception is complex and detailed, suggesting that it cannot be reduced into a single factor, since users' emotional responses to a space are influenced by multiple design parameters such as light, space, and material. Thus, designs should consider these multifaceted interplays rather than isolated variables in order to provide structured spatial designs that enhance user experience and their emotional reactions to the space.

7.1. 3D MATRIX CORRELATION WITH FINDINGS

As previously stated, the aim of the 3D matrix is to serve as a holistic tool for analyzing the integration between light, material and space aspects and their interconnected effect on users' spatial perception.

The perception measurement that were assessed includes openness, brightness, perceptual effect, spaciousness, ambiance and texture effect, while emotional responses included pleasantness, excitement and energy. In figure 6, each measured perception is linked to key spatial, lighting and material aspects, as observed in the results. The outcome extracted from the validation studies are visually supported by the 3D matrix diagrams, which map the interrelation between the aspects of light, material and space to both perceptual and emotional responses.

As illustrated in figure 7, aspects such as material brightness, material type and lighting intensity are centrally connected with perceptions of openness, texture effect and ambiance, among other perceptions.

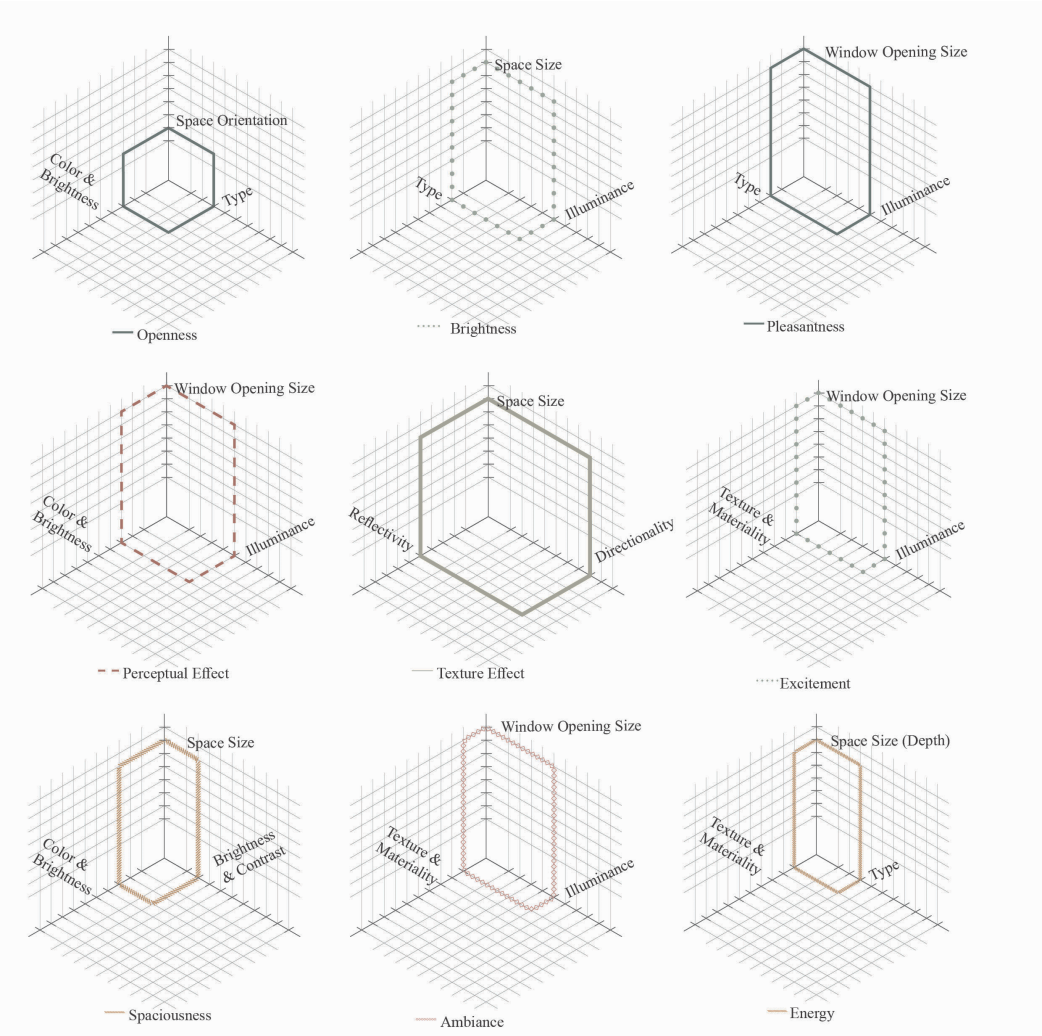


Figure 7. Individual Aspects and the 3D Matrix Connections in terms of Perceptual and Emotional Responses.

By mapping the results such as the effect of wall brightness and light intensity on perceived openness, ambiance and excitement, the matrix reinforces patterns identified in the qualitative and quantitative findings. Additionally, the matrix aligns with past literature studies that were focused on spatial parameters and perception, validating the impact of the connected design aspects on spatial experience. The diagram shows how the sub-parameters across all three axes intersect to visualize the connection between the complex responses, offering a clear framework for mapping perceptual and emotional qualities based on design configurations.

7.1.1. Perceptual and Emotional Dimensions

The findings show that the interplay between light, material and space parameters significantly affect spatial perception. In terms of openness, it was influenced by material brightness and color, as well as daylight type and space orientation.

User associated brightness perception with material type, light intensity and small window size. For example, smaller spaces paired with textured, bright materials and high light intensity were perceived as brightest. Moreover, the perceptual effect was also found to in increased levels in spaces with large windows, bright textures, and low-light intensity. Brighter materials and light wall materials enhanced perception of spaciousness, especially in spaces with compact layout and small windows. In terms of ambiance, users associated ambiance perception with material texture and window size. Spaces with soft, smooth surfaces combined with low light levels provided a satisfying atmosphere. Conversely, spaces characterized with high light intensity often led to discomfort.

In terms of emotional responses, pleasantness was reported in high levels in spaces with smooth walls, larger windows and lower-light intensity, while high-light intensity and compact spaces were associated reduced emotional comfort. Excitement was stimulated by textured materials paired with large windows and low lighting, suggested that balanced and moderate stimulations engaged users emotionally. Lastly, energy perception was associated with bright textures, space size and balanced light types.

These results are presented in figure 8, which shows the interconnectivity between design aspects and their effect on tested emotional and perceptual responses.

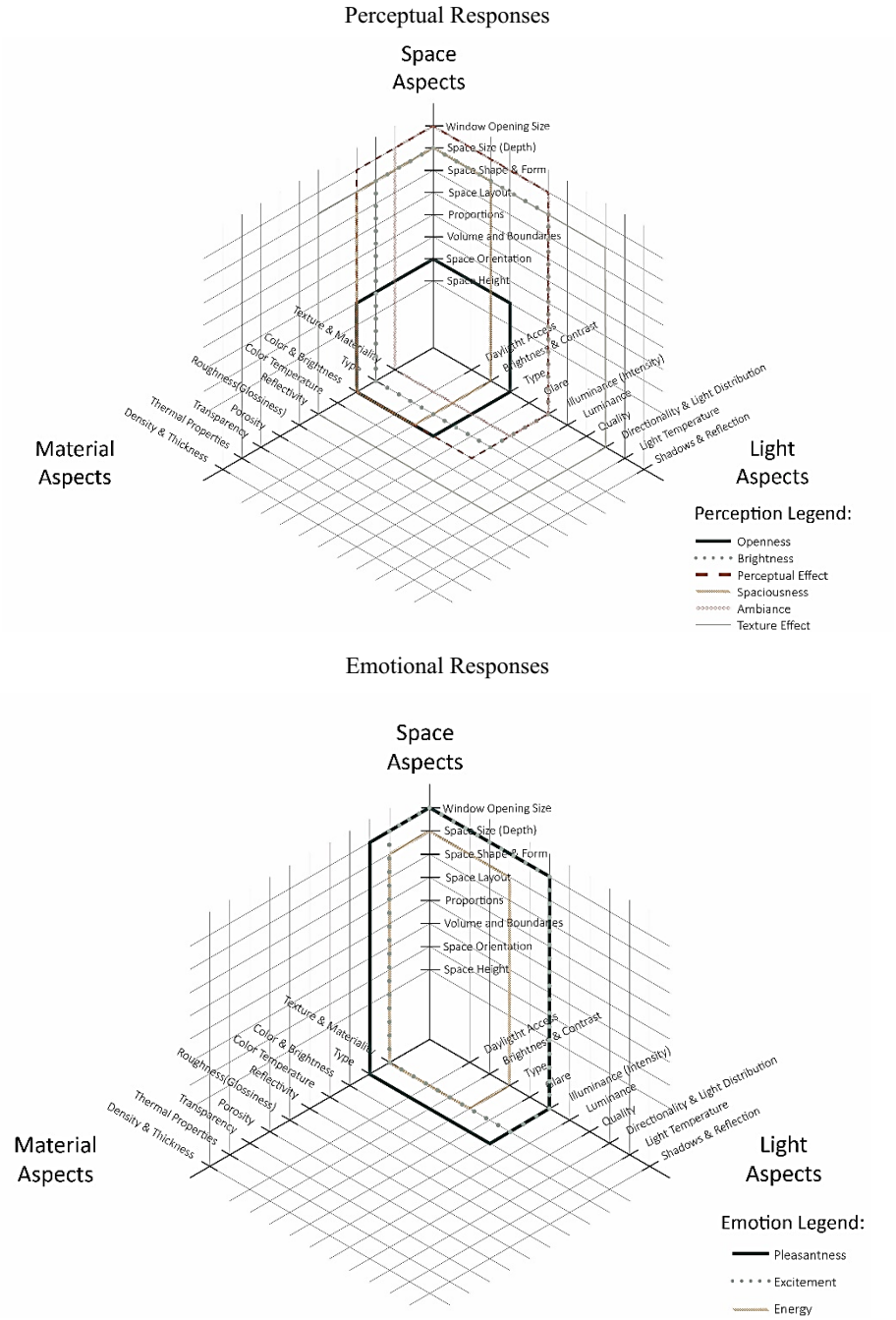


Figure 8. Design Aspects and the 3D Matrix Connections in terms of Emotional and Perceptual Responses

8. **Conclusion**

The interplay of light, material and space and their interconnected impact on users' spatial perception and emotions were analyzed in this research. A The validation of the 3D matrix has been supported through the variation of immersive architectural environments that were simulated through the utilization of VR as a tool, enabling accurate measurement of human perception and their emotional responses. The findings highlight the significant role of these interconnected aspects, such as window size, light intensity and material texture, in shaping user perceptions and in generating spaces that connects with users in a sensory relationship.

The outcome of the research is the structured 3D matrix linking design aspects (light, material and space) to their interconnected effect on perception and emotional responses. The 3D matrix does not only visualize the interdependencies between spatial parameter and user perception, but also functions as a transferable design tool. By highlighting the importance of tacit design knowledge and its impact on spatial experience, the 3D matrix enables architects to predict and test user-centered outcome in methods that are reproducible, evidence-based and adaptable to future studies.

The study also developed a framework that connects the impact on perception with design parameters, and their supporting insights from previous studies, integrating quantitative statistical data with qualitative observation to study the interconnected aspects of light, material and space and their effects on users.

8.1. LIMITATION AND FUTURE WORK

The experiment's reliance on a single VR Headset was a limiting factor in terms of the experiment's scalability and speed. While it ensured technical consistency, it constrained the sample size and provided practical challenges with scheduling pressure and variations in alertness across different tines of the day. Similarly, the relatively small participant (n=30) might restrict the generalizability of the findings across different cultures or typological differences.

While the study provides valuable insights and statistically significant trends, future research could expand the framework by incorporating additional spatial and perceptual aspects. Analyzing adjustable lighting and modular configurations along with variations in daytime and seasons may also offer deeper insights into the dynamics of perception and spatial experience. By

integrating these factors, future studies can build on those foundations to simulate a more realistic and accurate architectural simulations.

Acknowledgments

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DIGITISATION OF HERITAGE SITES VIA AUGMENTED REALITY

Accessibility of Suzhou Gardens for the Differently Abled - A state of the art review of empirical studies

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Abstract. Many heritage sites in China present substantial accessibility obstacles for differently abled visitors. This study aims to answer the research question of how AR technologies are used to enhance the experience for cultural sites' visitors, particularly for differently-abled persons. After filtering the literature on accessibility, inclusivity, and AR, 32 papers were retained, with four directly addressing the digitalisation of Chinese gardens. The review of the articles showed that AR technology has shown potential in enhancing visitor experiences at heritage sites, including in Chinese gardens, and is beneficial for differently-abled communities. It can mitigate physical obstacles and offers long-term preservation and documentation benefits; however, it needs careful integration to balance with the site's value. Inclusivity in tourism is crucial, yet there are still barriers for individuals with disabilities. Clear accessibility standards, legislative frameworks, and collaborative strategies are needed, along with enhanced training and public awareness

campaigns. AR and assistive technologies present promising opportunities for cultural heritage management and social inclusion. By addressing ethical, accessibility, and user-experience challenges, they can enrich and preserve cultural heritage and promote a more inclusive society.

Keywords: *Heritage Sites, Augmented Reality, Accessibility, Suzhou Gardens.*

1. Introduction

Improving the accessibility of heritage sites is important to ensure everyone, including differently-abled people can navigate within the sites without any difficulties. However, many heritage sites, such as the classical gardens in Suzhou, China, present substantial accessibility obstacles for differently abled visitors, primarily due to their historical designs and unusual structural configurations. Against this backdrop, this study aims to answer the following research question: In existing studies, how are Augmented Reality technologies used to enhance the experience for visitors of cultural sites?

Through a systematic review of empirical studies, this study aims to explore the impact and potential of the application of Augmented Reality (AR, henceforth) technologies within heritage sites, with a particular emphasis on how these technologies can be used to better accommodate the diverse needs of differently abled individuals. By analysing a wide range of case studies and experimental research, the review aims to identify best practices, innovative solutions, potential challenges in utilising AR to enhance accessibility and ultimately to identify knowledge gaps within the current studies.

Furthermore, the paper summarises the effectiveness of current AR implementations, discusses their limitations, and proposes future directions for research and practice. A systematic review approach is utilised to synthesise and critically analyse the body of existing research within the field to provide a thorough and up-to-date overview of the current state of knowledge.

The preservation and accessibility of cultural heritage sites are crucial for ensuring that they can be enjoyed by all members of society, including visitors with physical disabilities. However, many heritage sites, such as the classical gardens of Suzhou (China), present significant accessibility challenges for differently abled individuals due to their historical design, architectural barriers and natural landscapes (Marconcini and Pracchi, 2019). Suzhou city in Jiangsu province, known for its classical Chinese gardens, is home to the UNESCO World Heritage Centre. Among these, the Suzhou

Gardens stand out as exemplars of traditional Chinese landscape design (Yang et al., 2024).

The Suzhou classic gardens, renowned for their intricate designs, aesthetic beauty, and cultural significance, often feature uneven terrains, narrow pathways, and delicate structures; thus, many gardens are not easily navigable for individuals with mobility impairments or other disabilities. There are currently 108 gardens in Suzhou that have been included in the "Suzhou Garden List" by Suzhou government and under protection, of which nine have been listed as World Cultural Heritage. The earliest of them can be traced back to the Song Dynasty (960-1279 AD). In the context of the times, these gardens were once private territories, so that they do not consider the needs of differently abled persons. Consequently, differently abled visitors may find it difficult or even impossible to fully appreciate and engage with these sites' heritage and cultural significance (Gillovic and McIntosh, 2020). While adaptations such as tactile paving exists, the interplay of Suzhou Gardens' micro-features—rockeries limiting GPS signals, water reflections disrupting AR visibility, and winding paths complicating navigation—creates compound barriers unaddressed by generic accessibility solutions. Current AR proposals lack empirical validation in these environments, risking misalignment with actual user needs (Gillovic and McIntosh, 2020; Yang et al., 2024)

In response to the need for greater accessibility, there is a growing emphasis on adapting these historical sites to make them more welcoming to differently-abled travelers. Enhancements such as wheelchair-friendly pathways, clear signage, and multimedia guides are used (Yang et al., 2024; Zhang and Sikka, 2023), significantly improving the experience for differently-abled visitors. The inclusion of sensory elements, which appeal to visually impaired individuals, can potentially add depth to the experience, allowing them to connect with the garden's natural beauty in innovative ways.

AR technology enables the overlay of digital information onto the physical world, providing opportunities to recreate and reimagine the experience of visiting heritage sites in a more accessible manner. Using AR-enabled devices, visitors can engage with virtual reconstructions of the gardens, complete with historical context, interactive features, and guided tours. These virtual elements can be customized to meet the specific needs of differently-abled users (Yang et al., 2024), offering alternative sensory experiences that compensate for physical barriers present in the actual gardens (Dania et al., 2021).

2.Research Methodology

A literature review was conducted utilising the following search approach. In the first stage, this search is conducted searching on Google Scholar, Web of Science, Scopus, and CuminCAD repositories and filtering via primary keyword: “virtual reality”, “augmented reality”, “accessibility” and “heritage”. The following step was to proceed with a qualitative selection of publications. This search, represented in Figure 1, reported 716 research papers published on the topic of AR in cultural heritage. Publications that are not directly relevant to the research topic were excluded, even if they met specific keyword criteria.

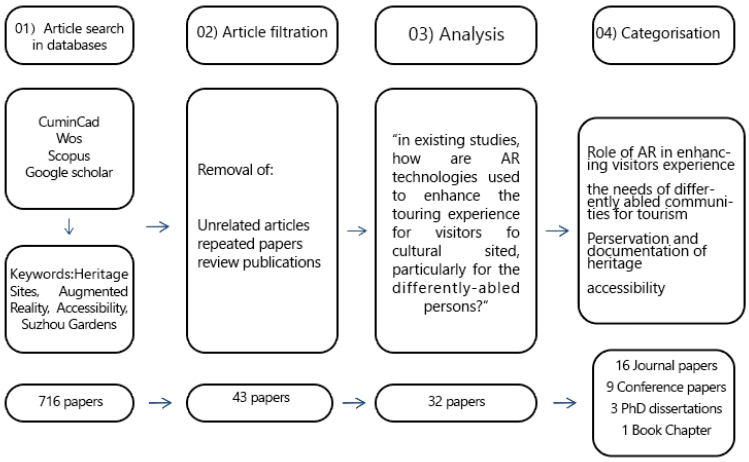


Figure 1. The Process of Literature Review

After filtering the literature based on the focus of this study on issues of accessibility, inclusivity, and the use of AR for individuals with disabilities, 32 papers are retained. Ultimately, four studies directly address the digitalisation of Chinese gardens, including Suzhou Gardens (Cao et al., 2018; Jia et al., 2022; Yang et al., 2024; Zhou et al., 2019). These studies discuss the unique architectural and cultural aspects of Chinese gardens and explore how AR can enhance accessibility and visitor experience, particularly for differently-abled individuals.

3. Discussion

Table 1 summarises four critical tenets of discussions and mentions references in the remainder of this paper, derived from thematic analysis of

the gathered literature. They span from the role of Augmented Reality to improve visitor experience, highlighting the tourism needs of differently abled communities, the importance of preserving cultural heritage, and lastly, the accessibility aspect of cultural sites.

TABLE 1. Key themes and selected references

Theme	Tools and Methods Used	References
3.1 The role of augmented reality in enhancing visitor experience	AR techniques, PoeticAR	Balbi, B., & Marasco, A. 2021.; Gardner et al., 2024; Liebermann 2029; Delgado N &Escudero F,2011; Tian et al, 2023; Partarakis. N., and Zabulis, X, A. 2024; *M, Žilak*., *Ž Car*., *I Čuljak*., 2022;Li, J. et al 2023;
3.2 Needs of differently abled communities in tourism	RFID system, Maya, GPS positioning	Altinay et al., 2016; Gillovic & Mclntosh, 2020; Han et al., 2019; Vila et al., 2015; Wan, 2024; Yang et al., 2024; Yang, Z., et al.2024; Yung, R., & Khoo-Lattimore, C., 2019
3.3 Preservation and Documentation of Heritage	GIS, Unreal Engine	Guedes et al., 2023; Guimaras et al.,2015; Innocente et al.,2023; Pirrone et al., 2023; Ruiz-Rodrigo et al., 2024;Fang & Zhao. 2021; Sood &Bhandari, 2023; Wang, Y., et al. 2024
3.4 The accessibility	GPS positioning, Blender	Jia et al., 2022; Lauria, 2016; Marconcini & Parcchi, 2019; Zhang & Sikka, 2023; Ahmetovic, D 2021

3.1. THE ROLE OF AUGMENTED REALITY IN ENHANCING VISITOR EXPERIENCE

One of the primary advantages of AR technology is its ability to enrich the visitor experience through interactive and immersive presentations. Traditional methods of engaging with heritage sites often rely on static displays, brochures, and guided tours, which may not fully captivate or educate visitors (Balbi and Marasco, 2021). AR enables users to use their smartphones or AR glasses to access additional layers of information overlaid on the physical site (Gardner et al., 2024). This can include three-dimensional reconstructions of ancient structures, visual storytelling

elements, or contextual historical data that provides a deeper understanding of the site's significance (Liebermann, 2019; Marconcini and Pracchi, 2019).

For example, when a visitor points their device at a fragment of an ancient wall, AR can render the original structure in its entirety, showcasing how it looked in its prime. This capability not only captivates audiences but also enhances educational outcomes, as the information presented can be tailored to different audiences, addressing varying levels of interest and expertise (Navarro Delgado and Fonseca Escudero, 2011). However, Suzhou Gardens' high visitor density and confined spaces (e.g., <2m-wide corridors) challenge AR's core assumptions. Audio guides may drown in ambient chatter; haptic feedback risks causing collisions; visual overlays compete with intricate scenery. No reviewed study addresses these trade-offs, despite their centrality to accessible design (Marconcini and Pracchi, 2019). While promising, high-fidelity AR documentation faces scalability challenges in resource-limited heritage sites like regional Suzhou gardens. Current studies prioritize technical experimentation over cost-benefit analysis, neglecting low-cost alternatives suggested by (Sood, M., and Bhandari, H. 2023) but untrialled in Chinese garden contexts.

The literature highlights the transformative potential of AR in enhancing visitor experiences at heritage sites by offering interactive and immersive presentations, which contrast with traditional static methods like displays, brochures, and guided tours. Tian et al (2023) developed initial prototype of PoeticAR, an AR interface to present poems based on physical scenery of Jichang Garden in Jiangsu province in China; and found out that the AR interface significantly motivated tourists' interest in poems. In return, this also enhances the cultural and aesthetic tour experience in the garden. In addition, AR leverages smartphones and AR glasses to overlay additional layers of information, including three-dimensional reconstructions, visual storytelling, and contextual historical data, thereby deepening understanding and captivation.

For example, AR can virtually reconstruct ancient structures, showcasing their original form and enhancing educational outcomes by tailoring information to different audiences. However, critical analysis reveals challenges such as technological accessibility and the potential distraction from the physical site, necessitating careful integration to balance AR's immersive benefits with the site's inherent value and visitor experience.

3.2 THE NEEDS OF DIFFERENTLY ABLED COMMUNITIES IN TOURISM

The tourism industry plays a pivotal role in global economic growth (Han et al., 2019), but the sector's accessibility for individuals with disabilities remains a significant concern. Organisations such as the United Nations emphasise the importance of inclusive tourism, asserting that travel should

be accessible to everyone, irrespective of physical capabilities (Vila et al., 2015). It is necessary to look into the specific needs of the differently-abled community within the tourism sector, examining existing research that addresses barriers, accessibility standards, and the roles of various stakeholders in promoting inclusive tourism (Vila et al., 2015).

Numerous studies highlight the barriers faced by differently-abled individuals in tourism settings (Gillovic and McIntosh, 2020; Vila et al., 2015; Wan, 2024). These barriers often include physical obstacles such as inadequate facilities, inaccessible transportation, and poorly designed attractions. These limitations restrict the full participation of differently-abled tourists in various tourism activities. Additionally, the accessibility needs vary for different types of disabilities, each requiring tailored solutions.

Clear accessibility standards are essential for creating an inclusive environment. In many regions, legislation aimed at improving access is in place, such as the Americans with Disabilities Act (ADA) in the United States (Altinay et al., 2016). Since the 2004 World Heritage Conference in Suzhou, China's first "World Cultural Heritage Monitoring Center" has been established there. This centre monitors building movement, humidity, and visitor volume in real time, reporting data directly to the State Administration of Cultural Heritage and UNESCO. In 2018, Suzhou was designated the world's first "World Heritage Model City," and its conservation model is considered a model for the Asia-Pacific region. Any innovation must assume exemplary responsibility. AR technology must ensure that it does not compromise authenticity, integrity, or violate the ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites. If serious violations are not addressed, UNESCO may inscribe the Suzhou gardens on its List of World Heritage in Danger or even revoke their World Heritage designation. Dresden, Germany, was previously removed from the list due to the construction of a new bridge that disrupted the valley landscape, demonstrating UNESCO's strict adherence to the principle of integrity.

However, Suzhou Gardens' national heritage status imposes unique constraints: rockery-protection laws forbid widening <1.2m pathways; UNESCO aesthetics guidelines limit AR visual intrusions. Current accessibility frameworks fail to reconcile these conflicts—evidenced by Yang et al. (2024)'s AR prototype violating 3/5 World Heritage Operational Guidelines. This policy-implementation gap necessitates context-sensitive AR design balancing preservation mandates with multi-disability access (Gillovic and McIntosh, 2020). Comprehensive strategies that incorporate universal design principles are also advocated to ensure equitable access in tourism infrastructure.

Various stakeholders, including government agencies, tourism operators, and local communities, play crucial roles in promoting accessible tourism. Collaboration among these entities is essential for developing tourism experiences that cater to the needs of differently-abled travellers (Gillovic and McIntosh, 2020; Yang et al., 2024). Training and awareness among service providers can enhance the overall travel experience for differently-abled individuals. Public awareness campaigns can also foster more inclusive attitudes within the tourism sector.

3.3 PRESERVATION AND DOCUMENTATION OF HERITAGE

One way to preserve the cultural heritage is through digitalisation. Fang and Zhao (2021) suggest that the digital dissemination of Chinese classical garden is mainly reflected in three aspects: construction and protection, scenic area management and three-dimensional display. Along with the potentials, they also listed key problems in the digital dissemination related to the intrinsic value of gardens, lack of systematic and integrated promoted strategy and further expanded dissemination channels.

Sood and Bhandari (2023) emphasised the significance of integrating smart technologies in the heritage interpretation of historic gardens. In the case study of Ram Bagh in Amritsar, India, they demonstrated that limited and outdated interpretations had a detrimental effect on the understanding and appreciation of the historic garden. Along with AR, their study proposed different smart technologies to contribute to the visitor experience, such as Internet of Things in the form of RFID tags or QR codes, IoT-based Global Positioning System (GPS) tracking software, a cloud computing platform to store various types of garden-related information, virtual reality and mobile applications with gamification elements such as Scavenger hunt games. As archaeological sites are subjected to environmental degradation, urban development, and tourism pressures, the ability to digitally document these sites becomes essential (Innocente et al., 2023; Pirrone et al., 2023; Ruiz-Rodrigo et al., 2024). Sood and Bhandari (2023)'s RFID system maps barrier-free routes at 1/10 LiDAR's cost yet remains untested in Suzhou gardens' stone-intensive environments. Contrastingly, Suzhou's 9 UNESCO gardens use LiDAR for conservation, but there are no datasets that integrate accessibility features, for example, wheelchair turning radii. AR can store detailed information about the physical conditions, structural integrity, and historical context of heritage sites so as to become invaluable data for future restoration efforts and ongoing conservation initiatives.

Furthermore, as parts of cultural heritage become lost or deteriorate over time, AR technology allows for effective virtual reconstructions (Navarro Delgado and Fonseca Escudero, 2011). Applying AR techniques, developers can recreate lost features, providing both a visual guide for restoration and a

means for educational engagement. This approach not only assists conservationists but also ensures that the narrative of the heritage site continues to evolve and engage future generations (Ruiz-Rodrigo et al., 2024).

Establishing a personalised user interaction with natural heritage space is crucial for conveying its narrative and aesthetic essence while exploring alternative means of immersing users in the environment. Accordingly, Guimaraes et. al (2015) integrate Augmented Reality technologies with concepts of Transmedia Storytelling, applied explicitly to garden settings, as a framework for developing media-art digital artefacts. Despite its benefits, the integration of AR in heritage sites is not without challenges. One significant concern is the balance between technological enhancement and the preservation of the site's authenticity. Guedes et al. (2023) argue that the introduction of digital elements may overshadow the physical presence of the heritage itself, leading to a commodification of cultural experiences. Therefore, it is crucial to ensure that AR applications do not detract from the intrinsic value of the historical site but rather augment it in a complementary manner.

Additionally, there are practical considerations regarding the implementation of AR technologies. Access to devices and the digital literacy of visitors can vary significantly, impacting the overall effectiveness of AR experiences (Marconcini and Pracchi, 2019). Heritage organisations need to consider how to make AR technology accessible to a broader audience, ensuring inclusivity regardless of socioeconomic status or technological familiarity.

The digitalisation of heritage sites through AR technology offers transformative possibilities for both visitors and conservationists. AR represents a promising avenue for the future of cultural heritage management, as the technology was found to enhance visitor experiences (Innocente et al., 2023; Lauria, 2016). However, in leveraging this technology, careful consideration must be given to ethical implications, authenticity, and accessibility to ensure that the integration of AR serves to enrich, rather than detract from, the profound legacy of our shared cultural heritage.

3.4 THE ACCESSIBILITY

Accessibility for differently-abled individuals, encompassing visually impaired, hearing impaired, and wheelchair-bound populations, has become a critical area of research and technological development. The term differently-abled serves as a broad umbrella to account for diverse

disabilities, promoting an inclusive perspective that recognises the unique challenges faced by each group (Liebermann, 2019).

Categorising individuals as differently-abled rather than disabled reflects a shift in the normalisation of societal attitudes toward disability. This terminology acknowledges that while these individuals may face challenges, they possess capabilities that should be recognised and valued (Marconcini and Pracchi, 2019). The varying nature of their disabilities, ranging from sensory impairments to mobility restrictions, requires a nuanced approach to accessibility that goes beyond conventional definitions of disability (Balbi and Marasco, 2021).

The field of assistive technologies, often referred to as special assistive technologies, has seen significant advancements aimed at enhancing the lives of differently-abled individuals. These technologies have evolved to address specific needs, including mobility aids for wheelchair users, auditory assistance devices for the hearing impaired, and navigational tools for the visually impaired (Pirrone et al., 2023; Ruiz-Rodrigo et al., 2024). However, the development of these tools often varies based on technological and knowledge accumulation limitations, leading to disparities in accessibility solutions available to different groups.

A critical challenge in creating effective assistive technologies lies in the need for experience-centred design. The primary objective is to provide differently-abled individuals with experiences that allow them to engage fully with their environment (Guedes et al., 2023). By understanding the unique perspectives and needs of these populations, researchers can develop technologies that facilitate a more inclusive experience (Lauria, 2016). This emphasises the importance of user experience as an integral part of the design process, where the focus should not solely be on technological accumulation but rather on creating meaningful interactions.

3.5 SUMMARY

Current research exhibits significant gaps in the context of Suzhou Gardens. First, there is a lack of systematic analysis of the gardens' unique physical barriers (e.g., narrow pathways and rockery layouts) and locally adapted AR designs that integrate aesthetic characteristics. Second, existing AR solutions primarily target single disability types, failing to establish interactive systems compatible with combined visual, auditory, and mobility impairments. Third, outdoor AR faces unresolved technical challenges in Suzhou Gardens, including GPS positioning inaccuracies under dense foliage and interface visibility in bright light. Finally, long-term empirical validation of AR's effectiveness for differently-abled visitors in this specific heritage context remains absent. Addressing these gaps requires

interdisciplinary collaboration to develop cost-effective, multi-modal AR frameworks tailored to Suzhou Gardens' distinctive heritage landscape.

One of the pressing challenges in researching and implementing accessibility solutions is the relatively small population base of differently-abled individuals. This demographic limitation complicates efforts to gather quantitative data that can inform scalable solutions (Marconcini and Pracchi, 2019). As each subgroup may face distinct issues, developing a tailored approach for individual needs may present logistical challenges and raise questions about the feasibility and value of such targeted interventions. Moreover, while customising assistive technologies for specific individuals can yield significant benefits, it also raises concerns about the broader applicability of these solutions (Liebermann, 2019). Questions regarding the sustainability and scalability of such projects often arise, particularly when considering their alignment with heritage and community needs.

4. Conclusion

This research seek to answer the research question, "In existing studies, how are Augmented Reality technologies used to enhance the experience for visitors of cultural sites?" The attempt to answer this question is reflected through the four key themes as laid out in the Discussions section, which is found to be rotating around the fourth theme, which is accessibility for differently-abled communities.

Firstly, in terms of the role of AR in enhancing the visitor experience, it can be seen that it positively acknowledges existing projects with AR utilisation around the world, including Chinese gardens. For differently-abled communities, allowing specific types of interaction has become a key concern across the different treatments of impairment: visual impairment, hearing impairment and wheelchair-bound populations. Secondly, in terms of the needs, mitigating the physical obstacles (inaccessible terrain of gardens, for example) through the use of AR might open up access to the interface from any part of the world. It also posits another question related to other types of obstacles apart from physical obstacles, for example, cognitive obstacles or access to technology, which is one of the fundamental gaps in the current studies. Thirdly, in terms of preservation and documentation of the heritage, AR, along with other smart technologies, shows long-term benefits. Lastly, in terms of accessibility, the focus for future studies can be directed towards a more experience-centered design for assistive technology.

AR has the potential to revolutionise heritage site experiences by providing immersive, interactive presentations that surpass traditional methods. AR's ability to overlay 3D reconstructions and historical data

enhances education and captivates audiences, but requires careful integration to balance these benefits with the site's intrinsic value and visitor experience. Inclusivity in tourism is also crucial, yet barriers like physical obstacles and inadequate facilities still limit accessibility for individuals with disabilities. Establishing clear accessibility standards, legislative frameworks, and collaborative strategies among stakeholders are essential for creating inclusive tourism experiences. Enhanced training and public awareness campaigns further promote inclusivity.

AR technology not only enriches heritage site visits but also serves as a tool for documentation, preservation, and educational engagement, enhancing conservation efforts. However, implementation must avoid overshadowing the sites' intrinsic value, ensuring digital enhancements remain complementary. Ethical considerations and accessibility issues necessitate inclusive design practices. Assistive technologies for differently-abled individuals reflect a shift towards more inclusive, user-centric design, addressing specific needs related to mobility, sensory impairments, and environmental engagement. Experience-centred design is crucial for creating meaningful, inclusive interactions.

AR in heritage sites and assistive technologies for differently-abled individuals offer promising avenues for cultural heritage management and social inclusion. AR technology plays a crucial role in heritage sites to enhance humanistic care for differently-abled people. AR can offer better experiences in the tours, providing an inclusive and caring experience.

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EXPLORING THE POTENTIAL OF AUGMENTED REALITY IN MULTI-LAYERED HISTORICAL CITIES

A Proposal for the "Hippodrome - Horse Square - Sultanahmet Square" in Istanbul

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Abstract. Multi-layered historical cities are urban landscapes shaped by successive periods of architectural, cultural, and social transformation. These cities host both visible and invisible traces of different civilizations, forming complex urban narratives that are often challenging to perceive in their entirety. Due to contemporary urban developments and the physical disappearance of many historical layers, visitors today struggle to grasp the spatial and historical continuity of such cities. In this context, Augmented Reality (AR) technologies offer a promising medium not only for visualizing lost or transformed structures, but also for building spatially coherent and semantically rich narratives. Rather than treating AR as a visual support tool, this study positions it as a narrative device capable of deepening the user's understanding of spatial continuity and historical transformation. The study proposes a spatially grounded, narrative-based AR experience, developed for the Hippodrome area in Istanbul. This site, layered with traces from Byzantine, Ottoman, and Republican periods, serves as a powerful testbed due to its historical richness and current physical emptiness. A route was designed based on on-site spatial analysis and historical research. The route structure features two interwoven narrative axes: a horizontal narrative, which presents the historical transformation of the entire area as users walk from one end of the square to the other, and vertical narratives at each point of interest (POI), providing focused stories about individual monuments. To evaluate the effectiveness of this narrative AR experience, a comparative user study is designed. The study investigates users' perception of spatial continuity, ability to reconstruct historical transformations, and cognitive engagement with layered urban history. Ultimately, this research contributes a narrative

framework for AR applications in heritage contexts, shifting the focus from static historical visualizations to immersive and context-aware urban storytelling. It aims to enhance spatial literacy and historical understanding in complex, stratified urban environments through a place-based, layered, and semantically informed AR experience.

Keywords: *multi-layered historical city, place-based storytelling, narrative design, spatial experience, augmented reality*

1. Introduction

Over time, cities that have witnessed uninterrupted settlement have evolved into multilayered urban environments, formed by the accumulation of architectural, cultural, and administrative traces from different historical periods. These multilayered cities not only embody a physically accumulated urban memory but also offer a conceptual space in which the past, present, and future can be simultaneously contemplated. However, today, these layers have become largely invisible; as structures disappear, meanings erode, and contemporary urban interventions dominate, these stratifications persist mostly in archives, maps, or excavation sites. Yet, these layers are not merely archaeological or architectural data, they are carriers of collective memory. Therefore, preserving them is not sufficient on its own; presenting them in a meaningful and intelligible way is equally essential (Altınöz, 2002; Yüksel, 2021).

Perceiving historical continuity in multilayered cities is only possible not through the physical presence of structures alone, but through the relationships between them across time and the semantic networks they form within the urban space. In this sense, cities must not be viewed simply as accumulations of architectural remains, but as narrative structures layered with changing regimes, cultural shifts, and spatial organizations. Ensuring the sustainability of this stratification, both physically and in terms of meaning, increasingly relies on the tools provided by digital technologies. Extended Reality (XR) platforms—especially Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—have become powerful instruments in visualizing and re-experiencing historical stratification.

Each XR technology carries its own strengths. VR disconnects users from the physical world and immerses them in a fully virtual environment. MR allows for a more seamless integration between digital and physical elements. However, in open urban spaces where the physical environment continues to be actively experienced, AR emerges as a more practical solution. AR enables users to access contextual information through visual and auditory digital layers superimposed on real space, using mobile and

location-based devices. The fact that it does not isolate the user from the physical site but instead enhances it with digital content makes AR particularly suited to urban stratification studies.

However, this study does not treat AR as a mere visual support tool but rather positions it as a narrative medium that constructs spatial meaning. While much of the literature on AR applications in heritage focuses on presenting individual buildings or offering factual data, these approaches often fall short in conveying the broader historical and spatial context. In contrast, in multilayered cities, the meaning of a structure is not isolated—it is defined through historical transitions, urban ruptures, and shifting cultural associations. Therefore, this study proposes a narrative-driven AR experience that not only tells what existed but invites users to understand how it evolved, where it stood in different eras, and how its meanings transformed over time.

The proposed AR approach operates on two intertwined narrative axes: horizontal and vertical. The horizontal narrative provides a spatially coherent storytelling flow along a route, allowing users to grasp the overall urban transformation. The vertical narrative, on the other hand, zooms in at each point of interest (POI) to deliver a focused, temporally layered story about individual monuments. This dual structure enables users to mentally reconstruct not only what changed but also the urban logic and symbolic roles of those changes.

Importantly, the narrative content is not based on a standardized formula but is developed through contextual analysis of each site's historical, spatial, and semantic attributes. This flexibility ensures that the AR experience is tailored to the specific dynamics of the urban environment. In this sense, the question is not only "what is being shown in AR?", but also "how is it sequenced?" and "why is it presented that way?"—marking a shift from static visualization to contextual narration.

In conclusion, this study explores how users experience multilayered urban environments, how they interpret spatial and historical relationships between layers, and how AR can support this process. Going beyond conventional AR applications, it proposes a site-specific, narrative-based AR framework that fosters both temporal and spatial cognition, offering a new approach to engaging with cultural heritage in complex urban contexts.

2. Background

In the study conducted in 2023, which is designed to discuss the concepts of multi-layered historical cities, it is stated that these terms have emerged in the last twenty years. It is stated that in order to classify a city as a multi-layered historical city, the time dimension must have an effect on the city

itself, and that these cities have witnessed the passage of time and have undergone continuous settlement, change and development over long periods (Eren, 2023). The implicit, partial and explicit coexistence of traces of different historical, cultural and social periods is what defines these cities themselves, their cultural and historical heritage and today. The preservation and interpretation of historical traces play a crucial role in understanding and protecting a city's history while passing its cultural and historical heritage to future generations (Nilson & Thorell, 2018).

In this context, it can be said that Extended Reality technologies, which include Augmented Reality, Virtual Reality, and Mixed Reality, have significant potential in this context. Youn and Ryoo (2021) show how VR and AR can facilitate public engagement and memory preservation in multilayered heritage sites by offering non-invasive digital restoration alternatives. Studies exploring the potential of digital technologies, particularly tools such as augmented reality (AR), virtual reality (VR), and CAD, to revisualize and experience historical layers can be multiplied. Fei (2023) introduces systems that reconnect aristocratic museums in Rome with the past through AR-enhanced narrative; Yang and Huang (2024) demonstrate how historical continuity can be spatially conveyed through VR-enhanced landscape design. Brusaporci et al. (2017) demonstrate how AR functioned as a narrative tool between history and memory in the post-earthquake reconstruction of L'Aquila. These studies demonstrate that digital tools can play a decisive role not only in presenting but also in reinterpreting and experiencing layers.

As discussed in the introduction, AR offers more than just a visualization tool in multi-layered historical cities—it becomes a narrative interface that enables users to spatially experience historical continuity and transformation. Recent studies demonstrate the increasing focus on narrative-driven AR applications that are site-specific and temporally layered. Liestøl (2014) emphasizes the importance of structuring narratives not only around fixed points but along spatial trajectories, as in his Appian Way project. He argues that AR narratives should be designed in non-linear, multi-layered formats to reflect the complexity of historical environments (Liestøl, 2019). Similarly, Shin and Woo (2023) introduce the concept of “spacetelling,” where narratives are embedded in spatial routes and linked to user movement. This spatial engagement fosters deeper cognitive mapping of historical transformations. Other works have explored the participatory and experiential dimensions of AR storytelling. Echavarria et al. (2022) present a model for co-creating narratives with local communities that are then transformed into AR experiences. This not only personalizes the narrative but also enhances place attachment and identity. Trichopoulos et al. (2021) highlight how personalized, layered storytelling enhances spatial and

temporal understanding of heritage sites. Informed by this literature, the proposed project adopts a two-dimensional narrative structure—horizontal and vertical—that connects the overall historical transformation of a site with in-depth stories tied to specific POIs. This allows users to engage with both spatial continuity and temporal rupture, making AR a vehicle for layered historical understanding.

3. A Proposal for the "Hippodrome – Horse Square – Sultanahmet Square" in Istanbul

Having served as the capital of various empires for centuries, Istanbul constitutes a unique example of multi-layered historical cities. The Historical Peninsula, in particular, is one of the richest areas where we can observe this multi-layered structure, with its layered settlement pattern, cultural continuity, and physical traces of successive periods. Indeed, in studies emphasizing the need to consider this structure in planning processes, different regions of the Historical Peninsula have been examined within the context of a multi-layered city structure, and the integration of archaeological and geological data has been suggested (Emre & Erbaş, 2020). In Tokay and İsmailoğlu's (2018) study on Atatürk Boulevard, multi-layeredness is discussed through the documentation of the physical fabric and the redefinition of conservation approaches.

In this context, the Hippodrome area, located in the heart of Istanbul and known today as Sultanahmet Square, was selected for this study's spatial narrative-based AR application. The Hippodrome was chosen not only because it bears the traces of successive civilizations, but also because these traces have largely been physically lost. The area; It encompasses structures, memories, and spaces from the Byzantine, Ottoman, and Republican periods; however, today's user experience is often limited to a few remnants within the square. While no remains of the Hippodrome structure are visible within the square, the square is shaped by its traces. The structural section of the Hippodrome still stands. However, to access it, one must leave the square. The three significant columns in the center of the Hippodrome currently maintain their monumental character, both physically and semantically. However, observations suggest that a significant portion of visitors, while exploring and learning about these important structures, know nothing about the Hippodrome. The site holds significant potential for creating and testing a narrative route within the context of this study.

In the process of developing the narrative, the available historical phases were reviewed, literature on periodic construction and transformations was reviewed, and visual and textual content was collected from various archival sources. Subsequently, on-site explorations were conducted at various points

within the area to analyze spatial character, visibility relationships, and circulation potential. Based on these analyses, a site-specific route was determined. The Hippodrome, a vital urban structure that has almost completely disappeared, is physically depicted and its historical history is presented horizontally, while other monumental structures located within the area are integrated into this horizontal narrative through vertical narratives.

The route begins at the edge of Sultanahmet square, where visitors are shown the Hippodrome's original state, laying the foundation for the horizontal narrative. Users are then guided outside the site, allowing them to perceive the structure's past physical integrity from the outside, aiming to establish context based on first impressions and historical context. During the subsequent walk, visitors continue to encounter vertical narratives about the Hippodrome's history through monumental sculptures at specific POI points. These sculptures are designed not only as visual elements but also as narrative nodes symbolizing the transition between times. After vertical narratives, horizontal narrative of the route continues from the Obelisk of Theodosius to The German Fountain, explores the destruction following the Crusades, its reuse during the Ottoman period, and the transformation of public squares after the Republic. In this process, the transformation of the space's layers of meaning is conveyed to the user, as much as the superficial transformation of the space. The German Fountain, the final stop on the route, is the final vertical element of the narrative, both as a late-Ottoman structure and as a powerful visual element in today's user experience. It presents the symbolic narrative of Ottoman modernization. The horizontal narrative concludes at this point, reflecting the current physical and social context.

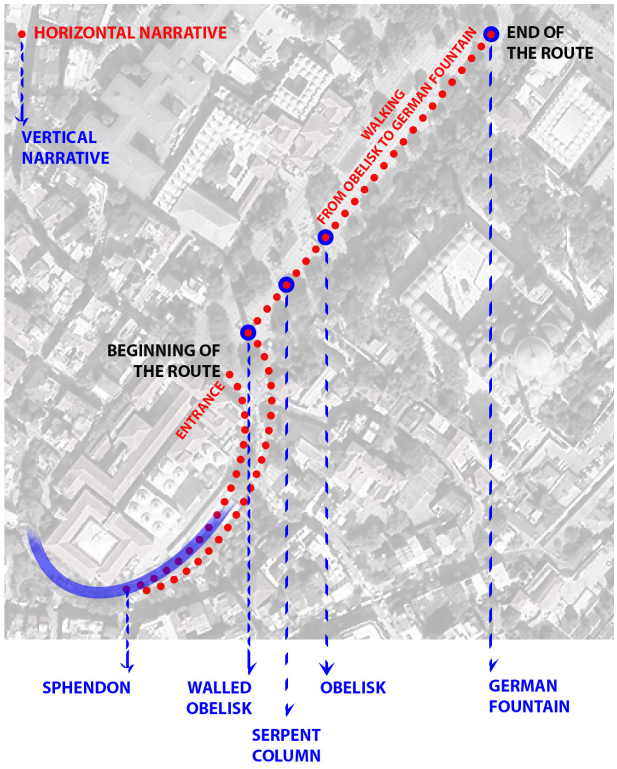
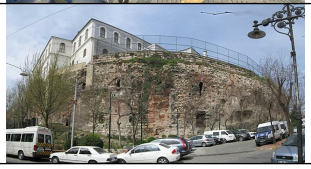
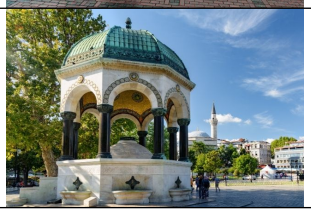


Figure 1. Route of Narrative

To better illustrate how this narrative structure is constructed spatially, the main POIs used along the route are presented below. Each stop either explains the interlayered historical transformation of a monument or serves as a horizontal narrative segment regarding the overall historical context of the site.

TABLE 1. Structure of the Narrative Route and AR Content Design

POI (Points of Interest)		CONTENT		
		Audio	3D	Narrative
Entrance of Sultanahmet Square		architectural details usage in social life of the Hippodrome	3D model of the Hippodrome	a scene of the Chariot Races
Sphendon (South End of the Hippodrome)		structural features of the part of the Hippodrome	3D model of the structure overlayed the existing	a scene of usage in Byzantine time

Walled Obelisk (Constantine Obelisk)		construction process artistic and symbolic meaning	3D model of Bronze plaques placed on the obelisk	simulation depicting the disappearance of the bronze plaques from the obelisk
Serpent Column		origin and importance story of the lost snake heads	3D model of lost snake heads positioned on top of the column	animation of moving snake heads
Obelisk (Theodosius Obelisk)		historical background the reliefs and inscriptions	3D model depicted reliefs	simulation of reliefs
Walking from Obelisk to German Fountain		The transition process from Byzantium to the Ottoman	3D models of the area during different periods	scenes representing Byzantine, Crusade, Ottoman Period
German Fountain		historical context architectural and aesthetic details	-	Scenes describing historical context

In an area like the Hippodrome, which has diminished visible structures and contains numerous historical layers, this approach aims not only to provide the user with information but also to construct a mental framework of historical spatial relationships. A user research framework is proposed to explore relationship between the narrative structure and concepts such as urban memory, continuity, and transformation within such multilayered contexts.

4. User Research Framework Proposal

This section presents a proposed research framework for evaluating the perceptual effects of narrative-driven augmented reality experiences in multilayered historical urban spaces. Rather than describing a completed user study, the framework outlines a future methodological structure designed to assess how narrative-based AR experiences shape users' understanding of spatial continuity and historical transformation. The framework builds on the conceptual premise that AR, when structured through a spatially grounded narrative, can move beyond its visual representational role and act as a tool for reconstructing historical experience and urban memory. The proposed framework is structured around the following research questions:

Q1: How does a narrative AR experience affect users' ability to establish spatial continuity in a multilayered urban space?

Q2: How does a narrative AR experience affect users' understanding of historical transformation over time and their spatial positioning of these transformations?

Q3: Does the presence of a narrative structure increase users' ability to establish semantic connections between the physical environment and historical layers?

The development of the proposed framework was informed by a preliminary audio-based narrative test conducted in the study area prior to AR content design. This early test aimed to evaluate the spatial rhythm, logical flow, and cognitive accessibility of the proposed narrative route without using any visual components. During this pre-test, participants were guided through the route with only audio narration, describing historical layers and transitions. Their feedback indicated that the narrative effectively conveyed a sense of historical continuity but required refinements in pacing and density to improve comprehension across different points of interest (POIs). These insights guided the development of the narrative AR scenario, ensuring that the digital content aligns with both spatial movement and user attention flow.

The research framework thus focuses on understanding how narrative-structured AR experiences can foster a holistic perception of multilayered historical sites. It contrasts two design paradigms: (1) a narrative-based AR experience, in which users follow a spatially and temporally sequenced route with guided storytelling; and (2) a non-narrative AR experience, where users interact freely with 3D visual content and brief informational text without narrative linkage. Comparing these two forms enables the isolation of the narrative's cognitive and experiential impact.

The framework proposes a three-phase methodological structure—pre-experience, experience, and post-experience—that can be adapted for future

empirical testing. The intention is not to prescribe fixed procedures but to provide a structured model for evaluating perceptual and cognitive change resulting from AR interaction.

Phase 1: Pre-Experience

In this phase, participants would engage in a short period of free exploration within the site, followed by tasks designed to assess their baseline spatial awareness and historical understanding. The framework suggests incorporating:

- A cognitive mapping activity, allowing participants to draw or describe perceived structures and their spatial relationships.
- A pre-experience survey focusing on three thematic axes: (1) prior familiarity with AR or the site; (2) perceived historical awareness; and (3) expectations regarding digital representation of history.

These data would serve as the baseline for assessing how participants' mental models evolve through the AR experience.

Phase 2: Experience

Participants would then experience one of the two AR conditions described earlier. In the narrative-based condition, the experience would follow a structured route defined by specific POIs that connect individual monuments through both horizontal and vertical narratives. Each stop would combine 3D visualizations, audio narration, and contextual storytelling to convey the coexistence of multiple historical layers. In the non-narrative condition, the same POIs and 3D content would be accessible, but without route guidance or temporal linkage. Users would explore the space freely, engaging with information at their own pace. The framework suggests that data collection during this phase may include:

- System logs tracking POI visit frequency, time spent at each stop, and interaction with visual elements.
- Observational notes focusing on spatial behavior, attention shifts, and patterns of engagement.

Phase 3: Post-Experience

The final phase would aim to capture how participants integrate spatial and temporal information after the AR experience. Rather than focusing on recall accuracy, this phase would examine how users mentally reconstruct historical continuity and transformation. The framework proposes:

- A layered mapping task, in which participants visually or verbally represent perceived spatial relationships between different historical layers.
- A semi-structured interview centered on thematic domains rather than fixed questions: perception of historical continuity and disruption; cognitive visualization of structures across time; the role of narrative or absence of narrative in constructing meaning; the sense of immersion, orientation, and spatial coherence.

Analytical Approach

Data analysis under this framework would employ a mixed-methods strategy. Qualitative data (interviews, mapping outputs, and observation notes) would be analyzed thematically, focusing on categories such as spatial continuity, transformation logic, and narrative coherence. Quantitative indicators (e.g., number of POIs visited, time per location, and Likert-scale responses in future adaptations) could complement qualitative insights by identifying measurable patterns of engagement.

This framework does not claim to provide finalized results but rather establishes a replicable foundation for future studies seeking to evaluate how AR-based narratives mediate spatial understanding in complex historical contexts. The preliminary audio test demonstrated that even non-visual narratives can significantly influence users' perception of historical continuity, supporting the hypothesis that narrative structure plays a defining role in shaping spatial cognition and memory in augmented environments.

5. Discussion

This study proposes that AR can serve as a narrative medium for interpreting multilayered historical urban spaces, advancing beyond its conventional role as an information or visualization tool. The proposed framework and narrative structure developed for this context demonstrate how AR can be structured to activate users' spatial and temporal understanding through carefully designed narrative flows. Instead of focusing solely on visual reconstructions, the approach emphasizes how these reconstructions are embedded within a spatial route and temporal sequence that reflect the city's multi-layered character.

Within this framework, the horizontal and vertical narrative logic serves as a dual mechanism for perception: the horizontal dimension links multiple periods through continuous spatial movement, while the vertical dimension deepens historical understanding at each point of interest through focused storytelling. This dual-axis structure allows AR to mediate both large-scale transformations and localized, monument-based interpretations. It situates the user as an active participant in reconstructing historical continuity, not as a passive recipient of information.

The preliminary narrative pretest conducted in the study area demonstrated that spatial narrative design itself—independent of visual augmentation—has measurable potential to enhance cognitive engagement. Participant feedback from this early test informed adjustments to the sequence of points of interest (POIs), pacing, and thematic connections, which will serve as critical input for the subsequent AR prototype.

The proposed user research framework, rather than reporting finalized data, establishes a foundation for future empirical validation of these narrative principles. By comparing a narrative-based AR experience with a non-narrative, freely navigable version, future studies will be able to isolate and assess the specific perceptual effects of narrative mediation—particularly in fostering spatial continuity and comprehension of historical transformation.

Ultimately, this research contributes a novel methodological and conceptual model for employing AR in multi-layered urban contexts. It repositions AR as a spatial narrative tool—capable not only of visualizing what has been lost but also of reconstructing the mental and experiential links between different historical layers. Furthermore, the framework proposed here has potential applicability to other heritage sites where spatial stratification and temporal layering define urban identity. By emphasizing user-centered design and narrative coherence, it offers a replicable model for future AR heritage projects that aim to merge technological representation with cognitive and experiential depth.

6. Future Studies

This study argues that the proposed narrative-based AR model has the potential to transform the transmission of historical knowledge and spatial experiences in multilayered urban spaces. This will be explored in the proposed research. However, it is crucial to test its effectiveness with larger sample sizes, particularly to understand its impact on users of different age groups, education levels, and technological familiarity. Future studies could consider the following:

Expanding comparative user studies: Narrative-based AR experiences can be tested comparatively with different user profiles to detail which content structures are experienced by which user groups and how.

Examining different areas using similar methods: The method and scenario developed in this study can be applied to similar areas in other multilayered cities to test the model's international validity.

Enriching narrative structures through interaction: Experimental scenario models can be developed where the user can direct the narrative flow and create choice-based routes.

Analyzing the relationships between spatial and historical cognition using neurocognitive methods: The effects of AR experiences, particularly in terms of cognitive processes such as navigation, recall, and spatial orientation, can be examined in more depth.

In conclusion, the route and narrative model presented in this study not only serves as an example but also opens a wide research area for the development of user-centered, layered and contextual narrative structures in AR-based historical presentations.

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MULTISENSORY PERCEPTION AND MEMORY FORMATION IN DIGITAL SPACES

Sound-Driven Spatial Experience in Virtual Environments

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Abstract. Digital space is not merely a virtual representation of physical environments; it is a multilayered realm of existence where sensory experiences, cognitive processes, and perception converge simultaneously. This dynamic convergence profoundly influences architectural engagement in Virtual Reality (VR), yet most current research on digital space perception remains primarily focused on visual input, neglecting the crucial role of multisensory integration in holistic architectural experience. This research addresses this gap by examining the cognitive impact of synchronous auditory and visual stimuli on spatial perception and the stability of mental representations, or perceived memorability, in VR environments. This study aims to explore how isochronic tones (Alpha: 10 Hz, Beta: 20 Hz, Delta: 3 Hz) influence users' spatial awareness and perceived memorability. The core question is: How do synchronized audiovisual stimuli affect the perception and mental representation of architectural spaces in VR? An experimental VR environment was developed in Unreal Engine 5.3, consisting of 36 rooms across three spatial typologies, each paired with three sound frequencies. To establish a unique temporal parameter, the duration of light in each room was synchronously mapped to a temporal rhythm mechanism derived from the room's Sabine RT60 reverberation estimate, reflecting spatial dimensions rather than acoustic realism.

A total of 28 architecture students and professionals participated, providing qualitative self-report data through open-ended and Likert-type post-experience surveys. Qualitative analysis suggests a differential effect: high-frequency Beta tones may enhance attention and facilitate mental visualization and orientation within digitally complex geometries. Conversely, low-frequency Delta tones tend to foster sensory calm and stronger emotional connections in simpler spaces, potentially strengthening perceptual clarity. These findings offer strong evidence to reposition sound in digital architecture as an active cognitive tool that influences memory traces and orientation, thereby underscoring the necessity of multisensory design for creating cognitively resonant virtual experiences.

Keywords: *Spatial perception, sensory experience, auditory and visual perception, virtual reality (VR), memory*

1. Introduction

Space is more than just a void; it is a realm of existence, the carrier of experience and perception (Norberg-Schulz, 1980). This concept of space, a major topic of debate in the architectural discipline in recent years, has been transformed by technology beyond physical boundaries and has re-emerged in virtual environments (Korkut & Surer, 2023). These technological developments not only change the definition of space but also shape virtual spaces as a dynamic flow interacting with perception. The concept of virtual space began to find its place within architecture in the late 1990s with the development of three-dimensional spaces (Barfield et al. 1995). The existence of these discussions led to a rethinking of the concept of space, openly questioning the role of perception in perceiving space, and enabled today's virtual spaces to find a place in the literature as a specifically experienced form of space. In this context, the concepts of space presented by Roth in his 2018 book are noteworthy (Roth, 2018). Roth's typologies, which examine space in four different contexts, are valuable due to their classification of space, but they remain weak in terms of the relationships established with space. However, space is both a perceptual and experiential formation (Casey, 2000; Tuan, 1977). In this respect, the study, based on Roth's principle of space, also offers an experimental field created through perceptual and experiential virtual spaces.

While the primary element of perception is often thought of as visual sensation, multisensory perception forms the basis for change in the cognitive consequences of experience. Before the emergence of the concept of oculocentrism in design, architecture was a sensory concept (Pallasmaa, 2005). Auditory perception, particularly in combination with visual

sensation, is one of the most influential forms of perception in shaping spatial perception.

In recent years, this topic has become more important in studies that connect architecture and neuroscience. Hearing can help us understand direction, size, and volume better than vision alone (Blesser & Salter, 2007; Pallasmaa, 2014). In virtual reality, where people interact with digital spaces, the use of sound together with visuals helps users feel more connected to the space, both mentally and emotionally (Serafin et al., 2018). How does sound influence spatial memory and perception in virtual environments?

The primary goal of this research is to understand the effects of sound on visual perception by offering an alternative interactive experimental environment and to consider sound as a cognitive phenomenon rather than merely an aesthetic or technical concept.

2. Theoretical Framework: Digital Space, Perception, and Sensory Architecture

While architectural design traditionally aimed to represent space through tools such as plan, section, and perspective in its representational forms, digital technologies have the potential to create an interactive experiential paradigm by directly connecting with space beyond these definitions. Virtual Reality technologies transform the user into a present subject, not merely an observer, in their relationship with space. This concept shapes space as an active cognitive interface, transforming it from a static representation to a more dynamic one. This transformation also brings with it post-digital design approaches. Digital spaces now transcend material boundaries and become entities responsive to data flow with the user, algorithmically structured, and connected to the mind and attention plane. Virtual Reality technologies are one of the most effective tools for embodying this relationship. When we consider Norberg-Schulz's (1980) concept of "place," virtual reality technologies allow us to redefine the concept of "place." With the transformation of digital technologies and virtual reality environments into architectural representation tools, the perception of these place concepts through the senses and their representation in memory maps have begun to be rethought (Jerald 2016, Steuer 1992).

The view that auditory input enhances perception across multiple sensory components and influences memory is increasingly accepted (Blesser and Salter 2007; McLuhan 1964). At this point, sound can be considered not merely a stimulus heard but a type of cognitive mapping tool that influences how space is perceived and remembered. In digital environments, in

particular, we can observe that sound functions more like a navigation code, guiding how the user moves within those boundaries than simply defining the boundaries of space. Voegelin's (2010) definition of sound as "making the absence of things audible" supports this notion.
Examined in this context, sound creates a form of kinetic memory. The experiencer moves according to the direction of the sound, the sense of depth is shaped by the echo, and the surface material can be perceived based on frequency changes. Auditory stimuli represent not only how architectural surfaces resonate but also how our relationship with that surface changes. Especially in interactive VR environments, sound has the potential to be an event initiator, a boundary marker, or a sensory memory trace. For this reason, it was decided that the spaces to be used in the research would be virtual spaces and that these virtual spaces would be designed in Roth's four basic space types, titled (1) Spaces restricted by boundaries consisting of walls and floors, (2) Sensory–perceptual spaces, (3) Spaces of memory, (4) Behavioral spaces.

When examining studies on spatial perception in virtual reality, it is clear that most research in the literature remains influenced by osterocentrism and focuses on visual perception (Loomis & Knapp, 2003; Konrad, Angelopoulos, & Wetzstein, 2020; Korkut & Surer, 2023). However, in architectural practice, the joint use of multiple senses has the potential to alter cognitive outcomes in perception (Malnar & Vodvarka, 2004). This is where the sense of hearing becomes important. While vision is physically open to self-manipulation, hearing cannot be self-manipulated as long as the sound source and conductors are present. This can also be given as an example of how hearing shapes space through sound waves while restricting vision with obstacles on the focal point during the action (Rasmussen, 1993). At this point, the sense of vision can be defined as linear, while the sense of hearing can be defined as spherical. However, both senses are insufficient without each other, so their simultaneous use deepens and transforms the perception of space (Pallasmaa, 2014).

The sense of hearing is shaped by attentional selectivity in environments with multiple competing sounds (Sussman, 2017). In such complex auditory scenes, attention functions as a filtering mechanism (Bergson, 1896), suggesting that mental states can be modulated by influencing the perceptual system. Within this context, two auditory stimulation techniques—binaural beats and isochronic tones—have drawn increasing interest. These methods have been observed to enhance attention, memory, and mental clarity (Aparecido & Kanzler, 2021). This raises the question: Could such sound-based neuromodulation techniques, which aim to entrain brainwave activity to specific frequencies (Gruzelier, 1996), positively impact memory when

integrated into spatial perception studies within the discipline of architecture? A typical individual can perceive auditory frequencies ranging from 20 Hz to 20,000 Hz (20 kHz). Frequencies between approximately 200–300 Hz and up to 10 kHz are considered most sensitive to human auditory perception (Møller & Pedersen, 2004), with 200 Hz being a dominant frequency in everyday speech. Moreover, this frequency range constitutes the fundamental basis of many musical instruments (Önen, n.d.).

Isochronic tones are sound technologies that aim to direct the brain toward specific frequencies by increasing or decreasing the amplitude of a sound at a specific rate (Huang & Charyton, 2008). This can be likened to our reactions to rapidly flashing lights; rhythmic sound pulses have the potential to direct brain waves with synchronized stimuli (Aparecido-Kanzler, 2021). A review of the literature has revealed studies showing that some isochronic tones have strengthening effects on memory and are used to improve cognitive function. When examining isochronic tones due to their structure, three distinct frequencies stand out in the process of brainwave attunement.

Some of these frequency patterns are listed in the literature as alpha, beta, and delta. Alpha frequencies range from 8-13 Hz, and studies have shown that they have effects on visualization, creative process management, and relaxation. Furthermore, this wave type attunement has been recognized by the neuroscience community as a potential tool for memory optimization and the treatment of memory disorders (Klimesch, 1999). Beta waves range from 13-39 Hz and are associated with focus, concentration, and attention. When applied to individuals with attention deficit hyperactivity disorder (ADHD), these waves have been observed to have positive effects on some of their symptoms. Beta waves also facilitate environmental engagement. Experiments conducted by Bauchene and colleagues in 2016 revealed remarkable effects of the 15 Hz Beta wave pattern. Tested on healthy young individuals, this wave pattern was observed to have positive effects on short-term visual-spatial working memory in experimenters and was found to increase cortical connections in the brain. Another wave pattern thought to have an impact on memory is Delta frequencies. This frequency pattern, which ranges from 0.5-4 Hz, is a very low and slow wave and is associated with the deepest and most unconscious state of sleep. When the Delta frequency pattern is applied, the individual experiences an introspective experience, experiencing a state of mental empathy where they feel more connected to themselves, which the mind interprets as a state of happiness. This enhances intuition while also positively triggering memory and demonstrating its potential to have an impact on memory (Szentirmai et al., 2007). To attune the brain to these frequency types, isochronic tones use a

carrier frequency. In this experiment, a 200 Hz carrier frequency was used because it is also the fundamental sound frequency of everyday speech and musical instruments.
To attune the brain to the Delta frequency (0.5-4 Hz), a sine wave tuned to the 200 Hz carrier frequency is cycled on and off four times per second, creating harmonic synchronization.

Based on all this research on memory, it was thought that Alpha, Beta, and Delta isochronic tone wave adaptations could also have an impact on spatial memory, and therefore, the decision was made to use these three wave types in the experiment. Three melodies were composed using the Audacity program, one for each wave type, using the artificial intelligence Chat GPT 4.0, using melodies in the Alpha (10Hz), Beta (20Hz), and Delta (3Hz) wave types on a 200Hz carrier frequency. The primary objective of this experiment is to understand the effects of isochronic tone sounds on users' spatial perception and memory development in virtual reality environments.

3. Methodology

The research is based on a qualitative experimental model. Virtual rooms, based on Roth's spatial typologies, are structured around three basic room types. These room types can be examined in Table 1 below.

TABLE 1. Room configurations based on Roth's (2018) spatial classifications.

Room Type	Description	Roth's Definition
Room A	Physically limited, but formally simple and rigid.	(1) Spaces restricted by boundaries consisting of walls and floors
Room B	A fluid form that formally deviates from the classical definition of cylindrical space. It creates a sensory–perceptual awareness in the user.	(2) Sensory–perceptual spaces

Room A′	The basic form is identical to the "Type A" rooms, but the wood used as the material creates a difference in perception. Wood is a sensually warm material, creating a sense of calm in the mind and positively triggering memory, with the potential to leave a deep impression (Burnard & Kutnar, 2015).	(3) Spaces of memory
Virtual Spaces	Rooms A, B, and A′ were created in virtual spaces. A controlled, interactive spatial experience was provided.	(4) Behavioral spaces

These room types, each characterized by a different configuration, are shaped by two forms and two materials. The goal is to provide two constant variables. Only one formal parameter (depth, height, or geometry) was manipulated in each room, while other conditions (e.g., surface material, base area) were held constant. This approach allows us to analyze the effects of spatial variables in isolation, enabling a comparative assessment of the effects of depth, height, and deformation on perception and memory.

The experimental setup consists of 12 room types, designed according to three key variables. The rooms were modeled using 3sMax and Rhino Grasshopper, and the materials and lighting details of the virtual rooms were created in Unreal Engine 5.3. The experiment aims to provide an interactive experience. Lighting, sound, and VR algorithms were developed using Unreal Engine 5.3 BluePrint software. The research also presents an experimental system, parametrized for different environments.

The basic variable subheadings are as follows:

- Form Type
  - A (square)
  - B (cylindrical)
  - A’ (square)
- Material
  - Drywall cladding and concrete (A and B)
  - Wood cladding (A’)
- Form transformation and architectural element details
  - Each form type is shaped by four different formal variations;
  - Basic type

Depth enhanced – deepened with repeated formal elements
Height enhanced – height perception emphasized with staircase details
Geometrically disorientated – perceptual distortions

The configuration of the virtual rooms is illustrated in Figure 1.

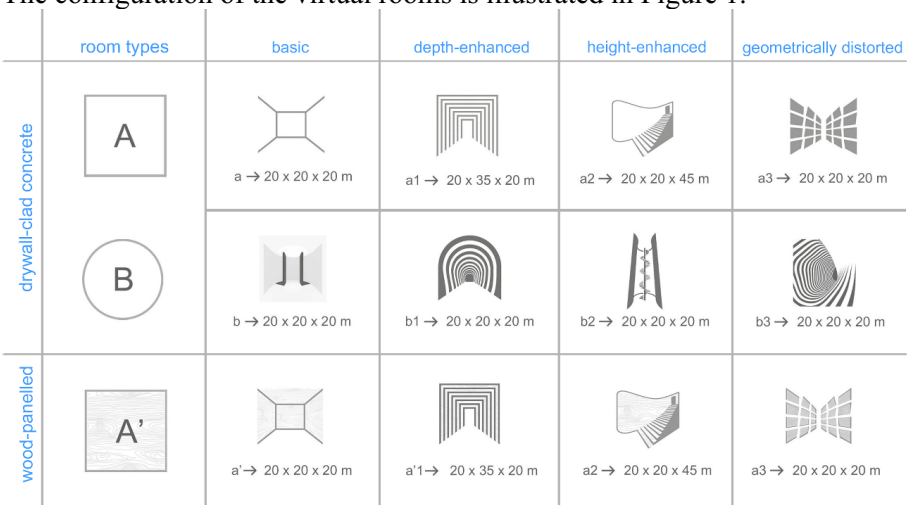


Figure 1. Illustration of virtual rooms

To ensure the internal validity and reproducibility of the experiment, specific details regarding the hardware and auditory delivery were controlled.
All participants used the same VR headset (Meta Quest 2) with its integrated headphones. The sound level was maintained at a nominal 70% volume throughout the experiment. No Head-Related Transfer Functions (HRTF) or advanced auralization techniques were utilized; the isochronic tones were presented as monofonic sound sources. Furthermore, participants were administered a brief hearing screening prior to the experiment to confirm normal hearing ability. The study begins with the question: Can spatial compositions constructed through the simultaneous operation of light and sound create an experiential space that can support memorability?
In this context, the duration of light used within the rooms in the experiment was directly proportional to the number of seconds it would take for the designed frequency of a melody emitted by a sound source located within the actual volumes of the designed rooms to acoustically decay. Crucially, this mapping was a conscious, experimental parametrization decision intended not to provide a realistic acoustic simulation (auralization) within the VR environment, but to create an abstract, temporal rhythm mechanism for audiovisual synchronization derived from the spatial dimensions of the room's volume. The sound-acoustic decay times of the actual volumes of the

rooms in the designed system can be calculated using the Sabine Formula (Nowoświat & Olechowska, 2015).

The formula is as follows;

$$RT60 = \frac{0.161 \times V}{A} \quad (1)$$

V: The volume of the room (m^3)

A: Total sound absorbing surface (sabins)

$A = \alpha \times S$

α: Absorption coefficient of the material

S: Total interior surface area of the room (m^2)

When the user puts on VR headsets, they wake up in the middle of a circle surrounded by 36 doors. Each of these doors leads to a different room. The teleportation system allows for semi-restricted movement and allows for the user to choose any door. There are no door selection rules. The user can pass through the doors according to their desired algorithm. Upon arriving at the door, the experiencer automatically transits through the room and encounters only darkness upon first entering each room. Using the trigger button, they simultaneously activate sound and light. Rooms differ in shape, form, texture, and element. Sound and light modulations operate simultaneously within the room, but this duration varies for each room. The duration of light and sound in the room is tabulated for various times, which can be analyzed. Each room can be spent for a maximum of 30 seconds. After 30 seconds, the system automatically returns the user to the starting point.

The synchronized decay times of sound and light for each room, calculated using this formula, are illustrated in Table 2 below.

TABLE 2. Decay times of sound and light for each room.

Room	Form	Dimensions (m)	Cladding	Reverberation Time (s)
A	Cube	20×20×20	Drywall	8.94
A1	Height-extended Cube	20×35×20	Drywall	10.44
A2	Depth-extended Cube	20×20×45	Drywall	10.98
A3	Geometrically Distorted Cube	20×20×20 (Deformed)	Drywall	10.32
A’	Cube	20×20×20	Wood	4.61

A'1	Height-extended Cube	20×35×20	Wood	5.38
A'2	Depth-extended Cube	20×20×45	Wood	5.66
A'3	Geometrically Distorted Cube	20×20×20 (Deformed)	Wood	5.32
B	Cylinder	Ø20×20	Drywall	8.94
B1	Horizontally Extended Cylinder	Ø20×35	Drywall	10.44
B2	Vertically Extended Cylinder	Ø20×45	Drywall	10.98
B3	Spirally Twisted Cylinder	Ø20×45 (Spiral)	Drywall	10.98

A previously entered room cannot be re-entered. Each time they return to the starting point, the door to the previously entered room turns black. The experiment ends when all 36 rooms are completed. After the experiment, the experiencers answer a survey with open-ended, Likert-type questions.

A total of 28 architecture-related individuals (students and graduates) participated in the experiment. This experimental profile was chosen because they had received basic design and architectural design training. The selection of a domain-expert sample (N=28) was a deliberate decision for this qualitative, exploratory study, aiming to elicit richer, more in depth, and technically explanatory spatial descriptions and perceptual concepts.

It was expected that the participants' spatial descriptions and perceptual concepts would be more in-depth and explanatory. Participants were not provided with any information about the experiment before or after, and they agreed to participate entirely voluntarily throughout the experiment.

4. Findings & Analysis

In this research, the concept of digital space exists not only as areas modeled as 3D designs but also as a cognitive field of experience created by the simultaneous experience of auditory and visual perception. Based on the experiencers' responses and observations recorded throughout the experiment, the effects of sound on spatial perception were evaluated. It is critical to note that the findings presented in this section are derived from the thematic, qualitative coding of open-ended survey responses (self-report data). Therefore, the resulting figures and graphs represent coded frequency

counts rather than inferential statistical findings, and they are offered for exploratory interpretation.

4.1. FORMAL PERCEPTION IN DIGITAL SPACE SECOND

The experimenters were asked, "What shapes of rooms did you see?" and their responses revealed that digital spaces were described using different formal codes. Frequently repeated words in the responses include:

- "Square, rectangular, spiral, oval, and intricate rooms"
- "Rooms with spiral staircases, amphitheaters, and glass"
- "High-ceilinged, low, semicircular spaces"

These definitions may indicate that digital spaces are perceived not only as volumes associated with their shapes but also with dynamic and directional concepts.

When these concepts were evaluated and matched with the sounds within the rooms, the most frequently described rooms, based on the responses to this question, were found to be b2, a2, a1, b3, b1, and a3. The words used to describe these rooms were categorized into six different forms, and their relationship to the sounds within the rooms was examined through a graph. The graph generated based on the analysis (Figure 2) displays the qualitative coding frequency (counts) of descriptive terms used by participants and their association with the auditory stimuli.

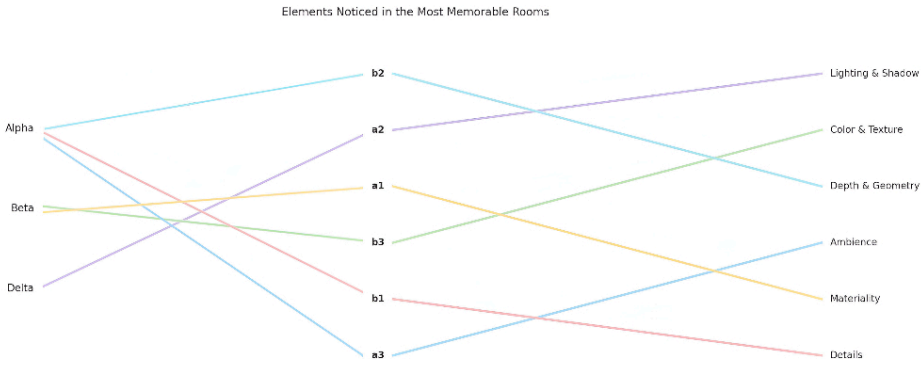


Figure 2. The most memorable rooms with sounds.

The alpha melody was paired with multiple rooms and themes. This suggests that this sound, particularly associated with spatial awareness, material perception, and detail, may be effective in creating perceptual unity.

The beta melody was paired with restrictive yet distinct themes such as ambiance and spatial depth perception, reinforcing the potential for subtle

details requiring attention to be perceived with this sound. The delta melody, on the other hand, was defined solely by words associated with color and texture, suggesting that its impact is more limited but may be prominent on a sensory level.

4.2. PERCEPTUAL RESPONSES

An analysis of participants' responses to the question, "Write down the three rooms that most impressed you," highlighted three spatial features:
• Type A1 rooms, with glass windows and an outside view, were frequently preferred due to their comfort and sense of connection to the outdoors.
• Room B2, with its spiral and staircase structure, was observed to stimulate movement and orientation.
• The use of phrases such as "with a view, guided by light, overlooking trees" may indicate that the digital space creates a realistic perception of the outside world beyond indoor spaces.
Based on these experiences, it can be observed that virtual spaces can produce sensory-perceptual outcomes.

The graph in Figure 3. was created based on the analysis of sound-room-concept mappings based on the responses to this question, representing the qualitative frequency counts of concepts reported as "impressive" by the participants.

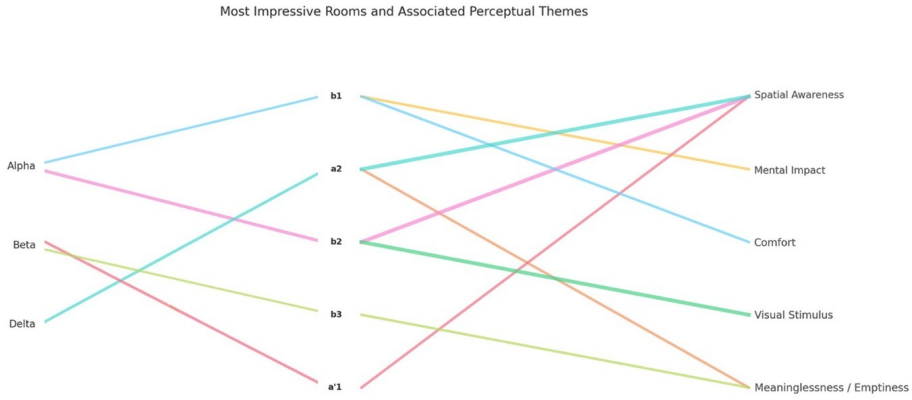


Figure 3. The most impressive rooms with sounds.

The graph shows that the Alpha melody is associated with rooms b1 and b2, which are associated with the concepts of "spatial awareness" and "comfort." The Beta melody, on the other hand, is mostly associated with the concepts of "mental impact" and "visual stimulus," which are prominent in rooms b3

and a1. This suggests that the Beta sound may strengthen the mental effect by triggering visual stimulation.
The Delta melody, on the other hand, is associated with room a2, where the concepts of "meaninglessness/emptiness" are dominant. This may suggest that the Delta sound may elicit a sensory response.

4.3. HARD-TO-RECALL DIGITAL ROOMS

Two concepts stand out as the most frequently used concepts in the responses to the question, "What was the most difficult room to remember, and why?"

- Experiencers' responses highlighted two key factors that made recall difficult, reminding us of the importance of light in visual memory.
- Orientation uncertainty: Definitions such as "ring-shaped structure" and "amphitheater but directionless" are concepts used by many people, despite requiring more specific details.

Based on the participants responses to this question, the conceptual associations are presented in Figure 4, illustrating the coded frequencies of concepts used to describe the most difficult rooms to recall.

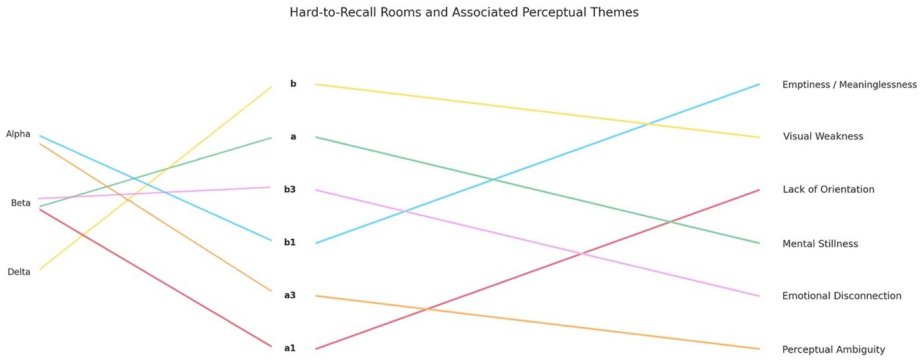


Figure 4. Hard-to-Recall Digital Rooms.

This graph shows that rooms that are difficult to remember are more often associated with concepts such as visual weakness, disorientation, and perceptual ambiguity, and a significant portion of these matching rooms are associated with Beta and Delta melodies. The prominence of the Delta melody in rooms associated with cognitive confusion such as perceptual uncertainty and disorientation highlights the potential effects of this

frequency on spatial memory. Conversely, themes of visual weakness and emptiness are also observed in rooms associated with the Alpha melody

4.4. DIGITAL PERCEPTION SHAPED BY AUDITORY STIMULI

Responses to the questions, "Was the rhythm of the sound related to your perception of the room?" and "Were there any moments when you felt like you could better grasp the structure of a room through sound?" may indicate that auditory stimuli contribute significantly to the spatial analysis process in digital spaces.

• 60% of experiencers stated that they established a connection between the rhythm of sound and spatial perception based on their responses to this question.

• "Pulsating" and "slow" sounds were predominantly described as key words that facilitate mental visualization.

• Phrases such as "The space expanded with the sound," "The space became clearer with the light," and "I was able to orient myself better with the rhythm" were frequently used in the responses.

These responses suggest that digital spaces are not only visual but also rhythmically and experiential spaces that interact with time.

4.5. VISUAL MEMORY AND SOUND

Participants were asked, "How long did you hold the image of the room in your mind after the sound ended?"

Their responses suggest that the mental representations of the images, which began with the sound, continued after the sound ended.

- 70% of the experiencers stated that they could remember the rooms for "a few seconds to 10-15 seconds" after the sound ended.
- Some experiencers provided contextualized responses, such as "I tried to remember by constantly turning it on and off" or "I remembered it until I left the room."

These findings suggest that a time-dependent, temporary memory trace in digital spaces can be strengthened by the influence of sound.

5. Conclusion

The aim of this research is to conduct an experiment to analyze the experiential potential of digital architecture through multisensory stimuli and systematically examine the impact of sound on the perception of digital space. Based on the data obtained from the experiencers' responses, it was

observed that space can be not only a visual interface but also a multilayered experiential space constructed through sound, light, and time. In particular, the lighting system created by light, which works synchronously with the rhythm, frequency, and duration of sound, demonstrates that digital spaces have the potential to become structures that leave a lasting impression in the experiencers' memories, shape their minds, and resonate emotionally.

Analysis and concept maps have shown that high-frequency (beta) sounds have the potential to increase spatial clarity in digital rooms with more complex geometries, facilitate orientation, and trigger attention, enabling the perception of details. On the other hand, low-frequency (delta) sounds foster a sense of serenity in rooms with simple formal features or modeled with warm materials like wood. They facilitate an emotional connection with an introspective way of thinking, and can be studied as being susceptible to performance that can have positive effects on memory. These diverse effects provide us with strong evidence to consider digital spaces as experiential contexts shaped not only by formal but also by auditory-temporal patterns.

The vast majority of experiencers stated that they perceived and remembered the structure of rooms more clearly with the accompaniment of sound. Expressions such as "the room opening up with light," "orienting with sound," and "time stretching in spiral or glass rooms" demonstrated that the masses in digital spaces can cease to be fixed 3D models. In this context, digital spaces are also susceptible to transforming into cognitive structures that unfold over time. Furthermore, the fact that the most difficult spaces to remember are dark and poorly oriented spaces reminds us once again of the decisive role of perceptual cues in digital architecture.

The study began with the idea that spaces designed in a digital environment can acquire meaning not only through visual aesthetics but also through multisensory stimuli. In this context, sound is not merely a passive element providing atmosphere. On the contrary, it has the potential to be positioned as an active architectural component that triggers processes of memory, orientation, and affect. Considering all of this, when developing experimental designs for the future of digital architecture, not only how a space "looks" but also how it "sounds and feels" should be considered.

The research began with the idea that sound in digital space design is not merely an aesthetic choice but also a fundamental tool that provides cognitive and sensory depth, and a set of experiments was presented. Experiences designed with the rhythmic and frequency properties of sound in virtual reality environments facilitate the creation of mental images of the space, and these images have the potential to strengthen memory traces. Based on these findings, the study highlights the importance of multisensory design in digital architecture and suggests a rethinking of architectural

experience. This study, with its proposed method, is valuable in offering an alternative experimental field to which researchers interested in similar topics can adapt their own experiments. This exploratory study carries several methodological limitations that future research should address. Firstly, the findings rely solely on qualitative self-report data gathered through post-experience surveys, which is susceptible to recall bias. The absence of objective, behavioral memory tasks (e.g., object localization or route recall) or physiological measures (e.g., EEG/GSR) means claims regarding "memory formation" are interpreted cautiously as "perceived memorability." Secondly, the small, specific sample size of N=28 architects and students limits the generalizability of the findings, as domain expertise may bias spatial descriptions and cognitive engagement.

Future studies should employ larger, more diverse participant groups and integrate inferential statistics (such as ANOVA or regression analysis) alongside behavioral metrics (e.g., navigation time, task accuracy) to substantiate the cognitive claims made herein. Furthermore, adapting this method using more advanced technologies, sound-isolated environments, and different sound types could yield more comprehensive data on the cognitive effects of auditory design in digital architecture.

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PLANETARY ARCHITECTURE

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Abstract. Planetary Architecture seen through three lenses: 1] Planet-Conscious Architecture, 2] Outer Space Architecture, and 3] Comprehensive World Building. The common denominator is the bold, visionary, technology-driven design concepts that create the unknown, the alien. The BORG CUBE [1993, Star Trek, Q Who episode], the primary vessel of the BORG Collective, incorporates many aspects of planetary design. Ad 1: The BORG CUBE, measuring 3x3x3km3, is a planet in itself with advanced self-healing properties, and can thus be considered Planet-Conscious architecture. Ad 2: BORG's CUBES reside in outer space, operating from the Delta Quadrant of our Milky Way. Ad 3: The BORG CUBES are imaginary self-contained worlds that operate according to a consistent internal logic, yet are far different from Planet Earth's logic. The first image of Earth from outer space [1967, NASA] gave a boost to Planet-Conscious Architecture. The Planet-Conscious projects discussed here are bold design statements that either aim to make the world a more sustainable, fair, and just place [1991, City Fruitful, Kas Oosterhuis et al.] or criticise existing urban planning [1969, Continuous Monument, Superstudio]. Outer Space Architecture includes studies for habitats in Outer Space [1975, NASA, Space Settlements], and planetary student design projects [2024, INDA Chulalongkorn, Utopia_Dystopia]. Planetary Architecture, as Comprehensive World Building, is represented by historic proposals from artists [1920, Tatlin, Monument for the Third International] and architects [1784, Boullée, Newton Cenotaph], as well as currently ambitious projects under development [2020-2030, NEOM, THE LINE]. Simple yet strong, conceptual ideas that infuse future thinking into a present form the basis for Planetary Architecture. The imagined world becomes part of the real world, an Another Now [2021, Varoufakis, Another Now]. Comprehensive World Building investigates possible futures, some of which actually were built [1967, Montreal World Expo, Buckminster Fuller], while others have been developed in academia [2008, Hyperbody, Multiplayer Design Studio 751], and are currently under construction in the real world

[2025-2030, MUKAAB]. The 400x400x400 m³ MUKAAB multifunctional building in Riyadh is an Earth-landed version of the BORG's CUBE, integrated into the urban fabric of Riyadh, materialized from a suggestive science fiction series into reality within the span of one generation.

Keywords: *Planetary Architecture, Planet-Conscious Architecture, Outer Space Architecture, Comprehensive World Building, Artificial Intuition*

1. Planet-Conscious Architecture

In 1976, I wrote my first architectural essay, focusing on the work of Archigram. To capture the zeitgeist of their work, I included as the first illustration an image of Planet Earth seen from outer space [1967, NASA]. For the first time, the entire Earth was captured in a single, colourful picture, showcasing both its uniqueness and fragility. The awareness that we are living on Spaceship Earth [1969, Buckminster Fuller, Operating Manual for Spaceship Earth] gave a boost to Planet-Conscious architecture. Just as the BORG's CUBE incorporates aspects of Planetary Architecture in science fiction series, in architecture, Archigram projects address all elements of Planetary Architecture: Planet-Conscious Architecture [1969, Archigram, Monte Carlo], Outer Space Architecture [1963, David Greene and Mike Webb, The Story of the Thing], and Comprehensive World Building [1966, Ron Herron, Walking City].

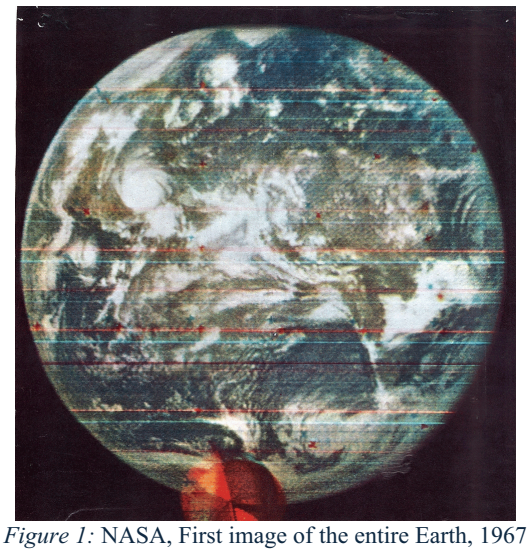


Figure 1: NASA, First image of the entire Earth, 1967

1.1. CITY FRUITFUL

Some ONL [Oosterhuis_Lénárd] projects exemplify Planet-Conscious Architecture. City Fruitful [1991, Oosterhuis et al.] is a self-sufficient city of 1.500 homes, with emphasis on urban farming, CO2 capture, and the walkable city. Cars are parked in the parking garage, while their exhaust fumes [CO2] enhance the growth of fast-growing O2-producing peppers and tomatoes. City Fruitful has a circular shape, which is a typical feature of a Planet-Conscious design. The circle is a design metaphor for Earth. The circle consists of two parts: collective and individual housing, divided by a multi-storey urban farming structure powered by LED lights. City Fruitful exports exceptional produce, but is unable to compete on the market with large agricultural producers. Today, a circular plan refers to the circular economy, "defending" the values of Planet-Consciousness. Recent Planet-Conscious studies are examining the Earth as a whole system [2018, WHY Factory, Planet Maker], exploring statistical "What if" scenarios using a three-dimensional representation.

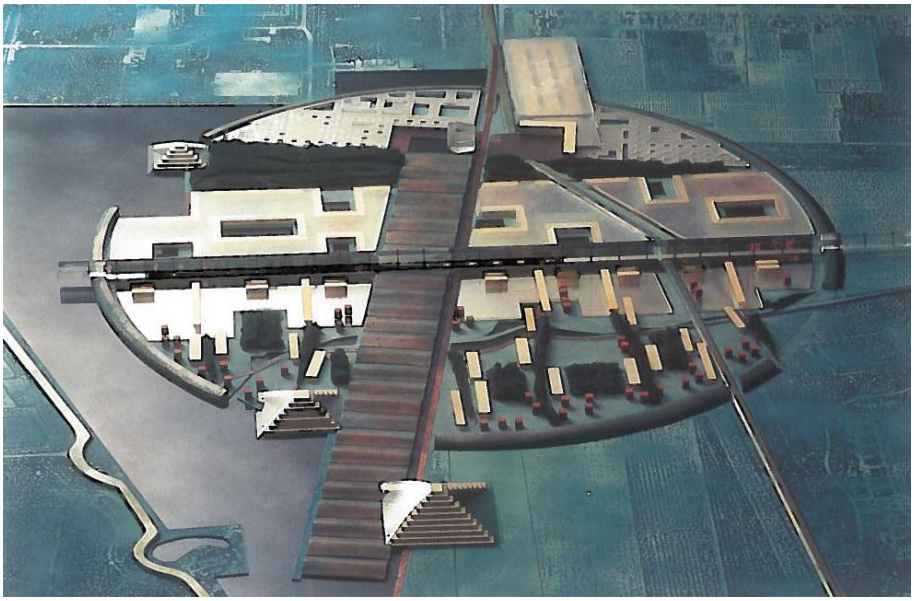


Figure 2: Oosterhuis et al., City Fruitful, 1991

1.2. THE LINE

Linear cities are the unfolded counterparts of circular cities. Instead of minimizing contact with the world around them, linear cities maximize their boundary-to-surface ratio by being excessively slim and long, thereby establishing a maximum of open non-defensive relations with the surrounding landscape. Being familiar with the desurbanist linear city of Magnotigorsk [1930, Leonidov] and the Continuous Monument project [1969, Superstudio], my master's thesis project is a 200km long linear strip [1979, Oosterhuis, Strook door Nederland]. The main characteristics of the design are: 1] The shape of the law, 2] Rule-based design, and 3] Maximum contrast between the strip and the natural environment. One of the possible rules governing the strip I proposed was to refrain from any government interference concerning the architectural style of the buildings, a free zone. Passing the border of the strip would feel like crossing a border between nations, whereas every nation typically has its own rules and building regulations. A more radical rule I considered was to relocate all new housing projects inside the strip, thus creating a huge linear attractor 5km wide and 200km long, intensifying the density inside the strip. Parallel to this rule, I advocated for returning much of the existing farmland to its natural state, thus creating a maximum contrast between the built environment and raw nature.

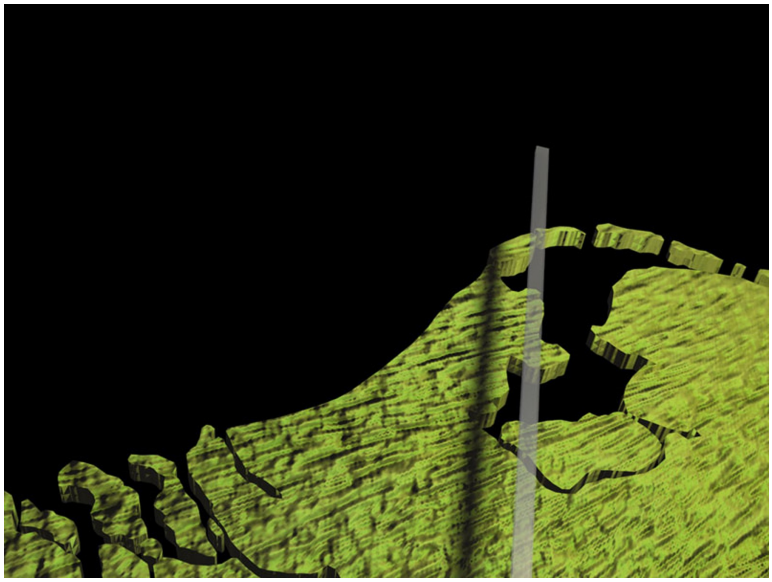


Figure 3: Oosterhuis, Strook door Nederland, 1979

While my thesis project was considered a radical urban proposal, it remains a modest plan compared to THE LINE, the ambitious 170km-long, 200m-wide, and 500m-high linear city launched as part of Saudi Vision 2030 [2017, Mohamed Bin Salman]. THE LINE will be home to 9 million people. THE LINE condenses the traditionally distributed buildings of a city into a series of 800m-long sections. Each module measures 200 x 500 x 800 m^3 and houses 80,000 people, or 1,000 m^3 per person. Conceptual architectural models of the units, designed by a select group of renowned architects, were showcased at the 2023 Venice Architecture Biennale. These models typically featured a 50% porosity, with mostly green canyons between the lateral built-up areas, which were externally clad with reflective glass to mirror the surrounding desert and mountains. A prototype for such a reflective glass-clad stand-alone building in the desert stands in Alu Ula [2019, Gio Forma, Al Maraya]. Facilities such as fitness centers, restaurants, lobbies, and shops could account for another 50% of the built-up area, leaving 250 m^3 for a single person. That calculation is realistic when compared to typical 300m2 homes of Middle Eastern families [2025, UAE, House of the Future competition].

The open question is whether NEOM will be able to attract millions of middle-class and upper-class families to inhabit THE LINE. THE LINE is intentionally a "green" city, self-sustaining in terms of energy, food, and water. Similar to Magnitorgorsk and the Strook door Nederland, one of the main qualities will be the immediate proximity of nature, i.e., the desert and the mountains. NEOM stretches along the Red Sea coast of Saudi Arabia, which is quickly developing to become a new Mediterranée. THE LINE does not contain everything inside its boundaries. Water distillation from seawater, solar farms, wind parks along the Red Sea shore, and worker camps are outside THE LINE proper, which means that large parts of the desert will be urbanized to feed THE LINE. Where will the maids, nannies, cooks, gardeners, guards, and retail personnel who serve the middle- and upper-class inhabitants live? Where will they park their SUVs, considering that in the Middle East, a family typically has two cars? Apart from the central transportation hub, what additional infrastructure will be around THE LINE? Where do the building materials come from, and at what costs? The reality of the new town of Brasilia [1960, Lucio Costa, Oscar Niemeyer] is that to support the 600,000 middle-class and upper-class inhabitants, satellite cities around Brasilia have a combined population of 2.8 million people. Time will tell whether such an imbalance will be the fate of THE LINE.

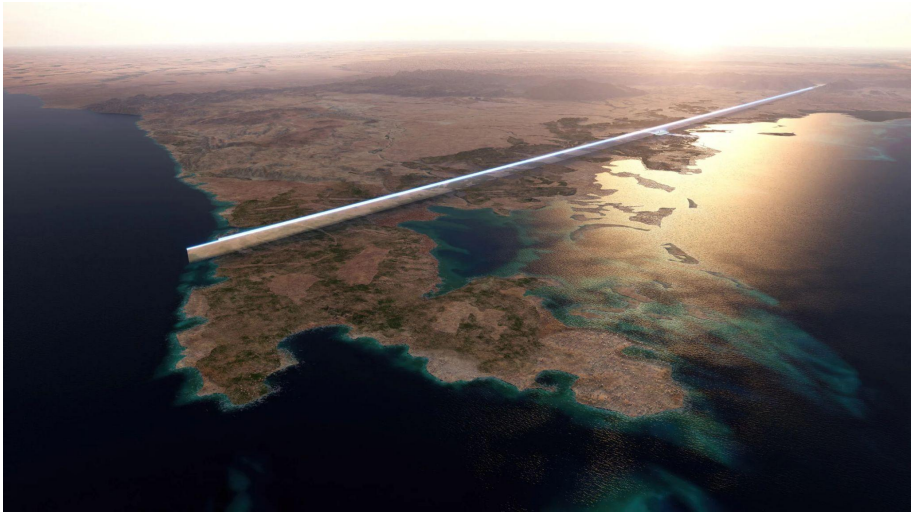


Figure 4: NEOM, THE LINE, 2021

1.3. THE CONTINUOUS CITY

With a peak in the 1960s, architects developed Planet-Conscious design strategies to critique what they saw as urban malpractices and the unwanted commercialization of the built environment. The Continuous Production Conveyer Belt City [1970, Superstudio], one of the 12 Cities, questions explicitly the obsession with growth and transformation in capitalist urbanism, pushing it to the extreme where architecture has no permanence. Paradoxically, the hypercapitalist LINE draws its inspiration from a radical conceptual critique of capitalist society that now serves as a positive example of how to build a city, adopting the design aesthetics from the Continuous Monument [1969, Superstudio]. The Continuous Production Conveyer Belt City is a unique combination of a continuous production machine, an inhabited city, and a demolition zone all in one, thereby also serving as an example of the third aspect of Planetary Architecture: Comprehensive World Building. The Grand Factory is moving the city forward by transforming materials from the landscape to build the city. At the tail end, the city is impoverished and eventually demolished. The Continuous Production Conveyer Belt City integrates all aspects of a city's rise and fall. In this sense, it is a rare Planet-Conscious fusion of societal critique and what is today referred to as circularity.

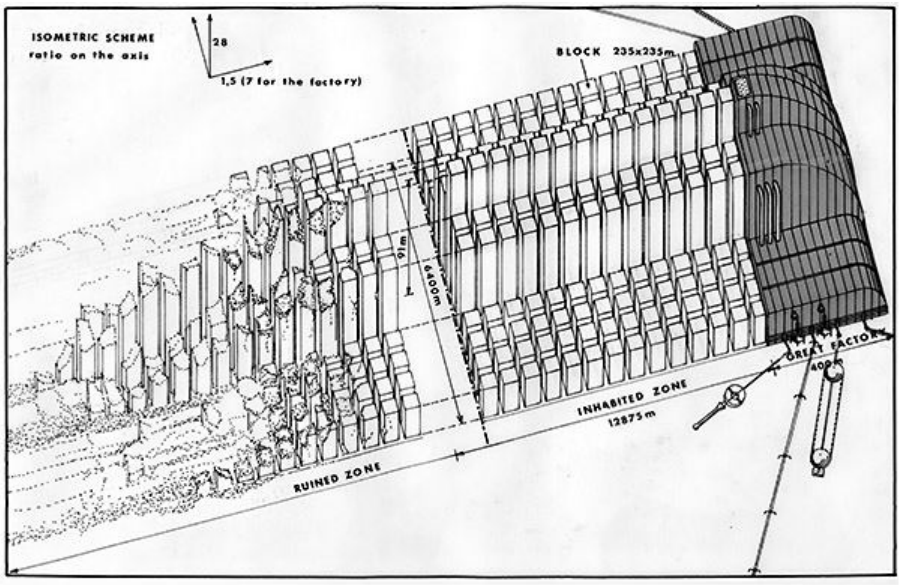


Figure 5: Superstudio, Continuous Production Conveyer Belt City, 1970

2. Outer Space Architecture

2.1 SPACE SETTLEMENT

Another one of the 12 Cities projects is Spaceship City, a mini-city that rotates in space to simulate gravity, measuring just 50m in diameter. The proportions of the design concepts for the 12 Cities are more indicative than at a proper scale. While Spaceship City is a critical statement of an extreme hyper-technological logic, NASA's Space Settlement [1975, NASA] is a meticulously undertaken, detailed research on how a population of 10.000 people could live and thrive in a space settlement. The proposed location in space is the Earth-Moon Lagrange points, specifically Lagrange point 5 (L5). These are gravitationally stable points in the Earth-Moon system where a significant orbital habitat could remain in position with relatively little fuel for station-keeping, maintaining its position at a constant distance from both Earth and the Moon. The Moon would be close enough for mining and close enough to Earth for transporting equipment and people. Anticipating THE LINE, the interior of the Space Settlement is a green habitat, featuring a human-friendly seventies-style assembly of architectural elements. While THE LINE aims to impress its inhabitants with 500m-high, canyon-like green atriums, aesthetically inspired by dystopian video games, the Space Settlement makes

its inhabitants feel at ease, causing them to forget that they live 400,000 km away from Earth in an artificial gravity environment.



Figure 6: NASA, Space Settlement, 1975

2.2 GLOBAL SATELLITE

The early years of the Internet inspired us to think globally. The Internet quickly became the global exo-brain of every inhabitant of Spaceship Earth. The rise of the Internet went hand in hand with the development of virtual reality, based on imagined realities created from bits and bytes rather than bricks and mortar. At the Zonnehof Museum in Amersfoort, Ilona Lénárd and I organized the event "The Synthetic Dimension" [1991, ONL], which included the International Global Satellite Workshop. We asked participants from all over the world to transfer designs for satellites, using what was then state-of-the-art modems, Bulletin Boards, and File Transfer Protocols [FTP] for uploads and downloads. Based on the intuitive gestural work of visual artist Ilona Lénárd, we asked participants to sketch freely in a weightless space, unencumbered by architectural conventions or artistic preoccupations. Satellites in Outer Space are not subject to gravity and can have virtually any shape.

The aesthetics of the Global Satellite brief are inspired by Ilona Lénárd's autonomous art, characterized by impulsive, rapid, and intuitive sketching, executed faster than the brain can evaluate [2020, Ilona Lénárd, Powerlines].

Her art creates a new, autonomous reality out of nowhere, essentially shaping the "unknown." The Global Satellite workshop sketches, as well as those of the following Artificial Intuition workshops [1990, Artificial Intuition, Galerie Aedes; 1991, Artificial Intuition, TU Delft Department of Architecture], explored the lightning-fast intuition of designers, only to be rationalized afterwards into possible built constructs.

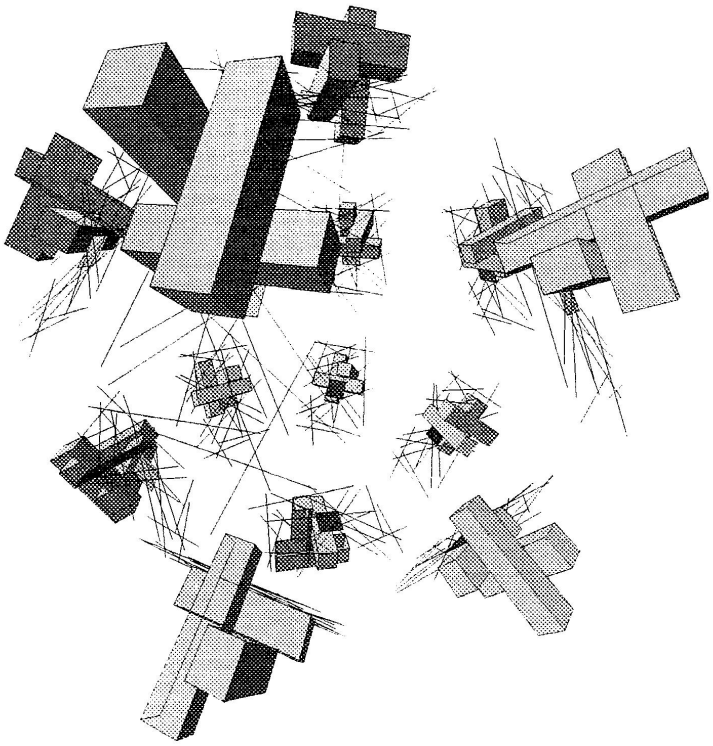


Figure 7: Oosterhuis et al., The Synthetic Dimension, Global Satellite Workshop, 1991, local XYZ coordinates and free sketches

2.3 UTOPIA/DYSTOPIA

The Global Satellite Workshop aimed to liberate design energy from regulations and the usual cultural, juridical, and technical constraints, thereby enhancing unrestrained design thinking and a real-world utopian approach. In a hypercapitalist society, what is utopia for one person is dystopia for another. As a visiting professor at INDA Chulalongkorn University [2023-2024] in Bangkok, we found ourselves living and working in Utopia and Dystopia simultaneously. As the BORG, Bangkok has been the inspiration for dystopian

movies, especially the shadowy worlds underneath the brutalist BTS Skytrain [1999], even more dystopian when the seasonal heavy rains pour down at the end of the afternoon. However, in daily life, Bangkok is in many ways a relaxed utopian city, with shiny happy, fashionable young people celebrating life, expressing themselves in spontaneous collective K3-like street-dance, shopping in upmarket shopping centers along the BTS as a social activity, dining out in supersized food courts, having a bite at street food stalls, strolling along restaurants and candy bars, never in a rush because it's hot and humid. Dystopian movies [1982, Blade Runner] combine chaotic yet colorful Asian street scenes with superimposed criminal plots involving cyborg cops and vicious CEOs of powerful companies plotting to take over the world.

At INDA, I directed a 4th-year design studio, asking students to reflect on the theme of Utopia/Dystopia through conceptual design thinking [2024, Oosterhuis et al.]. The results exceeded my expectations in the extent to which they were willing to stretch their imagination. Much of their inspiration comes directly from the out-of-this-world aesthetics and often violent storytelling of video games. The Crown Prince of Saudi Arabia, MBS, is famously known for playing video games every morning in his youth. The thrills and aesthetics of virtual environments in video games have served as a source of inspiration for the bold concepts of NEOM and MUKAAB [2023, New Murabba Development Company], projects directly overseen by MBS.

2.3.1 Asteroid City

My INDA students boldly went where no one had gone before [2024, Research Book]. INDA Y4/S2]. Tanakorn Changchun [nickname Nine] envisioned a space settlement, Asteroid City, located in Outer Space, that would host space travelers and a crew to support the mining of rare-earth minerals for Mars habitats. He envisioned different levels of gravity, ranging from Earth-like gravity to zero gravity in rotating rings at various speeds. The 3d layout of Asteroid City seems at odds with logic. The rings rotate perpendicular to each other, seemingly crashing into each other. However, a clever system of interrupted rings lets the rings that are perpendicular to them pass. Such an intricate system makes Nine a pioneer in the realm of Outer Space Architecture, curiously exploring new territories.

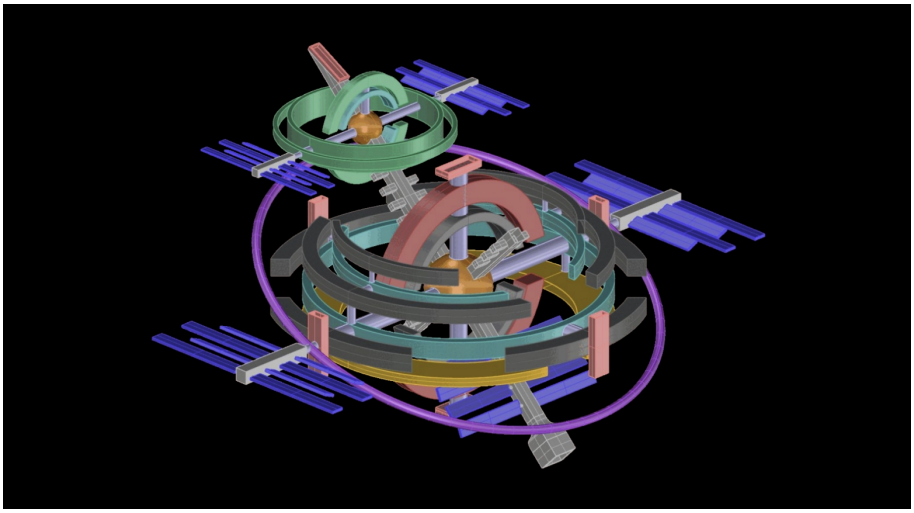


Figure 8: Tanakorn Changchun [Nine], Asteroid City, 2024

2.3.2 A Dance between Utopia and Dystopia

While Nine's Asteroid City is an example of positive, forward-looking, and ultimately buildable utopian design, others dived into next-level dystopian futures, inhabiting doomsday scenarios. Two of my INDA students designed an entire artificial planet, complete with spatial scenarios for densely packed buildings on the surface of the spherical planet, the deep interior of the planet, and portals that allow players to transit from the exterior to the interior and vice versa. Taechit Chinachatchawarat's [nickname Bape] planetary outer space design is titled "A Dance between Utopia and Dystopia, Reflecting Business Realities". His planet is abundant with AI-generated high-rise towers; between the towers, deep, red-colored canyons. People might accidentally fall or are being pushed into these canyons, into the deep interior, the Inverse, where towers point inward; the canyons are mountains that rise toward point zero. "In contrast with the towers populated by successful businessmen, the dystopian future presents a bleak depiction of subjugation and hopelessness for the workers. They suffer in deplorable circumstances, bound by insufficient salaries, unstable job security, and relentless monitoring" [Bape, 2024]. While the gravitational force is zero at the center, the pressure would be enormous because all the mass of the planet is exerting a downward force. Even though you feel no gravitational pull, one would be living in total despair.

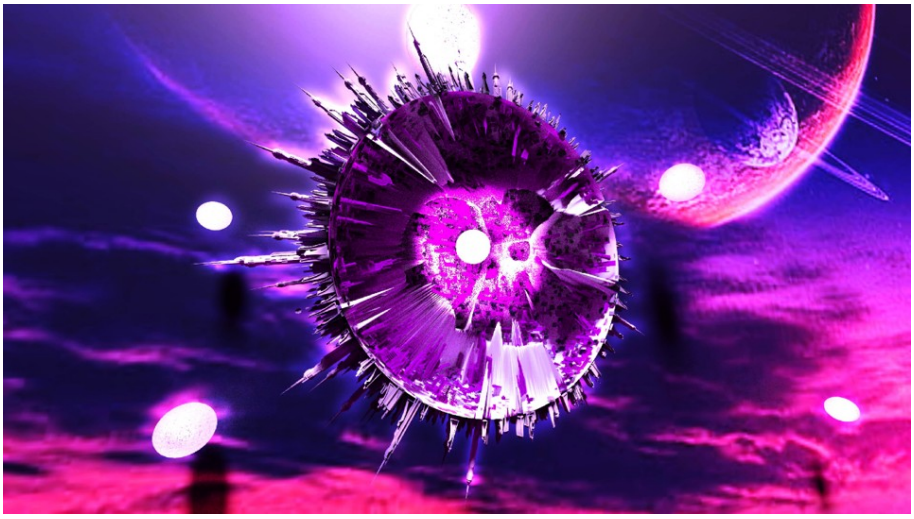


Figure 9: Taechit Chinachatchawarat [nickname Bape], A Dance between Utopia and Dystopia, 2024

2.3.3 Vicious Loophole

Akkarapat Neeyapan [nickname Nick] designed the Vicious Loophole [2024, Research Book, INDA Y4S2], a metaverse that plunges players into a labyrinthine odyssey through the depths of their subconscious. Nick has drawn inspiration from iconic dystopian tales, such as "Akira [1988, Katsuhiro Otomo], "Berserk" [1988, Kentaro Miura], and "Gotham" [2014, Bruno Heller]. "This immersive experience transports participants into a chaotic and surreal cityscape born from the collective subconscious of those who faced near-death during the Earth's original apocalypse. In this inescapable city, players must navigate a maze of emotions and traumas that define the human experience" [Nick, 2024]. The Vicious Loophole is a densely populated, high-rise environment on a small artificial planet, as well as a no-gravity interior of floating bars in the X-, Y-, and Z-directions, loosely inspired by Escher's impossible ascending and descending [1953, Escher, Relativity]. People engage in his subconscious game on three levels: walking on piers, walls, and ceilings. On the third level, the emotions run deep, tinged with shades of red [fear, desperation, and despair] that resonate with the darkest recesses of the human psyche. The ultimate goal is to regain consciousness and warp back to the city. Nick's planetary design is mildly dystopian; a narrow escape remains possible.

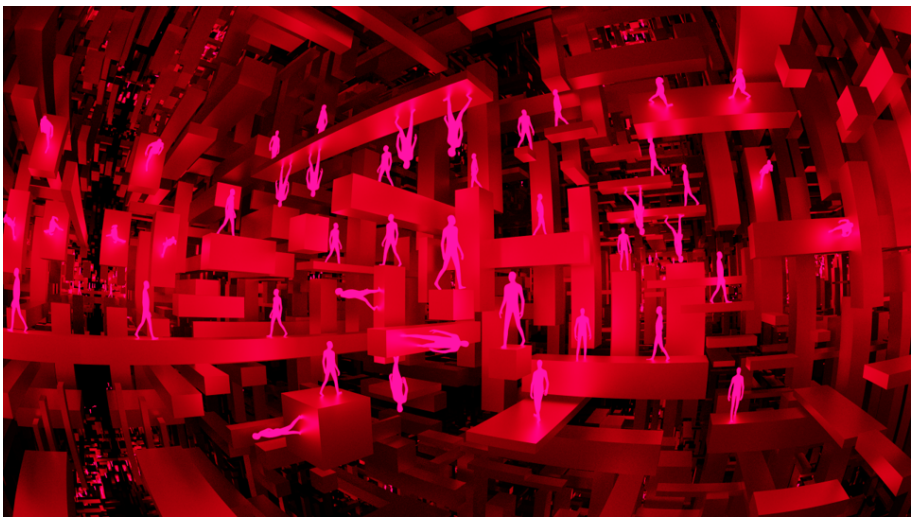


Figure 10: Akkarapat Neeyapan [nickname Nick], Vicious Loophole, 2024

2.3.4 The BORG

Planets in Outer Space are spherical due to gravitational forces that pull matter inward from all directions. Gravity applies to planetary bodies with a diameter greater than 600 kilometers. Gravity has a negligible effect on the shape of a small planet; it can be cubical without being deformed by its gravitational forces. The BORG CUBE is a spaceship measuring 3 x 3 x 3 km³, and is considered a planet in itself. The BORG CUBE, a model for utopian/dystopian world-building, is a massive, labyrinthine block built up from open lattice structures, functioning as an intricate laboratory-like ductwork, subject to artificial gravity. The BORG CUBE is a self-healing structure that produces drones, requiring no external materials to sustain itself. Any organic or inorganic material inside the CUBE, including the bodies of dead drones, is broken down to the molecular level and reused. The BORG CUBE represents Planetary Architecture in all three aspects: 1] It is Planet-Conscious Architecture, across all scales, braking matter down to its molecular levels and building new implants for the drones, 2] It is Outer Space Architecture, not just an engineering achievement, but also a design statement, and 3] It is an example of Comprehensive World Building, which includes the design of a living species with a hive mind [1993, Star Trek, Q Who episode]. The Borg is Dystopian, a fearless cyborg enemy to the multi-species crew of the Starship Enterprise, yet utopian since the crew and the environment operate as a fused cyborg hive mind, and because of its highly efficient way of recycling both hard and soft matter. The cinematographic BORG CUBE models as a prototype for the 7.5 times smaller real-world MUKAAB [2023, New

Murabba Development Company], a spin-off from the BORG that has taken root on EARTH.

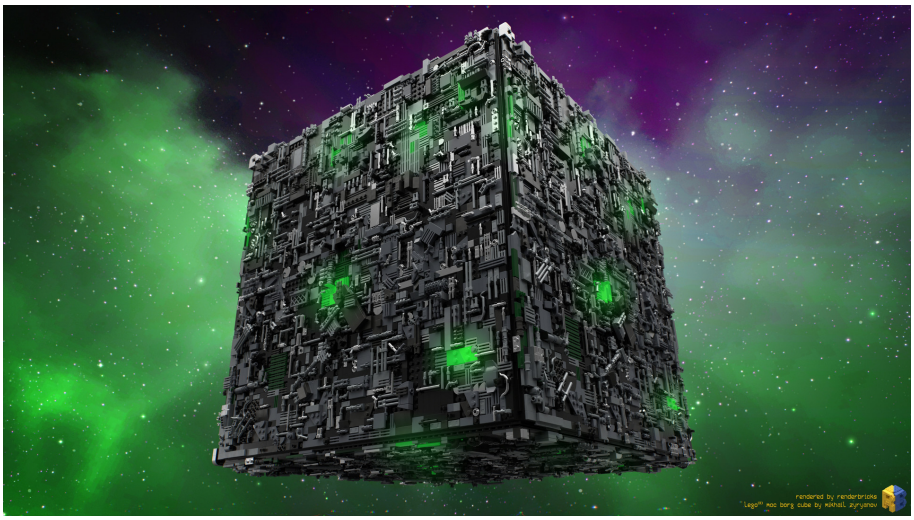


Figure 11. BORG CUBE, 1989

3. Comprehensive World Building

In the history of architecture, there are sublime examples of Comprehensive World-Building, condensers of a comprehensive worldview. The imposing appearance of the empty tomb for Sir Isaac Newton [1784, Étienne-Louis Boullée, Newton's Cenotaph] defies traditional notions of what architecture is, by its size, the story that translates into a buildable structure, and the immersive experience it offers visitors.

The 400 m high, a-symmetrical, leaning tower, the Monument to the Third International [1920, Vladimir Tatlin], represents the revolutionary spirit of the socialist revolution that overthrew the Russian Tsarist regimes. From the robust steel framework, four large geometric structures are suspended, each rotating at a different speed. The Monument for the Third International features large, pristine prismatic forms to express its universality.

A memorable event was the 1958 World Expo in Brussels, notably for its main symbol: the 102m-high Atomium [1958, André Waterkeyn]. The nine interconnected spheres, each with a diameter of 20m, represent a 160 times enlarged layout of the iron crystal. The monumental gesture bridges the very

small and the very large, the microcosmos and the macrocosmos, reflecting the rise of microbiology and space travel alike. The Atomium is a prime example of Planetary Architecture across scales, stretching between the infinity of our observable universe and the quantum world.

3.1 THE SEVEN DAUGHTERS

During my professorship at Qatar University [2017-2019], a team of bright young Jordanian and Syrian architects and I designed a planetary monument for the increasingly leading public role of women in Qatar. The design refers to the Story of the Seven Daughters, a popular tale associated with the constellation of Ursa Major, which in turn points to the Northern Star that travelers in the desert use to orient themselves at night. The Seven Daughters structure is a spatial translation of the brightness of the stars and their relative distance to Earth. The brighter the star, the larger the sphere, the further away it is from Earth, the further down the Y-axis in the 3D model. Unlike the masculine geometric volumes of earlier spatial constructs in Planetary Architecture, The Seven Daughters communicates feminine power.

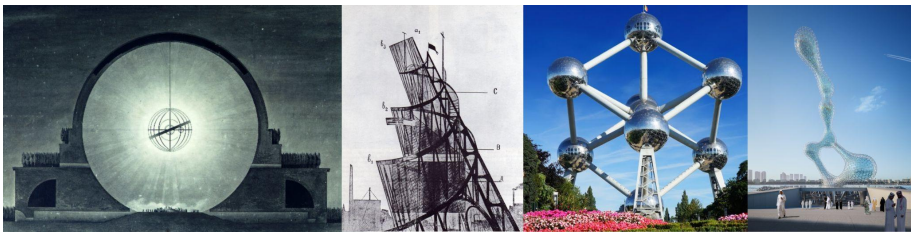


Figure 12: Boullée Cenotaph 1784, Tatlin Monument for the 3rd Internationale 1920, Waterkeyn Atominum 1958, and Oosterhuis The Seven Daughters, 2020

3.2 751 MULTIPLAYER DESIGN STUDIO

Inspired by a wooden three-dimensional spherical puzzle, I asked my Hyperbody master students at TU Delft in 2008 to design each one of the 23 interlocking pieces, the three-dimensional building plots that comprise the 400m diameter sphere [2008, Hyperbody, 751 Multiplayer Design Studio]. The 751 Sphere would touch the ground lightly in the 751 district in Beijing, a dysfunctional, half-abandoned industrial area between the 4th and 5th ring roads. Each student designed a piece of the puzzle in their preferred architectural style. The simple rule is that they communicate with their nearest neighbors only, like the birds in a swarm. Following this rule, none of the students would have a notion of the sphere as a whole, just as no bird has an

idea of the shape of a swarm. The 751 Sphere is a self-contained city, landed from Outer Space, and building a worldview. It appears to come from an alien civilization that operates as a hive mind, much like the BORG. The master plan of NEOM's THE LINE shares similar, yet simpler, hive mind characteristics: each 800m-long module has a distinct style, by a well-known architect in collaboration with young Saudi designers, connected underground by the mass transit system, and above ground only to its nearest neighbor.



Figure 13: Hyperbody, Beijing 751 Sphere, 2008

3.3 THE N-SPHERE

The *n*-SPHERE [Oosterhuis, 2025], my entry for the SHIFT competition [SHIFT, 2025] draws inspiration from bespoke landmark designs, notably their planetary scale [Étienne-Louis Boullée, Cenotaph, 1784], their transparent geodesic design [Buckminster Fuller, Expo pavilion, 1967], their elementary systemic [André Waterkeyn, Atomium, 1958], their immersive environments [Atkins, MUKAAB, 2023], their celebration of knowledge [Ivan Leonidov, Lenin Institute, 1927], their revolutionary symbol [Vladimir Tatlin, Monument fo the Third Internationale, 1920], their galactic shape [ONL /QU team, Seven Daughters, 2019] and their interactive technology [Louis Kalff, Evoluon, 1966]. The *n*-SPHERE takes the shape of an

icosahedron, a crystalline volume composed of twenty equal-sided triangular, structurally triangulated surfaces. The *n*-SPHERE's planetary wooden inner SPHERE, measuring 80-100m in diameter, seems to float, structurally suspended from the outer shell. The stainless steel and glass *n*-SPHERE reaches a height of 120m. Urban farming, water harvesting, and the solar energy panels [FEW NEXUS], form the *n*th dimension of the three-dimensional nuclear SPHERE. The *n*-SPHERE project is a planet-conscious design, a planetary spaceship that has landed on Earth. By its virtual environments that immerse the public in possible dystopian or utopian, sustainable futures, the *n*-SPHERE is a Comprehensive World-Building.

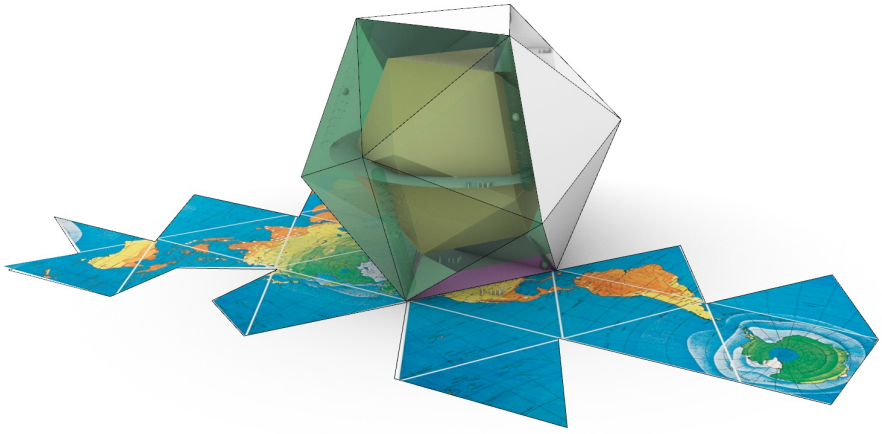


Figure 14: Oosterhuis, n-SPHERE, 2025

3.4 SAUDI VISION 2030

The Saudi Vision 2030 document proudly states that "With the diversity of opportunities and comprehensive transformation that the Kingdom is witnessing, an empowered generation has emerged, enjoying a stimulating environment that instills ambition and enables success and innovation, which contributes to enabling young people to lead the Kingdom at a steady pace to a future with new and diverse horizons" [Saudi Vision, 2020]. This ambition aligns with historic heroic planetary designs. Saudi Vision 2030 encompasses initiatives in culture, sports, innovation, technology, housing, and indeed Planetary Architecture. THE LINE, MUKAAB, Trojena, FIFA 2028, Red Sea Resorts, the King Salman Park, the Royal Arts Complex, and large-scale urban renovation projects are an integral part of Saudi Vision 2030. Saudi Arabia has the financial means to build a new society on the foundations of its ancestral Bedouin culture. They realize that the money pouring from the oil and gas industry is finite and that they must invest in new sources of income

within the next few decades. The tourist industry, the high-tech sector, space technology, the building industry, urban farming and agriculture, renewable energy sources, the entertainment industry, leisure, and sports are poised to become the pillars of their vibrant new economy.

3.5 MUKAAB

The MUKAAB in the New Murabba district is one of the pillars of Saudi Vision 2030. The MUKAAB will be a premium destination offering a range of retail, cultural, and tourist attractions, as well as residential and hotel units, commercial spaces, and recreational facilities. The MUKAAB is a massive 400x400x400m³ building, featuring an ample interior atrium space with a 300m-high central entertainment tower, conceived as a stack of flattened riverstones. Atop a spiral base, the tower will showcase cutting-edge technologies and the latest holographics to create an immersive experience. A continuous LED screen comprises the interior façade, spanning 360 degrees at a distance from the tower over its full height, culminating in a dome at the top to create the illusion of celestial infinity. Large-scale AI-generated immersive environments inhabit the indoor space, which is twice the size of Boullée's Cenotaph. Traditional Najdi architecture, native to central Saudi Arabia, of which Riyadh is part, is the source of inspiration for the architectural style of the MUKAAB. Typical Najdi style elements include triangular openings for ventilation and flocking together to form decorative patterns in the exterior walls. The MUKAAB combines a new interpretation of the Nadji style with the often intricate, open mashrabiya patterns in multiple layers, aesthetically indebted to the façade patterns of the BORG CUBE. Mashrabiya patterns convey a sense of openness and intimacy, passively "breathing" the air in and out. The MUKAAB bears a striking resemblance to another Superstudio project: NY-Brains, which shows a golden cube in a trashed area. As with THE LINE, the MUKAAB transcribes Superstudio's critical connotations into a positive appreciation of modern society.

3.6 AQUELLUM

Effectively, the inverse of the MUKAAB, a similar BORG-style concept, is evident in the design of Aquellum [2023, LAVA]. Aquellum, one of a dozen high-end luxury resorts along the Red Sea coastline, is a large, cubic volume carved out of a seaside rock formation; the hotel rooms face inward toward a vast open indoor space. LAVA describes Aquellum as an upside-down skyscraper. Life inside feels like browsing the metaverse. Everything one expects to experience in a science fiction movie and video game becomes a

reality in this rock-solid, meticulously crafted showcase of Comprehensive World-Building.

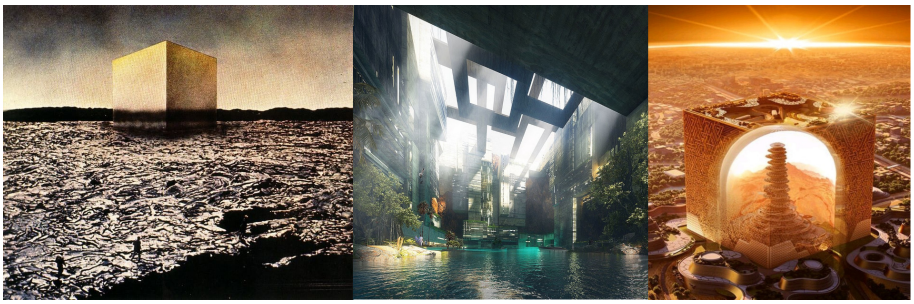


Figure 15: Superstudio NY-Brains 1970, LAVA Aquellum 2023, and Atkins MUKAAB, 2023

4. Planetary Architecture

Planetary Architecture is the epochal movement of the 21st century. Planetary Architecture is deeply rooted in the beginning of the space age in the second half of the 20th century, and has come to fruition in the 21st century. The moon landings [1969, NASA] and missions to Mars [1975, NASA] are space-age machines that are technological yet tinkered, robust yet delicate, straight from the laboratories, but without an architectural style. The International Space Station [1998, NASA, Roscosmos, ESA, JAXA, CSA] established a unique global collaboration within the world of science and technology, thus forming the basis for Planetary Architecture.

Mature Planetary Architecture, as a significant 21st-century movement, has a broad scope, fusing elements of Planet-Conscious Architecture, Outer Space Architecture, and Comprehensive World Building. While Planet-Conscious Architecture generally adopts a benign grassroots attitude, Outer Space Architecture typically aligns with videogaming, Comprehensive World Building, however, integrates elements of Planet-Consciousness and Outer Space Architecture into a new vocabulary that is both local and global, grassroots and out-of-this-world, aligns with bigness [1995, OMA, SMLXL] and "Small is Beautiful" [1973, E. F. Schumacher], is down-to-earth and highly technological, populist and elitist, egalitarian and autocratic at the same time. In Comprehensive World Building, the architect serves as the shaper of scenarios and futures across various scales and materials.

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